Characterization of Seismic Sources from Military Operations on Urban Terrain (MOUT): Examples from Baghdad

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Abstract On 10 October 2006, a mortar attack on the U.S. Forward Operating Base Falcon, south of the Iraqi Capital Baghdad ammunition supply point, resulted in an ammunition “cook off” accompanied by numerous explosions. The explosions shook the base and damaged surrounding structures, and were both felt by Baghdadi residents and seismically recorded at the single broadband seismometer at the Baghdad seismic observatory BHD. The mortar activity, ensuing explosions, and accompanying military activities provided a wealth of information on the nature of seismic and acoustic wave generation and propagation resulting from nearby battlefield sources. Seismic records from the observatory show a variety of waveforms that can be qualified as different types of battlefield-related sources including weapon rounds, mortars, rockets, mines, improvised explosive devices, vehicle-borne improvised explosive devices, and airborne vehicles. These different kinds of “military operations in urban terrain” (MOUT) are characterized and quantified by correlating their recorded military activity with observed seismic records and various aspects of the signals’ wave propagation.

# Introduction

Most recent military conflicts have become increasingly urban and asymmetric in weaponry. The identification, characterization, and understanding of urban battlefield acoustic and seismic sources are important for military operations in urban terrain (MOUT). Generally, a wide variety of battlefield acoustic and seismic sources accompany MOUT, including different-caliber gunshots, artillery fire, mortar fire, shell impacts, explosions, helicopter transport, and the flight of unmanned Aerial Vehicles (UAVs, or “drones”). Understanding the seismic and acoustic sources and their wave propagations at scales of meters to kilometers has many military and forensic applications (e.g., Ottemöller and Evers, 2008).

During the fighting that has gone on in Baghdad, the BHD seismic station has recorded numerous events such as mortar blasts. The most clearly recorded events are those located close to BHD. Examples from closely detonated mortar rounds and a vehicle-borne improvised explosive device (VBIED) have been well-recorded. Figures 1 to 3 compare the seismic signals of the firing and explosions of mortar rounds as well as an improvised explosive device (IED) from the vertical component waveforms recorded at BHD, showing the different frequency characteristics of each.

Media outlets such as the Washington Post and ABC News reported on 6 December 2006 that multiple explosions from mortar firing and other sources had occurred within Baghdad on that day (See Data and Resources Section). Figure 1a shows a time series of this military activity on 6 December 2006 in Baghdad. For clarity, shorter time segments of these activities are displayed in Figures 1b and 1c. These waveforms were recorded during the 23:00 UTC hour on 6 December 2006 (UTC time in Iraq is local time minus 3 hours). The amplitude spectra of these activities (Figures 1d and 1e) reveal that the mortar-firing signal is excessively rich in high-frequency energy (peaked at ~10 Hz) in comparison to the explosion signal (peaked at ~5 Hz), which is probably due to loose coupling between the mortar baseplate and the ground. Most mortar energy is naturally coupled to the atmosphere, which provides unobstructed pathways for airwaves.

Waveforms recorded during nearby mortar activity are shown in Figure 2a. A shorter time segment is shown in Figure 2b. These waveforms were recorded at approximately 17:32 UTC on 31 May 2006. ~~Independent documentation on Iraqi civilian deaths from violence confirms the occurrence of mortal fire at this time (IBC, 2014, incident k3149).~~ The high-amplitude peaks on the trace are the airwaves that result from the firing of the rounds (Figures 2a-c). Of note are the similarity and repetitiveness of the waveforms, indicating similar sources. The energy is concentrated at higher frequencies, as demonstrated by the flat amplitude spectrum above 10 Hz (Figure 2d), ~~but the observed amplitude peak at 3 Hz is characteristic of mortar shell explosions~~.

Figure 3 shows waveforms from two VBIEDs (exact locations are unavailable). Their waveforms appear different, likely due to their different paths and different methods of detonation. The waveform in Figure 3a was recorded at BHD at approximately 4:05 UTC on 20 December 2006. For these kinds of sources, records on the general timing, location, and type of military incident are available through various counter-terrorism intelligence agencies. These sources (InteCenter, 2008; NCTC, 2008; IBC, 2014, incident k4937) reported that the source of this event was a suicide bomber who drove his vehicle into a police checkpoint by the gate of Baghdad University. Figure 3b shows a waveform recorded at approximately 7:39 UTC on 17 June 2006 (IBC, 2014, incident k3280). This incident was described as a car bomb targeting a police patrol in Al-Karradah, Baghdad. ~~(the BHD station is located within the Al-Karradah area).~~

The waveform for the nearby VBIED in Figure 3a is much simpler than the more complicated waveform for the VBIED in Figure 3b, which is located at a point farther from BHD, based on the IBC reports. The VBIED for the record in Figure 3a was detonated in a more open location than the one for the record in Figure 3b, which may also contribute to the difference in the complexity of the signals (the VBIED for Figure 3b was detonated within a two-way road bordered by several-story buildings, which likely produced complex reverberations). Figures 3c and 3d are the amplitude spectra of the waveforms shown in Figures 3a and 3b. The spectrum of the time series from the closer VBIED (Figure 3a) has a peak at ~ 5 Hz, which is consistent with what we have noticed from explosion spectra (Figure 1d). The spectrum of the farthest VBIED (Figure 3d) has energy peaked at frequencies that are less than ~ 5 Hz. The VBIED weapons vary in sizes and arming styles, though they generally consist of a motor vehicle (any size or type) filled with unexploded shells of any caliber available in addition to an added explosive. Consequently, VBIED waveforms are generally complicated by the nature of the composite source, the damage to the destroyed targets and surrounding structures, and the complex signals added from the diffraction, refraction, and reflection of waves through urban environments. Unfortunately, vehicle bombs are often the weapon of choice for terrorists, allowing large quantities of explosive to reach the intended target in a clandestine manner.

On 10 October 2006, mortar and/or rocket rounds fired by Iraqi insurgents destroyed the Forward Operating Base Falcon (FOBF, U.S. Forward Base Falcon [as-Saqr Base] in Sukkaniya in the southern Baghdad suburb of ad-Durah) ammunition supply point (ASP) (Figure 4), located only about seven kilometers south of the Baghdad seismic observatory (Figure 5). This attack ~~involved~~ caused a series of explosions, lasting for hours, that rocked the base and were widely felt within Baghdad, and were broadcast live on local TV channels and CNN News. Seismic signatures produced by the explosions and other related activities were digitally recorded at BHD (Figure 6). Media sources and the Pentagon reported that mortar and rocket attacks occurred in the late evening hours of the day.

At least one enemy mortar shell ~~(Figure 6a)~~ hit the ammunition depot and initiated an ammunition “cook off,” which is the premature firing of ammunition caused by unexpected heat within the environment. The initial major explosion occurred at 10:40 p.m. local time (19:40 UTC, Figure 6b)) and was followed by a series of explosions of varying sizes over the following hour (Figure 6c), which extended into the next day. Flashes of incandescent fragments and the appearance of mushroom-shaped clouds accompanied some of these explosions, which at the time led some local observers to erroneously presume nuclear weapons had been detonated. Those explosions were initially audible up to several kilometers away from the FOBF, involving significant acoustic energy at frequencies of >20 Hz.

This incident and its seismic recordings provided an opportunity to improve our ability to understand the generation and propagation of seismic waves from such an unplanned incident. The diversity in explosion sources, containment conditions, and propagation environments within urban warfare conditions adds layers of complexity to the already challenging problem of the quantification and classification of manmade sources. Making interpretations even more difficult in this case is the lack of infrasound recordings from the explosions, preventing direct correlations of the acoustic energy released during explosion events with the recorded seismic energy.

Although the instruments at BHD recorded waveforms from MOUT sources, most of the observed parts of the MOUT sources are from the airwaves, with body wave signals often obscured by ambient noise and attenuation. Distinguishing the difference between MOUT signals caused by an IED and by mortar fire or heavy traffic is a challenging problem. To fully understand the differences between the waveforms of the various MOUT sources and distinguish between them requires a level of ground truth (exact times and explosive yields) that is not available in this case. However, significant insights into the nature of these MOUT sources can be gained by studying their frequency contents, ~~time and frequency distributions~~ frequency-amplitude variations with time, and propagation paths.

# ~~Data~~ Signals and Noise from the Baghdad Seismic Observatory (BHD)

As part of an on-going seismic deployment in Iraq (Ghalib *et al*., 2006), the Baghdad seismic observatory was equipped with a broadband seismic station. The station consisted of a Streckheisen STS-2 seismometer and Quanterra Q330 acquisition system with Global Positioning System (GPS) timing, provided by the Incorporated Research Institutions for Seismology (IRIS) PASSCAL instrument center. The broadband data were recorded at 100 samples per second. The seismic observatory in Baghdad was originally built in 1978, installed with a vault room containing an L-shaped concrete slab connected to the tops of three deep concrete columns.

~~Figure 6 shows three consecutive hours of vertical-component ground velocity recordings at station BHD, which is 7 km from the FOBF. The evening hour of 9 p.m. (local time) is marked by mortar and rocket-round activities (the peaks between 18:40 UTC and 19:40 UTC in Figure 6a) that lead up to a major explosion at 10:40 p.m. (local time) (the peak at 19:40 UTC in Figure 6b), followed by numerous similar explosions (Figure 6c) continuing into the next day.~~ Though the FOBF explosions on 10 October 2006 were random in time (Figure 6), ~~though~~ their waveform characteristics are strikingly similar to one another (Figure 7). To further investigate this similarity, for each explosion we constructed a time series window starting 1 s before and extending 1 s after the airwave. We then we cross-correlated the time window from the explosion of 10 October 2006 at 19:40 UTC (Signal #5 in Figure 7) with the 11 other explosion-generated airwaves shown in Figure 7. Most of FOBF explosions waveforms are highly similar to each other and have cross-correlation coefficients that range between 0.48 and 0.97.

~~Preceding the explosion at 19:40 UTC, seismic records show impulsive sources (Figure 6a) that were most likely related to the mortar and rocket activities that triggered the 19:40 UTC explosion. Visual reports suggest that these explosions ejected incandescent fragments, generated mushroom-shaped clouds, and were accompanied by large audible booms heard throughout Baghdad.~~

In addition to ~~body~~ direct seismic waves, ground roll and ambient noise, the FOBF explosions perturbed the atmosphere, generating substantial energy in the infrasonic bandwidth (below 20 Hz) that arrived as ~~atmosphere~~ air-to-ground airwaves (airblasts). A sample seismogram from the FOBF explosion contains an emergent P-wave onset, surface waves, and pronounced direct airwaves (Figure 8a). The ~~direct~~ arrivals of the airwaves are the strongest signals observed; their onsets are sharp and they are dominated by acoustic signals at frequencies >4 Hz. The generation and propagation of airwaves has been extensively studied (Press and Ewing, 1951; Jardetzky and Press, 1952; Press and Oliver, 1955; Haskell, 1951; Mooney and Kaasa, 1962; Tanis, 1976; Alcudia and Stewart, 2007). The frequency content of the airwaves is shown in the Fourier spectral amplitude plot in Figure 8b. Most of the energy of the explosions is concentrated at 1-5 Hz, with peak seismic energy at ~ 5 Hz.

An examination of the ambient noise characteristic of BHD shows the station to have high levels of noise at high frequencies. The power spectral density (PSD) was calculated for the two days of 9 and 10 October 2006 from 24-hour BHD seismic time series. Figure 9 shows acceleration noise PSD, in units of dB related to 1 (*m*/*s*2)2/*Hz*, as a function of period. Included in the figure are the high-noise and low-noise models of Peterson (1993). The short-period noise at BHD is very high, as expected from being a deep-sediment site that is just a short distance (5 m) from the employee offices. The BDH station also records vibrations from heavy auto traffic as well as vibrations from explosions, flying drones, and helicopters. The BHD noise spectrum for 10 October 2006 in Figure 9 shows a strong peak at 0.2 s, presumably from explosions. Nonetheless, for the signals from 10 October 2006, both the airwaves and P wave (Figure 8) are reliably above the noise levels.

# MOUT Acoustic-Seismic Partitioning

During a chemical explosion at or near Earth’s surface, as with the FOBF MOUT explosions, the atmosphere is perturbed by the rapid release of energy, generating non-linear shock waves that subsequently expand at supersonic velocities before reaching equilibrium with the surrounding air. As the pressure waves radially expand, the Mach number decreases until they ultimately decay into acoustic airwaves that travel at ambient sound speeds (~ 340 m/s). As the airwave travels through the atmosphere, energy is continuously injected into the solid earth in the form of seismic waves. The physical properties of the air-surface interface determine the nature of the exchange of energy across the interface and therefore the nature of the propagating waves within both the atmosphere and ground. Recorded seismograms therefore involve a combination of seismic, air-coupled, and infrasound energy [Note: air-coupled waves have sometimes been referred to in the literature as “ground-coupled” waves (Mooney and Kaasa, 1962)].

Tanis (1976) described the two modes of coupling between airwaves and seismic waves. Acoustic airwaves can couple directly into the seismometer or the proximal ground area as a structural-borne sound. Airwaves may also continuously couple into the ground as they propagate along the surface at nearly grazing angles and frequencies with apparent seismic velocities that are very close to speed of sound in the air, exchanging energy with existing surface waves that travel in the near-surface layer and generate air-coupled Rayleigh waves that propagate at the speed of sound. Local ground media influence the relative contributions of these two modes of coupling. For example, air-coupled Rayleigh waves will dominate if the layered structure of the ground supports the strong propagation of Rayleigh waves at these high frequencies (Tanis, 1976). Sound waves and seismic waves propagate with different group velocities and have different frequency contents; therefore the use of a multiple-filter analysis (MFT) (Dziewonski *et al.*, 1969; Herrmann, 1973) allows for their separate isolation and independent identification.

~~In Figure 7, an MFT is applied to the seismic signal from the initial large explosion at FOBF in Figure 6a to identify the various wave types based on their dispersion characteristics. In this figure, dispersed surface waves as well as direct airwaves can be observed. Dispersion curves of the higher-mode Rayleigh wave (Figure 7b) and fundamental-mode Rayleigh wave (Figure 7c) are the most conspicuous. The ground-coupled surface waves (Figure 7d) arrive after the fundamental-mode Rayleigh waves and slightly resemble the fundamental-mode dispersion. An impulsive direct airwave arrival (Figure 7e) arrives at 0.35 km/s, followed immediately by the direct airwave packets (Figure 7f).~~ The MFT involves frequency-domain narrow-band-pass filtering of the signal using time-domain energy envelopes to find the velocities of energy packets at different and possibly overlapping frequencies. To isolate overlapping waveforms of interest, the MFT determines group velocities of energy packets that are used to provide estimates of signal phase spectra that bring the signals to a zero lag in the time domain; the resulting signals are then windowed and isolated (Herrin and Goforth, 1977; Russell *et al*., 1988).

~~In Figure 8, a phase-match filter within the MFT is used to isolate the different waveforms. The initial large FOBF explosion (Figures 6a and 7) is analyzed at a set of distinct frequency bands that correspond to the various dispersion patterns. These include surface-waves, airwaves, and ground-coupled Rayleigh waves. Ground-coupled Rayleigh waves arrive slightly earlier than the acoustic waves.~~ When the MFT is applied to the large initial explosion at FOFB shown in Figure 8a (repeated in Figure 10a), several different phases can be identified and their dispersion curves quantified. The most conspicuous arrivals are the higher-mode Rayleigh waves (Figures 10b and 11a) and fundamental Rayleigh waves (Figures 10c and 11b). As can be seen in both Figures 10 and 11, these arrivals are highly dispersive, with velocities varying significantly over short frequency ranges. A slightly dispersive air-coupled Rayleigh wave is isolated in Figures 10d and 11c, which arrives after the Rayleigh waves but before the acoustic airwaves. The non-dispersive acoustic airwaves are shown at both low-frequencies and high-frequencies in Figures 10e-f and 11d-e. ~~Direct~~ Airwaves are attached to air-coupled Rayleigh waves, which are formed by the advancing shock front of the traveling airwaves as they move along the surface. Generally, it seems that near-surface explosions have significant levels of acoustic energy that couple with the atmosphere as well as to the ground. Unfortunately, with the lack of infrasound recording, air-coupled atmospheric energy was not directly observed.

# MOUT Sources and their Seismic Signatures

In identifying and classifying the sources of MOUT, we use several aspects of the seismic signals pertaining to the relative energy level of the signals, including the zero-crossing rates and ~~time-frequency~~ the characteristics of frequency amplitude variations with time.

Impulsive sources such as chemical or nuclear explosions and artillery fire release energy over a broad spectral range that extends down to frequencies lower than 0.5 Hz and propagate large distances without significant attenuation (other than from geometrical spreading). The signals of the different sources have differing characteristics. For example, mortar blasts produce both airwaves (generated during muzzle blasts and shell bursts) and body waves (generated from gun recoil and shell impacts) (Tanis, 1976). Mortar detonations (the firing of the mortar, as opposed to the blast of the explosion) are expected to excite energy at higher frequencies than the ensuing explosions, attributed to the short time duration of the confined muzzle blast.

Non-impulsive sources such as flying fighter jets, helicopters, and unmanned air vehicles (UAVs, or “drones”) produce seismic signals that display the harmonic oscillations from engines and/or rotors. These harmonics have frequencies ranging from several kHz down to 25 Hz or less. Movements of jet fighters, helicopters, and UAVs toward or away from the receiver produce Doppler-shifted harmonics; examples of Doppler harmonics are seen in some of the records at BHD.

The signal processing methods considered for analysis are based on the frequency content of the MOUT signals. Generally, the frequency content of battlefield-related sources of interest span both the acoustic (> 20 Hz) and the infrasound (< 20 Hz) ranges. For similar source-receiver distances, underground seismic wave propagation undergoes significant attenuation in comparison to the airwaves propagating through the atmosphere. The resulting frequency-domain effects can be used to characterize MOUT sources. For time-domain characterization, analyses of seismic signal energy levels and zero-crossing rates can be used.

*Short-term Energy and Zero-Crossing Rate (Time domain measurements).* The short-time energy (STE) and the short-time zero-crossing rate (STZCR) are widely used functions by the acoustic community (e.g., Jalil *et al*., 2013) to distinguish between voiced and unvoiced speech. The STZCR gives an approximate measure of the frequency content of a signal and can be used in conjunction with the STE (or magnitude) to discriminate between various MOUT sources. The STE and STZCR can show distinguishable features related to whether or not the signal is relatively rich in high-frequency content and can discriminate between mortars and other kinds of explosions.

The STE is an indication of the amplitude of the signal in the interval around time that the analysis window is centered on, and is expressed as

where is the time series, is the hamming window, is the sample that the analysis window is centered on, and is the window length. The window slides across a sequence of squared values, selecting intervals for processing. In this case, high energy would be indicative of either mortar fire or explosions.

The STZCR of a digitally sampled seismic signal is a measure of the number of times in a given time interval that the signal amplitude passes through a value of zero. It can be illustrated by:

where , and is the time series. The algebraic sign of x[m] and will determine whether is zero (same signs) or 1 (different signs).

Figures 12 and 13 demonstrate the identification of MOUT sources from STE and STZCR analyses by using two 15-minute time intervals. One interval precedes the large explosion at 19:40 UTC on 10 October 2006 (19:22:00-19:37:00 UTC) and the other is taken after it (19:48:00-20:03:00 UTC).

Figure 12a shows bursts of activity during 19:22-19:24 that have relatively high zero-crossing rates (Figure 12b) and relatively low STE (Figure 12c), in comparison to the values for the interval 19:26:30-19:27:00, which has low zero-crossing rates and comparatively high STE. Figure 13a, between 19:48 and 20:03, shows a series of signals that correspond to low STZCR (Figure 13b) and elevated STE signatures (Figure 13c). Also seen in Figure 13 is a low-energy signal at 20:01 that is associated with an elevated zero-crossing rate, indicating a non-impulsive source emitting high-frequency signals, likely due to the nearby passing of a helicopter. STE levels are significantly affected by the source energy; explosions have a higher STE than mortar launches. However, mortars have a higher STZCR than explosions.

*Time-Frequency Analysis*. The time intervals in Figures 12 and 13 and the observed sources in those intervals can also be analyzed through time-frequency analysis, with spectrograms (showing frequency-amplitude variations with time), as shown in Figures 14 and 15. Within the first five minutes of the interval in Figure 14 there appears high-frequency energy that is characterized by narrow vertical broadband signals. This energy corresponds to impulsive events that are probably related to mortar activity and may represent a combination of the Mach waves of the projectiles and waves from gun muzzles (Tanis, 1976). The energy peaks that are at ~2 Hz are probably related to the detonation of a high-energy projectile after its impact with the ground.

~~Two~~ Other noticeable signals are shown in Figure 14. One is a Doppler-shifted signal that starts at a frequency of 22 Hz and drops to 17 Hz by 19:32 (Label “1” in Figure 14). The first overtone is more easily observed (Label “2”), which can be seen emerging at around 19:27:30 at 44 Hz (Label “A” in Figure 14b) and dropping to 34 Hz by 19:32 UTC (Label “B” in Figure 14b). This Doppler-shifted signal is characteristic of the fly-by of an airborne vehicle such as a helicopter or drone. ~~The other~~ Figure 14 also shows a high-amplitude signal from an undocumented explosion that has an energy peak of ~5 Hz at 19:36. This explosion likely played a significant role in the ammunition cook-off at FOFB that began about 4 minutes later, at 19:40. This is likely the blast at the ammunitions depot that led to the later major on-site explosions.

~~The explosions in Figure 12 have a peak energy concentrated at ~5 Hz.~~ At 20:01 (Figure 15) there is a Doppler-shifted signal similar to what was seen about thirty minutes earlier (Figure 14). ~~However~~ This signal corresponds to the high STZCR and low STE signal observed in Figure 13. The dominant frequency shifts from ~13 Hz to ~9 Hz over about a half-minute (Label “1” in Figure 15). ~~corresponding to the maximum amplitudes in the spectrogram~~. This drop in frequency is explained by the engine and/or rotors of a moving airborne helicopter that changes direction and speed relative to the recording station as it passes by. Several overtones are also observed (Labels “2,” “3,” and “4”). The frequency drop is most easily observed for the second overtone, where it falls from 38 Hz (Label “A”) to 27 Hz (Label “B”). The drop in frequency as the airborne vehicle passes can be used to determine the vehicle’s speed, vH, which equals *vsound* × *∆f* / (*2fmean*), with the speed of sound waves at *vsound* = 1245 kph (at the average temperature in Baghdad in October of ~25°C). For the airborne vehicle in Figure 14, the speed is calculated to be ~160 kph, and the speed of the airborne vehicle in Figure 15 is calculated to be ~210 kph. These values are appropriate for the cruising speeds of modern day combat helicopters.

Figure 16 shows the time period between Figures 14 and 15, when the main blast at the FOBF occurs, just after 19:40 UTC. This blast is significantly larger than any of the signals that arrive before it (note the difference in scale). There are a series of many smaller explosions that occur before the 19:40 blast, similar to one at 19:36 that was in Figure 14. It is likely that those small explosions first alerted the FOBF residents to seek safety and helped to trigger the ammunition cook-off that began with the major explosion of 19:40 UTC.

Figure 17 shows a set of large explosions that occurred within the hour following the 19:40 UTC explosion. Some of these later explosions released more energy than the original 19:40 explosion. As the cook-off progressed, other well-contained large ammunitions began to explode. As with previous explosions, the peak energy of these events is concentrated at ~5 Hz.

*Airwave Modeling.*The determination of a shallow shear-wave velocity model is essential for characterizing explosion ground motion. The fundamental-mode Rayleigh wave group-velocity dispersion curve (Figure 11c) was inverted for a plane-layered shallow shear-wave velocity model (Figure 18) using Herrmann (2013) ~~Herrmann and Ammon (2002).~~ ~~To gain insight into how the incorporation of an atmospheric layer into this model affects the synthetic seismogram, we computed synthetic seismograms (Figure 16), using a wave-number integration technique (Herrmann and Wang, 1985) for two cases, with and without a 40-km thick atmospheric layer. In Figure 16, for both cases, the synthetic seismograms of the fundamental-mode Rayleigh waves (Figures 16e and 16c) are comparable to the observed seismograms (Figure 16b and 16d). Adding an atmospheric layer and locating the explosion source above the ground surface incorporates airwave energy into the signals (Figure 16e). This arrival seems to arrive close in time to the ground-coupled Rayleigh waves (Figures 7d and 7e, and 8d and 8e) and modify their shape.~~ For this inversion, the starting model used was a layered half-space. The group velocity inversion runs iteratively (18 iterations, in this case) or until the solution converges to an acceptable fit between the observed and final model group velocities. Figure 18 shows the shallow velocity-depth model obtained from the linear inversion of the group velocities. In this model the shear-wave velocity gradually increases with depth and their values reflect the sedimentary sequence expected for the Baghdad area. Seismic traces of FOBF explosions have both ground motion and atmospheric (Pressure) signals, so synthetic seismogram calculations were done including an atmospheric layer that was added to the velocity model obtained from the inversion (Figure 18).

To simulate significant observed features of FOBF explosions, we used the wave number integration method (*e.g.*, Wang and Herrmann, 1980; Bouchon, 1981; Herrmann and Wang, 1985). In cases where the pressure wavefield of airwaves was considered, the method of Herrmann (2013) was used, which includes the use of negative layer thicknesses at the top of the velocity model to indicate layering above earth’s surface. Figure 19 displays synthetic seismograms for the two cases, with and without a 40-km thick atmospheric layer. For both cases, the synthetic seismograms of the fundamental-mode Rayleigh waves (Figures 19c and 19e) are comparable to the observed Rayleigh waves (Figure 19b). For the pressure waves (airwaves) to appear in the seismogram, the atmospheric layer model was required, involving an explosive source positioned 5 meters above the ground surface (Figure 19e). The travel time of the synthetic airwaves is comparable to the travel time of observed airwaves (Figure 19d).

# Explosion Source Characteristics

Characterizing above-ground explosion sources is complicated due to the complex coupling between the air and ground. Therefore, while determining the scaling laws that associate radiated energy with the seismic source size is important for seismic source characterization and quantification, questions as to whether explosions are self-similar and follow a constant scaling relationship between explosion moment and size or whether there is a non-constant scaling relationship has yet to be determined, and exact energy scaling relationships remain unresolved. ~~The flat part of the spectrum at frequencies lower than the corner frequency is proportional to the source size (seismic moment).~~ Infrasound records of airwaves from explosions can be used to estimate explosion sizes (Arrowsmith *et al*., 2012; Gitterman and Hofstetter, 2012; Herrin *et al.*,2008; McKenna and Herrin, 2006; Koper *et al*., 2002), but this is not straightforward for airwaves recorded on seismometers. Attempts made by the authors to use available scaling relations relating the airwaves’ predominant frequencies and yields in in order to determine yield estimation were not encouraging. Therefore, the analysis here is limited to estimating the source size from the broadband spectra of the P waves.

~~This technique assumes that the low-frequency asymptote of the spectrum has the traditional strong dependence on yield. For an explosion source, the spectrum can be modeled with the simple form~~ Given a set of observed P-wave spectra from FOBF explosions, a grid search technique is used to minimize the root mean square error (RMS) between the observed and calculated spectra. The calculated seismic displacement spectrum is expressed, using the Brune (1970) source model, as

~~which is able to provide constraints on three parameters,~~ *~~S~~~~o~~*~~,~~ *~~f~~*~~, and~~ *~~ψ~~*~~. The low-frequency constant amplitude level, , is proportional to the static displacement and is a measure of the seismic moment. The observed spectrum falls off beyond a corner frequency at a rate of of . We employed a three-parameter grid search to minimizing the root-mean-square error between observed and calculated spectra. The low-frequency spectral level is used to find the explosion moment by~~ where is the calculated amplitude spectrum, is the long-period level of the spectrum (which is proportional to the static displacement and can be used to calculate the scalar moment), is the corner frequency (which is inversely proportional to the duration of the earthquake rupture), is the frequency, and *n* is the slope of the high-frequency fall-off, . Theoretically, this model predicts that the displacement amplitude spectrum is flat at frequencies lower than the source corner frequency. We use grid-search techniques to constrain the three parameters , , and which describe the spectrum.

Each grid is defined by three variables, each variable has range of values, and each range is divided into a set of discrete values. Similar to Koper *et al*. (2002), the grid search seeks values of the three unknowns that minimize an objective function measuring the difference between the RMS of the calculated amplitude spectrum and the observed P-wave amplitude spectrum. The search range of is defined between two values chosen from the low and high of the observed spectrum and is divided into 200 values; is allowed to vary between 3 and 15 Hz, in steps of 0.184; the fall-off, *n*, varies along 50 values between 2 and 8. The result is a grid-search with 65000 iterations. Figure 20a shows P-wave arrival time windows of the five explosions. The time windows are constructed with 128 data points from 0.3 s before the P arrival to 1.0 s after the P arrival.

Figure 20b shows the amplitude spectra of the P arrivals from Figure 20a, as well as the noise amplitude spectra for a 2 s time window before each of the P arrivals. The P arrival spectra are fairly constant at low frequencies and fall off sharply at frequencies above the corner frequency. The noise spectra have two peaks, one at ~3 Hz, probably related to ground motions, and another at ~4.5 Hz, possibly related to airwaves from multiple previous explosion sources.

Before carrying out the grid search, the observed P-wave amplitude spectra are resampled at 0.01 Hz intervals using a cubic spline interpolation in the manner of Hong and Rhie (2009). An example of the model fit to an observed P-wave spectrum is shown in Figure 21, where the 10 October 2006 19:40 UTC explosion spectrum is fit well with an ( spectral fall-off. The offset of the flat part of the spectrum at frequencies below the corner frequency is proportional to the source size (seismic moment,) and is given by

where is the rock density at the source (kg/m3), *r* is the epicentral distance in meters, and *c* is the P-wave velocity (m/s), which depends upon the component of ground motion used. For vertical-component P-waves, the two constants 0.60 and 2.0 represent an average P-wave radiation pattern and free-surface reflection coefficients (Havskov and Ottemöller, 2010). Values of and used in the calculation in Equation 4 (3230 m/s and 3000 kg/m3, respectively) are taken from the velocity model obtained from the group velocity inversion (Figure 18). The scalar moment, , was converted to a moment magnitude, , using the standard conversion *Mw* = (log10*Mo*)/1.5 – 10.73, where *Mo* is given in dyne-cm (Kanamori, 1977), which is only approximate in this case because it was established for earthquake sources assuming a stress drop of 50 bars (Stein and Wysession, 2002). The conversion relation of Lahr (2000) was then used to convert event magnitude into TNT equivalent. This formulation uses the Gutenberg-Richter magnitude-energy relation to obtain the corresponding energy release, *E*, through log*E* = 1.4*Mw* + 11.8 (Kanamori, 1977). The equivalent TNT (trinitrotoluene) mass is obtained from the event energy using TNT (tonnes) = *cE*/(4.18 × 1016), where *c* is a constant (1000/15) that compensates for the inefficiency of seismic wave generation (Lahr, 2000).

Table 1 shows the corner frequency, slope of high-frequency fall-off, moment, and moment magnitude values from P waves for the five FOBF explosions and one VBIED explosion obtained through the parameter grid search. ~~These results are obtained for five FOBF explosions and one VBIED. It is found that~~ The values of the slopes of the high frequency fall-off (*n*) are steep and are higher than the standard *n* = 2. Ford et al. (2009) attributed a steeper fall-off to detonations occurring within loose material, as opposed to underground burial of explosives, and FOBF and VBIED explosions, which are detonated above ground, appropriately qualify. No obvious scaling is observed between the corner frequencies and moments, which is usually seen with earthquake sources. The small moment magnitude values are in agreement with the observations that the explosions were felt but had no accompanying widespred reports of building damages beyond the immediate vicinity of the explosions.

Another approach to evaluating explosion sources is to determine their source-time functions, which reveals information about the physical mechanism and excitation process at the source of the explosion. ~~A small and simple explosion can be used as a Green’s function, representing path effects, so that when it is deconvolved from a larger and more complex event, the explosion source-time function is revealed (Ligorria and Ammon, 1999). This process assumes that the different events are co-located and have similar mechanisms, differing only in magnitude and duration.~~ This objective cannot be attained without removing the complications due to seismic wave propagation path and site effects. In such situations, the use of empirical Green’s functions (EGFs) is often employed (e.g., Frankel and Kanamori, 1983; Hutchings and Wu, 1990; Hough, 1997; Prieto et al., 2004; Kane et al., 2011). For an event to be considered as an EGF, it has to meet several characteristics. It should be significantly small in size and co-located with respect to the main event, and should have a relatively impulsive response so that a more complex source time function can be represented as a convolution of the EGF with an arbitrary time function. In order to help eliminate the influence of a non-zero source time function for the EGF event itself, Hutchings and Viegas (2012) suggest filtering the EGF event waveforms below the corner frequency, effectively generating an impulsive point source for a particular frequency range.

Most of the FOBF explosions are small and impulsive enough to meet those EGF criteria, and several were chosen in order to carry out a relative source function estimation (RSTF). Figure 22 shows the spectral levels of the noise, the airwaves from a small explosion chosen as an EGF (20:50:46 UTC on 10 October 2006), and the airwaves from the large explosion at 19:40 UTC on 10 October 2006. Both the EGF and larger explosion airwaves (solid line and dashed line, Figure 22b) have significant energy above that of the noise (dotted line, Figure 22b) in the 3 - 10 Hz range. An envelope function is used as a guide in choosing an EGF for the RSTF estimation. To define the frequency content and window length for the airwaves of the chosen explosions and the EGF, we 1) remove instrument responses and convert signals to ground displacement; 2) window the airwaves between 0. 5 s before and 2.0 s after the airwave arrival time; 3) pad the window length with zeros to 256 points; and band-pass filter the windowed signals at 1 - 20 Hz with a 3rd-order causal filter. An iterative time-domain deconvolution algorithm (Ligorria and Ammon, 1999) for constructing the RSTF is used with positivity constraints and a Gaussian smoothing filter that controls the frequency range of the resultant RSTF. In this case, the Gaussian width effectively provided a low-pass cut-off frequency of 14 Hz.

Figure 23a shows the airwave arrivals from five different explosions, with the bottom record chosen as the EGF. Three of these explosions (E1, E3, E4) also had their yield estimates calculated from P waves, as shown in Figure 20 and Table 1. The small explosion (EGF) is used as the empirical Green’s function and is deconvolved from the airwaves of the other four larger explosions. Figures 23 b,c show relative source-time functions and their spectral amplitudes for the four larger explosions, displaying a well-defined attenuated impulse with subsequent energy release over the following several seconds. Based on the source time function, relative differences between source amplitudes can be deduced. The largest of the four non-EGF explosions (explosion E3 in Figure 23) is about 3 times larger than the smallest of the four (explosion E4), and larger than the other two by nearly a factor of two. This is roughly in agreement with the yields calculated from the P waves (see Table 1).

The calculated ~~values~~ parameters presented in Table 1 do not take into account signal attenuation from explosion source containment, which can play a significant role in size estimation. It is not publicly known what kind of ammunition was stored at the FOB site, and any explosions from bombs will have a different apparent yield than a standard chemical blast. The effect of the metallic casing of the shell and how it splinters can significantly affect the size estimation: the presence of a shell can reduce yield estimates, but shell splintering produces additional acoustic energy.

# There are, in fact, many possible sources of error when doing analysis with a single station; the explosions from FOBF were recorded at just one broadband seismic station (BHD). No additional equipment for recording infrasound or acoustic energy was available. This limited the capacity to locate sources and understand the nature of the wave generation and propagation, as well as the relative partitioning of energy between acoustic and seismic waves. The particular FOBF-to-BHD path geometry introduces a seismic characteristic that cannot be isolated without the availability of other stations. The same holds true for the other MOUT signals shown here. A number of assumptions are made in calculating the explosion sizes; for example, the explosion source models, radiation pattern corrections, geometrical spreading, and density and velocity structures could bias the estimations.

# Conclusions

Detecting and characterizing seismic and acoustic sources from an urban battlefield can be a challenging problem. The 10 October 2006 FOBF explosions provided an excellent opportunity to study seismic signals from unplanned detonations, demonstrating a range of seismically observable characteristics. As the examples from the Baghdad station BHD show, there are a wide range of MOUT sources that all have characteristic seismic signatures. The spectral content of battlefield signals can provide information on source distance and type. Both time-domain and frequency-domain spectral techniques can take advantage of signal characteristics to differentiate between different kinds of stationary impulsive and non-impulsive moving sources. During mortar activity, the zero-crossing rate is relatively high compared to that of explosions. However, the short-time energy is relatively low for mortar signals compared to the seismic energy for explosions. Displaying the frequency amplitude variations with time is useful for distinguishing helicopter rotor noise as it has high zero-crossing rates and low short-time energy. Dispersion analysis shows that direct airwaves generate ground-coupled Rayleigh waves, formed by the transformation of airwaves on the ground that travel along the surface at speeds less than but comparable to the speed of sound with Earth’s shallow surface layers.

Preliminary velocity analysis of the shallow ground structure using group velocity dispersion provided a model for validating phase arrivals in the observed data. P waves from FOBF explosions permitted the estimation of explosion sizes. ~~FOBF explosions produce a linear increase in peak amplitude with explosive weight. Source scaling factors were observed to be strong for the 4-8 Hz pass band, but to show strong frequency dependence.~~ Special attention should be paid to develop scaling relationship between observed airwaves (seismometer recordings) and yield estimation, as airwave characteristics are probably modified by the structure (site response) transfer function and observed airwave characteristics may mainly reflect path effects. The deconvolution of the empirical Green’s function (obtained from a small explosion) from larger explosions illustrates that the airwave source-time functions are similar, irrespective of size. For future studies, the co-location of microphones with seismometers would help in recording how body and surface waves travel through the uppermost ground layer, interacting with the air-ground interface, as well as the direct airwave, ambient air noise, and traveling airwave along the surface. These recordings would enhance our understanding of the wave phenomena associated with energy transfer at the air-ground interface, better enabling discrimination between seismic and coupled arrivals observed in the seismic time series and providing a deeper understanding of the physical nature of the explosions. This type of research contributes to force protection, ammunition Depot management and engineering, and the characterization of MOUT sources.

# Data and Resources

* The data used in this study are from the North Iraq Seismographic Network (NISN) operated by the Directorate General of Meteorology and Seismology, Kurdistan, Iraq. These data are not publicly available.
* The synthetic seismogram, deconvolution, gsac, and surface wave inversion programs use codes in the Computer Programs in Seismology Package (last accessed February 2015) (Herrmann, 2013).
* Information about the firing of mortar rounds and ensuing explosions on 6 December 2006 was obtained from ABC News (<http://abcnews.go.com/International/story?id=2704681>) (last accessed March 2015) and the Washington Post (<http://www.washingtonpost.com/wpdyn/content/article/2006/12/06/AR2006120600324.html>) (last accessed March 2015).
* Information on a suicide car bombing on 20 December 2006 was obtained from NCTC reports <http://www.fbi.gov/stats-services/publications/terror_08.pdf> (last accessed March 2015).
* Figure 4 is from http://proliberty.com/observer/20061105.htm (last accessed February 2015).
* Figure 5 was created using ArcGIS v10.2.2 (ESRI). Service Layer Credits: ESRI, DigitalGlobe, GeoEye, i-cubed, USDA, USGS, AEX, Cetmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community.
* Synthetic seismogram codes used in this study can be found in Herrmann (2013), an Overview of Synthetic Seismogram Computation in Seismology 3.30.
* The Seismic Analysis Code version 106.6 is found at [www.iris.edu/dms/nodes/dmc/software/downloads/sac/](http://www.iris.edu/dms/nodes/dmc/software/downloads/sac/) utilized in processing and plotting (last accessed February 2015).
* The SEIZMO MATLAB toolbox, found at <http://epsc.wustl.edu/~ggeuler/codes/m/seizmo/> (last accessed February 2015), was used in processing and plotting seismic data.
* MATLAB and MATLAB utilities, <http://www.mathworks.com/matlabcentral/fileexchange/7237-simpgdsearch>, and <http://www.mathworks.com/matlabcentral/fileexchange/23571-short-time-energy-and-zero-crossing-rate/content/stezcr/zcr_ste_so.m>, were used in processing, grid search, zero-crossing, and plotting (last accessed February 2015).
* The factor that converts TNT tonnes to equivalent tonnes of TNT, to account for the inefficiency of TNT explosions in generating seismic waves, is taken from http://www.jclahr.com/alaska/aeic/magnitude/energy.txt (last accessed February 2015).
* IBC (Iraq Body Count) was a source of information on some of the explosion events, http://www.iraqbodycount.org/database (last accessed February 2015).

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Table 1

Source parameters for five FOBF explosions from 10 October 2006 (A-E) and one vehicle-borne improvised explosive device (VBIED) from 20 December 2006 (E6). Parameters are calculated using an optimized grid search: is the corner frequency, is the high frequency fall-off, is the seismic moment calculated from the displacement spectra, is the moment magnitude calculated from the moment, and the TNT tons and equivalent tons are computed from Lahr (2000).

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| # | Time (UTC)  H:M:S  Before Origin | Corner  Frequency | Slope | Moment | Moment Magnitude | TNT  Tons | TNT  Equivalent  Tons |
| E1 | 19:40:091 | 14.1 | 7.3 | 3.6244e+12 | 2.31 | 0.044 | 2.9 |
| E2 | 20:05:07 | 12.2 | 6.3 | 1.5484e+13 | 2.73 | 0.19 | 13 |
| E3 | 20:13:56 | 11.6 | 6.0 | 1.2355e+13 | 2.66 | 0.15 | 9.8 |
| E4 | 20:20:57 | 12.0 | 6.4 | 4.9421e+12 | 2.40 | 0.060 | 4.0 |
| E5 | 22:04:33 | 12.9 | 6.5 | 3.7891e+12 | 2.32 | 0.046 | 3.0 |
| E6 | 2006.354.04.  05.50 | 12.2 | 4.3 | 2.6748e+10 | 0.89 | 0.00024 | 0.016 |

~~Results of a grid search of the optimal values of events parameters, based upon spectral amplitude analyses, for six explosions that occurred on October 10th, 2006, including one Vehicle Borne Improvised Explosive Device (VBIED) from 20 December 2006 (last row). We multiply the TNT ton by 1000/15 to account for the inefficiency of the TNT in generating seismic waves (Lahr, 1988).~~

# Figure Captions

**Figure 1.** (a) One-hour time series of vertical-component ground velocity, starting at 23:00 UTC on 6 December 2006, illustrating various explosions from mortars and other sources. (b) Three-second time window at about 23:08 UTC showing the seismic character of the firing of a mortar. (c) Four-second time window at about 23:20 UTC showing the seismic character of a typical explosion. (d, e) Corresponding amplitude spectra of (b) and (c), showing that the mortar-firing signal is higher-frequency (with an energy peak at ~10 Hz) in comparison to the explosion (peaked at ~5 Hz). No smoothing was used in the calculation of this or other amplitude spectra in the paper.

**Figure 2.** (a) Vertical-component ~~2-minute~~ 80-second seismogram recorded at ~~approximately~~ ~16:32 UTC on 31 May 2006, illustrating ~~mortar activities~~ the firing of military rounds of unknown origin. (b) Segment of (a) showing the general character of signals from the ~~mortar~~ rounds, which are very uniform. (c, d) Time series of the recording of a single ~~mortar~~ round firing and its amplitude spectrum.

**Figure 3.** Example of vertical-component waveforms ~~illustrating~~ from two vehicle-borne improvised explosion devices (VBIED). Both signals are band-passed at 1-20 Hz and show the arrivals of both P waves and airwaves. (a) Waveforms from a car bomb detonated close to BHD at 4:05 UTC on 20 December 2006. (b) Waveforms from a car bomb detonated at 7:39 UTC on 17 June 2006 at a farther distance from BHD with respect to the VBIED in (a) (note the change in amplitude and time scales from Figure 3a). (c, d) Amplitude spectra of the waveforms in (a) and (b). Note how the VBIED waveforms become more complicated with increased distance from BHD.

**Figure 4.** Photograph of the U.S. Forward Operation Base Falcon (FOBF) following the attack on 10 October 2006, showing damages sustained from both the enemy shelling and the ignition and “cook-off” of the ammunitions depot.

**Figure 5.** Map of Baghdad, Iraq, shows the locations of seismic station BHD and the U.S. Forward Operation Base Falcon (FOBF).

Figure 6. Vertical-component waveforms recorded over a three-hour span between 18:00 and 21:00 UTC at BHD on 10 October 2006. All records use the same vertical scale. (a) Waveforms recorded at 18:00 UTC reveal mortar activities. (b) Waveforms recorded at 19:00 UTC show the first major explosion at FOBF with a peak at 19:40 UTC, which was preceded and followed by smaller explosions. (c) Waveforms recorded at 20:00 UTC show multiple strong explosions at FOBF.

Figure 7. Filtered records of vertical-component displacement waveforms from twelve explosions of different sizes that occurred at FOBF and were recorded at BHD between 19:40 UTC and 22:04 UTC on 10 October 2006, band-passed at 1-20 Hz. The airwaves are the large signals that arrive at about 29 seconds. Each record is normalized in amplitude in the figure, but the signals are ordered from largest to smallest in signal amplitude. The initial large explosion of 19:40 UTC is shown in signal #5. Note the high similarity between all waveforms. Cross-correlation coefficients between the airwave in signal #5 and the airwaves from the other explosions range from 0.48 to 0.97, demonstrating similar source processes and ray paths from the FOBF explosions to station BDF, irrespective of size.

Figure 8. (a) Vertical-component displacement seismogram of the explosion at

19:40 UTC at 10 October 2006. Large-amplitude airwaves arrive ~20 s after the origin time (shortly before the P-wave arrival). Three horizontal short lines indicate the time segments of a noise window, a window around the P-wave arrival, and a window around the airwave arrival. (b) Comparison of the amplitude spectra of the three windowed signals, with the dashed line for the noise window, the solid line for the P wave, and the dotted line for the airwave. The airwave spectrum shows a peak at about 5 Hz. The P-wave spectrum is distinguishable from the seismic background noise at 1 - 3 Hz and again at frequencies >6 Hz.

**Figure 9.** Average power spectral density (PSD) computed for the vertical component of motion recorded at the station BHD on 9 October 2006 (solid black line) and 10 October 2006 (solid grey line). These curves are the average of the 24 hourly PSDs. Note that the 10 October 2006 PSD has higher noise levels at high frequencies than the 9 October 2006 PSD does, due to the ammunition depot explosions at FOBF. The high and low global seismic noise models (thin lines) marked as NHNM and NLNM are from Peterson (1993). Note the peak in the 10 October spectral energy at a period of about 0.2 s (5 Hz), from the large number of explosions on that day.

**Figure 10.** Illustration of the various types of arrivals that comprise an FOBF explosion ~~waveform~~ signal, including surface waves, air-coupled waves, and airwaves, isolated using a multiple filter analysis (MFT). Numbers on the left are the peak amplitudes of each wave type; notice that the air-coupled surface wave has the smallest peak amplitude. (a) Waveforms from the vertical-component broadband seismogram of the 19:40 UTC, 10 October 2006explosion. (b) Isolated higher-mode waveform. (c) Isolated fundamental mode waveform. (d) Isolated air-coupled surface-wave waveform. (e) Isolated direct non-dispersive low-frequency airwave waveform. (f) Isolated high-frequency airwaves.

Figure 11. ~~Result of MFT analysis applied to the waveform (a) of the vertical-component seismogram of the 2006:283:19:40 UTC explosion. Contour lines illustrate the amplitude of the signal envelope. At each frequency, four largest maxima of the envelope with squares, circles, triangles, and diamonds symbols are identified. A continuous sequence of the envelope maxima traces the dispersion curves. Curves (b) and (c) are higher and fundamental mode Rayleigh wave peaks that form the dispersion curves, (d) is the dispersed arrival, identified as ground-coupled surface-waves, (e) is the direct non-dispersive low frequency airwave, and (f) are the higher frequency airwave arrivals. Waveforms of (b), (c), (d), (e), and (f) are shown in Figure 8.~~

Group velocity dispersion curves of the various signals shown in Figure 10, obtained using an MFT, associated with the explosion at 19:40 UTC on 10 October 2006. (B, C) The higher and fundamental mode Rayleigh wave dispersion curves. (D) Dispersion curve for the air-coupled surface-waves. (E, F) The non-dispersive low-frequency and high-frequency airwaves.

Figure 12. (a) Vertical-component ground motion time series between 19:22:00 and 19:37:00 UTC recorded on 10 October 2006. (b) Short-time zero crossing rate (ZCR) for the record in (a), which shows the rate at which the signal changes between positive and negative values. (c) The short-time energy (STE) for the record in (a), which is the square of the signal magnitude. The waveform at 19:26:15 is an explosion at FOBF, and is characterized by a low short-time zero-crossing rate with a high short-time energy. The large signals just after 19:20 and just before 19:25 are likely ~~to be~~ to have been mortar blasts, characterized by both high zero-crossing rates and high short-time energy.

Figure 13. (a) Vertical-component ground motion time series between 19:48:00 and 20:03:00 UTC recorded on 10 October 2006. (b, c) Short-time zero crossing rate and short-time energy, respectively, for the time window in (a). The signal ~20:01 has an anomalously high short-time zero crossing rate but low short-time energy, which is characteristic of a helicopter emitting high-frequency energy.

**Figure 14.** (a) Vertical-component seismogram for the time window between ~19:22:00 and 19:37:00 UTC on 10 October 2006, which is the same as in Figure 12. (b) Corresponding spectrogram, which is the power spectral density (PSD) in decibels normalized so that 0 dB is the maximum. A variety of signals are shown that are probably produced by mortar activity, projectile detonation, explosions, and airborne vehicles. High-intensity energy at frequencies of > 8 Hz is indicative of mortar activity; energy at 5 Hz corresponds to explosions, energy of 1 - 3 Hz is related to projectiles, and the continuous bands that start high at ~22 Hz at about 19:31 and drop low to ~17 Hz after ~19:33 (Label “1”) show the characteristic Doppler shift seen in flying helicopters and other airborne vehicles. In this case, the first overtone (Label “2”) is more easily observed, which can be seen emerging at around 19:27:30 at 44 Hz (Label “A”) and dropping to 34 Hz by 19:32 UTC (Label “B”). The gray scale to the right indicates the strength of the various signals delineated by the variations in their amplitude and frequency with time.

**Figure 15.** (a) Vertical-component seismogram for the time window between ~19:48 and 20:03 UTC on 10 October 2006, the same time period as Figure 13. (b) Corresponding spectrogram. High-intensity energy at ~5 Hz is related to explosions. As with Figure 13, this record shows a Doppler-shifted signal (at ~20:00-20:02) that is likely associated with a flying projectile or helicopter. In this case the dominant frequency is ~12 Hz (Label “1”), with three overtones observed at ~24 Hz (Label “2”), 36 Hz (Label “3”), and 48 Hz (Label “4:” just the lower-frequency tail of the highest of these overtones is observed). Letters A and B mark the high ~38 Hz and low ~27 Hz frequencies of the Doppler-shifted spectrum of the second overtone.

**Figure 16.** (a) Vertical-component ground motion time ~~series~~ window between 19:35:00 and 19:45:00 UTC ~~(22:35 and 22:45 local time)~~ recorded on 10 October 2006. This time window falls between the times shown in Figures 13 and 14, showing the main blast at the FOBF just after 19:40 UTC. (b) ~~(c) Short-time zero-crossing rate, and short-time energy, respectively for the time window in (a). The signal ~19:37 has an anomalously high short-time zero crossing rate but low short-time energy, which is characteristic of a helicopter emitting high-frequency energy, while signal at 19:40 has low short-time zero crossing rate but high short term energy, which indicates an impulsive source, (d)~~ Corresponding spectrogram. This blast, which is significantly larger than any of the signals that arrive before it, has high-intensity energy over a range of frequencies that peak at around ~5 Hz. In addition, a variety of Doppler-shifted are seen in the minutes leading up to and even following the main blast, which are suggestive of airborne vehicles moving varying combinations of away from and toward the station.

~~A variety of signals are shown that were produced by FOBF explosion. The high-intensity energy at frequencies of ~5 Hz is related to explosions, with both body waves and airwaves visible for the explosion in addition to Doppler effect signal ~19:37.~~

**Figure 17.** (a) A time window between ~20:13:00 and 20:28:00 UTC of vertical-component waveforms recorded on 10 October 2006. (b) Corresponding spectrogram. A variety of signals are shown that were produced by FOBF explosions. The high-intensity energy at frequencies of ~5 Hz is related to explosions, with both body waves and airwaves visible for each explosion.

Figure 18. ~~S- and P-wave velocity models for the structure~~ Velocity model including an atmosphere representing the earth structure along the path between FOBF and BHD. The velocity model was obtained through the inversion of fundamental-mode Rayleigh waves and was used in generating synthetic seismograms. The atmosphere was given a constant P-wave velocity of 0.34 km/s and a density of 0.0012 g/cm3.

**Figure 19.** ~~Various types of waves that comprise the explosion waveforms and a comparison with explosion synthetic seismograms with and without an atmospheric layer.~~ Example showing the effect on the synthetic seismogram of adding an atmospheric layer to the velocity model, resulting in the appearance of a pressure wavefield. (a) Vertical-component seismogram of the ~~2006:283:19:40~~ 19:40 UTC 10 October 2006explosion. (b) Isolated fundamental mode waveform. Note the smaller amplitude scale. (c) Synthetic seismogram using a velocity model without an atmospheric layer. (d) Isolated airwave waveform. (f) Synthetic seismogram using a velocity model with atmospheric layer; note the presence of airwaves about ~22 seconds after the origin time, corresponding to the relatively slow propagation speed of sound in air.

**Figure 20.** a) Broadband vertical displacement seismograms of P arrivals from five FOBF explosions. Waveforms align well, illustrating the repeatability of the P arrival among explosions. (b) The top five curves show the amplitude spectra of the five P wave arrivals shown in (a). Lower curves show the noise spectra for 2-second windows that precede the P arrivals by 6 s. The two peaks in the noise spectra are due to the ground motions (peak at ~ 3Hz) and airwaves (peak at ~ 5 Hz) that reverberate from the multiple explosions occurring on 10 October 2006. The labels, E1 – E5, correspond to the listings of calculated source parameters shown in Table 1.

Figure 21. (a) ~~Example~~ ~~of~~ Vertical-component P-wave displacement amplitude spectrum for ~~both a VBIED explosion at 04:06 UTC on 10 October 2006 (crosses), and the best fitting spectral model (solid line).~~ ~~(b) Similar example for the large ammunition explosion at 19:40 UTC, 10 October 2006~~. the large ammunition explosion at 19:40 UTC on 10 October 2006 (dashed line). The solid line shows the best fit using a Brune source model and the black dot indicates the corner frequency. The offset of the flat portion of the spectrum is used in calculatimg the yield.

Figure 22. An example of the relative energy levels of a typical noise segment (dotted line), the airwaves from a small explosion (20:50:46 UTC on 10 October 2006) chosen as the empirical Green’s function (EGF: dashed line), and the airwaves from the large explosion at 19:40 UTC on 10 October 2006. (a) Vertical-component ground displacements for the three signals. (b) Amplitude spectra for the signals in (a). Both the EGF and large explosions airwaves have a strong signal with respect to the noise at 3-10 Hz.

Figure 23. Example of the procedure used to examine source-time function variations among different explosions using airwaves. (a) Vertical-component seismograms of airwaves from 5 different explosions, some of which were also used in the P-wave analysis are are listed in Table 1 (the second signal was not used in the P-wave magnitude analysis, but appears as record #3 in Figure 7). Seismograms are sorted by amplitude. The smallest signal (bottom) is selected as an empirical Green’s function (EGF). (b) Estimated relative source-time functions for the the 4 explosions in (a) obtained by deconvolving out the EGF ~~Green’s function~~. ~~Because all of the source-time functions in (b) involve a small, wide pulse ~1.9 s after the main pulse, it is likely that this signal is not present in the assumed Green’s function (bottom).~~ (c) Amplitude spectra of the four source-time functions show that the difference in energy is at maximum at ~~the~~ low frequencies ~~region~~. At the higher frequencies ~~above~~ >5 Hz the difference is less because of the rapid high-frequency attenuation. Note that the the source time function of the largest explosion in (b) shows increased complexity and its spectrum in (c) shows increased high-frequency energy.