

# Investigation of microphones as near-ground sensors for seismic detection of buried landmines

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Commercially available microphones were investigated as near-ground sensors to measure the acoustic pressure and the vertical pressure gradient of evanescent air-acoustic waves associated with audio-frequency seismic waves. Measurements in close proximity to the surface and the use of waveguides were found to improve the microphone signal's quality, the comparison of its seismic sensitivity to its sensitivity to propagating sound (ambient acoustic noise and nonseismic reverberation). Landmine images formed using microphone data collected in a laboratory experimental model clearly locate buried inert landmines but exhibit more clutter than images of the same objects formed with seismic displacement data collected using other techniques.

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## I. INTRODUCTION

Experimental seismic landmine detection techniques use noncontact<sup>1–5</sup> and ground-contacting<sup>6</sup> sensors to measure surface-normal displacements due to the propagation of seismic waves and their interactions with shallow-buried objects. In previous research, landmines and minelike objects were found to be characterized by resonant scattering of incident seismic waves in the low audio-frequency range (50 to 2000 Hz).<sup>7–9</sup> In this study, microphones were investigated as an attractive low-cost alternative to noncontact sensors such as radar, ultrasound, and laser-Doppler vibrometer systems<sup>1–5</sup> for seismic landmine detection.

Cook and Wormser<sup>10</sup> first reported the use of microphones for landmine detection in 1973. Their system used a reciprocal speaker as a microphone to sense seismic waves produced by a ground-contacting source.

For seismic landmine detection, the use of a microphone in lieu of a vibrometer dictates the use of a ground-coupled seismic source, rather than an airborne source. This is because propagating acoustic-field components directly generated by the source can easily overwhelm the measurement of the acoustic field generated by the ground's surface motion. Thus, sources should be chosen that maximize the ratio of energy in the source-generated seismic wave field to the energy in the source-generated propagating acoustic field.

The predominant surface waves generated by ground-coupled sources for seismic landmine detection systems may be referred to as Rayleigh waves. These are the lowest order *P-SV* (coupled pressure and vertical shear wave) mode that is guided by the interface between a vertically heterogeneous medium and the overlying air. In soil, over the frequency range of interest, these waves typically propagate at speeds between 70 and 160 m/s.<sup>11,12</sup> For the measurements reported here, Rayleigh wave speeds were measured at approximately 80 m/s. Because they are subsonic, soil-borne Rayleigh waves produce evanescent acoustic fields in the air above the

soil. Below 2 kHz, these signals have been measured with microphones up to 10 cm above the air-soil interface.<sup>13,14</sup>

The evanescent field decays in amplitude with increasing distance from the ground's surface. Since the higher frequency (shorter wavelength) waves decay more quickly, it is desirable to measure the acoustic pressure as close to the surface as possible in order to preserve the full bandwidth of the seismic wave field in the measured data. The obvious limit to this is when the microphone physically contacts the ground. Here, the microphone can still function as a near-ground rather than a ground-contacting sensor if only the case of the microphone touches the ground and the sensing element is separated from the surface by air. Recent work with ground-contacting vibrometers has demonstrated that ground contact is not inherently problematic for a landmine detection system, provided that the contact force is sufficiently small.<sup>6</sup> In the case of the microphones used in these experiments, which weigh only 1.5 N as freestanding sensors, ground contact is not problematic.

## II. EXPERIMENTAL SETUP

To investigate the capabilities of microphones for seismic detection of buried landmines, measurements were conducted in the experimental model shown in Fig. 1. Seismic surface waves were generated with an electrodynamic shaker coupled to the ground with a 1.27 cm wide (normal to a wavefront) by 21.6 cm long (along a wavefront) aluminum foot to preferentially excite Rayleigh waves.<sup>15</sup> Two Behringer ECM8000 microphones, used for all of the measurements, are shown in Fig. 1 on the positioning system that was used to scan the microphones through the region of interest; an inset photograph shows the microphone with and without the flexible (translucent latex rubber) and rigid (red plastic) waveguides used in the experiments. Damp, compacted sand was used in the experimental model, because its properties are typical of soils and it allows for easy burial

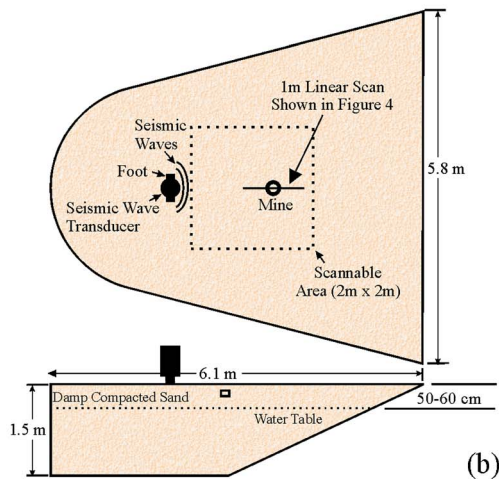
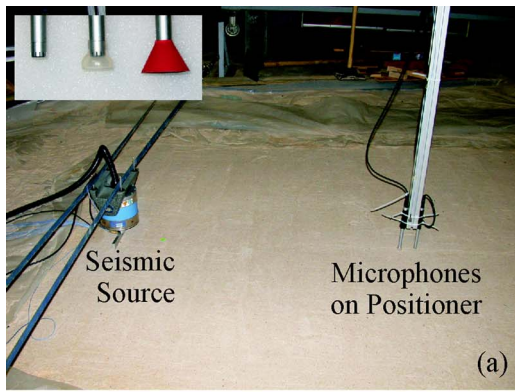


FIG. 1. Experimental model in (a) photograph with seismic source and microphone sensors (inset photograph show waveguides and microphones with 5-cm center-to-center spacing between microphones) and (b) drawing of scan region.

and compaction to maintain lateral homogeneity and repeatability of measurements.<sup>12,16–20</sup> For all of the experiments, incident seismic signals were excited by chirps spanning a band from 100 Hz to 2 kHz in 4.096 s. These measurements were used to compute the response of the system to a differentiated Gaussian pulse with a 450 Hz center frequency.

### III. LANDMINE DETECTIONS

Images made from pressure data measured with a microphone and surface displacement data measured with a radar-based vibrometer over a buried landmine are shown in Fig. 2 for a 1 m<sup>2</sup> region. Measurements were made at 1 cm intervals in both directions for the radar sensor and at 0.78 cm intervals for the microphone sensor. However, the microphone has a larger effective sensing area than the radar sensor. Both images show clear indications of the landmine's location, although there is less clutter and higher resolution in the image formed from the radar data. Similarly, microphone measurements over a variety of other landmine burials have yielded images with more clutter and less resolution than those from the radar data.<sup>13</sup> These images were formed by filtering out the forward-propagating waves, determining the reverse-propagating energy at each location and the reflected energy from each location, and then combining the two energy levels as a weighted image.<sup>21</sup>

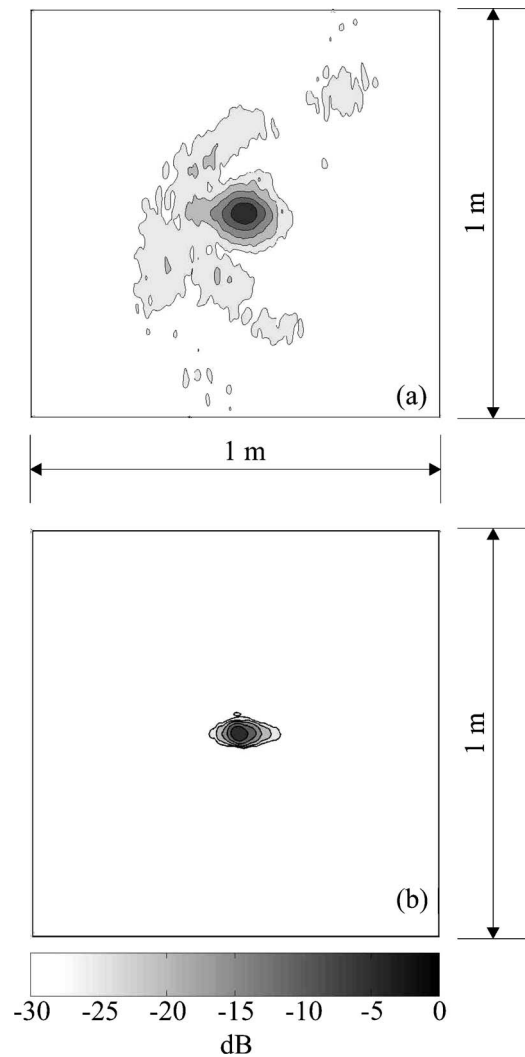


FIG. 2. Images of a TS-50 antipersonnel landmine (1 cm deep) made from data measured by (a) a microphone as a near-ground sensor 1 cm above the surface and (b) a noncontact radar vibrometer. Both images are plotted on a 30-dB scale relative to the maximum value in the image and show a 1-m<sup>2</sup> region in the experimental model.

In previous work, the measured acoustic signals were back-projected to the surface of the sand using near-field acoustical holography.<sup>13,14</sup> This, at best, minimally improved the resolution and clutter rejection.

The increased clutter in the microphone image is due to the microphones' comparatively high intrinsic noise, sensitivity to ambient acoustic noise in the laboratory, and sensitivity to the reverberant air-acoustic waves produced by the electrodynamic shaker. Both microphone and direct surface motion measurements are also susceptible to ambient seismic noise, which can be problematic in the experimental model.<sup>22</sup> The crescent-shaped artifact between the landmine and the source is caused by the multiple wave types that are present in the model. The time window used on the data includes some faster propagating components of the seismic wave field (prograde surface waves<sup>6,23–26</sup> and bulk waves). Because only the reverse-propagating components are used to form the image, these faster waves result in image clutter between the source and the buried objects. The microphone is proportionally more sensitive to faster waves, which decay at a slower rate away from the surface.

#### IV. SENSITIVITY IMPROVEMENTS

To improve the microphone's sensitivity to Rayleigh waves relative to propagating acoustic waves, two waveguides were tested. Measurements were made with the microphone in five configurations: (1) the microphone on the surface; (2) the microphone approximately 0.5 cm above the surface; (3) the microphone with the rigid waveguide on the surface; (4) the microphone with the flexible waveguide on the surface; and (5) the microphone with the flexible waveguide above the surface. The microphone has a 4.8 mm diameter opening for the electret sensing element surrounded by a 1.27 cm rigid case. The rigid waveguide was made of hard plastic and tapered linearly from the 1.27 cm diameter of the microphone case to a 3.8 cm diameter opening over a 2.54 cm length. The tip of the microphone extended approximately 1.27 cm into the rigid waveguide. The flexible waveguide, made of latex rubber, fit snugly over the end of the microphone case and expanded to a 2.54 cm diameter at the open end over a length of 1.27 cm. The tip of the microphone extended approximately 0.3 cm into the flexible waveguide. The microphone with the flexible waveguide was coupled to the ground by pushing the sensor into contact with the surface. This ensured that the waveguide was in uniform contact with the ground, but caused some deformation of its shape. The microphone with the rigid waveguide was simply placed upon the surface. Other waveguides including long pipes and flexible tubes were tested as methods to increase sensor standoff distance. These were not found to improve the surface motion sensitivity as well as the waveguides previously described. For comparison purposes, a ground-contacting accelerometer<sup>6</sup> was used to measure the surface motions. After burial of a VS-1.6 antitank (AT) landmine 5 cm deep in the middle of the scan region and careful recompaction of the experimental model, each sensor was scanned in rapid succession to minimize changes in the soil properties (particularly due to drying of the near-surface layers) during the experiment.

In Figs. 3(a)–3(e), 25 ms of data are plotted for each sensor configuration at a location 121 cm away from the source and 50 cm in front of the mine. All of the microphone data were normalized to the maximum microphone signal; the ground-contacting accelerometer signal was normalized by its own peak value. Three distinct waves can be seen in the data presented in Figs. 3(a)–3(e). The first arrival, the direct in-air acoustic wave, is only apparent with the microphone. Local excitation of the ground by this signal is negligible in comparison to sand-borne waves. The direct acoustic signal has fairly constant amplitudes and arrival times for all of the microphone configurations. The second and third arrivals, the prograde surface wave and the Rayleigh surface wave, respectively, are apparent in all of the data sets. Arrival times of the two different waves for the different sensor configurations change somewhat due to slight variations in the sensing area and measurement locations.

The goal of adding a waveguide to the microphone was to increase the amplitude of the Rayleigh surface wave relative to the response due to the in-air acoustic waves. This is most readily apparent through comparison of the measured

Rayleigh wave and the direct in-air acoustic signal. The direct in-air acoustic signal is not a significant practical concern because it can be removed by time gating; however, its strength is directly related to the sensitivity of the microphone to reverberant in-air acoustic waves, which cannot be removed by time gating because of their longer path lengths and their possible coincident arrival with the surface waves. In Fig. 3(f), the root-mean-square (rms) amplitudes of the measurement from three time windows (2.5 to 6.5 ms for the direct in-air acoustic wave, 6.5 to 10 ms for the prograde surface wave, and 10 to 25 ms for the Rayleigh surface wave) have been plotted for each sensor configuration. The rigid waveguide improved the relative sensitivity of the microphone to the seismic surface waves more than the other configurations, but the flexible waveguide also demonstrated increased sensitivity to the surface waves. The flexible and rigid waveguide measurements showed nearly the same rms level for the prograde wave, but the rigid waveguide measurement showed about twice the rms level for the Rayleigh wave as that measured with the flexible waveguide. The height dependence of the evanescent acoustic waves in air generated by the prograde and Rayleigh surface waves can be observed by comparison of the measured response of the ground-contacting and in-air microphones. The decay of the evanescent wave is more noticeable for the Rayleigh wave signal because of its shorter wavelength due to its slower propagation speed.

Waterfall plots of microphone data from this experiment are shown in Fig. 4 for (a) the microphone in air; (b) the microphone on the ground; and (c) the microphone with the rigid waveguide on the ground. Data are plotted as a function of time on the horizontal axis and as a function of measurement location (from 50 cm in front of to 50 cm past the center of the burial location at 1-cm intervals) along the vertical axis. The seismic source was located 71 cm in front of the first measurement location. For comparison purposes, the data presented have been normalized such that the maximum amplitude of the measurement at the first location is the same for all sensor configurations. The location of the VS-1.6 AT landmine is indicated by the shaded region in the center of the plots. The prograde and Rayleigh surface waves can be seen to propagate through the scan region, exciting a resonance of the landmine-soil system, and scattering surface waves. The direct in-air acoustic wave generated by the seismic source is apparent in all of the measurements. The results for the rigid waveguide clearly show its stronger sensitivity to the Rayleigh wave relative to the prograde and in-air waves. The front and back edges of the landmine reflect the incident waves. The resonance effects can be seen to persist over the landmine after the passage of the Rayleigh wave. Acoustic and seismic reverberation and noise contribute to the measured pressure following the passage of the Rayleigh wave. Some of the observed effects in the microphone measurements may be due to seismically induced motion of the microphone's case, but this was not investigated.

Vertical gradients are comparatively large in the evanescent field and virtually nonexistent in the direct air-acoustic field where the acoustic velocity is nearly parallel to the surface of the sand. This suggests that buried landmines could

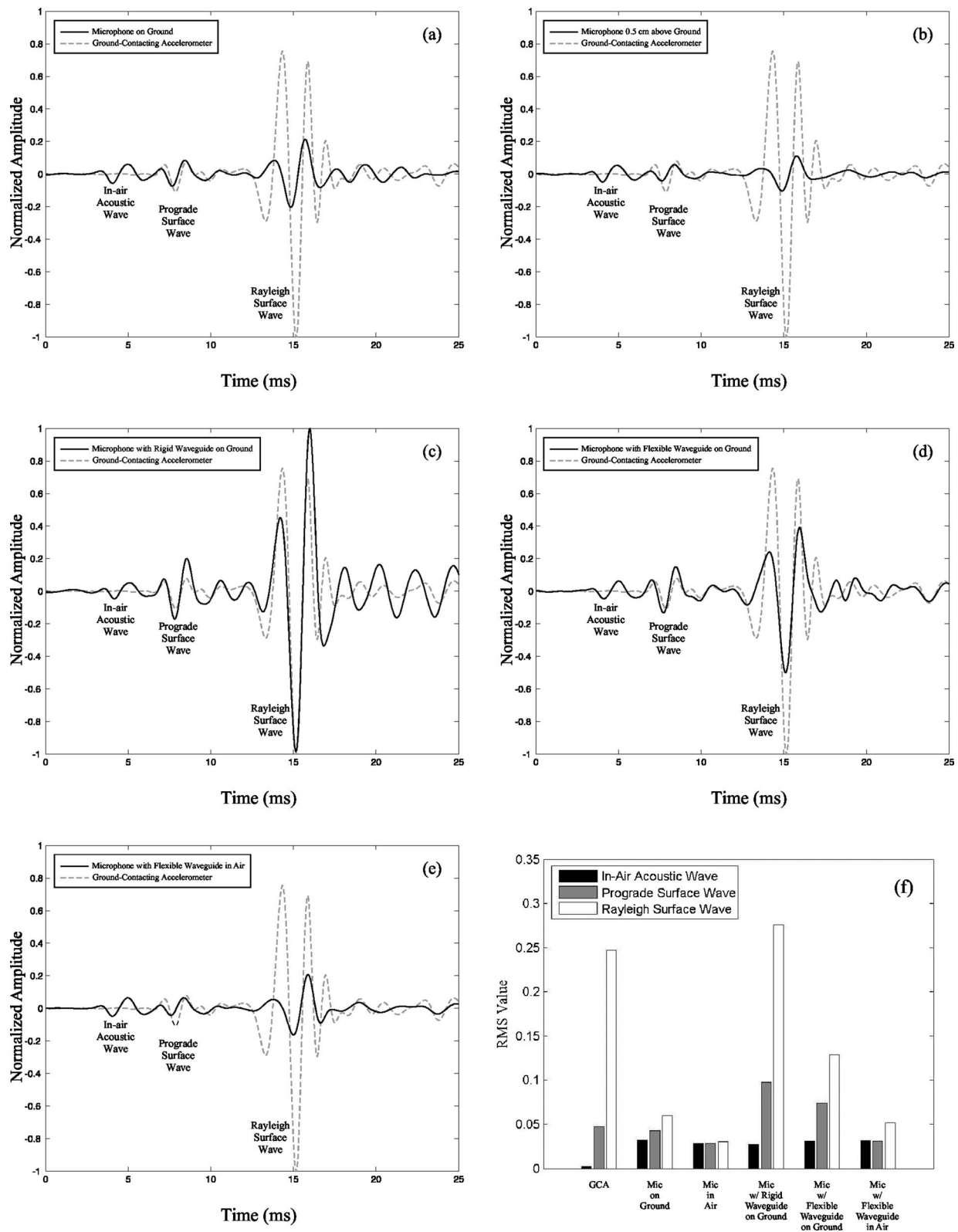


FIG. 3. Experimental measurements of normalized pressure as a function of time (a)–(e) and root-mean-square (rms) amplitude (f) with (a) microphone on the ground; (b) microphone in air approximately 0.5 cm above the ground; (c) microphone with rigid waveguide on ground; (d) microphone with flexible waveguide on ground; and (e) microphone with flexible waveguide in air. The normalized surface acceleration measured by a ground-contacting accelerometer is shown as a reference in all plots.

be detected via a pressure-gradient measurement more effectively than with a simple pressure measurement. By subtracting the measured in-air response of the microphone [shown in Fig. 4(a)] from the response of the microphone with the

rigid waveguide on the ground [shown in Fig. 4(c)], the approximate vertical pressure gradient can be synthesized from the data and plotted as a waterfall in Fig. 4(d). This technique reduced the effects from both the direct air-acoustic

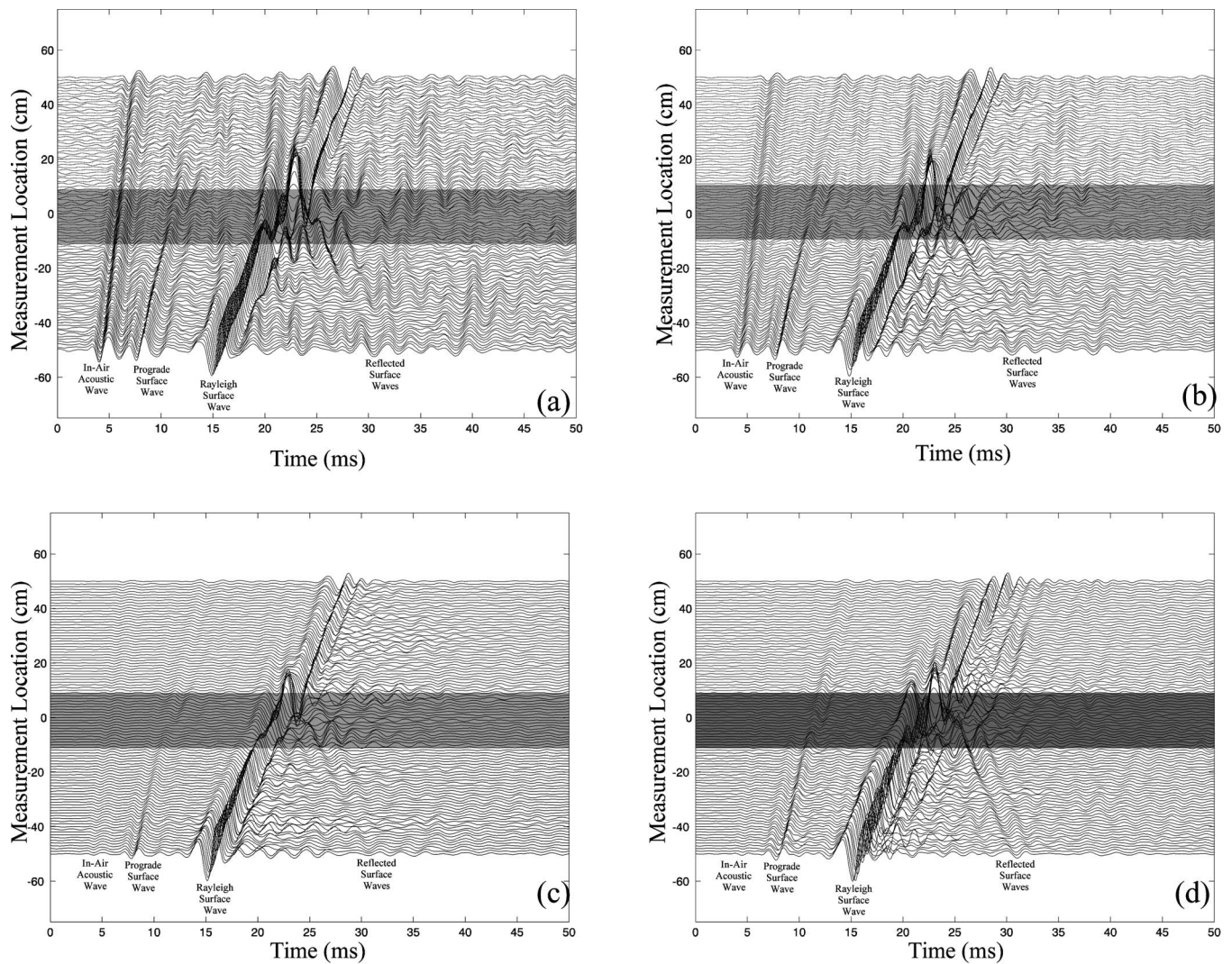


FIG. 4. Waterfall plots of surface motion measured by (a) the microphone 0.5 cm above the surface in the air; (b) the microphone on the ground; (c) the microphone with the rigid waveguide on the ground; and (d) the pressure difference between (c) the microphone with the rigid waveguide on the ground and (a) the microphone 0.5 cm above the surface in the air. A VS-1.6 AT landmine was buried 5 cm deep in the middle of the 1-m-long scan (location indicated by shaded region).

wave and the prograde surface wave relative to the Rayleigh wave. The effects of the prograde wave are diminished in the approximated gradient measurements because the prograde wave propagates faster than the Rayleigh wave in the experimental model.<sup>11</sup> The subsonic prograde wave (at approximately 180 m/s) produces an evanescent acoustic field in the air that decays more slowly with distance from the surface than the signal associated with the Rayleigh wave. Prograde waves have been measured as fast as 460 m/s at field test sites.<sup>11</sup> These would generate propagating air-acoustic signals with predominantly horizontal velocities that could be discriminated against by a measurement of the vertical pressure gradient.

One limitation of approximating the vertical gradient from this data is that the measurements were not conducted simultaneously for each location. Thus, fluctuations in the ambient noise between the different measurements can elevate the apparent noise floor in comparison to what would have been measured with a gradient microphone. However, these measurements were made with the same microphone,

which eliminates the mutual scattering and interaction effects that would be encountered with a gradient microphone and eliminates the problem of matching microphones' sensitivities. Subtraction of simultaneously recorded measurements from two different microphones with similar locations above the surface resulted in more apparent noise than the reported synthetic measurements.

## V. CONCLUSIONS

As near-ground sensors for seismic landmine detection, commercially available microphones can provide sufficient seismic sensitivity to detect and localize buried antipersonnel and antitank landmines. Images formed from microphone measurements clearly indicate the location and extent of buried landmines, albeit with more clutter than images generated with other vibration-sensing methods. Minimal distance between the microphone and the soil is desirable for optimal signal quality. The main drawback of increased standoff is decreased sensitivity to surface motion relative to the effects

of nonseismic noise and reverberation. The sensitivity of microphones to the Rayleigh surface wave, relative to in-air acoustic waves generated by the seismic source, was improved through the use of ground-coupling waveguides. A rigid waveguide in direct contact with the ground provided the most improvement among the configurations that were investigated. Signal quality was improved in measurements of the vertical pressure gradient above the surface, which also reduced the relative effects of prograde seismic waves.

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