INFRASOUND CALIBRATION EXPERIMENT IN ISRAEL: PREPARATION AND TEST SHOTS

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Sponsored by Army Space and Missile Defense Command

Contract No. W9113M-07-C-0189
Proposal No. BAA07-52

ABSTRACT

The Geophysical Institute of Israel (GII) started a new project of establishing a calibration infrasound dataset for the Eastern Mediterranean/Middle East region for improvement of monitoring capabilities of international network infrasound stations. The dataset is intended to characterize the infrasonic wave propagation in the region: travel times, spectra, amplitudes, dependence on source yield, and atmospheric conditions. To achieve these goals, a series of experimental surface shots will be conducted at Sayarim Military Range (SMR), located in southern Israel, Negev desert, including the main calibration explosion of 80 tons (TNT equivalent).

During the explosions numerous portable co-located infrasound and seismic systems will be deployed at near-source (0.1–1 km) (accelerometers), local (10–350 km), and regional distances (500–1500 km) in neighboring countries (during the main explosion). Tripartite arrays of low-frequency electret condenser microphones will be installed at close distances less than 100 km, and Chaparral sensors will be used for infrasound observations at larger distances.

Preliminary test explosions of broad yield range and various designs are planned during the first project year, on different days, including outdate ammunition detonations, conducted regularly at Sayarim Range, thus providing a wide range of atmospheric conditions. The test explosions are intended to fulfill a number of tasks: testing new infrasound recording systems; yield scaling signal amplitude/energy; testing charge design and preparations and conducting logistics for the big explosion; analyzing atmospheric effects on infrasound propagation in different azimuths, based on collected meteo-data about wind direction and velocity in different months; and validating safety estimations/conditions for successive increasing charges.

We collected GTI0 information and observations of acoustic phases at stations of the Israel Seismic Network and a few infrasound portable stations for a series of 7 experimental single shots (in the range of 0.4–1.2 tons) conducted by Israel Defense Forces (IDF) at Sayarim September 2007–February 2008. Just recently, June–July 2008, jointly with the IDF, we conducted another test series of 13 outdated ammunition detonations (in the range of 0.2–10 tons) and two special experimental project explosions of 1 ton each of pure different explosives (TNT and CompositionB). The two special experimental explosions, conducted close to and 10 minutes after an ammunition shot, were intended to estimate ammunition actual yield and also to check the feasibility of using one of such different explosives as a charge element for the large calibration explosion.

Analysis of signals recorded at seismic and acoustic channels of portable and permanent stations is presented, including charge scaling estimations, comparison of energy generation for different explosives, and examination of the influence of wind direction on parameters of infrasound phases. Results obtained from the test series will be used for elaboration of design and logistics of the main calibration explosion and selection of optimal experimental conditions and infrasound system locations.

Report Documentation Page	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE **SEP 2008**	2. REPORT TYPE	3. DATES COVERED **00-00-2008 to 00-00-2008**

4. TITLE AND SUBTITLE **Infrasound Calibration Experiment in Israel: Preparation and Test Shots**	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Geophysical Institute of Israel,PO Box 182,LOD 71100, Israel ,**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR’S ACRONYM(S)
	11. SPONSOR/MONITOR’S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

Proceedings of the 30th Monitoring Research Review: Ground-Based Nuclear Explosion Monitoring Technologies, 23-25 Sep 2008, Portsmouth, VA sponsored by the National Nuclear Security Administration (NNSA) and the Air Force Research Laboratory (AFRL)

14. ABSTRACT

see report

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**12**	

OBJECTIVES

Three major project objectives:

1. Conducting a surface calibration explosion of 80 tons at SMR (Figure 1), with deployment of a number of portable infrasound stations at local and regional distances up to 1500 km (jointly with ISLA, UH)
2. Establishing a calibration infrasound dataset for Eastern Mediterranean/Middle East region for improvement of monitoring capabilities of IMS infrasound stations
3. Characterizing the infrasonic propagation in the region: travel times, spectra, amplitudes, depending on source features and atmosphere conditions

A number of smaller test surface shots in different months are planned on the first stage with following goals:

- Testing new infrasound recording systems
- Yield scaling signal amplitude/energy
- Testing charge design and preparations/conducting logistics for the big explosion
- Analyzing the wide ranging effects of atmospheric conditions on infrasound propagation on different azimuths (based on collected meteorological data)
- Validating safety estimations/conditions for successive increasing charges

RESEARCH ACCOMPLISHED

During the first year of the project, the research was focused on three areas: (1) selecting, purchasing, assembling, testing, and characterizing new recording infrasound systems—in order to document and characterize the regional propagation effects; (2) conducting and observing experimental and outdated-ammunition explosions; and (3) collecting available local meteorological information—in order to characterize atmospheric effects on infrasound propagation for recorded explosions. A great deal of administrative effort was spent on organizing tenders and selecting subcontractors for explosives supply and conducting experimental explosions.

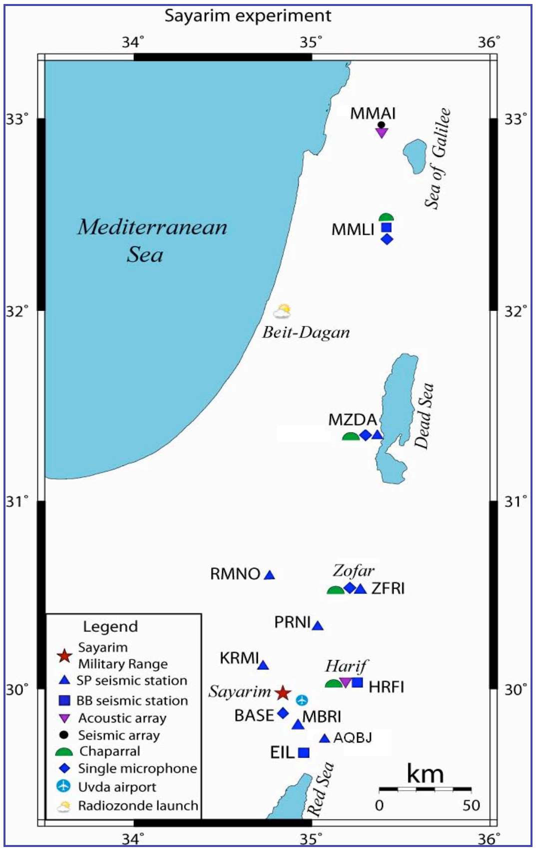


Figure 1. Location of the Sayarim explosion site, stations of the Israel Seismic Network that recorded acoustic phases, and portable infrasound stations installed for observation of the project explosions.

New Infrasound Sensors

We selected two types of sensors for local infrasound observations of the explosions. We purchased five Chaparral M25 sensors from Chaparral Physics Inc. (an old Chaparral 2 model had been purchased previously). To provide more observation points along propagation paths, we purchased electronic components, assembled and tuned 12 much-cheaper low-frequency electret condenser microphones WM-54D5 (Figure 2,a). No data sheets or instrument response tests were found for these sensors, so we tried to quantify their response and their absolute and relative sensitivity. Appropriate recording systems, including A/D cards, amplifiers, global positioning system (GPS) devices, and PC-based data-acquisition software were developed. Laboratory calibration tests were conducted, in which a group of six microphones was run alongside a reference Chaparral 2 sensor (Figure 2,b).

Infrasound signals for calibration were produced by sharply opening or closing the building's exit door (located ~30 m from the laboratory room). Sample signal records and appropriate amplitude spectra are shown in Figure 3. The software jSTAR, developed at GII (Pinsky et al., 2007), was used for amplitude measurements and spectral calculation. Unlike Chaparral 2, microphones are used with an amplifier during calibration tests (and field observations), and their amplitudes are respectively corrected when comparing the sensitivity of the sensors.

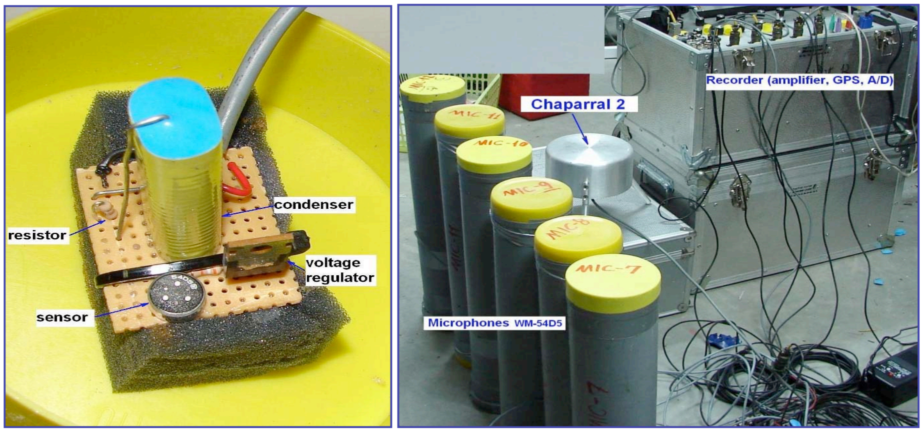


Figure 2. Low-frequency microphones (cartridge WM-54D5) (a), placed in resonance boxes, were calibrated in the GII laboratory (b).

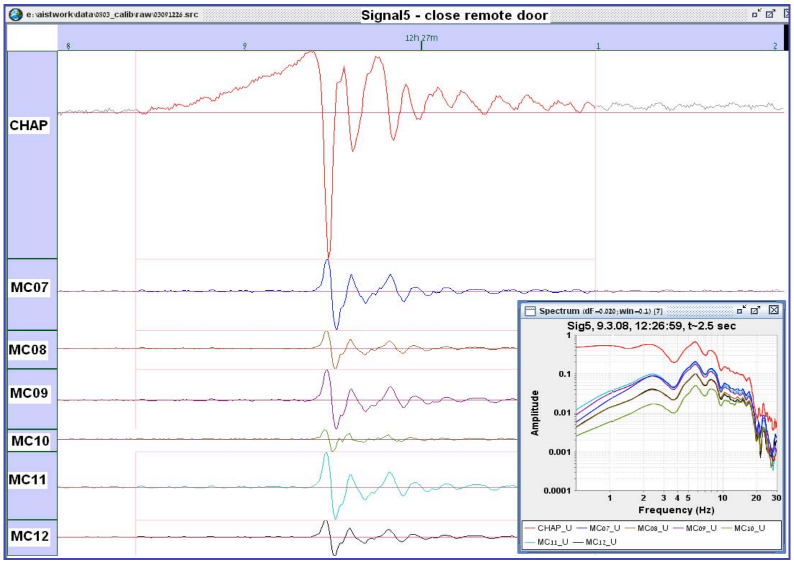


Figure 3. Sample records of signals from six microphones and Chaparral 2, produced by closing the exit door.

The results show large variation in sensitivity for different microphones (by 2 to 3 times), possibly caused by a large dispersion (~ 20%) of resistor and condenser values used in the microphone circuit, and another highly accurate electronic device should be tried to improve the sensor identity. The spectra clearly demonstrate different frequency responses from the microphones compared with the expected flat response of the reference Chaparral 2 sensor in the range of 0.1–30 Hz. We also compared signals from two co-located Sayarim ammunition shots that were recorded by both sensors at a remote location, and we calculated the amplitude spectra of the signals (Figure 4) and the spectral ratios of Chaparral signals to microphone signals as an estimation of the sensitivity ratio (SR) depending on frequency. These estimations generally correspond to the results of the laboratory calibration tests. We conclude that microphones represent well the amplitude and energy of signals for frequencies that are >3 Hz but significantly cut low-frequency energy for frequencies <1 Hz.

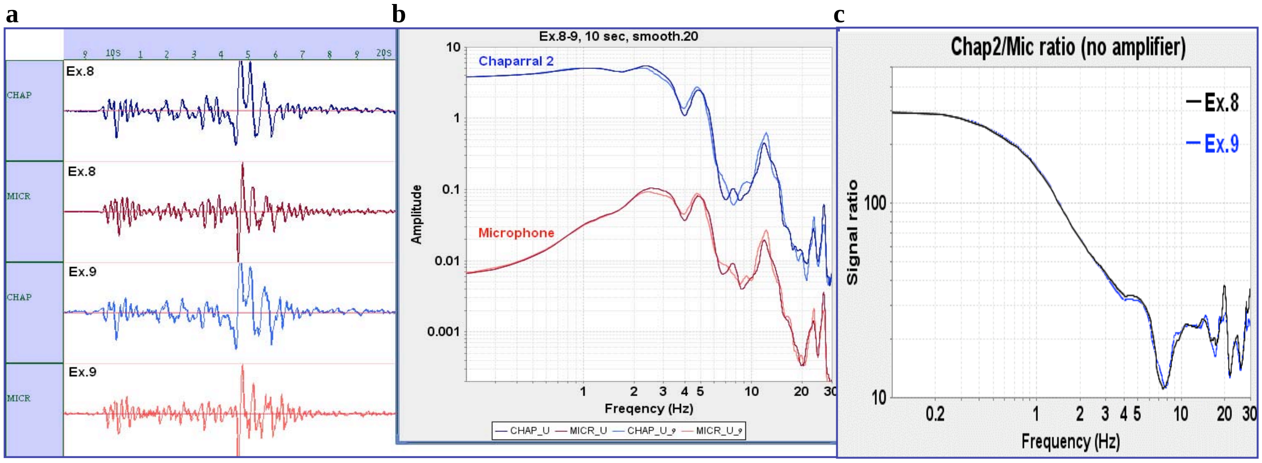


Figure 4. Infrasound signals (in relative scale) from two similar Sayarim ammunition shots February 27, 2006, (with a delay of ~2 minutes and explosives of ~7 tons) recorded at Zofar(r ~73 km), (a) appropriate smoothed spectra, and (b) spectral ratios of Chaparral to microphone signals (c).

Collecting Atmospheric Data

Atmospheric conditions along the infrasound propagation path, especially the local altitude distribution of wind direction and velocity and their changes on different days, strongly affect acoustic signal amplitudes, duration, and propagation time (e.g., Garces et al., 1998; Stump et al., 2002). This effect is regularly observed at ISN stations (Figure 1) where clear acoustic phases from Sayarim ammunition detonations are observed at distances up to 150 km. Figure 5 shows a striking example of antipodal manifestation of acoustic phases of the same explosion at two SP stations located at the same epicentral distance but in opposite directions (October 27, 2003); this ratio was changed to the opposite on another day in another month (November 6, 2003).

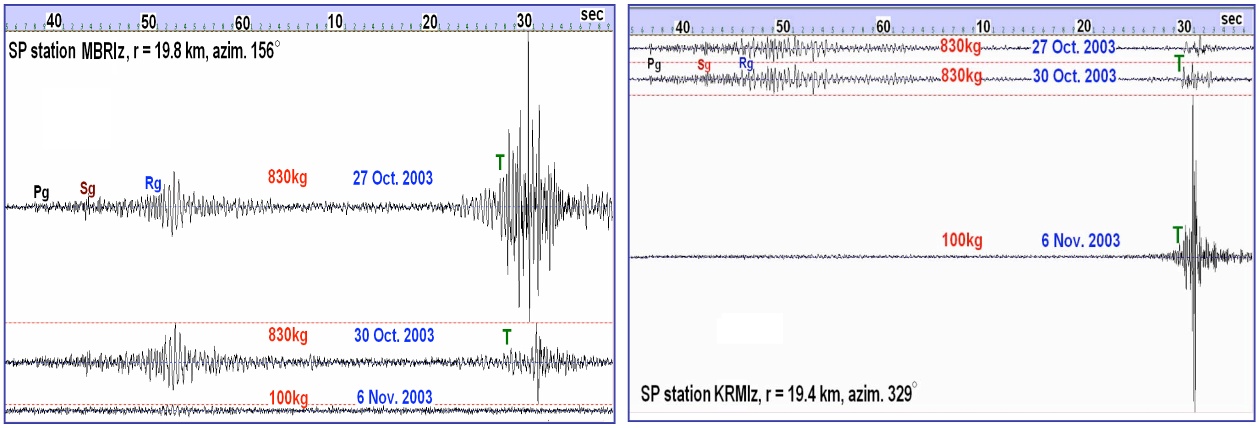


Figure 5. Observations of diverse acoustic phases (T) from Sayarim surface single shots in 2003 at two ISN seismic stations (plotted in absolute scale; filter 1–5 Hz is applied).

We collected archival meteorological information from the Israel Meteorological Service (IsMS) and processed the data. The information includes the data from a balloon-launched radiosonde system (at Beit Dagan, central Israel, see the map in Figure 1) measuring temperature and wind velocity and direction at altitudes up to 27 km. The data measured twice a day during 10 years (1971–1980) were averaged for different months. The average values were plotted as the function of altitude (Figure 6). Distinctive discrepancy is found for different months (seasons).

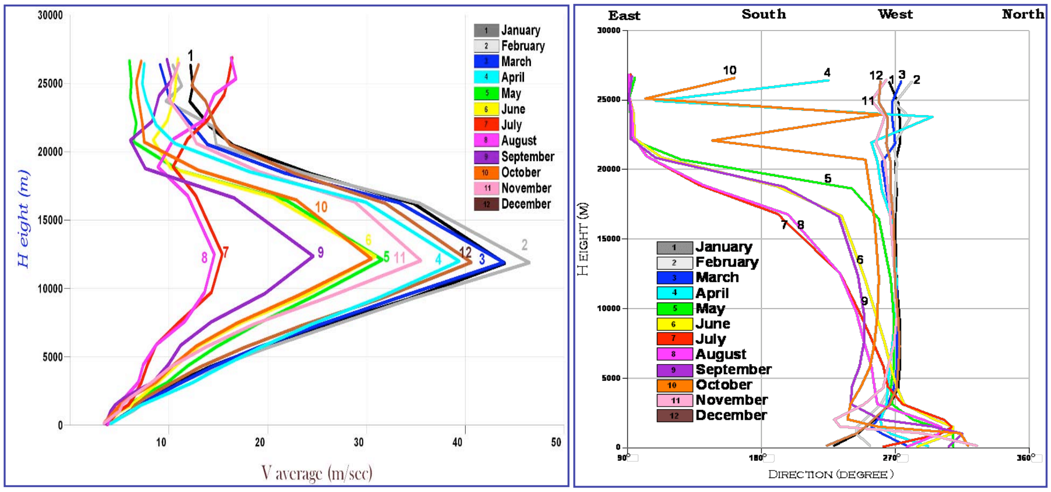


Figure 6. Local altitude distributions of wind velocity and direction from IsMS radiosonde data in different months, averaged for 1971–1980.

The IsMS can provide a full digital dataset of a balloon-launched radiosonde system (up to 25 km) for a specified day, at Beit-Dagan, central Israel. The private company Meteo-Tech conducts measurements of wind direction and velocity near the surface at the airport Uvda in the Negev, very close (~10 km) to Sayarim (see Figure 1). We purchased the data from IsMS and Meteo-Tech for specific days for which we provided infrasound observations, or clear acoustic phases were recorded at ISN stations for Sayarim explosions we collected ground truth (GT) information (Figure 7, Table 1). The data should assist in interpretation of observed variance of acoustic phases at the same station (see below) and will be used in the following for infrasound propagation modeling at local and regional distances.

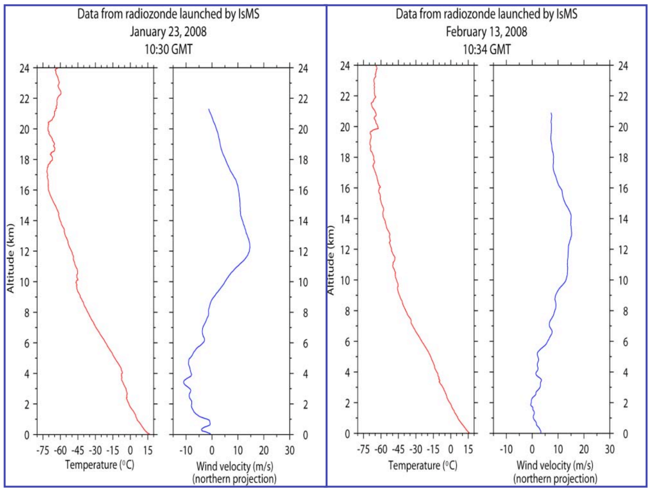


Figure 7. Altitude distribution of temperature and wind velocity in a northern direction on days of observed explosions H6 and H7 (see Table 2). Note the clear differences in the wind curves.

Table 1. Meteorological data (by Meteo-Tech company), measured at Uvda airport at ~2 m above the surface.

Date yy/mm/dd	GMT time	Wind dir (back-azim),°	Wind speed, m/sec	Temperature, C°
07/09/05	10:40	0	3.7	32.7
07/09/10	09:20	15	5.4	29.0
08/01/14	12:00	11	5.2	10.3
08/01/16	13:40	9	4.3	12.2
08/01/21	13:40	3	5.1	13.2
08/01/23	12:00	282	6.0	14.2
08/02/13	13:10	33	1.7	16.6

Series of Military Single Experimental Explosions Hashmonaim-3

Aiming at achieving the objectives mentioned above, we collected GT0 information and observations for a series of experimental single surface shots (Hashmonaim-3) at SMR, conducted recently by the IDF jointly with teams from the USA and UK, and participated in two of them (H6 and H7), measuring accurate origin (detonation) time (O.T.) and GPS coordinates and deploying portable sensors. The explosions were of different charge, explosives, and design (Table 2, Figure 8), placed on a small playground about 30 × 30 m. O.T. values for unvisited shots were estimated from a location procedure in jSTAR software, based on seismic signals recorded at ISN stations around SMR.

Table 2. Parameters of experimental surface explosions Hashmonaim-3 at SMR

Ex. #	Date yy/mm/dd	Origin time, GMT	Local coordinates		Design	Charge, kg	
			X, km	Y, km		actual	TNT equiv.
H1*	07/09/05	10:34:00.6*	183.18	429.45	Tower of 20 kg ANFO packs, height ~2 m	1800	1440
H2*	07/09/10	09:11:15.1*				1800	1440
H3*	08/01/14	11:48:26.6*			Cast TNT, hemispherical, on a wooden platform of height h~10 cm	830	830
H4*	08/01/16	13:32:08.9*				830	830
H5*	08/01/21	13:25:31.6*				830	830
H6**	08/01/23	11:45:18.14**	183.175	429.454		830	830
H7**	08/02/13	11:01:56.59**	183.200	429.449	36 mines (Composit.B), on 2 platforms, h~20 cm	360	400

** visited, O.T. is measured * not visited - GT info from IDF, O.T. is estimated from ISN records.

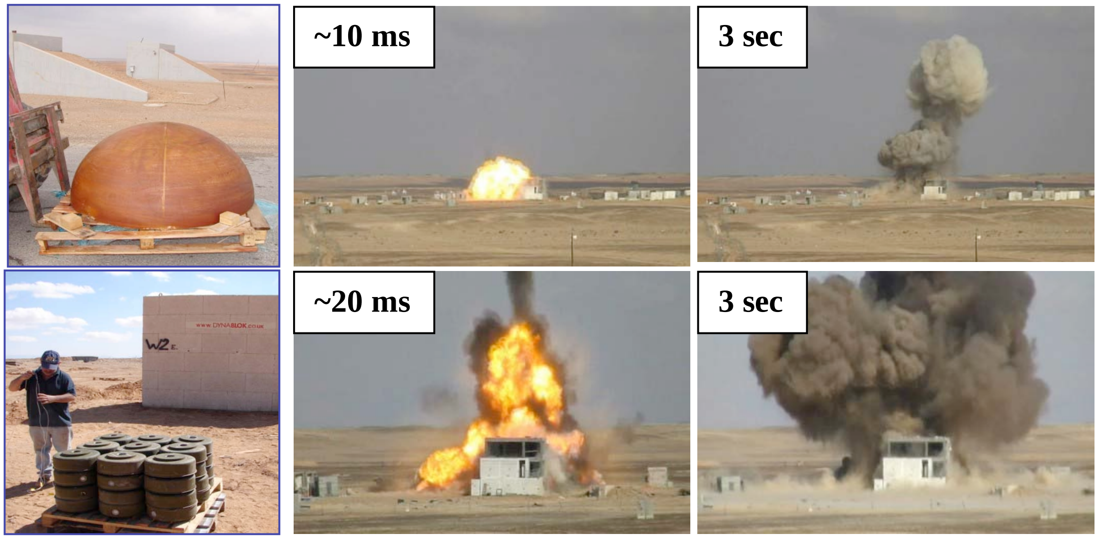
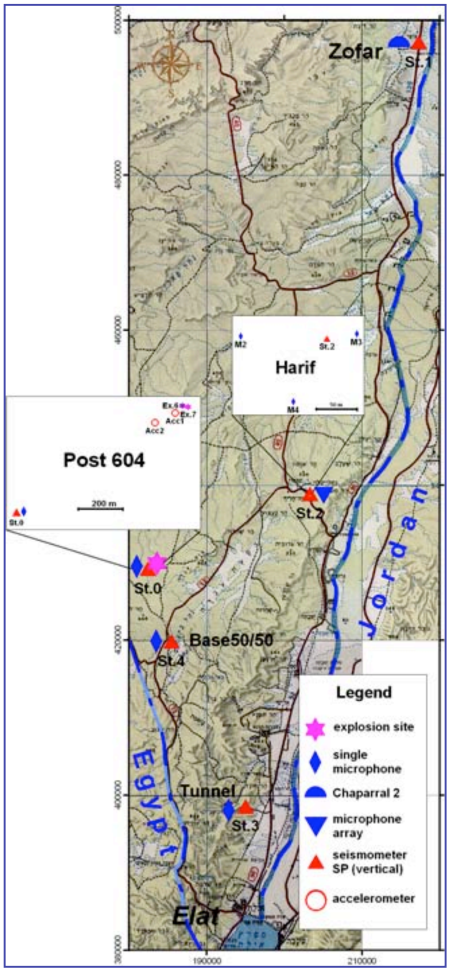


Figure 8. View of the charges and snapshots from video records for two shots: H6 (above) and H7 (below).

Video records of the shots provided visual observations of wind characteristics from movements of the dust column: a rather strong wind (~5 m/s) to the right (east-south) during H6 and almost still during H7 (Figure 8). These observations, confirmed later by the meteo-data (Table 1), helped to explain some differences in infrasound signals for the two shots (see below).

Near-source observations were also provided (Figure 9). For explosion H7, we installed, at close vicinity (64 m and 164 m), two accelerometers ETNA with GPS time (Figure 10,a). Strong air-shock phases were observed at both accelerometer records (velocity 424 m/s). The air-shock phases arrived within seismic signals and prevented measurements of peak ground acceleration (PGA) amplitudes and seismic energy in the near-source zone. For infrasound observations, five portable stations were installed before each explosion (H6 and H7). Usually a single microphone was used, complemented at St. 1 (Zofar) by Chaparral 2 sensor (the only Chaparral available at the moment); a tripartite microphone array was deployed at St. 2 (Harif) during explosion H7. Each station also included an SP vertical seismometer L4C (Figure 9).



The PC-based recording system (at 0.9 km) for measuring detonation time also included a microphone and an SP vertical seismometer (Figure 10,b). Acoustic signals were clipped but provided estimating infrasound (346 m/s); and seismic P-wave velocity was estimated (2140 m/s), characterizing subsurface sedimentary rocks.

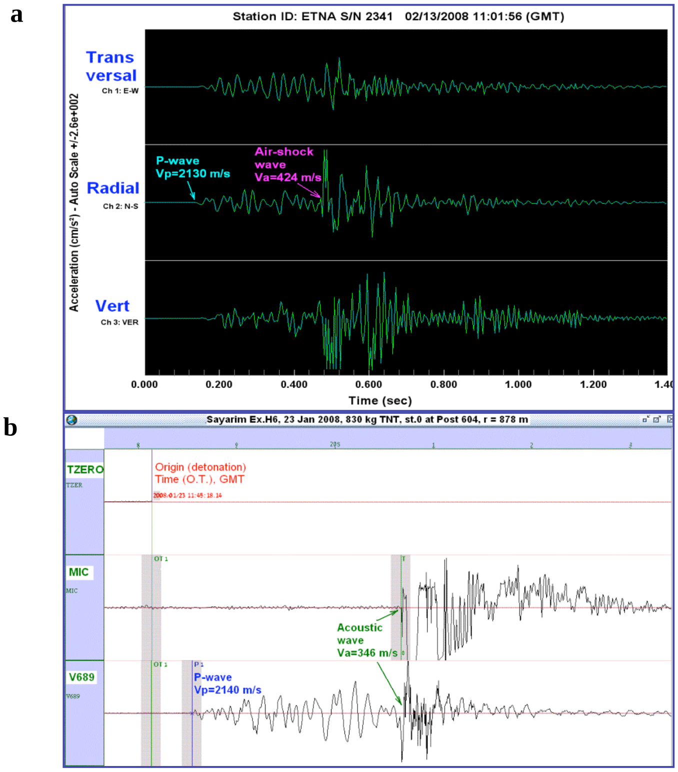


Figure 9. Location of explosions and portable stations during explosions H6 and H7.

Figure 10. Near-source observations by accelerometer at r ~0.16 km during explosion H7 (a) and by microphone and seismometer at r ~0.9 km (explosion H6) (b).

Similar clear signals were recorded at a remote Zofar station for co-located microphone and Chaparral sensors (Figure 11). A waveform modulation, clearly visible in the spectra, is different from signals recorded at this location from previous Sayarim shots (see Figure 4,a), and the spectra again show the cutting of low-frequency energy (f <2 Hz) by microphone compared with Chaparral and maximum energy in the 3–5 Hz range.

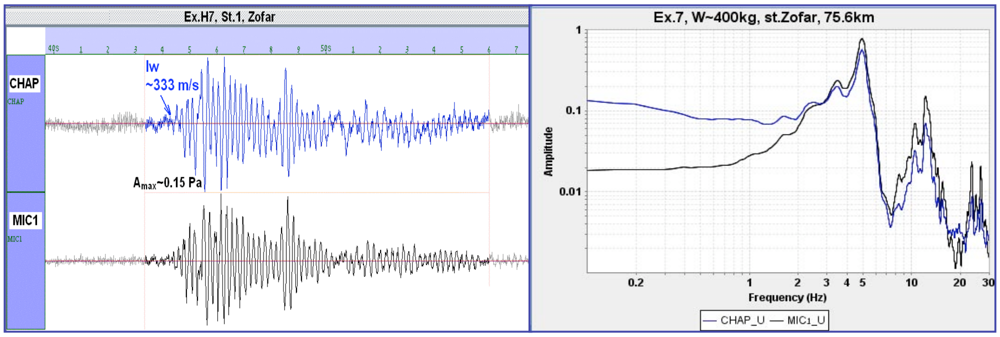


Figure 11. Infrasound phase Iw recorded at St. 1 (in relative scale) and appropriate spectra. Amplifier gain 40 dB was used for microphone recording.

Clear acoustic phases were recorded at several ISN network seismic stations located close to the Sayarim site, similar to many other observations (e.g., recent Stump et al., 2007; Gibbons et al., 2007). The same location of the series shots facilitated a comparison of seismic and acoustic phases at a fixed station. At all stations, seismic amplitudes clearly correspond to the charge size, whereas acoustic phases show a drastic variance of temporal structure and amplitudes from shot to shot and for different azimuths. Figure 12 shows sample records at SP MBRI and BB HRFI, located at similar distances from the shots but at different azimuths (see Figure 1), where distinctive acoustic phases for explosion H6 and H7 correspond in some way to the wind observations on the site and collected meteo-data (Figure 7, Table 1). The data provide a base for infrasound propagation modeling and verification.

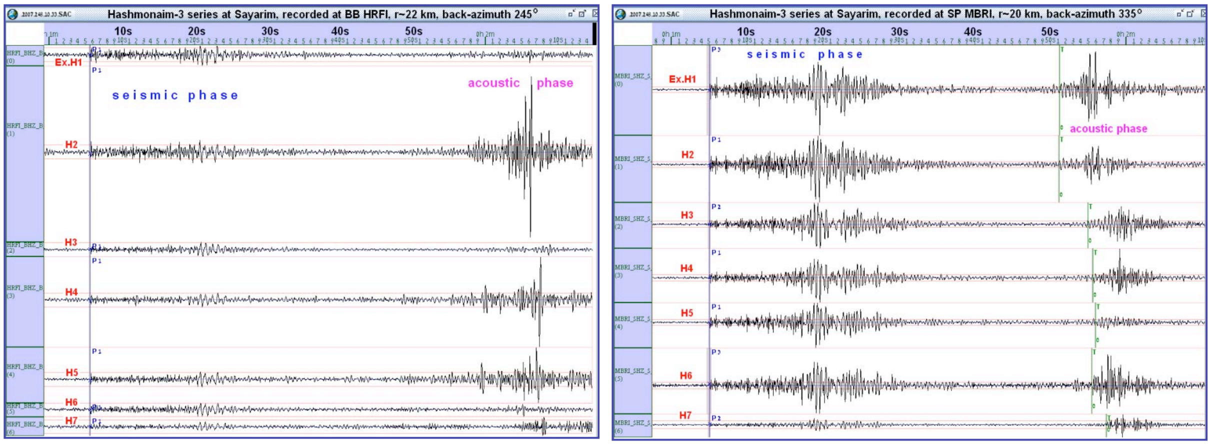


Figure 12. Seismic and acoustic phases from the Hashmonaim-3 series observed at vertical channels of two ISN stations. All seismograms (1–10 Hz, in absolute scale) are aligned according to P-arrival time.

Series of Ammunition Detonations and Single Experimental Explosions in June and July 2008

In June and July 2008, we conducted, jointly with the IDF, another series of 13 tests of outdated ammunition detonations in the range of 0.2 to 10 tons (TNT equivalent) and two special experimental project explosions of 1 ton each of pure different explosives (TNT and CompositionB) (Table 3). We visited and documented the first eight shots, measured coordinates and O.T.; charge parameters for the next shots were informed by IDF.

Table 3. Parameters of outdate ammunition and experimental surface shots at Sayarim, June–July 2008

Ex. #	Date	Origin Time, GMT	Coordinates		Design	Total charge, ton
			X, km	Y, km		
1	23 June	07:52:27.35*	180.864	433.697	Ammunition+chenamit emulsion 0.2 ton	0.2
2		12:24:45.3*	180.830	434.016	Ammunition+emulsion 6.0 ton	6.05
3		12:31:10.0*	180.864	433.697	Ammunition+CompB (18 mines) ~0.18 ton	0.18
4	24 June	08:52:50.4*	180.870	433.722	Ammunition+emulsion 4.9 ton	4.94
5		**09:01:39.2***	**180.831**	**434.039**	**Experiment: 1 ton TNT+CompB (2 mines)**	**1.02**
6		12:38:57.6*	181.336	434.156	Ammun.+emulsion 2.25 ton+mines 1.5 ton	3.77
7	25 June	10:27:48.1*	180.867	433.719	Ammunition+CompB (mines) 8.63 ton	8.63
8		**10:37:05.4***	**180.825**	**434.041**	**Experiment: 1 ton CompB+2 mines**	**1.02**
9	30 June	~07:00**	180.83	434.02	Ammunition+ emulsion ~0.25 ton	0.25
10		~09:15**	180.87	433.72	Ammunition+emulsion ~1 ton	1.0
11		12:27:30.7**	181.34	434.16	Ammunition+emulsion 6.25 ton	~6.5
12	1 July	11:53:14.6**	180.83	434.02	Ammunition+ emulsion 6.25	~6.5
13		11:56:14.9**	180.87	433.72	Ammunition+emulsion 6.25	~6.5
14	2 July	11:48:58.2**	180.83	434.02	Ammunition+emulsion 6.25 ton	~6.5
15		11:51:06.8**	180.87	433.72	Ammunition+emulsion 6.25 ton	~6.5

* visited, O.T. is measured ** not visited - GT info from IDF, O.T. is estimated from ISN records.

The two experimental 1-ton explosions, each one conducted close to and 10 minutes after an ammunition shot (~300–350 m), were intended to estimate actual ammunition yield, which otherwise can not be counted up. Second, we wanted to check the effectiveness of the used 1-ton charges, consisting of reclaimed explosives pieces placed in two wooden boxes (see Figure 13), as an element of the large calibration explosion of 80 tons (planned of TNT and CompB). Finally, the two closely located shots with identical charge weight allowed comparisons of the generation of acoustic and seismic energy from these explosives, at different distances. Some preliminary comparison results for close locations are presented in Figure 14. As expected CompositionB produced larger amplitudes of acoustic (air-shock) and seismic waves (however, a stronger acoustic phase on a seismometer is found for the TNT charge, Figure 14b).

Figure 13. Design of the experimental explosion #8 of 1 ton of Composition B (a), detonated ~10 minutes after the largest shot, explosion #7, in the series, in which outdated ammunition was destroyed by mines of 8.63 tons of Composition B (close to ~10 ton TNT equivalent) (b); as observed from a safe position at Post 604, at 5.3 km (c).

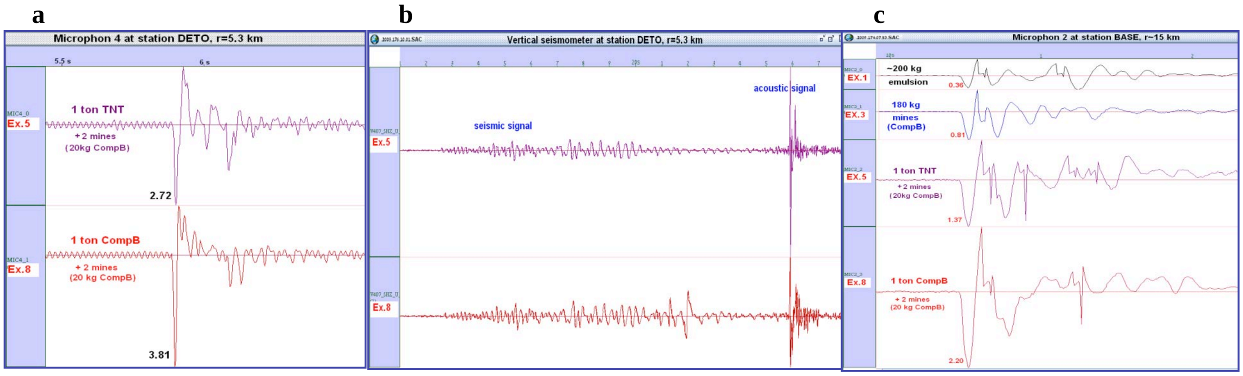


Figure 14. Comparison of signals from two experimental 1-ton shots recorded at ~5 km by microphone #4 (a) and vertical seismometer (b), and signals from four small shots recorded by microphone #2 at ~15 km (b).

A number of stations were installed at near-source, local, and regional distances for observation, infrasound, and seismic waves from the explosion series. Since the IDF uses radio signals to detonate large ammunition charges at a distance of 3–5 km, we could not use the old method of having an electric wire circle connected to the charge. Therefore, two accelerometers K2 were placed at ~150 m between a pair of ammunition and experimental explosions for measuring detonation time by a specially developed procedure (June 23–25 June only); another accelerometer Etna was placed at ~300 m. Strong seismic motions and air-shock wave arrivals were also recorded.

We used the same nearby station locations as before (Figure 9); three newly purchased and tested infrasound sensors, Chaparral M25, were installed at portable stations BASE, Harif, and Zofar. Two more new Chapparrals were placed jointly with single microphones at remote permanent ISN stations—MZDA (156 km) and MMLI (278 km)—where the records were transmitted on-line (Figure 1). Additionally, an infrasound array of three microbarometers MB2000 was installed by Israel NDC at Mt. Meron (340 km), co-located with three elements (C1, C5, and C7) of IMS seismic array MMAI (Figure 1). A sample seismogram of an ammunition explosion is presented on Figure 15. Collection, processing, and analysis of the extensive dataset of records and meteo-observations will be continued.

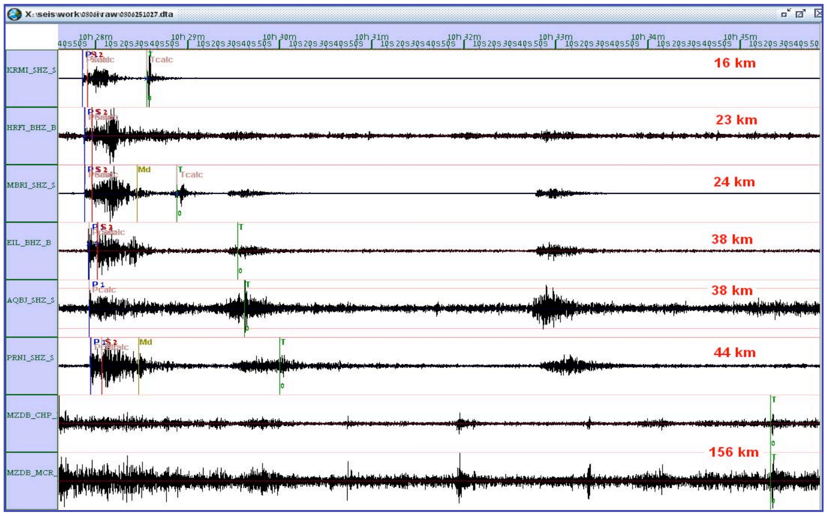


Figure 15. Recording of the largest ammunition explosion, explosion #7, showing seismic and acoustic phases (T) at ISN stations and infrasound signals at a temporarily installed microphone (MZDB.MCR) and Chaparral M25 (MZDB.CHP) at station MZDA (156 km).

CONCLUSIONS AND RECOMMENDATIONS

1. Newly acquired infrasound recording systems were tested in laboratory and field experiment conditions and showed good performance. The tests included cheap microphone gauges suitable for observations in the 5–100 km range.
2. The extensive dataset collection from preliminary test explosions in the broad charge range of 0.2–10 tons allowed the analysis of yield scaling relationships based on amplitude and energy of seismic and infrasound signals.
3. The experimental explosions proved the feasibility of using 0.5-ton charge units, consisting of reclaimed explosives pieces placed in a wooden box, as an element of the large calibration explosion of 80 tons, planned of TNT and Composition B, when more Composition B is preferable to use (if available).
4. Collected meteo-data provided a base for infrasound propagation modeling. Numerous records of acoustic phases from repeating similar sources at the same location helped to estimate the effects of atmospheric conditions on infrasound propagation on different azimuths and verification of modeling results.
5. Acoustic signals observed closely from increasing charges will serve for validation of safety estimations.

ACKNOWLEDGEMENTS

Thanks to Dr. I. Setter of IsMS for supplying valuable average meteo-data, to blast managers Y. Hamshidyan and E. Stampler of IDF's Experiment Division for conducting our experimental explosions and providing GT information, and to Dr. Y. Ben-Horin of NDC for organizing infrasound array deployment at Mt. Meron. We appreciate efforts of GII personnel: U. Peled for preparation and installation of portable stations and providing O. T. measurements and M. Kalmanovich and Dr. T. Meirov for preparing the presented maps and graphs.

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