The 7th July 2011 Abadan, Turkmenistan explosions: A seismo-acoustic analysis

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Introduction

- At 16:51 (11:51 UTC) on 7th July 2011, a series of explosions began in the Abadan district of Ashgabat, Turkmenistan (Fig. 1)
- The Turkmenistan government listed the cause of the accident as the ignition of pyrotechnic matter intended for fireworks, which then spread to military storage buildings (Boggs et al., 2013)
- An estimated 5,000 to 50,000 tons of ammunition was thought to be stored within a 0.64 km^2 military storage facility on the outskirts of the Abadan district (Boggs et al., 2013)
- Images of the military storage facility clearly show craters and charred areas following the explosion (Boggs et al., 2013)

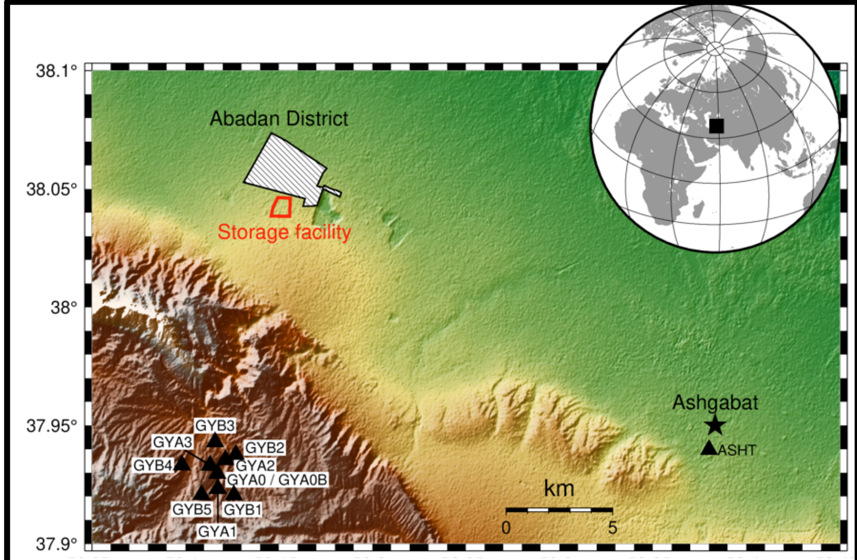


Figure 1: Location of the IMS GEYT array, ASHT seismic station and the military storage facility where the explosions took place. Globe at the top shows the location of the study area (black square).

Seismic observations

- GEYT:
  - 30 explosions observed (Fig. 2 a) & c))
  - Each event typically display a P-wave, Rg, and a single air-to-ground (A2G) coupled arrival at each element
- ASHT:
  - 30 explosions observed (Fig. 2 b) & d))
  - Each event typically display a P-wave, Rg, and two A2G coupled arrivals separated by ~5 s

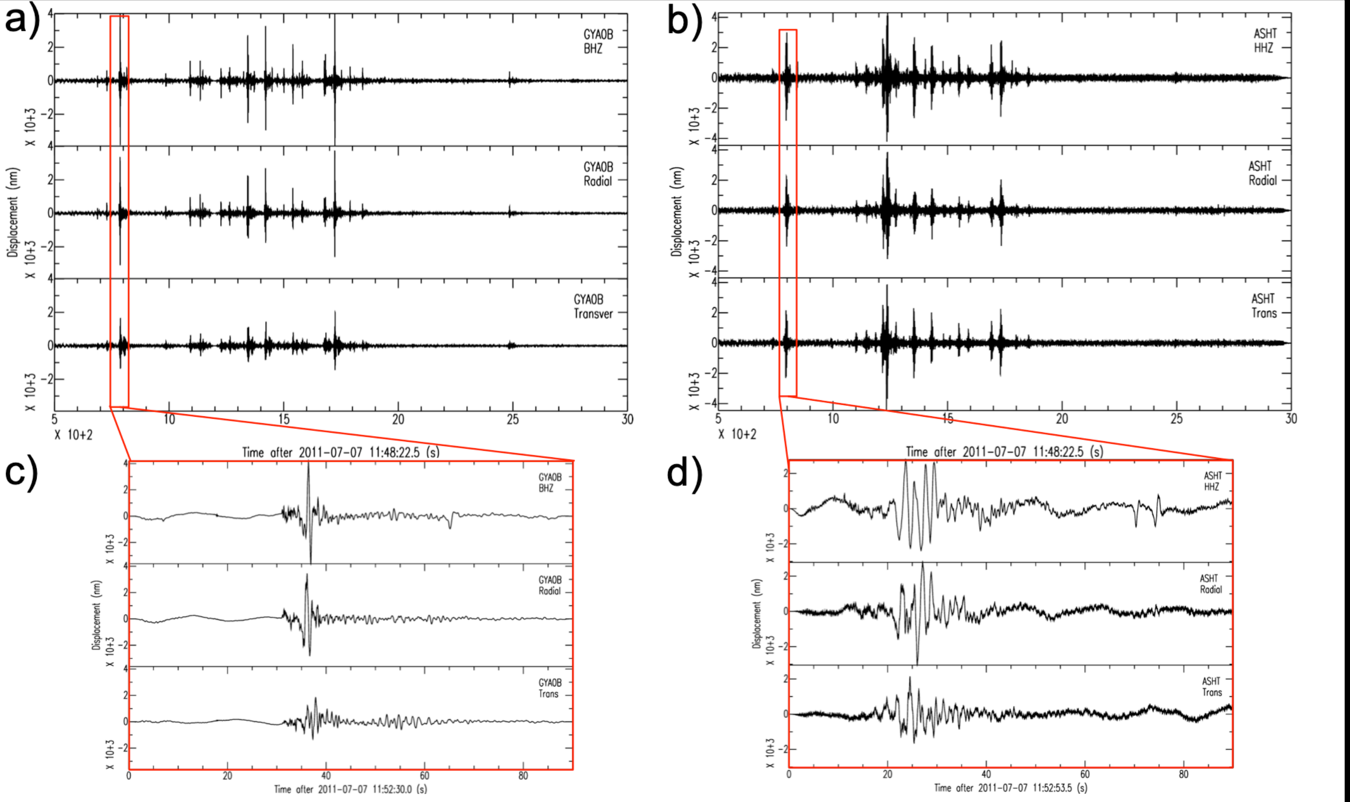


Figure 2: Example waveforms with the instrument response removed to give displacement. Complete sequence observed at a) GYA0B and b) ASHT. Event 03 (11:52:58 UTC) observed at c) GYA0B and d) ASHT.

P-wave yield: Y_P

- We estimate yield for each explosion using the zero-to-peak displacements of the P-wave arrival on the radial and vertical components (Koper et al., 2002)
- Pre-processing included: removal of instrument response, mean and trends, and applying a 1 – 5 Hz band pass filter
- Y_P for each of the explosions was estimated at GYA0B (the only 3-component instrument at GEYT)
- Y_P was estimated for 18 of the 30 events (Fig. 3.)
- The remaining 12 events had low signal-to-noise as they were buried within the coda of a previous event

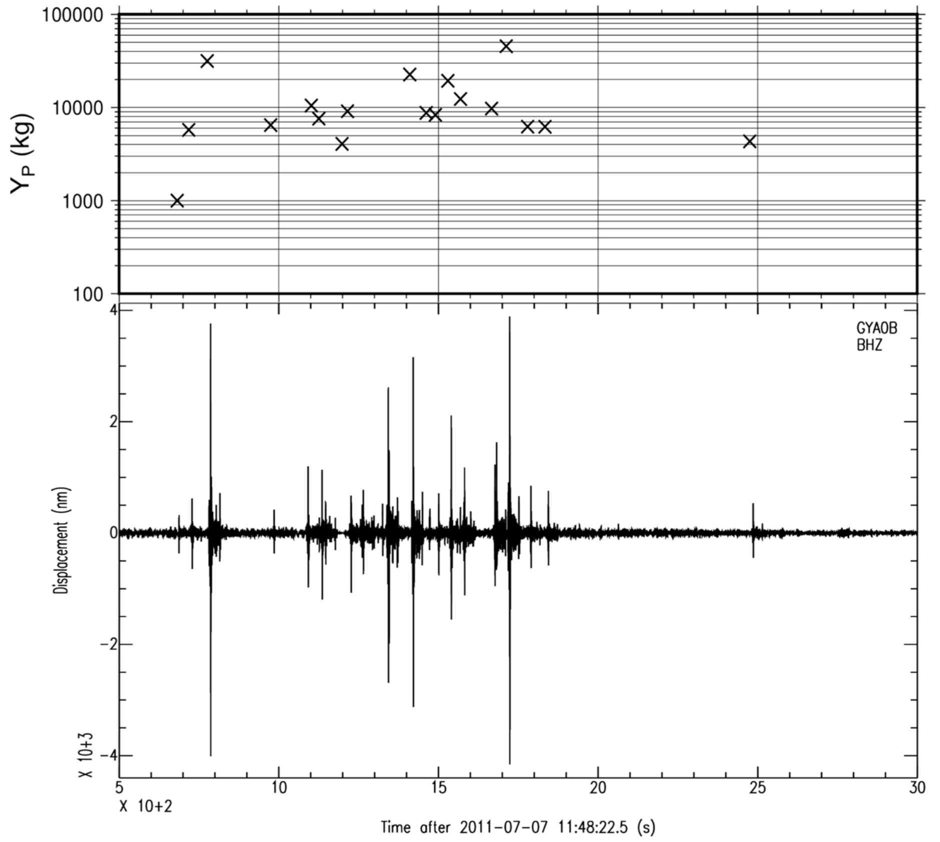


Figure 3: Calculated Y_P versus time (top), compared with an unfiltered vertical displacement seismogram at GYA0B (bottom).

Rg yield: Y_{Rg}

- Y_{rg} is based on the magnitude of short-period (1 s), fundamental mode Rayleigh waves, Rg (Bonner and Russell, 2013)
- Waveforms are corrected for instrument response, converted to displacement (nm) and filtered using a third order, zero phase, second-order Butterworth filter
- Y_{rg} was estimated for 25 events at each element of the GEYT array (Fig. 4.)
- The remaining five events had coda overlapping with the Rg arrival and a robust zero-to-peak amplitude measurement could not be made

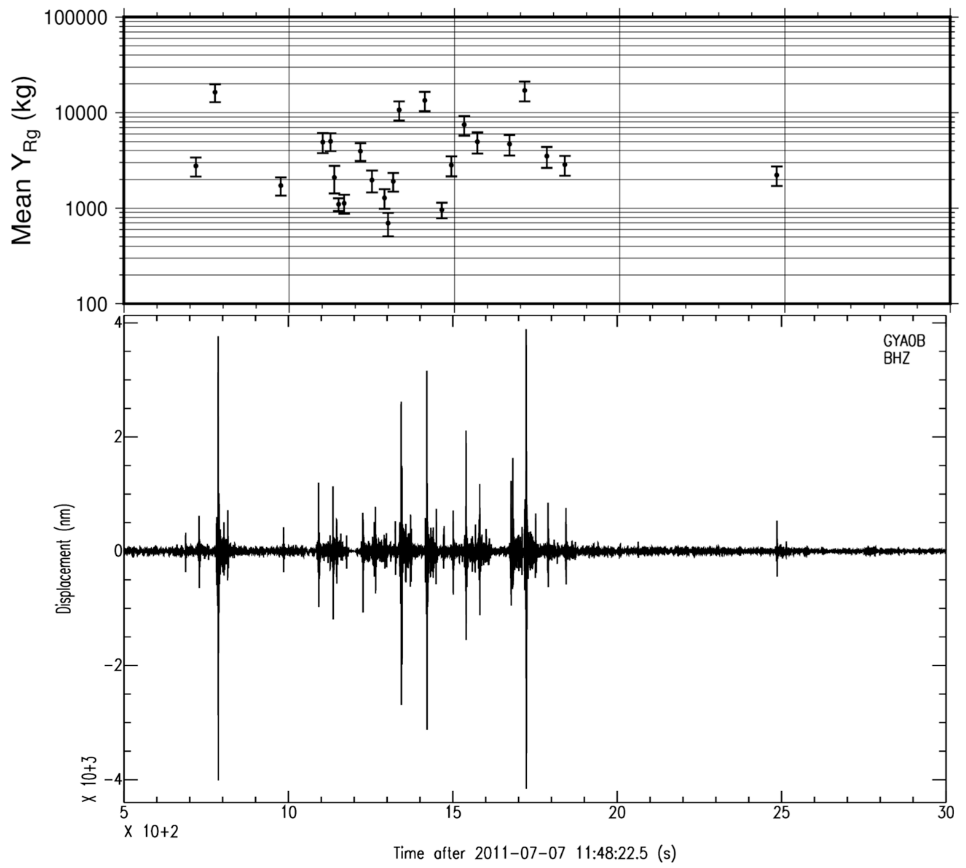
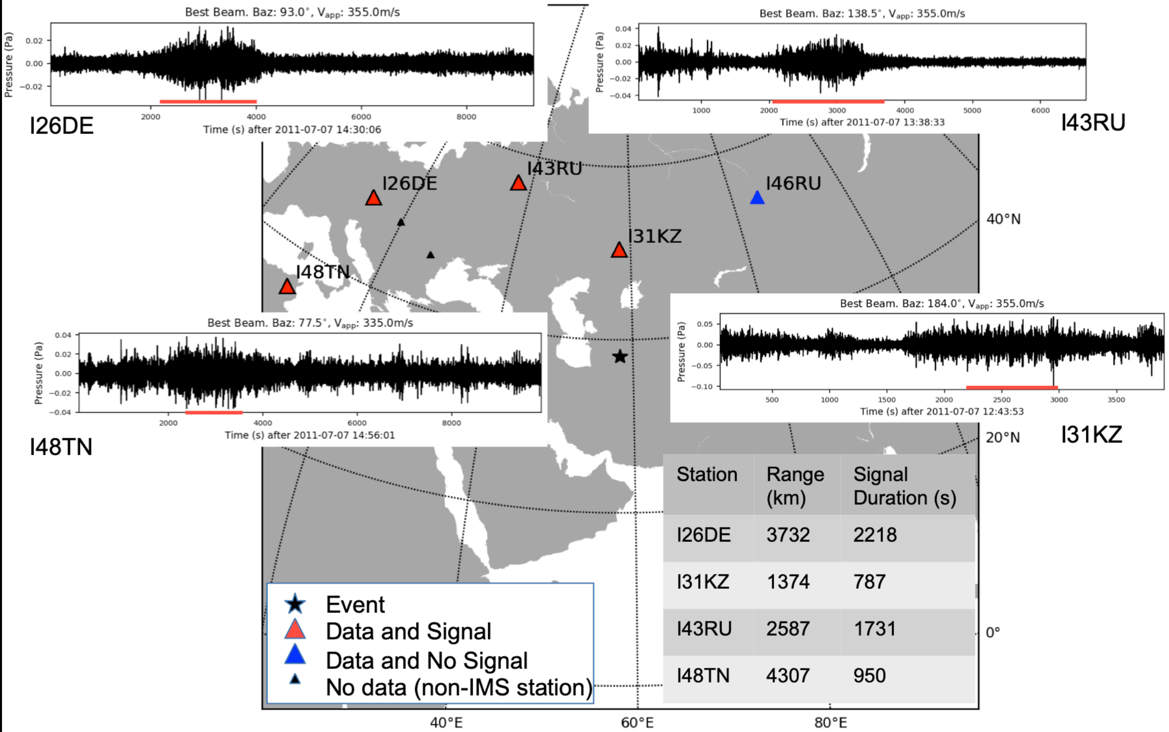


Figure 4: Estimated mean Y_{Rg} across all the array elements versus time (top), compared with an unfiltered vertical displacement seismogram at GYA0B (bottom).

Infrasound Observations

- Signals are observed to the west as expected for Northern Hemisphere propagation in July
- The long durations of the high SNR signals (I26DE and I43RU) are indicative of multiple explosions (Green & Nippress, 2019)
- Celerities at I26DE (0.33 km/s), I43RU (0.31 km/s) and I48TN (0.32 km/s) are fast (but physically plausible) for stratospheric arrivals, whereas at I31KZ (0.26 km/s) celerity is slow



Station	Range (km)	Signal Duration (s)
I26DE	3732	2218
I31KZ	1374	787
I43RU	2587	1731
I48TN	4307	950

Figure 5: IMS infrasound stations used in this study. For each station, best beam band-pass filtered 0.32 - 1.28 Hz, with signal duration (red horizontal bar)

Infrasound yield: Y_I

- We use a range of high pass filters on the best beams for I26DE and I43RU to provide an indication of the low period noise
- The high SNR signals at I26DE and I43RU both have a dominant frequency ~0.53 Hz
- Period estimates in the time domain [1.4s, 3.4s] are used to estimate equivalent chemical Y_I [4t, 90t] TNT equivalent (Whitaker, 2006)

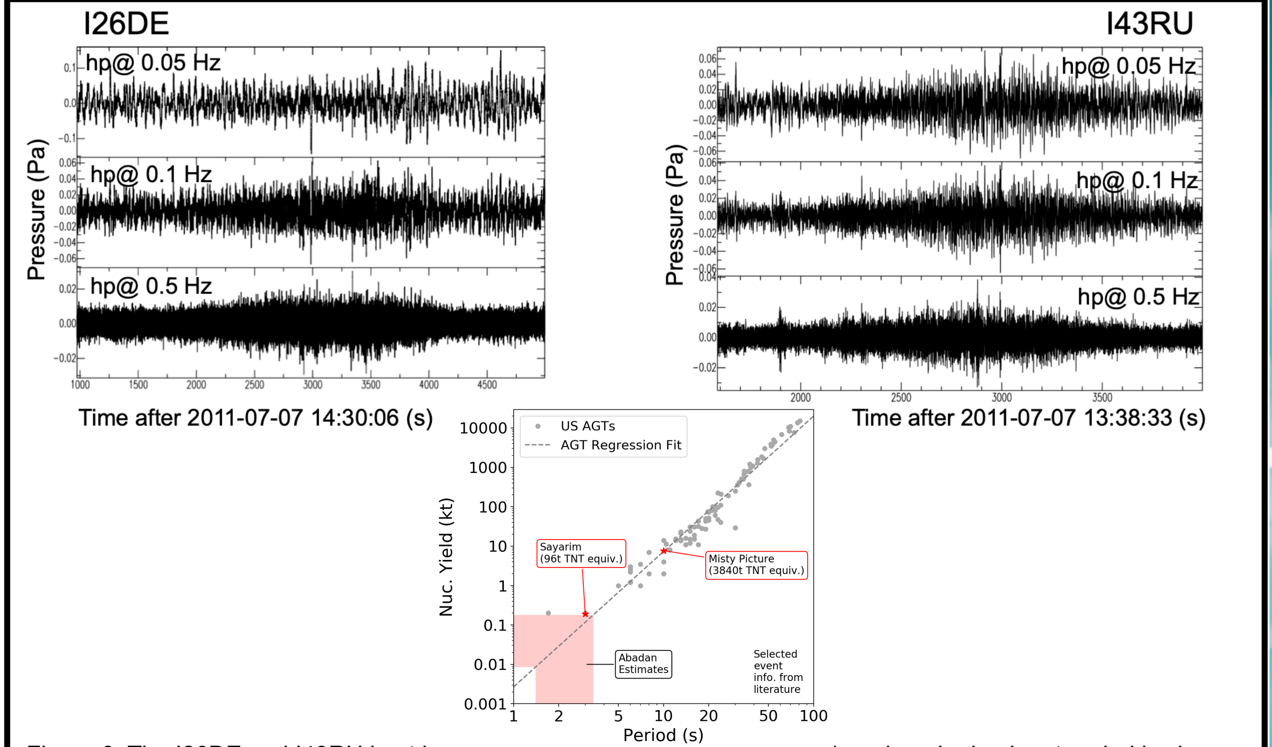


Figure 6: The I26DE and I43RU best beams. The estimated yield using the time domain dominant period is shown in comparison to the results from a dataset of US AGTs (Above Ground Nuclear Tests) (Whitaker, 2006).

Yield comparison

- Figure 7 compares the yields calculated using the P-wave and Rg arrivals at GEYT and the long range infrasound observations at I26DE and I43RU
- The estimated Y_{Rg} is smaller than the estimated Y_P
- The Y_{Rg} relationship was developed using data from buried explosive trials while the Y_P was developed from surface explosive trials data
- The Y_I is consistent with the largest Y_P and Y_{Rg} even though the long-range infrasound yield is determined from a wave packet that includes information from a number of explosions

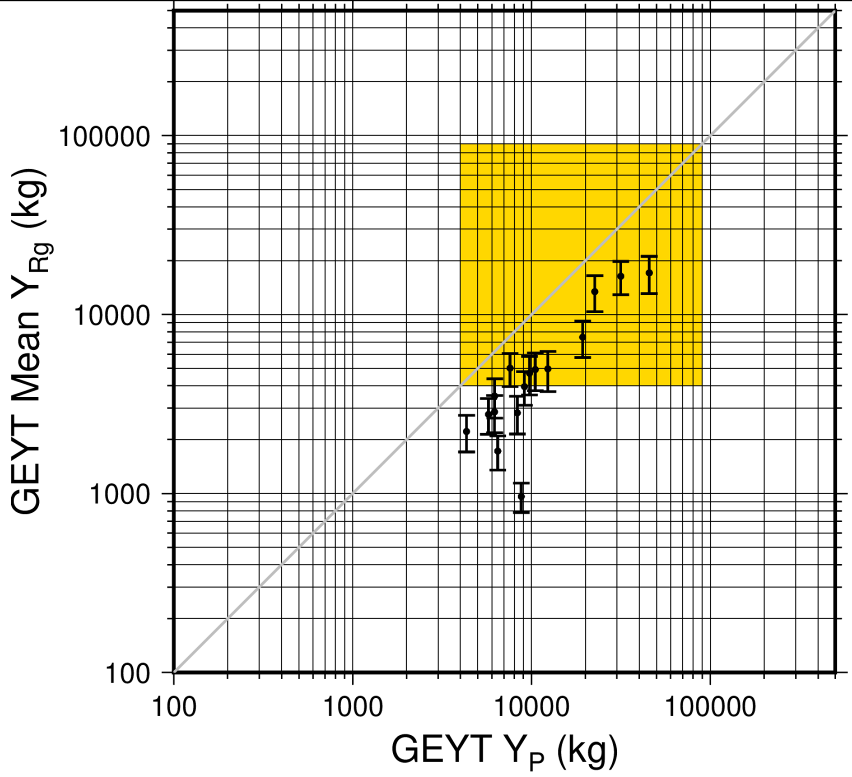


Figure 7: Comparison of yields calculated using both seismic and long-range infrasound observations. The gold square shows the bounds of the yield estimated using the long-range infrasound observations at I26DE and I43RU.

A2G coupled waves: Observations

- The A2G coupled waves are only observed on the vertical component of each station and exhibit downward first motions, consistent with an initial positive blast overpressure
- We compared the period and peak-to-peak amplitude of the A2G coupled waves in the time domain (in a variety of filter bands) to Y_P and Y_{Rg}
- No relationship between A2G coupled wave period and Y_P or Y_{Rg} is observed
- The peak-to-peak amplitude of the A2G coupled wave appears to increase with yield and then level off

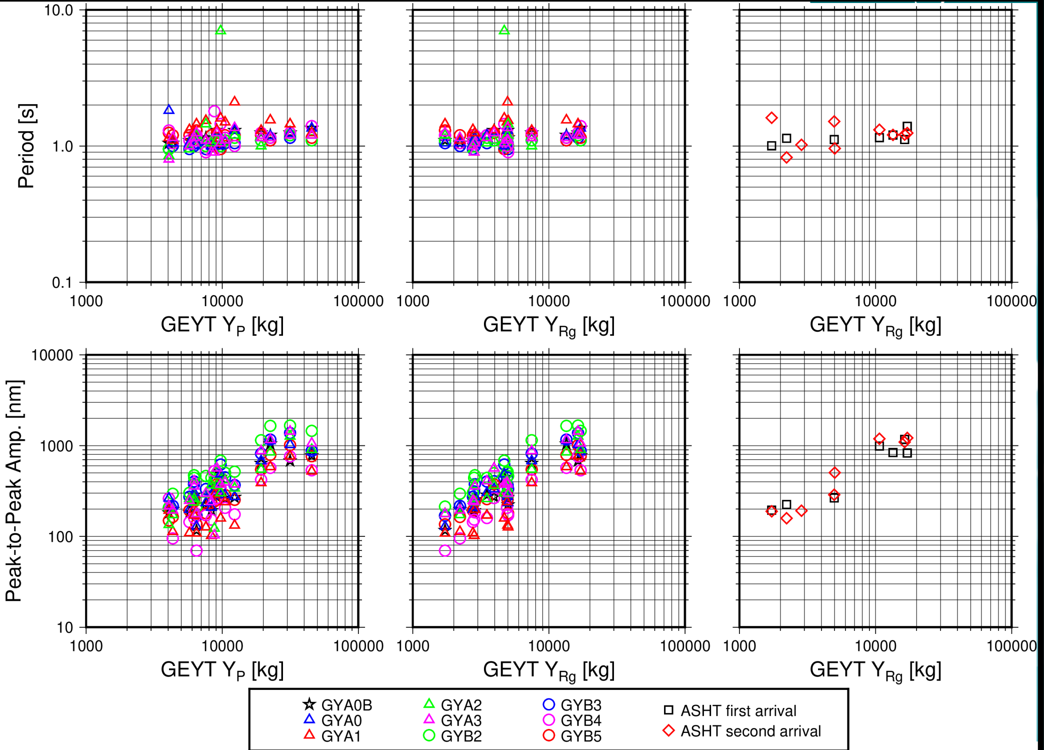


Figure 8: Comparison of GEYT Y_P (left), GEYT Y_{Rg} (middle and right) with A2G coupled wave period (top) and peak-to-peak amplitude (bottom). Waveforms were filtered using a 0.32 - 1.28 band-pass filter.

A2G coupled waves: Modelling

- We generate synthetics using:
  - Reflectivity code (Herrmann, 2013)
  - Simple 1-D velocity model
  - Ground-2-Space (G2S) atmosphere model (Drob *et al.*, 2003)
- Synthetic seismograms produce a single A2G coupled wave whose timing, period and amplitude vary in the same way as the observations
- Suggests A2G coupled waves are generated by an impulse response of the ground created by the airwave

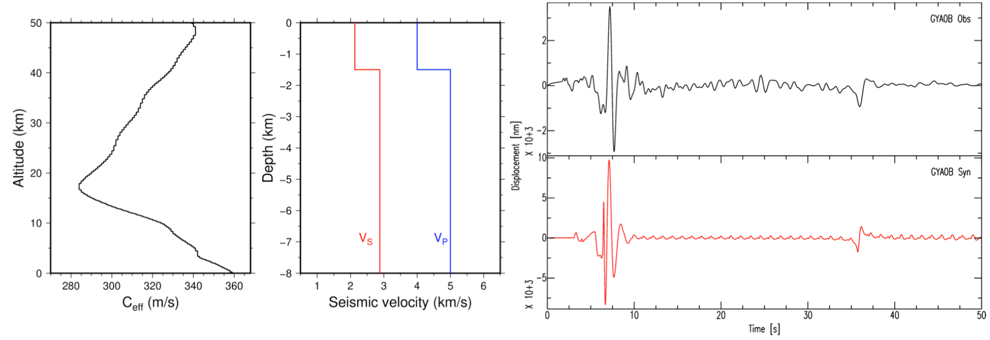


Figure 9. a) Effective sound speed derived from G2S model at the explosion site. b) 1D velocity models. c) GEYT observed (top) and synthetic (bottom) seismograms.

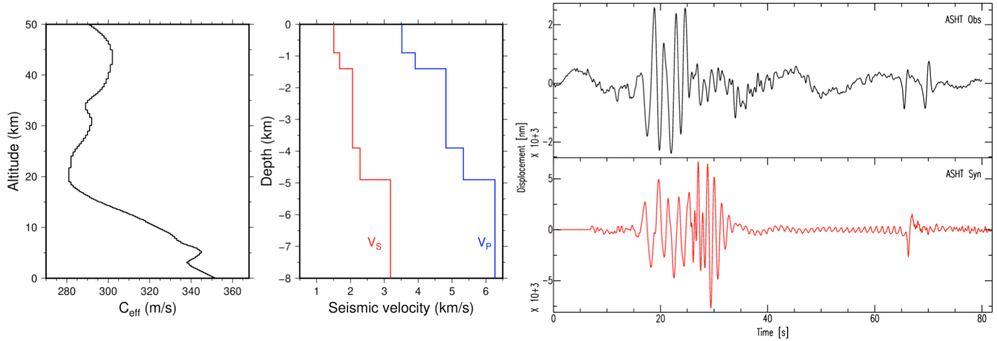


Figure 10. a) Effective sound speed derived from G2S model at the explosion site. b) 1D velocity models. c) ASHT observed (top) and synthetic (bottom) seismograms.

A2G coupled waves: Modelling

- We model the two A2G arrivals at ASHT as a partial reflection (Fig. 11)
  - The timing of the initial phase is consistent with a direct arrival
  - The timing of the later arrival is consistent with a reflection from 2.6 km altitude
  - Suggests low level winds not captured by G2S responsible for the later arrival
- Comparisons of the two A2G arrivals from various events at ASHT:
  - Show relative arrival time and amplitude differences for the later arrival between different events
  - This is consistent with a reflection from a slightly varying atmospheric path

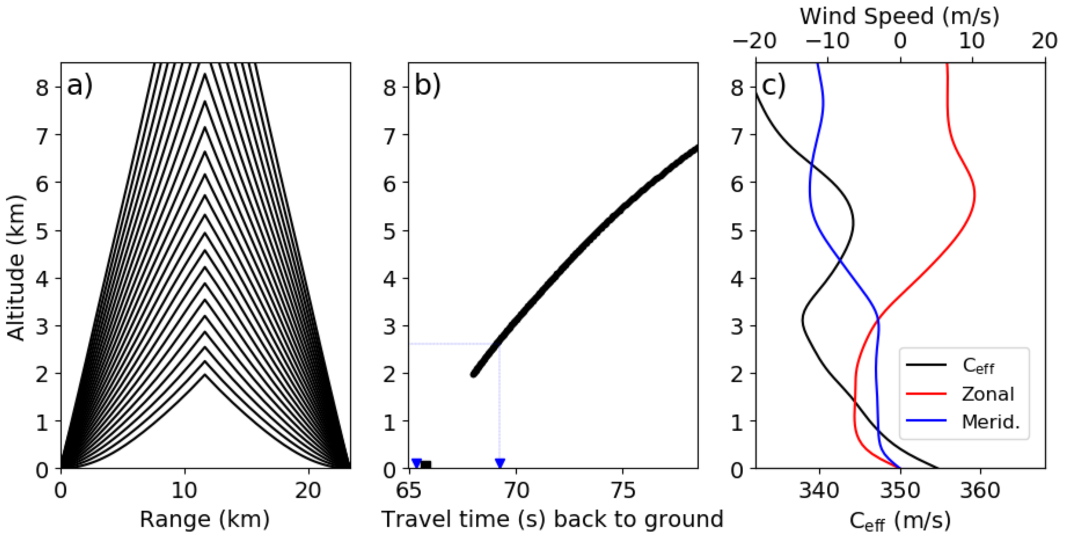


Figure 11: a) Model set-up; rays are shot from the source with increasing initial propagation angles. They are returned to the ground once the ray reaches the halfway distance to station ASHT. b) Predicted travel time (black squares) and observed arrival times (blue triangles). c) G2S model at the explosion site.

Summary

- We analysed a series of explosions at a military storage depot on the 7th July 2011 in the town of Abadan, Turkmenistan
- We are able to identify 30 explosions in a 30 minute period using observations at the IMS station GEYT
- Observations at GEYT are used to estimate Y_P and Y_{Rg}. The results are in good agreement and suggest the yield of the explosions range between 1000 – 40,000 kg
- The explosions are also seen at the IMS infrasound stations I26DE and I43RU
- Yields obtained from the infrasound compare well with those obtained seismically
- A2G coupled waves are seen for all explosions at GEYT and ASHT
- We show that the amplitude of these waves varies with yield but not the period
- We postulate that these arrivals are generated as airwaves and reflected arrivals that induce an impulse response of the ground surrounding each seismometer