GEOPHYSICAL RESEARCH LETTERS, VOL. 32, L01308, doi:10.1029/2004GL021660, 2005

Toward noncontacting seismology

K. van Wijk, J. A. Scales, T. D. Mikesell, and J. R. Peacock
Physical Acoustics Laboratory, Department of Geophysics, Colorado School of Mines, Golden, Colorado, USA

Received 1 October 2004; revised 29 November 2004; accepted 10 December 2004; published 12 January 2005.

[1] Buried land mines and chemical waste may provide the contrast in elastic properties within the soil needed to achieve detection via near-surface seismic methods. The hazardous nature of these targets strongly indicates the use of noncontacting sources and receivers. A home-made ultrasonic parametric array allows us to insonify the soil with an intense beam of sound; this acoustic energy is converted to elastic waves in the soil. Our noncontacting seismometer is a microwave Doppler vibrometer that can detect seismic waves, even through grass. We believe that developments along these lines will ultimately lead to the ability to probe large areas of the near-surface in a safe and reliable fashion, without physically touching the ground.

Citation: van Wijk, K., J. A. Scales, T. D. Mikesell, and J. R. Peacock (2005), Toward noncontacting seismology, *Geophys. Res. Lett.*, *32*, L01308, doi:10.1029/2004GL021660.

1. Introduction

[2] Many techniques are being investigated to detect land mines accurately, safely and rapidly. The combination of these requirements poses a formidable technical challenge. All methods to detect land mines rely on a contrast of some physical property of the land mine and the surrounding soil. Some of these methods are not sensitive enough, some are too sensitive, causing many false alarms; current methods investigate over 300 false alarms for every mine found. Also, most of these methods require contact with the surface, which increases the risk of accidental detonation. We are investigating the feasibility of fully noncontacting land mine detection based on a novel combination of microwave and nonlinear acoustic methods. Such a noncontacting seismic data acquisition system could prove extremely useful for problems besides detecting buried land mines [*Donskoy et al.*, 2002; *Xiang and Sabatier*, 2003], such as hazardous waste monitoring [*Kaduchak et al.*, 2000], monitoring of buried infrastructure [*Buyukozturk*, 1997; *Pla-Rucki and Eberhard*, 1995] and structural integrity, and other near surface geophysical applications.

[3] Some of the possible benefits of this noncontacting system over conventional (contacting) seismology include the

[4] • safety of remote sensing.

[5] • ability to scan the surface with both source and receiver, thereby measuring spatial waveforms.

[6] • flexibility of the source: we can program the source wavelet to be a broadband pulse, tone-burst, chirp or a continuous wave. All of which can be accomplished with a function generator. In addition, repeated shots are constant, since we are not disturbing the soil.

[7] • fidelity of the receiver: the microwave Doppler shift gives an absolute measure of particle velocity, with – in principle – unlimited dynamic range and no mechanical noise (ringing).

[8] Our idea is to excite the ground with a parametric acoustic array, using a narrow beam of ultrasound (which is easily collimated) and the nonlinear interaction of the ultrasound with air, to project focused low-frequency sound into the ground. Ground motion causes the land mine to scatter some of the acoustic energy, which will ultimately be detected – scanning near the source – with a noncontacting vibrometer. Characteristic resonance patterns of the land mine, as well as spatial characteristics of the wave field, may allow us to separate scattering from land mines from other inhomogeneities in the subsurface. This Letter describes developments in a low-cost and fairly robust noncontacting seismic source and receiver.

1.1. The Source

[9] It has been known for half a century that it is possible to exploit nonlinear behavior of ultrasound in a fluid [*Westervelt*, 1963]. In a linear system, the output frequency is always the same as the input frequency, whereas in a nonlinear system new frequencies can be created. For instance, a quadratic nonlinearity gives rise to second harmonics as well as sum and difference frequencies for modulated signals. Analogous to the way radio works, the nonlinearity can actually demodulate an amplitude modulated ultrasonic signal [*Yoneyama et al.*, 1983; *Pompei*, 1999]. *Kaduchak et al.* [2000] used an example of such a *parametric array* to excite elastic waves in metal barrels; an excellent application of safe, stand-off material characterization. (The term parametric refers to the fact that any nonlinearity which can be controlled by a parameter (voltage, temperature, magnetic field, etc.) is called a parametric nonlinearity.) We report a noncontacting collimated source for seismic exploration. The following paragraph is a brief account of the nonlinear theory. For a more detailed description, see *Lighthill* [1952, 1954].

[10] From the equations of continuity and momentum, the density $\rho(\mathbf{x}, t)$ in a fluid in the presence of small disturbances is

$$\frac{\partial^2 \rho}{\partial t^2} - c_0^2 \nabla^2 \rho = \frac{\partial^2 T_{ij}}{\partial x_i \partial x_j}, \qquad (1)$$

where c_0 is the average velocity, and the stress tensor for a perfect fluid (no viscosity) is

$$T_{ij} = \rho u_i u_j + p\delta_{ij} - c_0^2 \rho \delta_{ij}. \qquad (2)$$

0094-8276/05/2004GL021660$05.00

The hydrostatic pressure p can be expanded by a Taylor series about the equilibrium density. For large pressure levels, the second order term must be included, making expression (1) nonlinear. *Westervelt* [1963] simplifies expression (1) for the secondary field p_s:

$$c_0^{-2}\frac{\partial^2 p_s}{\partial t^2} - \nabla^2 p_s = -\rho_0\left(\frac{\partial q}{\partial t}\right), \qquad (3)$$

Now, the secondary field p_s is obtained by solving equation (3) with the nonlinear source term on the right side, where

$$q = -\rho_0^{-2} c_0^{-4}\left(1 + \frac{1}{2}\rho_0 c_0^{-2}\left(\frac{d^2 p}{d\rho^2}\right)_{\rho=\rho_0}\right)\frac{\partial p_i^2}{\partial t}. \qquad (4)$$

[11] Our parametric array consists of 50 Airmar AT200 (212 KHz resonant frequency, 16 mm diameter) air-coupled ultrasonic transducers mounted in a PVC housing (average distance between neighboring transducers is 1.5 mm) and driven in parallel with a function generator (Agilent 33220A). The programmed signal consists of a modulated 200 KHz carrier that is amplified by an ENI 2100L RF power amplifier so that nonlinear interaction in air creates the sum and difference frequency. These waves all travel in a collimated beam in air, but only the difference frequency is audible; it retains the same directionality and beam quality as the ultrasound, as numerically and experimentally shown by *Muir and Willette* [1972] and *Berktay* [1965], for instance. By pointing the parametric array at the ground, the ultrasound is reflected and absorbed by the soil, but a significant amount of the low-frequency harmonic signal penetrates the subsurface.

1.2. The Receiver

[12] The idea of vibrometry is to measure the Doppler shift induced in a monochromatic signal reflected off a moving target (in our case the Earth's surface) by mixing the reflected signal with a reference copy of the transmitted signal. Particle motion of the Earth causes a Doppler shift in the scattered signal that can be detected as a low frequency beat of the two-beam mixing product. The reflected signal is Doppler shifted according to the target velocity v:

$$f_d = 2v(f_0/c), \qquad (5)$$

where f_d and f_0 are the Doppler and transmitter frequency, respectively, and c the speed of light (3e8 m/s). The larger the Doppler shift, the greater the sensitivity with which one can measure the target velocity. From equation (5) it is clear that the transmitter frequency is linearly related to the Doppler shift, but as this carrier frequency increases, the reflected signal becomes more sensitive to absorption and scattering from rough surfaces. This limits the strength of the reflected signal, decreasing the signal-to-noise of the receiver. Therefore, in the field it is useful to have a vibrometer that is tunable to the local needs of the experiments to obtain an optimal trade-off between reflection strength and Doppler shift, for the best velocity resolution.

[13] Optical vibrometers have been successful under laboratory conditions [*Nishizawa et al.*, 1997; *Scales and van Wijk*, 1999, 2001; *Sabatier and Xiang*, 2001]. However, microwaves have many advantages for field seismology applications; for instance, microwaves penetrate foliage. Our experiments thus far use an inexpensive low-power ($\sim$mW) microwave transceiver operating at 24 GHz as the seismometer. The transmitted microwave signal is generated with a Gunn diode and mixed with the reflected signal in a Schottky mixer embedded in the same microwave cavity used by the transmitter.

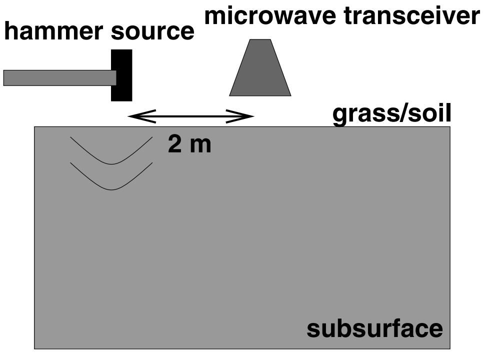

Figure 1. Side view of the geometry to test a microwave vibrometer as a seismic detector. Seismic energy is excited by striking the ground with a hammer. Energy generated by the hammer source is recorded at the surface on a microwave vibrometer that is suspended first above bare soil, then over grass.

2. Experiments

[14] Four experiments illustrate the feasibility of our noncontacting seismic system. First, we present two sets of data supporting the use of microwave vibrometry as a seismometer. Second, two experiments confirm the excitation of seismic energy from a parametric array.

2.1. Microwave Vibrometry

[15] The experimental setup has our microwave transceiver suspended over ground seismically excited by a hammer striking a plate (30 cm^2) on the ground (Figure 1) approximately two meters from the detector.

[16] First, the transceiver is hung by a string 2 cm above consolidated soil. The results are not sensitive to the height of the transceiver for distances from 2 to 10 cm, but since our transceiver only puts out a few milliwatts of microwave power, signal strength deteriorates for greater distances between the vibrometer and the soil. In comparison, a recording with a conventional geophone used in exploration geophysics is made at the same location. Note that these coil/magnet geophones are most sensitive under 100 Hz. After both data sets are averaged over 32 shots, passed through a 10–110 Hz band-pass filter, and normalized, the results are depicted in the top panel of Figure 2. The correlation between microwave and geophone recording is 0.96 for the main event and 0.91 for the entire trace. Identical recordings have a correlation of 1.

[17] The second experiment uses the same experimental parameters as the first one, except that the microwave detector is suspended over grass, and a microwave lens with a focal length of 11 cm is placed on the transceiver to focus the microwave signal. Compared to the experiment without the lens, the phase of the microwave signal is shifted roughly by π. This phase shift is the result of waves going through a focus, called the Guoy phase shift [*Lindner et al.*, 2004]. After correcting the raw data for this phase shift caused by

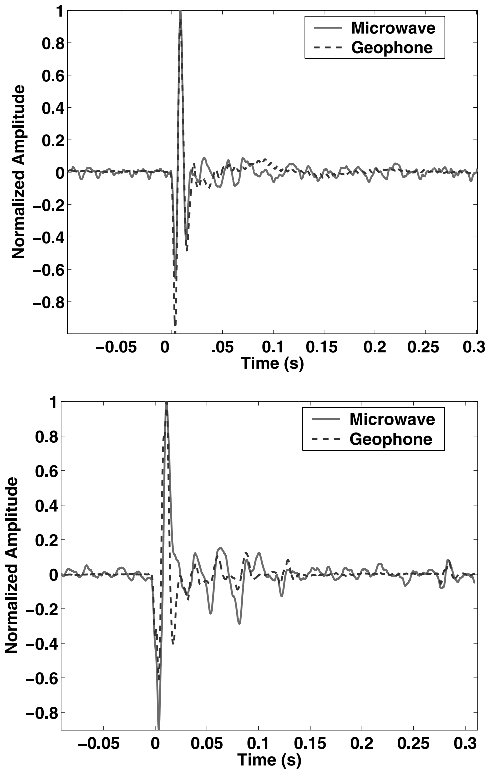

Figure 2. Top: comparison of processed microwave and geophone data in consolidated soil. The correlation coefficient for the main event is .96, and .91 for the entire record. Bottom: comparison between processed microwave and geophone data in grass. The correlation is .84 for the main event, and .77 for the entire record. Reflections are seen in these data (for example at 0.28 s in grass), which are likely caused by heterogeneity in the subsurface.

the lens, the correlation between the microwave signal and the data recorded with a conventional geophone in the same location is 0.84 for the main event, and 0.77 for the entire trace (bottom panel of Figure 2). Nevertheless, signal is observed in both data sets at 0.27 s, which is likely caused by scattering from heterogeneity in the subsurface.

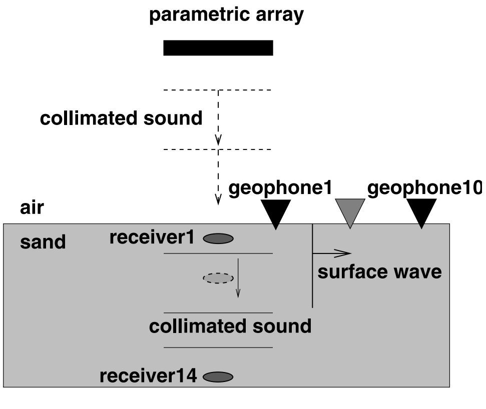

Figure 3. Experimental geometry to test the parametric array as a seismic source in unconsolidated sand. Pressure waves are measured by a buried piezoelectric transducer and surface waves by conventional geophones.

[18] Both microwave records in Figure 2 present 60 Hz noise from AC equipment, which is especially noticeable before the first arrival. No attempts were made to filter this, but more averaging and more power in the microwave system should diminish this source of uncorrelated noise and improve signal-to-noise ratios to where they are comparable to the conventional geophone.

2.2. Parametric Array

[19] To test our parametric source, the array is hung 85 cm above the surface of a sandbox (see Figure 3 for the general acquisition geometry). We drive the array with a tone-burst consisting of the sum of two sinusoids at 200 and 201 KHz. The resulting collimated beam of 1 KHz has a sound pressure level of ~mPa. The sand is ordinary playground sand and the dimensions of the sandbox are 130 × 100 × 20 cm. Note that unconsolidated sand is inherently attenuative to seismic waves, so that this particular test of our parametric array can be seen as difficult, compared to expected field conditions. A 500-KHz Panametrics Videoscan V101 ultrasonic transducer is buried in the sand. Such a transducer is clearly not in the optimal acoustic frequency band, but we had one in the lab so we tried it. The signal is then passed through a Stanford SR560 low-noise preamp and amplified 100 times. We record data at a rate of one million samples per second and average 600 tone-bursts.

[20] Figure 4 shows the wave field as we record deeper in the sand, after applying a narrow band-pass filter around the 1-KHz signal. An estimate of the compressional wave speed in sand of 116 ± 5 m/s follows from a regression on the maximum of the first phase of the wave. We have so far been able to penetrate up to 14 cm, the depth of our sandbox. These records are not individually normalized, or time-gained in any matter. Note that the geometrical

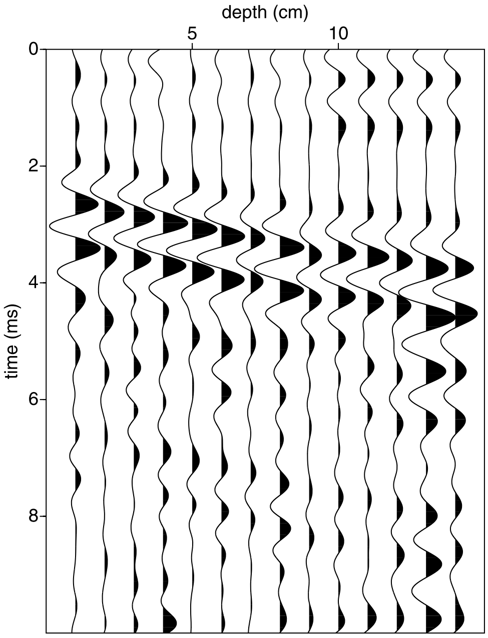

Figure 4. Measurements with buried piezoelectric transducers of a compressional wave excited in air penetrating the sand. Amplitude is well conserved with depth, because the plane-wave character of this parametric array source limits geometric spreading of its energy.

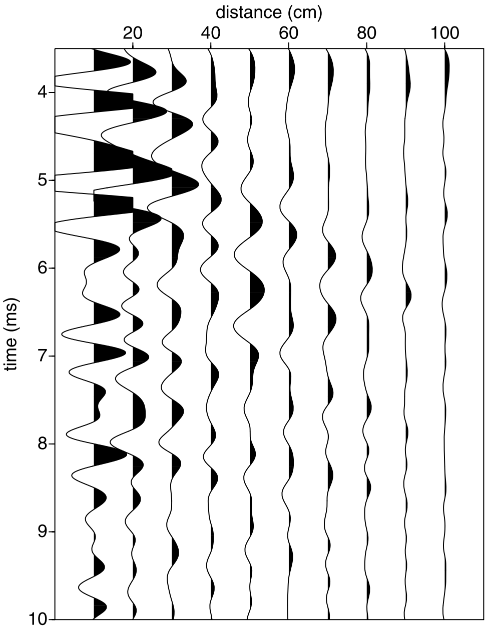

Figure 5. Wave fields recorded at the surface from the insonification spot outward. A weak but coherent surface wave is evident between 4.75 and 5.25 ms.

spreading from a point source such as a conventional speaker is absent in these data: even at the depth of the sandbox, the amplitude of the recorded signal is comparable to that recorded 1 cm under the surface. This advantage of the planar-wave character induced by the parametric array was also cleverly exploited by *Wingham* [1985].

[21] Finally, ten conventional geophones record the seismic energy propagating up to one meter away from the insonification point along the surface. Figure 5 shows that the parametric array excites a coherent event with a linear time-distance relation, indicating a surface wave at 52 ± 2 m/s.

3. Discussion and Conclusion

[22] Our experiments so far amount to a proof of concept for a noncontacting seismic system. The low sensitivity of the detector, combined with the limited power in our source, do not allow us to use the system as a complete noncontacting seismic data acquisition tool, yet. Instead, we have tested the parametric array source with contacting transducers and geophones. Nevertheless, both body-wave and surface-wave energy generated by the parametric array have been detected, even though receivers used are not designed for optimal sensitivity at the source frequency of 1 KHz. In addition, we have shown the ability to record seismic waves – at this stage hammer-generated – with a low-power microwave vibrometer, even in the presence of grass.

[23] We can increase the power in the parametric source by using more transducers or phasing the array. Existing arrays for other applications, such as the audio spotlight of *Yoneyama et al.* [1983], contain up to 600 ultrasonic elements, while the only commercial parametric array available claims pressure levels in the 1 Pa-range. In addition, we are pursuing vibrometry with more power and a higher carrier frequency, well into the millimeter band, so that the Doppler shift is increased. Also, we are building a heterodyne receiver which we expect to achieve markedly higher sensitivity. We believe that this will allow us to use a scanning parametric array/microwave setup for applications such as landmine detection, monitoring of buried pipes and cables, contaminated sites, as well as to answer questions on wave propagation in naturally disordered media: the proposed setup has the flexibility to collect the large amounts of ensemble-averaged data that are necessary to address multiple scattering phenomena, such as coherent backscattering [*Larose et al.*, 2004] or equipartitioning of waves [*Malcolm et al.*, 2004] in the near surface.

[24] **Acknowledgments.** This work is supported by the National Science Foundation (EAR-0337379) and the Army Research Office (DAAD19-03-1-0292). In addition, we thank Martin Smith and Mike Batzle for inspiring discussions.

References

Berktay, H. O. (1965), Possible exploitation of non-linear acoustics in underwater transmitting applications, *J. Sound Vib.*, *2*, 435–461.

Buyukozturk, O. (1997), Imaging of concrete structures, *NDTE Int.*, *31*, 233–243.

Donskoy, D., A. Ekimov, N. Sedunov, and M. Tsionkiy (2002), Nonlinear seismo-acoustic land mine detection and discrimination, *J. Acoust. Soc. Am.*, *111*, 2705–2714.

Kaduchak, G., D. H. Sinha, D. C. Lizon, and M. J. Fehler (2000), A non-contact technique for evaluation of elastic structures at large stand-off distances: Applications to classification of fluids in steel vessels, *Ultrasonics*, *37*, 531–536.

Larose, E., L. Margerin, B. A. van Tiggelen, and M. Campillo (2004), Weak localization of seismic waves, *Phys. Rev. Lett.*, *93*, doi:10.1103/PhysRevLett.93.048501.

Lighthill, M. J. (1952), On sound generated aerodynamically. I. General theory, *Proc. R. Soc. London, Ser. A*, *211*, 564–587.

Lighthill, M. J. (1954), On sound generated aerodynamically. II. Turbulence as a source of sound, *Proc. R. Soc. London, Ser. A*, *222*, 1–32.

Lindner, F., G. G. Paulus, H. Walther, A. Baltuska, E. Goulielmakis, M. Lezius, and F. Krausz (2004), Gouy phase shift for few-cycle laser pulses, *Phys. Rev. Lett.*, *92*, doi:10.1103/PhysRevLett.92.113001.

Malcolm, A. E., J. A. Scales, and B. A. van Tiggelen (2004), Extracting the Green function from diffuse, equipartitioned waves, *Phys. Rev. E*, *70*, doi:10.1103/PhysRevE.70.015601.

Muir, T. G., and J. G. Willette (1972), Parametric acoustic transmitting arrays, *J. Acoust. Soc. Am.*, *52*, 1481–1486.

Nishizawa, O., T. Satoh, X. Lei, and Y. Kuwahara (1997), Laboratory studies of seismic wave propagation in inhomogeneous media using a laser Doppler vibrometer, *Bull. Seismol. Soc. Am.*, *87*, 809–823.

Pla-Rucki, G. F., and M. O. Eberhard (1995), Imaging of reinforced concrete: State-of-the-art review, *J. Infrastruct. Syst.*, *1*, 134–141.

Pompei, F. J. (1999), The audio spotlight: Put sound wherever you want it, *J. Audio Eng. Soc.*, *47*, 726–731.

Sabatier, J., and N. Xiang (2001), An investigation of a system that uses acoustic-to-seismic coupling to detect buried anti-tank landmines, *IEEE Trans. Geosci. Remote Sens.*, *39*, 1146–1154.

Scales, J. A., and K. van Wijk (1999), Multiple scattering attenuation and anisotropy of ultrasonic surface waves, *Appl. Phys. Lett.*, *74*, 3899–3901.

Scales, J. A., and K. van Wijk (2001), Tunable multiple-scattering system, *Appl. Phys. Lett.*, *79*, 2294–2296.

Westervelt, P. (1963), Parametric acoustic array, *J. Acoust. Soc. Am.*, *35*, 535–537.

Wingham, D. J. (1985), The dispersion of sound in sediment, *J. Acoust. Soc. Am.*, *78*, 1757–1760.

Xiang, N., and J. M. Sabatier (2003), An experimental study on antipersonnel landmine detection using acoustic-to-seismic coupling, *J. Acoust. Soc. Am.*, *113*, 1333–1341.

Yoneyama, M., J. Fujimoto, Y. Kawamo, and S. Sasabe (1983), The audio spotlight: An application of nonlinear interaction of sound waves to a new type of loudspeaker design, *J. Acoust. Soc. Am.*, *73*, 1532–1536.

T. D. Mikesell, J. R. Peacock, J. A. Scales, and K. van Wijk, Physical Acoustics Laboratory, Department of Geophysics, Colorado School of Mines, 1500 Illinois St., Golden, CO 80401, USA. (kasper@acoustics.mines.edu)