NEAR-SOURCE AND FAR-REGIONAL INFRASOUND OBSERVATIONS FOR SAYARIM TEST EXPLOSIONS

Yefim Gitterman[1], Milton A. Garces[2], J. Roger Bowman[3], David Fee[2],
Hans G. Israelsson[3], Rami Hofstetter[1], and Vladimir I. Pinsky[1]

Geophysical Institute of Israel[1], Infrasound Laboratory of University of Hawaii[2], and
Science Applications International Corporation[3]

Sponsored by the Army Space and Missile Defense Command

Award No. W9113M-07-C-0189

ABSTRACT

During the second year of this project we continued preparations for a large surface calibration explosion of 80 tons TNT at Sayarim Military Range (SMR), Israel, planned for August 2009. The Geophysical Institute of Israel (GII) calibrated low-frequency electret condenser sample microphones at the Infrasound Laboratory, University of Hawaii (ISLA), using a specialized infrasonic source – a subwoofer rotary speaker. Signals were also referenced to Chaparral 2.2 and 5.0 sensors. The microphone sensitivity was found roughly flat to acoustic pressure over the range 3–17 Hz.

We also completed processing and analysis of observations for a series of ammunition detonations and experimental explosions conducted in summer 2008. An extensive dataset of near-source acoustic observations, for the broad charge range of 0.2–10 tons, allowed for the determination of a yield scaling relationship based on signal amplitude and energy. Some of the relatively small Sayarim explosions were detected at International Monitoring System (IMS) infrasound station I48TN (Tunisia, 2500 km), and I26DE (Germany, 2800 km), using array-processing techniques. These observations confirmed favorable westward infrasonic propagation conditions in the Mediterranean region during summer.

Additionally, two test explosions of 1 ton and 5 tons (mix of TNT, Composition B and RDX) were conducted at SMR in December 2008. The test explosions provided a means to train field and scientific staff in test preparation, coordination, logistics, charge design, and assembly in anticipation of the main explosion in August 2009. We measured high-pressures from the air-blast waves at close distances. High-speed video recordings provided validation of these explosives in anticipation of the main explosion, as well as estimation of TNT equivalent yields. Data obtained from the test series were used for the design and logistics of the main calibration explosion.

We analyzed signals from the December test explosions, recorded on seismic and acoustic channels of portable and permanent stations deployed at near-source and local distances. We compared energy generation for different explosives, including cratering conditions, and investigated the influence of wind direction on infrasound arrivals.

Modeling of the long-range atmospheric propagation of infrasound was conducted using global G2S atmospheric profiles and local atmospheric data. The optimal date and time window of the experiment (August 2009) as well as the locations of portable infrasound systems in Mediterranean region were selected based on experimental and infrasound modeling results.

OBJECTIVES

- Calibration of GII microphones;
- Analysis of observations of Sayarim explosions at IMS stations;
- Testing of explosives feasibility, charge design and assembling procedures for the main explosion;
- Analysis of seismo-acoustic signals from test explosions at near-source and local distances; and
- Modeling of long range atmospheric propagation of infrasound in the Mediterranean region.

RESEARCH ACCOMPLISHED

The activities and research during the project's second year included preparations for conducting the main surface calibration explosion at Sayarim, and observations of infrasound waves in a broad distance range.

Calibration of GII Microphones

We calibrated three low-frequency electret condenser sample microphones at ISLA, using a specialized infrasonic source – a subwoofer rotary speaker. Signals were also referenced to co-located Chaparral 2.2 and 5.0 sensors, which were recently calibrated (Figure 1). The testing setup consisted of a laptop and a wave file to generate a time dependant signal that increased in frequency (i.e., a sweep). This method allowed a well-controlled signal to be run through the rotary speaker to provide a relatively flat and broadband infrasonic output signal. A 12-minute frequency sweep test between 0.1–25 Hz was performed for all microphones, with the gain set to 14 dB (Figure 2). The microphone sensitivity was found to be roughly flat to acoustic pressure over the range 3–17 Hz, with values about 1.3 V/Pa.

a **b**

Figure 1. Calibration of GII microphones at ISLA by subwoofer rotary speaker (a), when a microphone (in a tube) was co-located with reference calibrated Chaparral sensors (b).

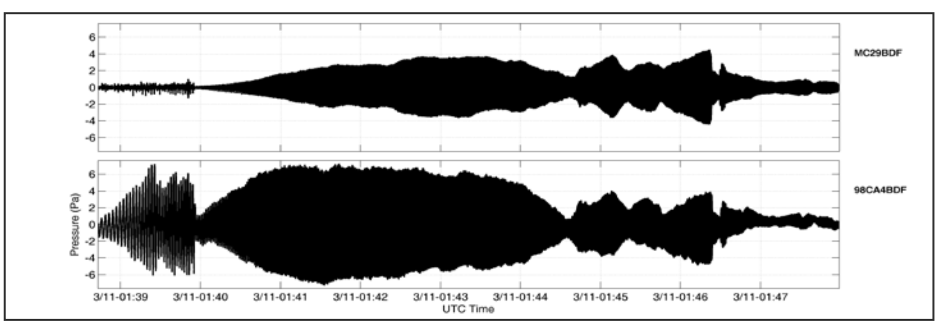

Figure 2. Waveforms for a frequency sweep test, with Mic29 on top and the reference sensor below (the scale is the same). The test started at low frequencies, where microphones have a diminished response. For higher frequencies, after ~01:44 UTC, similar amplitudes are observed for both sensors.

Observations of Sayarim Explosions at IMS Stations

GII collaborated with Science Applications International Corporation (SAIC) in the analysis of infrasound signals from Sayarim explosions observed at IMS stations. GII supplied SAIC with Ground Truth Information (GTI) for 148 old ammunition detonations conducted at SMR during 2005–2008. The explosions were recorded by the Israel Seismic Network (ISN), which provided estimations of location (accuracy ~1–2 km) and detonation time (accuracy ~0.3–0.5 sec). GTI0 for 12 experimental and ammunition explosions conducted within the project duration was also provided (exact yield, coordinates and detonation time, measured by GII team). Based on this GTI, the SAIC team analyzed records of four IMS infrasound stations close to SMR (Figure 3) and found clear infrasound signals for many SMR explosions. Special array-processing procedures, including the automated generation of plots and manual review of signal-processing plots to confirm signals were used to analyze data.

Two samples of this analysis are presented below.

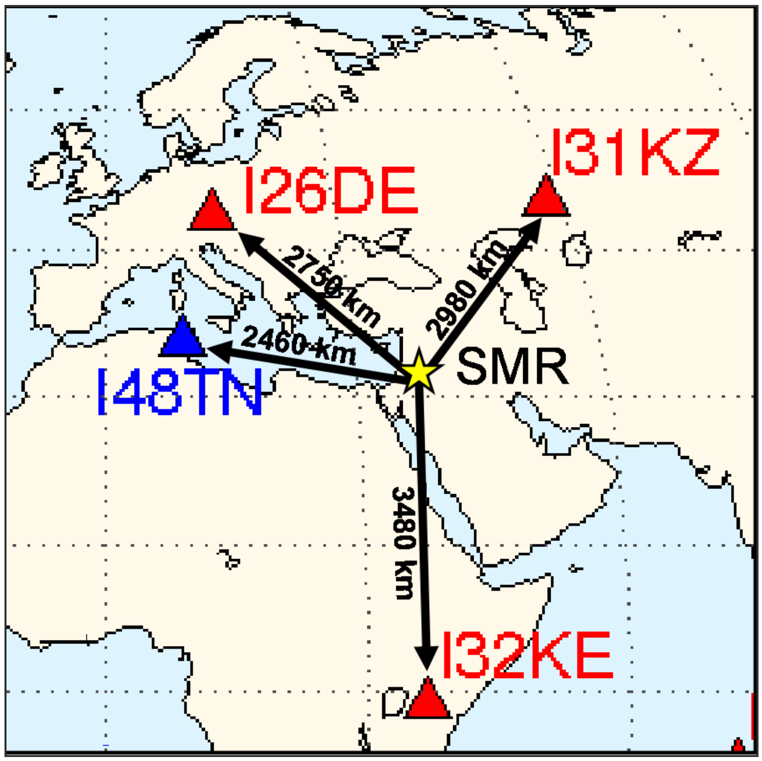

Figure 3. SMR shots were analyzed at the four closest IMS stations.

July 23, 2007 event. Two explosions were conducted at SMR with coordinates corresponding to the known place for demolition of old ammunitions (GTI0: 29.994N/34.805E), with a delay of 1 min 27 sec (Table 1). Clear acoustic phases were found at seismic channels of the ISN, confirming ammunition detonations (Figure 4).

Table 1. GTI parameters of two explosions at SMR on July 23, 2007.

No.	Origin Time, GMT	Latitude N	Longitude E	Local Magnitude	Charge**, tons
1	12:31:29.6*	29.9932*	34.7899*	2.3*	5-7
2	12:32:56.7*	29.9819*	34.7947*	2.3*	5-7

* estimation by ISN location procedure; ** estimation by the magnitude

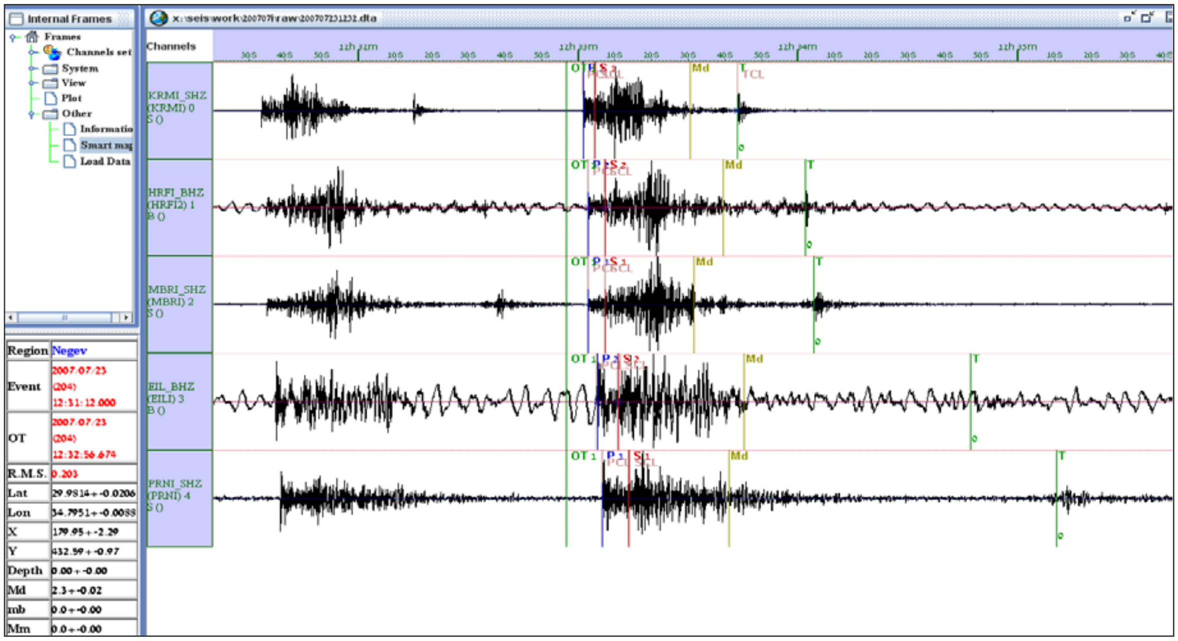

Figure 4. Seismogram of two explosions at SMR, showing clear acoustic phases at ISN seismic channels. Phase picking, estimation of the origin time, coordinates and local magnitude, provided by jSTAR software (Pinsky et al., 2007), are shown for the second explosion.

A wave group of about six to eight arrivals was found at two IMS stations (Table 2, Figure 5), corresponding to different infrasound phases that propagate through different atmospheric layers, from the two explosions on July 23, 2007. Due to the small time delay between the explosions, the infrasound phases from the two explosions are not separated, but merged into one group.

Table 2. Observations from two SMR explosions on July 23, 2007 at two IMS stations.

Station	Lat., N	Lon., E	Azimuth °		Distance, km	First arrival	Propagation time, sec	Group velocity, m/s
			Actual	Measured				
I48TN	35.8052	9.323	98	~100	2461.4	14:40:00	7710	320
I26DE	48.8516	13.7131	132	~130	2753.0	~14:57:00	~8730	~315

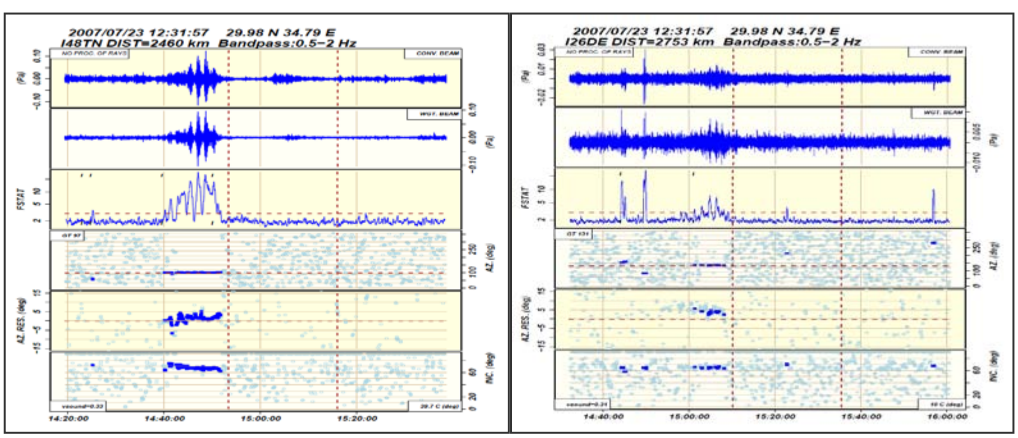

Figure 5. Observations of Sayarim explosions at two IMS stations on July 23, 2007: I48TN (a) and I26DE (b).

June 25, 2008 event. Two test explosions were jointly conducted by GII and the Israel Defense Force (IDF) at SMR, with an approximate ten minute delay: an ammunition detonation and an experimental project shot (Gitterman and Hofstetter, 2008). Accurate GTI was collected and measured (Table 3). Signals from the two shots, recorded at two close ISN stations with opposite backazimuths, showed a drastic difference in the amplitude ratio of seismic and acoustic phases (Figure 6).

Table 3. GTI parameters of two explosions at SMR on June 25, 2008.

No.	Charge, tons	TNT equiv., tons	Origin Time, GMT	Latitude, N	Longitude, E	Local Magnitude
7	8.63	10.36	10:27:48.1	29.99156	34.80462	2.5
8	1.02	1.224	10:37:05.4	29.99446	34.80417	2.0

Stronger signals are observed in the northwest direction and shown in Figure 6, caused by atmospheric conditions (wind velocity and direction). Favorable infrasound propagation conditions were also present towards IMS station I48TN, providing a clear signal observation from a rather small shot of ~1 ton, as shown in Figure 6 (Explosion 8).

Two separate groups of arrivals are observed at IMS station I48TN at 2460 km: six to seven arrivals from the ~10 ton explosion (Explosion 7) of old ammunition, and after about ten minutes, another three to four arrivals, evidently from the experimental ~1 ton explosion (Explosion 8) (Figure 7). Besides the suitable propagation times, the signal-event association is also confirmed by consistent array-estimated azimuths corresponding to the actual value (Table 4).

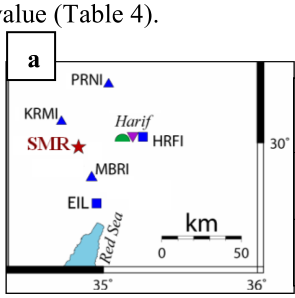

Table 4. Observations of two SMR shots on June 25, 2008 at IMS station I48TN.

No.	Distance, km	Azimuth, deg.		Arrivals	Propagation time, sec	Group velocity, m/s
		actual	measured			
7	2461.4	98	~100	First ~12:37:00	~7752	~317
				Max ~12:45:30	~8262	~298
8	2461.3	98	~100	First ~12:50:00	~7975	~307
				Max ~12:54:30	~8245	~299

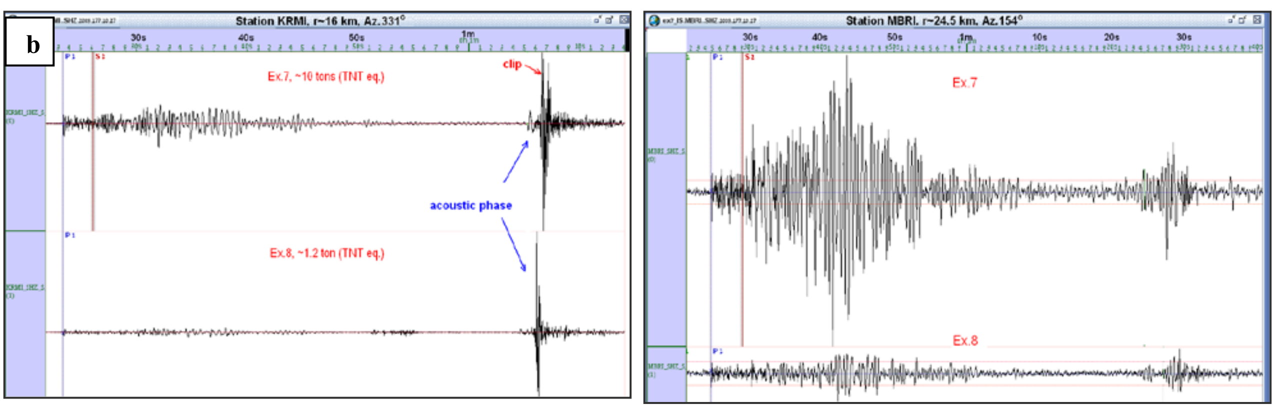

Figure 6. Map of local stations and recorded explosions at SMR (a) and seismograms of two shots at two ISN stations, with the absolute scale applied (b).

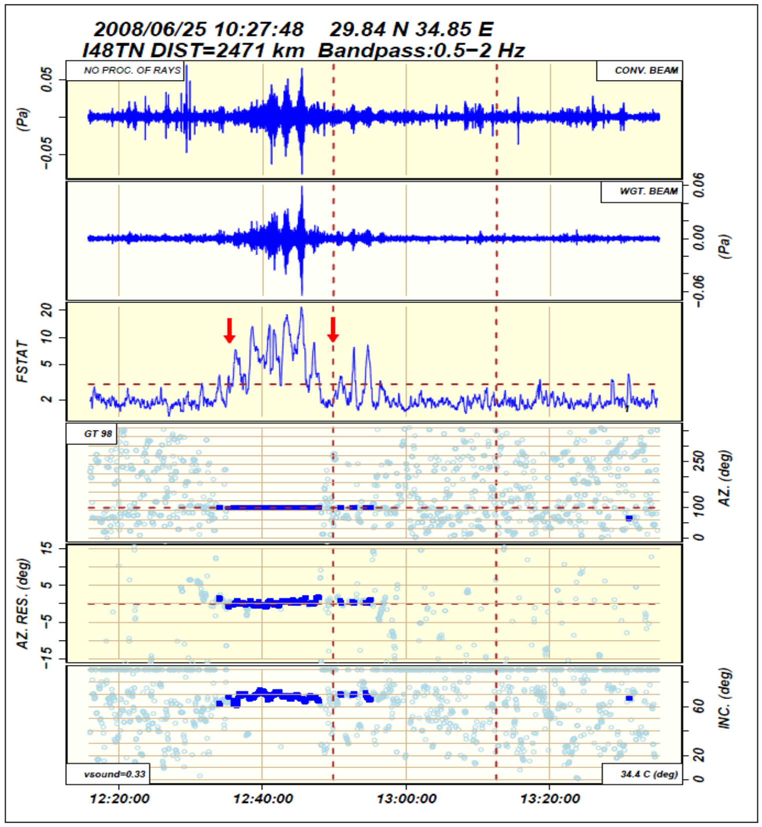

Figure 7. Observations of Sayarim shots at IMS infrasound station I48TN on June 25, 2008. Red arrows show two groups of arrivals.

Testing of Explosives Feasibility and Charge Design.

Two experimental surface shots of 1 ton and 5 tons (Series 3) were conducted in December 2008, with the goals of 1) training project staff in logistics operations, assembling of charge units, and charge building; 2) measuring high pressures and high-speed video, for the estimation of TNT equivalency for a variety of used explosives (recuperated TNT, Composite B and RDX); and (3) determining the efficiency of upward detonation with respect to charge design for maximizing the coupling of acoustic energy to the atmosphere.

Parameters of the explosions are presented in Table 5, and Figure 8 shows the charge view and successive snapshots from recording by high-speed video camera (Phantom-3, at 4000 frames/sec), installed at 600 m.

Table 5. Parameters of Sayarim explosions, December 2008 (coordinates 30.09007 N, 34.79499 E, h=523 m).

No.	Date	Origin Time, GMT	Local Coordinates		Design	Charge weight, ton
			X, km	Y, km		
1	12/2	13:12:35.9	179.978	444.642	Tower, 3 big bags	1.04
2	12/3	10:22:16.2	179.978	444.630	Cubic-like, 16 big bags	5.08

Figure 8. Recuperated explosives used in Series 3: cast TNT pieces and RDX powder to fill voids (a); view of the 5 ton charge, assembled of big bags containing pieces of explosives and red detonation cord, attached to the booster under a wooden platform (b); snapshots of high-speed video of the 1 ton shot during the first second after the initiation (c).

Some specific effects of the surface explosion were observed on the high-speed video: propagation of detonation in the detonation cord with a velocity of ~6500 m/s, the air-blast wavefront in the air, and spreading of the fireball. The observed fireball radius was roughly estimated as ~20–25 m for the 1 ton shot, and 35–40 m for the 5 ton shot; the predicted radius for the main 80 ton explosion is ~100-120 m; this estimate is important for planning near-source sensor deployment. Some optical effects of unclear origin were observed at 0.25 ms and 1 ms (Figure 8c).

Boosters were placed on the ground (Figure 8a), and upward detonation was applied in this experiment, unlike the downward detonation in the two 1-ton test shots in Series 2 in June 2008 (Gitterman and Hofstetter, 2008), in order to increase the explosive energy released to the atmosphere.

High-pressure measurements were made to validate the effectiveness of the charge design and the variety of recuperated explosives as well as to estimate the charge equivalency to homogenous pure TNT. Four XTL-190-5G pressure gauges (Figure 9a) were installed in the distance range 140–250 m. Both explosions were recorded well at all sensors (sampling rate 2 MHz). A sample record for 1 ton at the closest sensor is shown in Figure 9b; measured parameters are presented in Table 6. Predicted peak pressures were also calculated using DDESB Blast Effects

Computer Version 4.0 (BECV4) (Swisdak, 2000), for TNT explosives at open storage and actual altitude 523 m and temperature 20°C.

a **b**

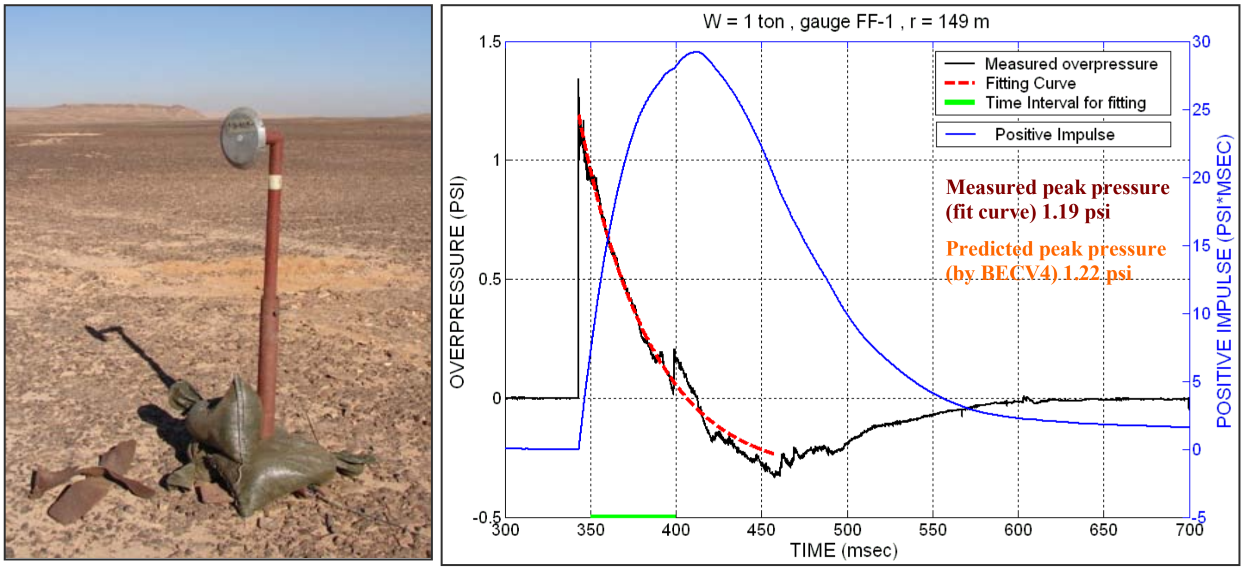

Figure 9. The closest high-pressure gauge FF-1 at 149 m from the 1 ton explosion (a), and the appropriate record (b). Predicted peak pressure is obtained by BECV4 for 1.04 ton TNT.

Table 6. High pressure measurements for the 1 ton explosion and predictions by BECV4 for the 1.04 ton TNT charge, altitude 523 m, temperature ~20°C.

Gauge	**Distance m**	**Peak overpressure, psi**			**Positive Phase Duration, msec**			**Positive Phase Impulse, psi*msec**		
		predicted	measured		predicted	measured		predicted	measured	
			Abs. Max	Fit curve		Actual	Fit curve		Actual	Fit curve
FF-1	149.4	1.22	1.34	1.19	55.7	68.8	64.5	29.9	29.2	28.5
FF-2	202.0	0.83	1.45	0.85	61.0	67.4	69.3	22.3	23.0	22.7
FF-3	199.4	0.85	1.35	0.90	60.7	82.8	71.8	22.6	21.9	21.8
FF-4	244.4	0.66	0.69	0.62	64.2	72.8	74.1	18.5	17.7	17.7

Due to some irregularities in the high-pressure time history (especially in the beginning of the signal), we estimated the time history using an exponential function. This yielded a more reliable estimation of the peak overpressure and positive phase duration values (see Figure 9b).

All measured peak pressure and impulse values correspond approximately to estimations of equivalent TNT (Table 6). Negative factors, such as inhomogeneity of the charges, variety of explosive types, and numerous air voids in the charge body, were compensated by a higher-than-TNT explosive energy for Composite B and RDX, and by the upward detonation.

Cratering effects observed for surface explosions can be considered an indicator for explosive energy partitioning between seismic waves in the ground and acoustic waves in the atmosphere. A striking distinction was found for the experimental project explosions at SMR with charges equivalent to 1 ton of TNT and Composite B with different detonation directions. For two explosions in Series 2 (TNT and Composite B), conducted in June 2008 (Gitterman and Hofstetter, 2008), the boosters were placed on the top of the charge (Figure 10a), providing the downward detonation. Both explosions produced large, deep (~0.5 m) craters (a little deeper for the explosion with more powerful Composite B) (Figure 10b). As presented above, the downward detonation was applied to the 1 ton explosion in December 2008, resulting in a very small shallow crater (Figure 10c, d). In the explosion area, the subsurface layer of ~0.5-1 m consists of powder, loose sediments, with consolidated sediments below.

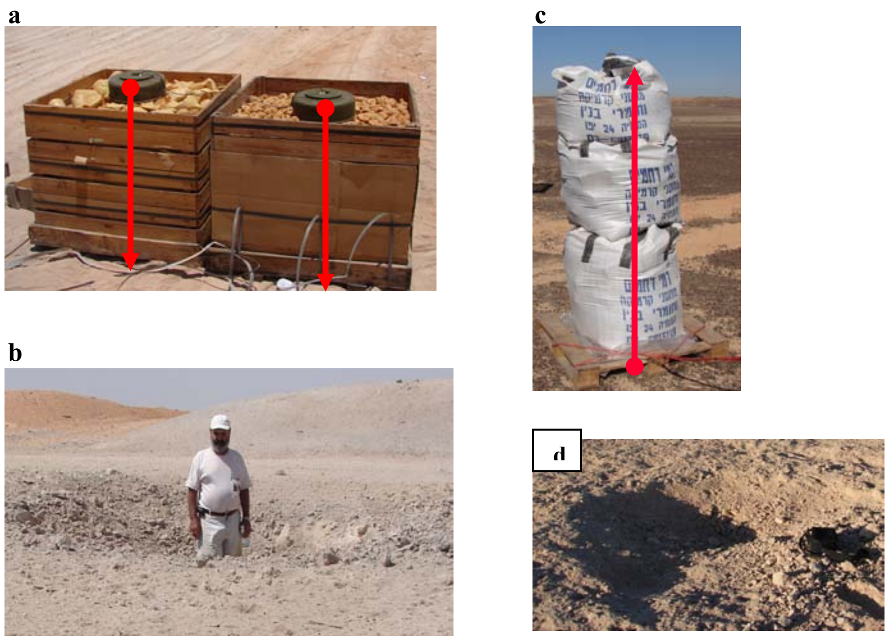

Figure 10. Cratering effects for two explosions in June 2008 at SMR of 1 ton TNT and Composite B, where downward detonation (a) created a large deep crater (b), and upward detonation, in December 2008 (c), produced a very small shallow crater (d).

A smaller crater for the upward detonation shows that more explosive energy was released to the atmosphere, and less energy was focused into the ground, compared to the downward detonation. Based on high-speed video and high-pressure observations, the TNT equivalency for the variety of charges (e.g., recuperated explosives) was proven, and the efficiency of the upward detonation and the charge design were also confirmed by cratering features.

Modeling of Long-Range Atmospheric Propagation of Infrasound in Mediterranean Region.

Preliminary modeling of the long-range atmospheric propagation of infrasound was conducted by the ISLA team using global G2S atmospheric profiles and local data collected for this experiment (Figure 11). These calculations demonstrated favorable conditions for infrasonic propagation in the Mediterranean in the western direction in the summer months (Figure 12). This was confirmed for the Sayarim explosions of ~10 tons and 1 ton in June 2008, which were well observed at IMS station I48TN (Figure 7). In the opposite direction, for similar explosions of 1 ton and 5 tons in December 2008 (Table 5), no signals were found at this station, indicating the effect of the change in stratospheric winds on regional propagation.

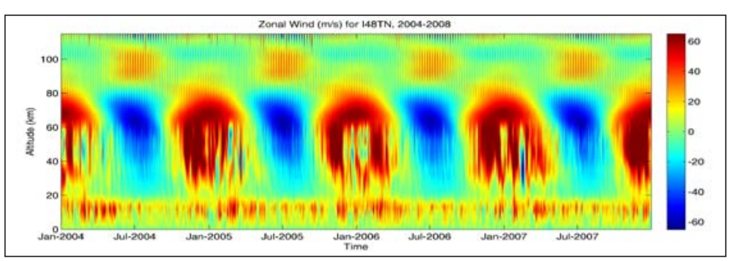

Figure 11. Atmospheric profile data (altitudes 0-140 km at 6 hr increments) for the direction to I48TN, for four recent years.

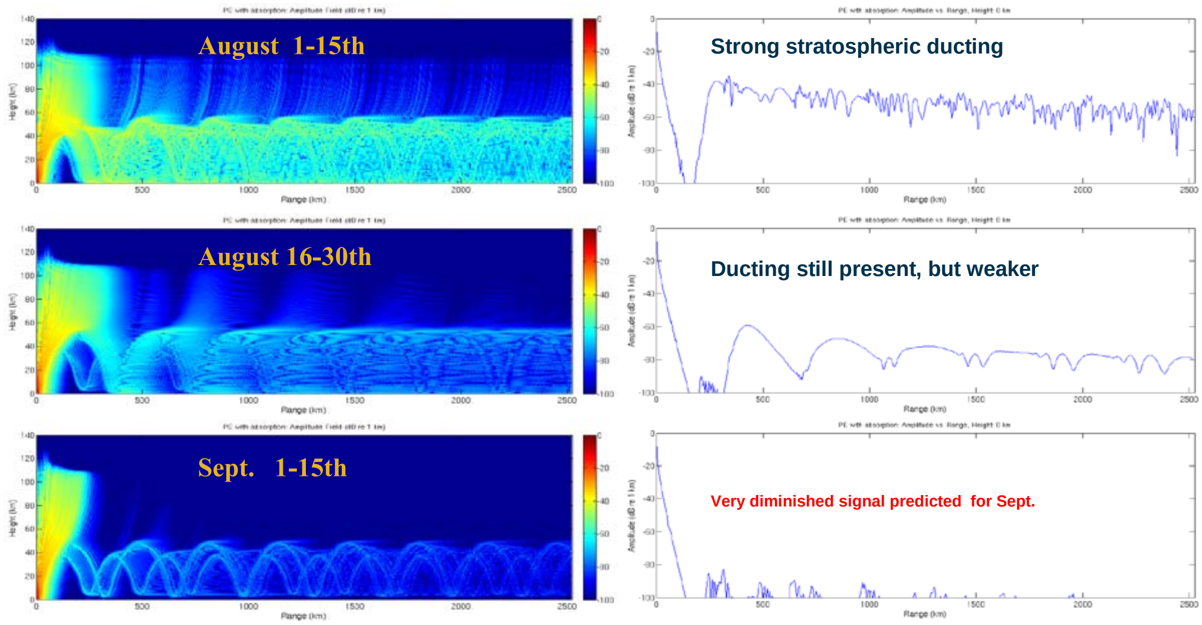

Figure 12. Average profile for infrasound propagation modeling for I48TN (Tunisia) at different periods.

Optimal date and time windows of the experiment and locations of portable infrasound systems in the Mediterranean region were selected (Figure 13) based on the following experimental and infrasound modeling results:

- Stratospheric easterly winds die out by early September:
  - Decreasing probability of detection for long-range westward stations past July;
- Cyprus station not as affected by prevailing stratospheric winds (due north location):
  - Stations from Crete to the west have likely stratospheric arrivals in July/August;
- Minor contribution from meridional (N-S) winds for all locations;
- Two week averages produce more reliable atmospheric models;
- Late night/early morning shot times give highest probability for detection:
  - Lowest ambient noise conditions,
  - Tropospheric Nocturnal Duct, and
  - Lowest effective sound speed at surface.

Based on atmospheric (wind) conditions and modeling of infrasound propagation to large distances, and also on the logistics of conducting the explosion and station deployment, the main explosion date was determined to be on August 26, 2009, the detonation time window: 6AM-9AM (local time), and possible locations of portable infrasound systems in the Mediterranean region were selected and surveyed (Figure 13).

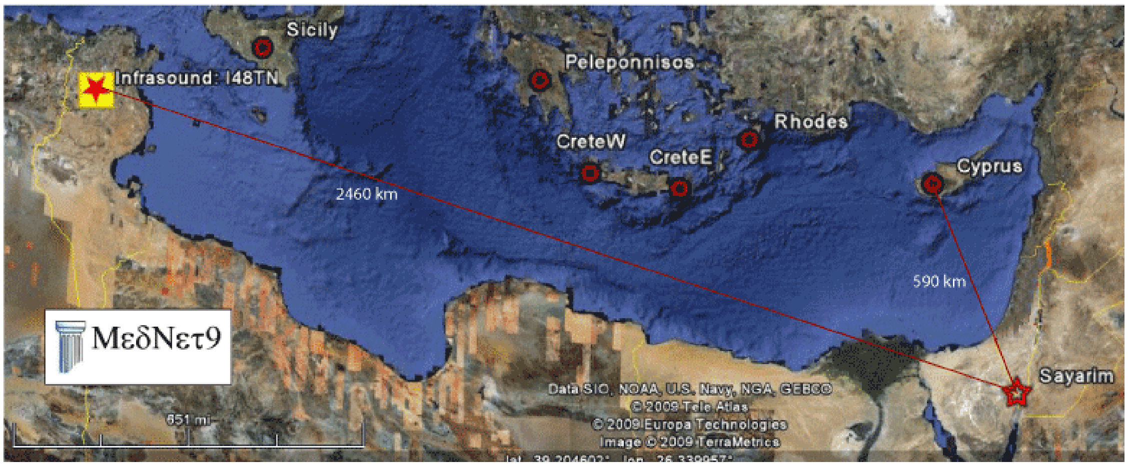

Figure 13. Planned portable deployment of infrasound arrays in the Mediterranean region during the Sayarim Calibration Explosion. Sites are also being considered in Turkey.

CONCLUSIONS AND RECOMMENDATIONS

- GII microphone sensor systems were calibrated at ISLA; frequency response and sensitivity were defined;
- Observations of rather small Sayarim explosions at the two closest IMS stations indicate the likely recording of the main calibration explosion at four and more IMS stations, placed at distances more than 3500 km;
- The conducted experimental explosions helped determine explosive feasibility, charge design, and assembly procedures for the main explosion; the TNT equivalency for the charges consists of a variety of recuperated explosives, and efficiency of upward detonation;
- Modeling of long-range atmospheric propagation of infrasound in the Mediterranean region provided a basis for the selection of the detonation time window of the main calibration explosion, and locations of long-range portable stations.

ACKNOWLEDGEMENTS

Thanks to blast manager Kobi Shimon of Elita Security Ltd. and his team for conducting the experimental explosions. E. Stampler and the team of IDF Experiment Division provided high quality video-recording and high-pressure measurements. We appreciate the valuable support and help of Dr. D. Havatzelet of the Israel Ministry of Defense in providing the experiment measurements. Thanks to GII personnel U. Peled for preparation and installation of portable stations and N. Perelman for processing and analysis of high-pressure records.

REFERENCES

Gitterman Y. and R. Hofstetter (2008). Infrasound Calibration Experiment in Israel: Preparations and Test Shots, in *Proceedings of the 30th Monitoring Research Review: Ground-based Nuclear Explosion Monitoring Technologies*, LA-UR-08-05261, Vol. 2, pp. 882–893.

Pinsky V., A. Polozov, D. Kadosh, A. Avirav, and R. Hofstetter (2007). New seismic system for acquisition and analysis in Israel. Abstracts of XXIV General Assembly of IUGG, July 2–13, 2007, Perugia, Italy.

Swisdak M. (2000). DDESB Blast Effects Computer, Version 4.0.