Time reversal acousto-seismic method for land mine detection

Alexander Sutin*[a, c], Paul Johnson[b], James TenCate[b] , Armen Sarvazyan[c]
[a]Artann Laboratories, Inc., 1457 Lower Ferry Road, Trenton, NJ, USA 08618
[b]Los Alamos National Laboratory, Los Alamos, Mail Stop D443,NM, USA 87545
[c]Stevens Institute of Technology, Hoboken, NJ, USA 07030

ABSTRACT

We present the general concept and results of a pilot study on land mine detection based on the application of Time Reverse Acoustics (TRA). Applying TRA is extremely effective at focusing seismic waves in time and space, significantly improving detection capabilities using both linear and nonlinear wave methods. The feasibility of the system was explored in the laboratory and in small scale field experiments. The system included a multi-channel TRA electronic unit developed at Artann, five speakers for seismic-wave excitation and noncontact (laser vibrometer) or contact (accelerometer) devices for measurements of the surface vibration. Experiments demonstrated the high focusing ability of the TRA system. We observed excitation of highly focused seismic waves in an area with dimensions of the order of one wavelength. In the presence of a buried mock mine, the method led to an increase in the surface vibration amplitude and to significant nonlinear distortion of the TRA focused signal. Localization via TRA depends on the frequency of excitation, the depth of the buried mine, and the form and size of a mine mock. The nonlinear acoustic effect – higher harmonic generation – provides higher contrast for the mock-mine signal-response than for the surrounding medium. We also successfully tested an inversion method of the nonlinear TRA measurements earlier developed for medical ultrasound applications.

Keywords: land mine detection, Time Reversal Acoustics, nonlinear acoustics

1. INTRODUCTION

The importance and complexity of mine detection fuels numerous efforts to develop reliable detection methods. There are now over 750 types of land mines, ranging in sophistication from simple pressure-triggered explosives to more complex devices that use advanced sensors. It is estimated that there are currently about 127 million land mines buried in 55 countries [1]. Land mines cause some 26,000 injuries and deaths each year.

Current conventional detectors and ground-penetrating radars rely mostly on detecting the metallic materials contained in landmines. The continuous struggle to negate the advances of the other side has led manufacturers to mass-produce non-metallic mines. Both types can be detected by acousto-seismic methods. These methods utilize an acoustic/seismic approach, which operates by creating an acoustic or seismic wave in the ground that reflects off the mine. This energy can be delivered in a number of different ways such as a loudspeaker, a seismic source coupled to the ground, and a laser striking the ground over the mine. In addition, there are different ways of receiving the signal from the target (electromagnetically through a Doppler radar or Doppler laser device, or acoustically, through a microphone). An acoustic system is one of the technologies that the Army is currently exploring for the Ground Stand-off Mine Detection System (GSTAMIDS)[1].

Established research in the acoustic-seismic method of mine detection is currently being conducted at the Center of Physical Acoustics, University of Mississippi, by a team headed by James Sabatier [2-5]. In a recent initial round of tests they detected 100 percent of the antipersonnel and antitank mines without a single false alarm. The system uses sound waves and laser beams to scan the ground's surface and identify vibration patterns produced by buried mines. The high frequency seismic technique of mine detection in combination with electromagnetic receiving system was developed at Georgia Tech [6].

Detection and Remediation Technologies for Mines and Minelike Targets X, edited by Russell S. Harmon, J. Thomas Broach, John H. Holloway, Jr., Proc. of SPIE Vol. 5794 (SPIE, Bellingham, WA, 2005) · 0277-786X/05/$15 · doi: 10.1117/12.609838

The problem one encounters with acoustical methods is distinguishing a land mine that is near some dense material such as an isolated cobble or group of cobbles. It is known that land mines are highly *elastically-nonlinear*. Nonlinear methods of land mine detection have been developed based on mines' nonlinear properties [7-9]. The nonlinear acoustic method utilizes the excitation of two frequency waves, that interact with the top surface of the mine, producing a different vibration frequency than the ground near the mine. This method provides the means to detect plastic antitank and antipersonnel mines.

Seismic waves, produced by a speaker or vibrator, propagate radially from the source and their amplitude dramatically decreases with distance. Only a fraction of the radiated acoustic or seismic energy reaches a mine unless the source is very close. In fact, if the source is placed at some distance from the mine, the amplitude of the induced mine vibration may be too small to produce nonlinear acoustic effects for application of nonlinear methods or, for that matter, to locate a mine using linear methods. It is known that nonlinear acoustic effects can be observed only when the level of the mine vibration is sufficiently high. This means that the source of the soil vibration has to be powerful and must be placed near mines in order to detect them, which highly limits the area of detection.

Recent work in Time Reversal Acoustics (TRA) demonstrates a new, effective way to focus acousto-seismic energy in time and space. This area of study has garnered much attention based on work by the team headed by M. Fink at the University of Paris VII [10 -12] who demonstrated the spatial control and focusing of an ultrasonic beam in inhomogeneous media using TRA. TRA can provide a high concentration of acoustic wave energy at any desired point and can detect a mine due to the high nonlinearity the mine produces (in contrast to a rock, for instance). Focusing via TRA in combination with fast scanning will allow mines to be detected from greater distances than can be done by common acousto-seismic systems. It will also increase the probability of detection. The results of the first research in TRA application for land mine detection are published in [13,14].

Figure 1 illustrates the concept of the TRA approach showing one of the possible implementations of the technology.

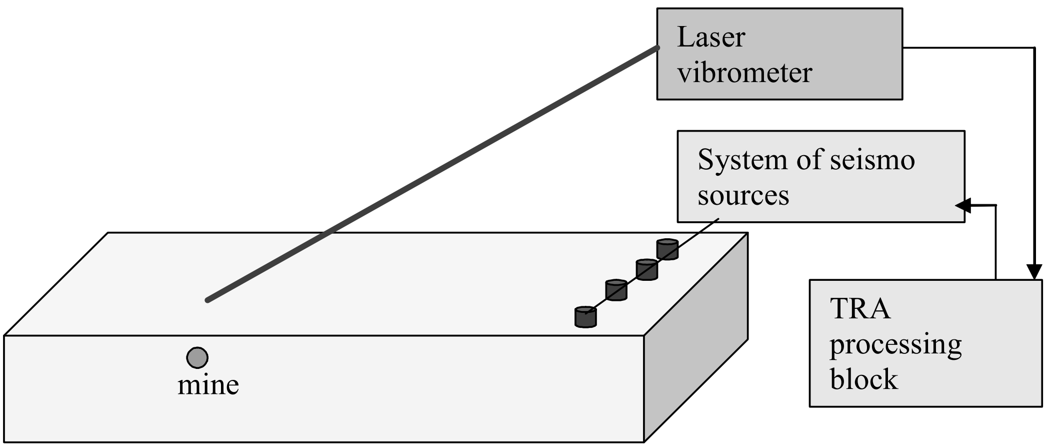


Figure 1: The concept of a TRA system for land mine detection.

The system would work in the following manner: A laser vibrometer, which measures wave displacement, would be pointed towards some location on the surface. A short acoustic toneburst signal is radiated by an acoustic or seismic source. The propagated signal is received by the laser vibrometer, time reversed, and stored in the memory of the TRA processing block. The same process is repeated for the second source, the third and so on. After all the TRA signals are collected they are re-radiated simultaneously. The radiated signals are concentrated in time and space at the measurement point. If there is a mine at the focal point the received signal has a different amplitude that without a mine and a high level of high harmonics due to the elastic nonlinearity of the mine. One could scan an entire region relatively quickly in order to extract a 2-D mapping.

2. DEVELOPMENT OF A MULTI-CHANNEL TRA SYSTEM FOR LAND MINE DETECTION

The existing multi-channel TRA system developed by us consists of a TRA electronic unit with a microphone preamplifier (Tube Ultragain Mic 100) and a six channel power amplifier (KLH Audiosystem, Dolby Digital EX6.1 Surrounding Receiver, R7000).

Figure 2 shows the setup for a small scale field experiment, comprised of the TRA electronic unit, a six channel power amplifier, six speakers (each box contains two speakers) and contact accelerometers as receivers.

Figure 2. General view of the small scale experimental setup: 1) TRA electronic unit. 2) A microphone preamplifier. 3) Six channel power amplifier. 4) Speakers. 5) Accelerometers.

Specifications of the TRA system developed by us are presented in Table 1.

Table 1. Specifications of the TRA system for acousto-seismic measurements.

Receiver channel	**Transmitter channel**	**Synchronization signal generator**
Sampling rates: 60kHz-1MHz Record length: 32768 points Amplitude Resolution: 16 bits after averaging. Frequency band: 20 –25000 Hz. Data transfer speed to PC: 1 MB/s	Number of channels: 6 Peak output power of each radiation channel: 50 W Sampling rate: 60 kHz - 1MHz Radiation duration: 32768 points Amplitude Resolution: 8 bits. Data transfer speed from PC: 1 MB/s	Repetition frequency: 0.5-5 Hz.

The data acquisition and processing software and the user interface of the TRA system provides control of a sequence of steps necessary for TRA signal processing. These steps include:

Step1. Application of short initial pulsed signal to the first transducer. The initial pulse is provided by loading an arbitrary waveform initial pulse. The program has a built-in signal generator with a library of the most common pulses used for the initial signal. The amplitude and frequency of the signal radiated by any channel can be changed independently. Thus the system can produce different initial signals for different channels that can be used for the investigation of the nonlinear interaction of signals with different frequencies.

Step 2. Recording of the received acoustic signal. The signal from the receiving sensor is amplified by the signal preamplifier having variable gain that provides a record of the signal in the range from 1mV to 1V. A high signal-to-noise ratio in the recorded signal is achieved by averaging the recorded signal and by band pass filtering. The number of averaging iterations and the filtering frequency band are set in the user interface. A useful feature implemented in the software is the possibility to select and eliminate portion(s) of the received signal that can disturb TRA focusing. For example, this feature can be used to eliminate the direct electromagnetic signal from the power amplifier.

Step 3. Amplification, time reversal, and normalization of the recorded signals. The normalization maintains the same amplitude for all radiated signals. The time reversal signals are kept in the memory of the TRA electronic unit and can be radiated simultaneously by all transmitters or by any combination of transmitters.

Step 4. Radiation of Time Reversal signal. The TRA signal is applied simultaneously to all 5 channels of the TRA system output. The signals are amplified by the power amplifier (Block 3 in Fig.2) and are radiated by the speakers. The amplitude of the radiated signal can be changed for any channel independently from 0.1 to 50 V (peak to peak).

Step 5. Recording and analyzing the TRA focused signal. The TRA focused signal is then recorded and analyzed by the same electronic part of the system that is used for recording the initial signal. The recorded signals are transferred to the PC for further processing.

Examples of the signals for test conducted in a laboratory sand box are shown in Fig. 3 where a speaker was used for wave excitation and a contact accelerometer was used for receiving.

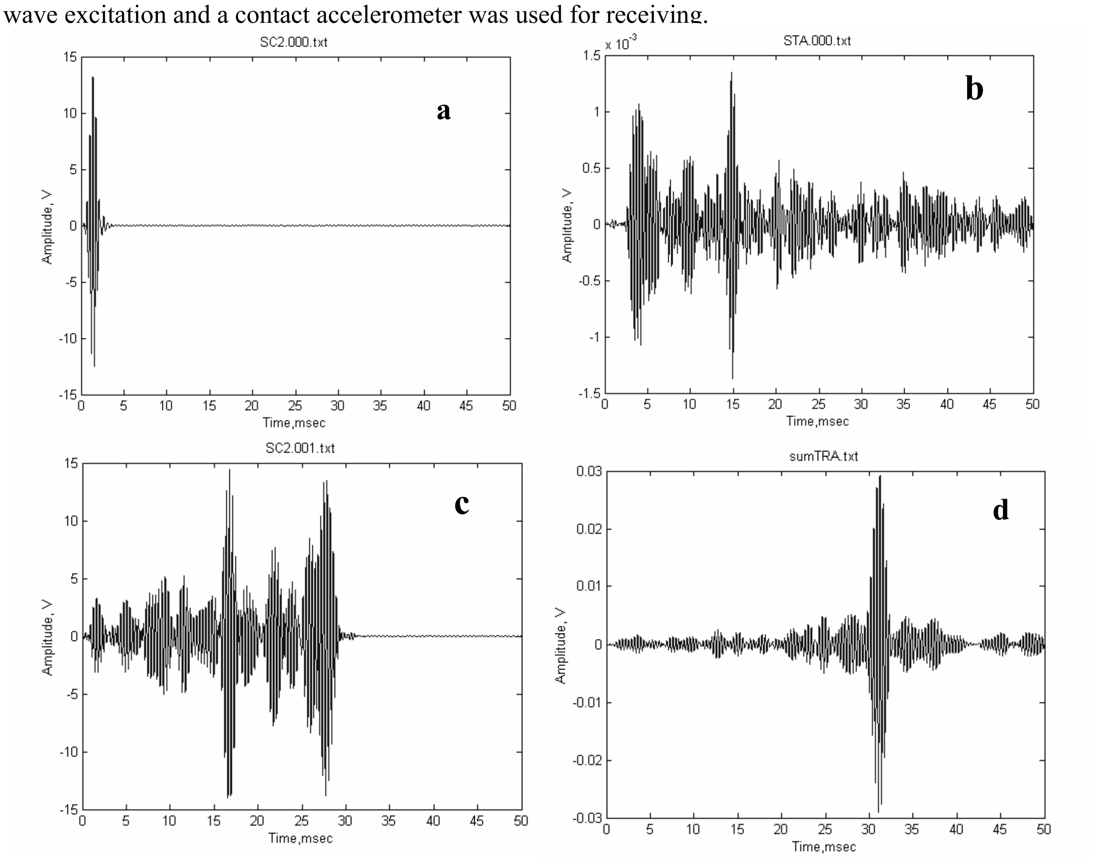


Figure 3. . Snap shots of the signals illustrating TRA focusing: a) initial R.F. signal with carrying frequency 2.8 kHz (step 1), b) direct received signal (step 2) , c) TR signal applied to the speaker (step 4) , d) TRA focused signal measured by the accelerometer (step 5).

3. DEMONSTRATION OF TRA SIGNAL FOCUSING

The laboratory and small field tests were conducted using the contact accelerometer and Laser Doppler Vibrometer to measure the surface vibration. The distance between the speakers and the focal point was up to 4 m in experiments where the contact sensor was used. We observed a very narrow focal region of the TRA system, on the order of one wavelength. Figure 4 shows spatial distribution for frequency 2.9 kHz obtained in laboratory experiment using contact accelerometer for signal receiving. The measurements of the TRA focused field structure in two spatial dimensions and one temporal dimension demonstrated that the TRA system provides a high concentration of seismo-acoustic signal energy in time and space.

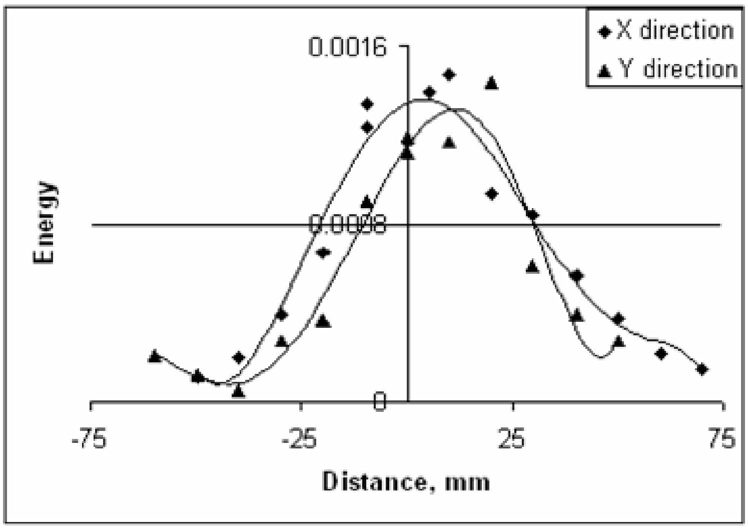


Figure 4: The spatial distribution of TRA focused signal for the frequency of 2.9 kHz. The half-power width of the signal is about 1.5 wavelengths.

Following these positive results, field experiments in topsoil, clay, gravel and grass were more challenging. Fig.5 shows the spatial distribution of the TRA focused signal for 3 frequencies. There are fluctuations of the signal amplitude due to contact conditions between the accelerometer and the ground surface. The width of the focal area is about 300 mm, which in on the order of 2-3 wavelengths. Nonetheless, the method works surprisingly well in normally adverse conditions for acoustical methods.

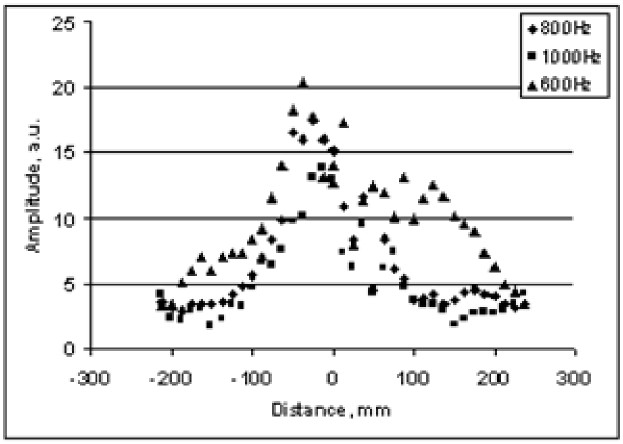


Figure 5. The spatial distribution of amplitude of the TRA focused signal applying different frequencies for a small scale field test.

4. VARIATIONS OF TRA SIGNAL PARAMETERS IN THE PRESENCE OF MOCK MINES

Laboratory and small scale field experiments demonstrated that the presence of a buried mock mine leads to an increase in surface vibration amplitude and to the nonlinear distortion of the TRA focused signal. These variations depend on the frequency of excitation, the depth of the buried mock, and the form and size of mock. Examples of the initial and TRA focused signals measured in small scale field conditions are shown in Fig.6. The TRA focused signal spatial profile was measured along the line crossing the buried mock. The mock was buried at 15 mm and the distance from the speakers was about 80 cm. Six successive pulses with carrier frequencies of 450, 600, 800, 1000, 1200, 1400 Hz were fired in a single shot (Fig. 6b). Not surprisingly, the low frequency band (450 Hz) provided the most sensitive detection of the mock due to its lower wave attenuation. The presence of the mock resulted in a 1000% amplitude change of the signal, as is shown in Figure 6.

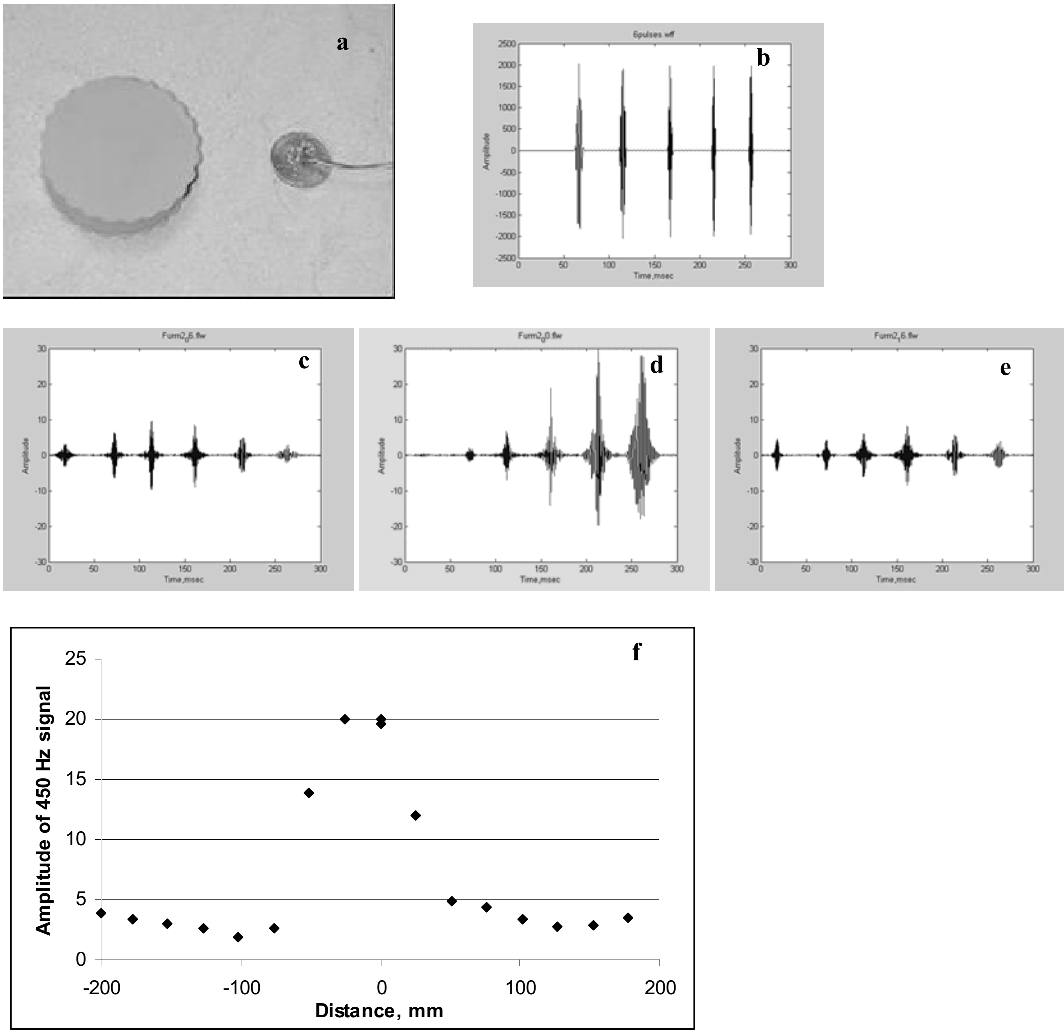


Figure 6. Illustration of the TRA focused signals in the presence of the buried mock, with a diameter of 55 mm (panel **a**). Panel **b** shows the initial sequence of multifrequency transmitted signals. Panels **c** and **e** show the TRA signal from a distance of about 200 mm on both sides of the mock, and panel **d** is the signal recorded above the mock. Panel **f** presents the spatial distribution of amplitude of the TRA focused pulse with frequency of 450 Hz. The maximum value of the signal is observed at the point corresponding to the point above the mock center.

The nonlinear acoustic effect – higher harmonic generation – provides an even higher contrast for the mock signal. The nonlinear TRA method has been tested previously for crack detection in solids [15-16]. The level of the second and third harmonics in the presence of the mock exceeded the background level by a factor of ten. Fig.7 shows the variations of the harmonic level in the TRA signal applying the frequency of 450 Hz for different burial depths of the mock.

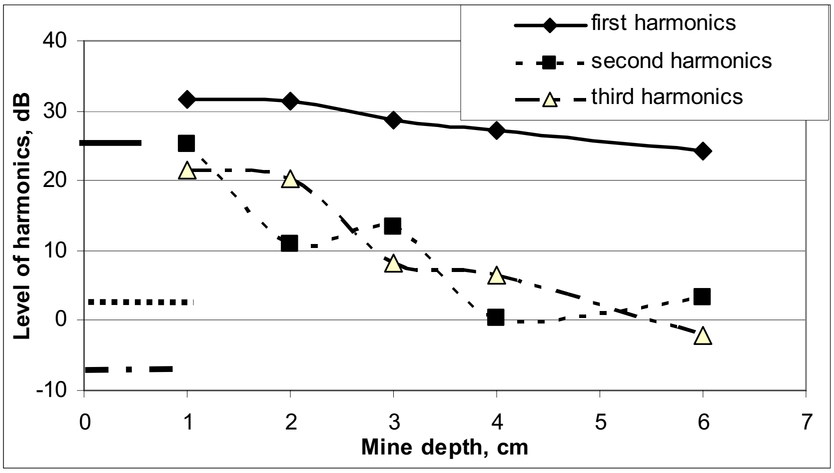


Figure 7. Variations of the level of harmonics in the TRA signal applying a frequency of 450 Hz for different burial depths of the mock. The horizontal lines left show the harmonic levels at the sediment surface without the mock.

5. NEW METHODS FOR IMPROVEMENT OF TRA RADIATION SYSTEM AND OBSERVATION OF NONLINEAR EFFECTS

Several new methods improving ability of TRA system of land mine detection were suggested and tested.

5.1. A 2-bit method of TRA signal generation

A 2-bit method of TRA signal generation was developed to provide higher amplification of the TRA focusing system. This method is based on compensating for acoustic attenuation and is a modification of the 1-bit method suggested by Dr. Fink and collaborators [12]. The 2-bit method was implemented in the developed TRA system and experiments demonstrated that it increases TRA signal amplitude by a factor of two. The increase of the signal amplitude makes the method more robust.

We investigated a method for increasing the amplitude of the TRA focused signal similar to that developed by Fink in the TRA system used for destroying kidney stones [12]. In Fink's experiment, instead of a complex waveform of the time reversed signal, a simple, two-level signal was used and the following time-reversed signal, $s(t)$, was generated: $+V$ if $s(t)>0$, and $-V$ if $s(t) < 0$, where V is the maximum amplitude of the input signal. This method worked perfectly in the case of a low attenuating media. Seismic waves, however, are highly attenuated, so a modification of Fink's approach was necessary. We introduced the 2-bit regime, where the TRA signal $U(t)$, with a maximum amplitude U_{max}, was transformed to a signal U_{2bit} according to the following expressions:

$$U_{2bit} = -U_{\max} \ if \ \ U \le -A$$
$$U_{2bit} = U_{\max} \ if \ \ U \ge A$$
$$U_{2bit} = 0 \ if \ -A < U < A$$

$$A = \alpha U_{\max}$$

The comparison between conventional TRA focusing and the 2-bit regime of TRA focusing was conducted under laboratory conditions in the sandbox using the new 5 channel TRA system. The efficiency of the 2-bit TRA focusing as a function of the threshold parameter α was investigated. The results of this study are presented in Figures 8 and 9.

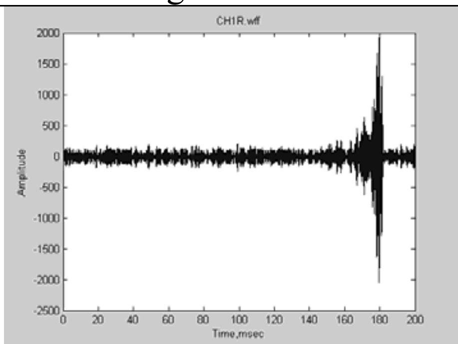
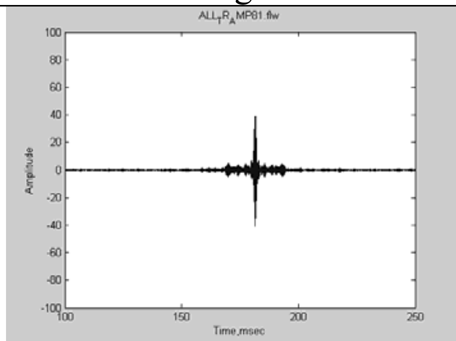
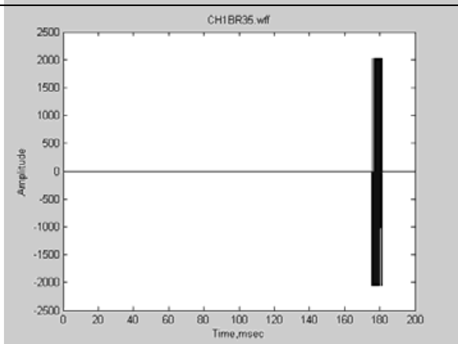
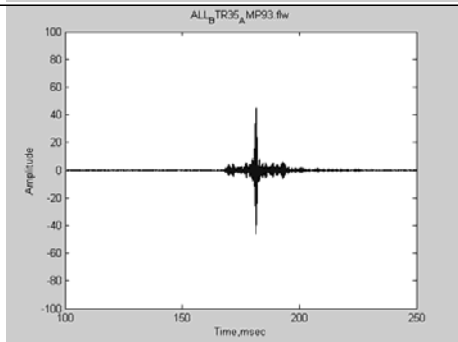
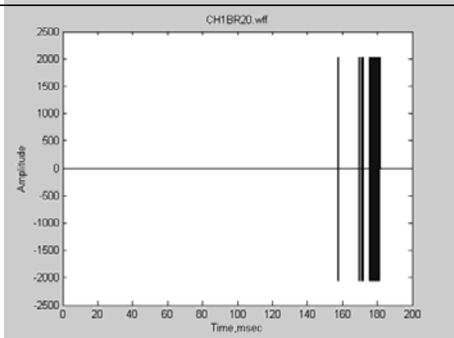
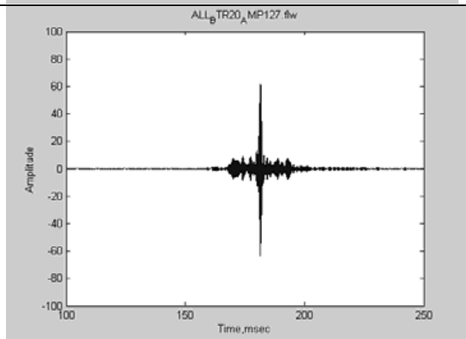
<table>
<tr><td></td><td>Radiated signal</td><td>TRA focused signal</td></tr>
<tr><td>Standard TRA focusing</td><td>
</td><td>
</td></tr>
<tr><td>Two-bit regime of TRA focusing (α=0.35)</td><td>
</td><td>
</td></tr>
<tr><td>Two-bit regime of TRA focusing (α=0.2)</td><td>
</td><td>
</td></tr>
</table>

Figure 8. Comparison of TRA focusing in the standard mode and the 2-bit regimes at different values of the threshold parameter α. Carrier frequency of the initial signal is 4 kHz

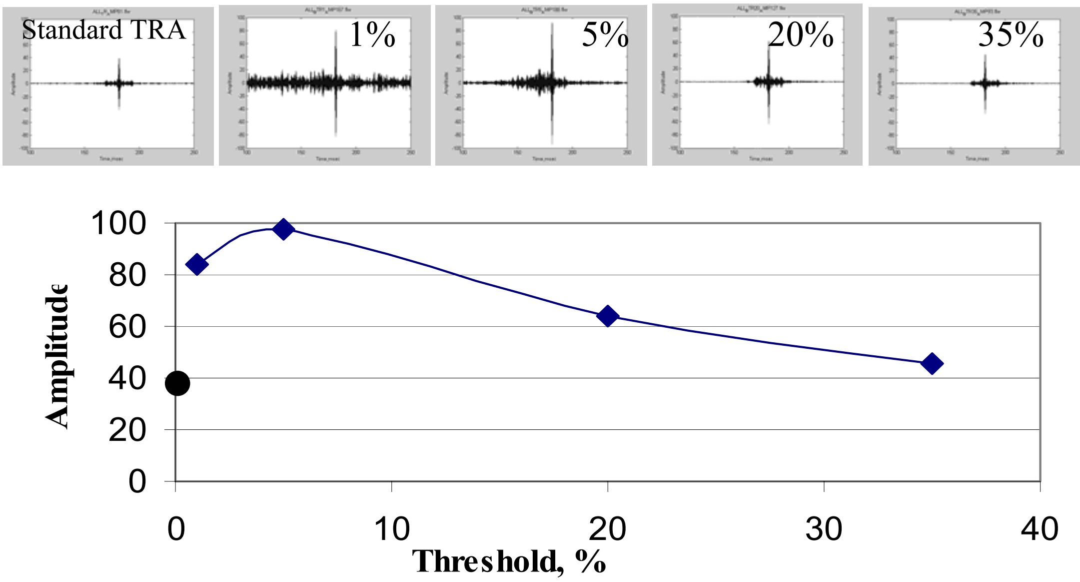


Figure 9. TRA focusing in the 2-bit regime at different values of the threshold parameter α. Panels at the top represent the TRA focused signal at different values of α. Dot on the y axis shows the TRA signal amplitude obtained using the standard TRA approach.

For the conditions of the experiment illustrated in Fig. 9, the 2-bit regime at the optimum value of α leads to a two-fold increase in the amplitude of the TRA focused signal. At the values of α below the optimum, a dramatic increase in noise and the appearance of side lobes in the generated acoustic field were observed. In summary, the 2-bit method demonstrated that it increases TRA signal amplitude by a factor of two. The increase of the signal amplitude makes the method more robust.

6.2. Phase-inversion method for detection of nonlinear response of the buried mine

The conventional nonlinear acoustic method of mine detection is based on the use of two acoustic beams having different frequencies and detecting the difference frequency generated in the presence of the mine. We have tested an alternative method of nonlinear mine detection – the phase-inversion method – which potentially could be more sensitive than the conventional technique. This method was initially proposed for medical applications of nonlinear acoustics [17].

The idea behind the method is that distortions in the acoustical signal caused by nonlinearities in a medium are different for two "mirrored," transmitted pulses as illustrated in Fig. 10. The acoustic source transmits the signal $U(t)$ and the inverted signal $-U(t)$. The received signals are distorted due to medium nonlinearity. These signals are recorded for further analysis in a computer. This analysis is very simple: normalizing and summing the received direct and inverted signals. In the absence of nonlinearity, the sum of the received signals is close to zero. In the presence of nonlinearities, the amplitude of the sum is proportional to the level of nonlinearity in the tested medium. This method has a higher sensitivity than the conventional method of nonlinearity detection based on spectral analysis. The greatest advantage of this method with regard to mine detection is its ability to use a short pulse signal.

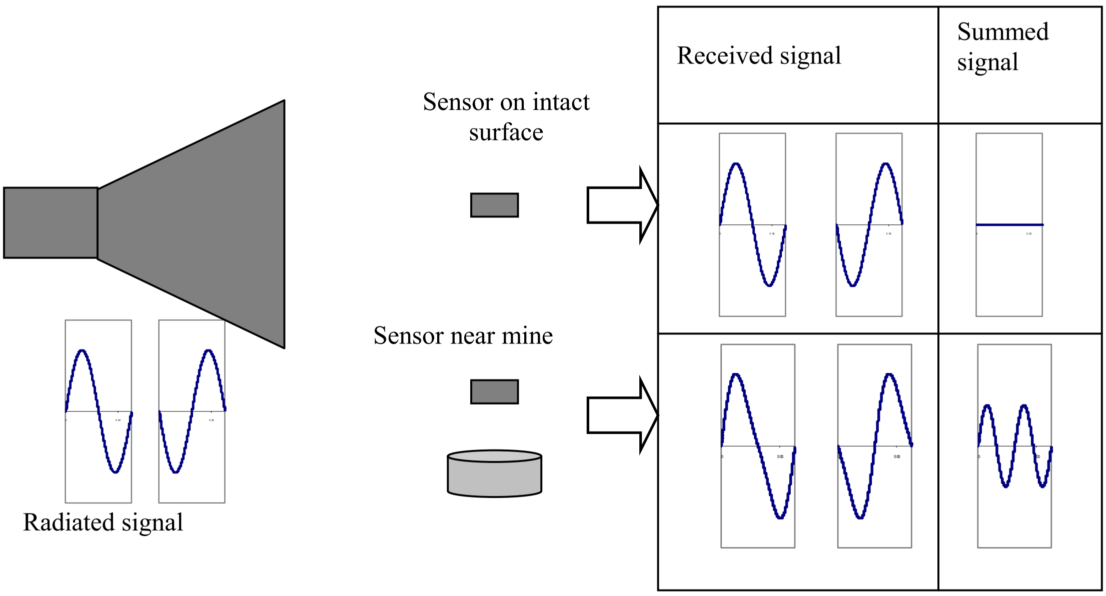


Figure 10. Illustration of the concept of the phase inversion method of nonlinear distortion measurements.

The phase-inversion method was incorporated into the five channel TRA system used in the small scale field test. In this test, the distance between the speakers and the mine imitator was 80-100 cm. The results of this test are presented in Fig. 11. This figure shows the sum of the phase-inversion signals recorded for the sensor placed on the intact sand and above the mock buried at two different depths. The successive, six pulses had carrier frequencies of 450, 600, 800, 1000, 1200, 1400 Hz. After the time reversal procedure, the TRA focused signal frequencies were recorded in reverse order, so the first pulse in Fig. 32 has a frequency of 1400 Hz and the last pulse has a frequency of 450 Hz. The plots show that the nonlinear part of the signal is most prominent in the low frequency band (450-800Hz).

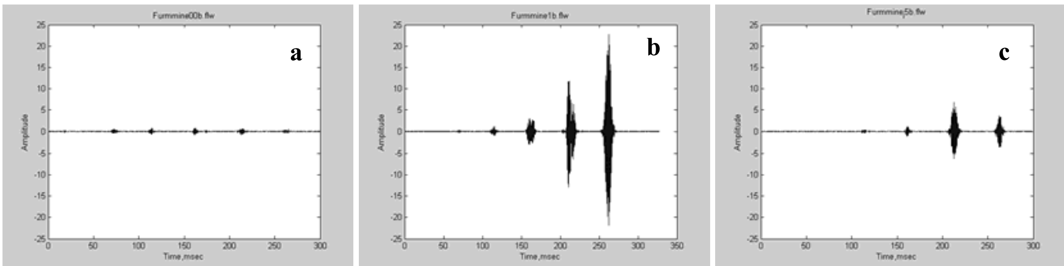


Figure 11. Results of testing the phase inversion method in the TRA based nonlinear mine detection. Panel **a** shows the sum of the direct and inverted signals measured on the intact ground, panel **b** shows the signals above the mock buried 10 mm deep and panel **c** is the signal for the mock buried 50 mm deep. The increased amplitudes of the signals shown in panels b and c indicate the nonlinearity connected with the mock vibration.

ACKNOWLEDGEMENTS

Work was supported by US Army RDECOM CERDEC Night Vision and Electronic Sensors Directorate.

REFERENCES

1. GAO-01-239 Land Mine Detection. Report to the Chairman, Subcommittee on Military Research and Development, United States General Accounting Office, Committee on Armed Services, House of Representatives, April 2001.
2. Xiang, N. and Sabatier, J. M. An experimental study on anti-personnel landmine detection using acoustic-to-seismic coupling. *J. Acoust. Soc. Am.,* 2003, 113, 1333-1341.
3. Xiang, N. and. Sabatier J. M. Land mine detection measurements using acoustic-to-seismic coupling. *Proc. SPIE*, A. C. Dubey, Ed., Orlando, FL, 2000, 645–655.
4. Arnott, W. P and. Sabatier, J. M. Laser-Doppler vibrometer measurements of acoustic to seismic coupling. *Appl. Acoust.,* 1990, 30, 279–291,.
5. Sabatier, J. M and Xiang, N. Laser-Doppler based acoustic-to-seismic detection of buried mines. *Proc. SPIE*, A. C. Dubey, Ed., Orlando,FL, 1999, 215–222.
6. Gregg, D. Larson, G.D., Martina, J.S., Rogersa, P.H. Scott, W.R, Jr., and McCall, G.S. Impact of nonlinear effects on a high-frequency seismic landmine detection system. *The Fifth International Symposium on "Technology and the Mine Problem"* Naval Postgraduate School in Monterey, CA, April 22-25, 2002.
7. Donskoy, D., Ekimov, A., Sedunov, N. and. Tsionskiy, M. Nonlinear seismo-acoustic land mine detection and discrimination. *J. Acoust. Soc. Am.,* 2002, 111 (6), 2705-2714.
8. Donskoy, D.M. and Sutin, A.M. Method and apparatus for acoustic detection of mines and other buried man-made objects *United States Patent* # 6,134,966. Issued Oct.24, 2000.
9. Donskoy, D.M. and Sutin A.M. Method and apparatus for acoustic detection of mines and other buried man-made objects *United States Patent* # 5,974,881, Nov. 2, 1999.
10. Fink M., Cassereau D., Derode A., Prada C., Roux P., Tanter M., Thomas J.-L., Wu F. Time-reversed acoustics. *Rep. Prog. Phys.* 2000, 63, 1933–1995
11. Fink M. Time reversed acoustics. *Scientific American*, 1999, 91-97.
12. Montaldo, G, Roux, P, Derode, A, Negreira, C, Fink M. Generation of very high pressure pulses with 1-bit time reversal in a solid waveguide. *J Acoust Soc Am,* 2001, 110, 6: 2849 – 2857.
13. Norville, P.D., Scott, W.R. Jr., Gregg D. Larson, G.D. An investigation of time-reversal techniques in seismic landmine detection. *Proc. SPIE*, 2004, 5415, 1310-1322.
14. Sutin, A., .Sarvazyan, A., .Johnson, P. and .TenCate, J. Land mine detection by time reversal acousto-seismic method. *J. Acoust. Soc. Am.,* 2004, 115, 5, 2384
15. Sutin, A.M., TenCate, J. and Johnson, P.A.. Application of nonlinear time reversed acoustics to isolate cracks in solids. *Ultrasonic International 2003*, Granada, Spain, Elsevier Science, 2003, 3.62D.
16. Sutin, A., Johnson, P. and Tencate, J., Development of NonLinear Time Reversed Acoustics (NLTRA) for applications to crack detection in solids, *Processing of World Congress on Ultrasonics,* September 7-10, 2003, Paris, pp. 121-124.
17. Krishnan, S. and O'Donnell, M. Transmit Aperture Processing for Nonlinear Contrast Agent Imaging, *Ultrasonic Imaging,* 1996, 18, 2, 77-105.