Evaluation of Seismic Noise for Landmine Detection System Development

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ABSTRACT

For several years a system has been under development at Georgia Tech that uses seismic surface waves to detect and image buried landmines. The details of this system have been previously reported in the literature. Current work involves the transition from a laboratory experimental system to a field-operable experimental system with the ultimate goal of creating an integrated field-operable prototype. Several issues have arisen in the transition to field testing. One of these is the nature and magnitude of the noise levels that limit system performance at field sites and the relevance of these for predicting noise that might be encountered in a realistic demining scenario. Noise introduced to the system sensor (a radar-based, non-contact displacement sensor) can arise from many sources (both natural and manmade). It may be received through a variety of mechanisms in addition to the sensor's primary transduction mechanism. Moreover, even noise which is received through the primary transduction mechanism need not involve purely seismic motion of the ground that is being interrogated. It might instead represent motion of the sensor's support structure or the purely local coupling of airborne noise into surface motion. To understand these effects, measurements have been made using ground contacting sensors at four field sites where other system-related measurements have also been made. The nature of the noise measurements has required that refinements be made to both the sensors themselves (triaxial geophones) and to the data acquisition system used for the measurement of the system's seismic interrogation signals (a 12-bit, PC-based digitizer).

Keywords: landmine, mine detection, ultrasound, seismic waves, ambient noise, field testing

1. INTRODUCTION

A landmine detection system has been developed at Georgia Tech [1]. Although several component configurations and transducer types have been considered for this system, the current system configuration is depicted in Figure 1. In operation, the system generates a signal in the earth at the ground-contacting seismic source which is an electrodynamic shaker. This signal is dominated by Rayleigh surface waves because these are the easiest propagation mode to excite, and the source has been coupled to the ground so as to accentuate them. The Rayleigh waves propagate outward from the source across the region that is to be interrogated for the presence of mines. Full time histories of the vertical surface displacement are measured on a rectangular grid across this region with an array of radar-based displacement sensors that have been constructed specifically for this purpose [2]. In most of the experimental work, this array is constructed synthetically by scanning a single sensor. In a field-operable system the array may be synthetic, physical, or a hybrid such as might be created by scanning a line array. When the incident Rayleigh wave interacts with a shallow buried mine, it produces a unique displacement signature at the soil surface above and near the mine which is measured by the radar and post-processed to form an image of the mine. The most notable source of this unique signature is a soil-loaded structural resonance of the mine case and trigger [3,4] although other motion, such as the rigid body motion of a mine-like object, may also be used to form an image [5].

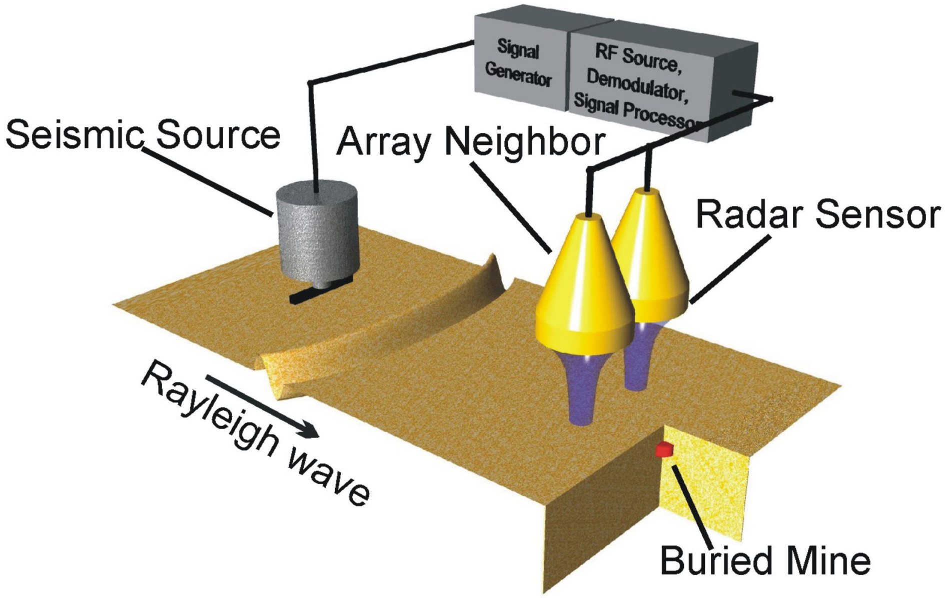

Figure 1: Experimental Landmine Detection System.

For almost two years, development on the seismic landmine detection system has involved a series of field tests in which the system has been tested, individual system components have been tested, and direct measurements of the nature of seismic propagation in soils have been made [6]. During these measurements, several attempts have been made to measure the ambient noise at the field sites. The focus of this effort has been to minimize the sensitivity of the noise measurement system to signals that are not associated with ground motion. Noise that is represented by actual ground motion is a limiting factor for the performance the mine detection system. This is because its effects cannot be mitigated by means other than increasing integration times (e.g. temporal averaging) or by attempting to exploit the modal content of the noise (e.g. spatial averaging). The ground contacting sensors which have been used for these experiments offer several advantages over the radar-based displacement sensor for measurements of this type. First, they are commercially available and have been used extensively for many years thereby avoiding the caprice inherent in equipment which is itself under development. Second, they offer an absolute rather than a relative measure of ground motion since they contain inertial masses with well-characterized suspensions (below resonance for the accelerometers and above resonance for the geophones). They are therefore not susceptible to backside motion (i.e. motion of the structure supporting the sensor) in the way that the radar sensor is. Third, their sensitivity to electromagnetic noise is different from that of the system sensor. They can therefore offer a clue as to whether noise is actually being transduced through the sensor's primary mechanism. Power line harmonics, for example, may be either received electromagnetically or they may result from ground motion produced by transformer hum. In the later scenario these signals would be perceived equally by the radar sensor, an accelerometer, and a geophone. In the former scenario, this would be highly unlikely.

2. ANTICIPATED SEISMIC NOISE

Seismic noise has been studied by several authors [7-12]. Most of this work is not particularly relevant to the mine detection problem because it has focused on measurements made at relatively low frequencies and/or relatively far underground. In general, the seismic community considers frequencies above a few Hz to be "high frequency", and the first meter of soil to be synonymous with the surface. For mine detection, it is necessary to examine frequencies in the range of 10 Hz to 1 KHz and the first 0.5 m of soil. These frequencies are six to eight octaves above those of concern to most seismologists, and these depths are much smaller than those in which they are interested.

An option which is usually available for seismic studies is to move further away from noise sources in order to mitigate their effects. This is clearly not an option for mine detection in that demining must occur in the places where mines are located irrespective of the noise sources that may be nearby. Since mines are buried at times of military conflict, these sources can be quite severe (low flying aircraft, tracked vehicles, blasting, etc.). The USGS new low noise model (NLNM) [9] represents the optimal noise floor scenario for seismic studies and is intended to be used as a guide for site selection. This is depicted in Figure 2 which has been reproduced from Wielandt [13]. The figure has been mirrored and the horizontal axis relabeled to indicate frequency rather than period as it did in the original. The frequencies between 10 Hz and 100 Hz are based on very limited data sets and are seldom included in the model [14]. The model does not extend at all to frequencies above 100 Hz and thus excludes a decade of the band of interest. A typical site will exhibit noise levels much higher than the USGS NLNM even for buried sensors in rural areas; however it serves as a reasonable baseline for the study of seismic noise. In Peterson's study that defined the low-noise standard, he reports noise at comparatively quiet sites that vary upward as much as 50 dB from the low noise standard [9]. Withers and Young have reported that high-frequency seismic noise (up to 50 Hz) can be 50 dB higher for at a single location when it is measured near the surface as opposed to at depth [7,12]. Taken together these observations suggest that seismic noise that is 100 dB above the USGS NLNM could easily be encountered in high-frequency surface measurements.

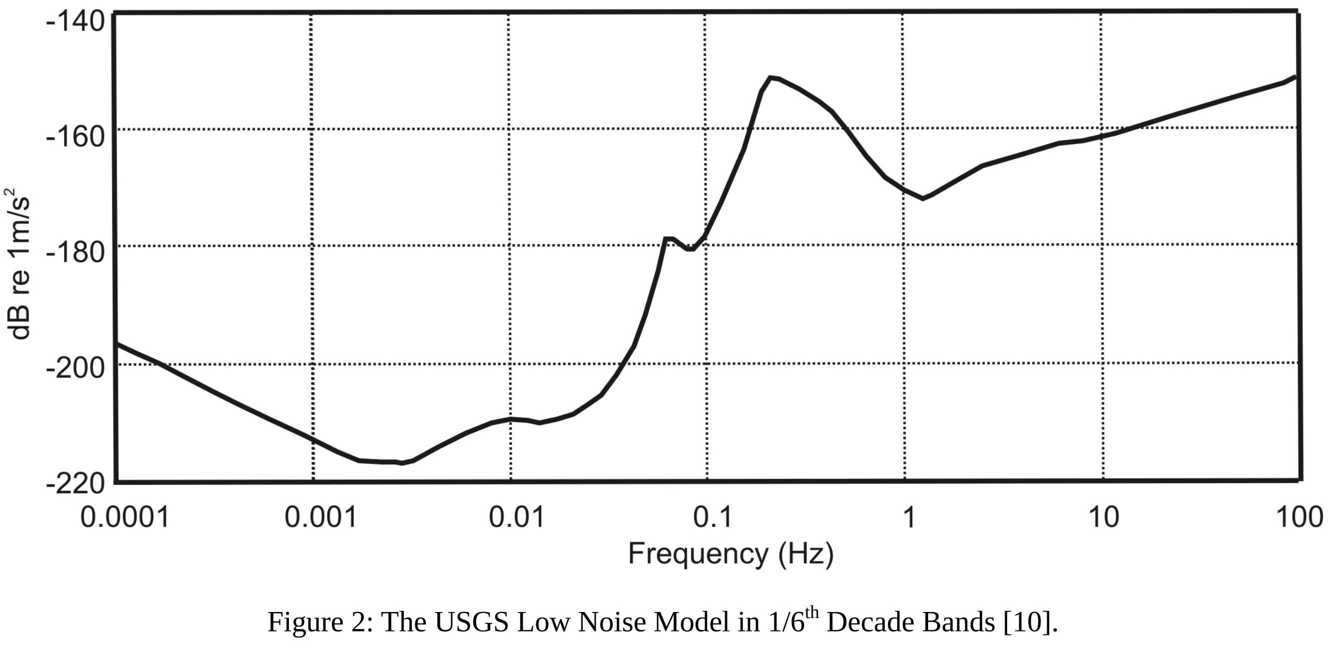

Figure 2: The USGS Low Noise Model in 1/6th Decade Bands [10].

In Figure 2, ocean wave action accounts for the peak between 0.1 Hz and 1 Hz (the principle microseismic band) and this can be broader and more exaggerated near the coast [9,11]. At higher seismic frequencies (up to 50 Hz), naturally occurring noise significantly higher than USGS NLNM predictions has been observed close to the earth's surface and is attributed to wind [7]. This can be quite pronounced in areas where winds are strong and the topography and vegetation enhance the coupling of wind energy into the ground. There are also reports in the literature of naturally occurring motion due to thunder that is easily discernable above the ambient noise floor [14]. Earthquakes, of course, produce very large displacements, but are sufficiently rare and low in frequency that their consideration is not relevant to the problem at hand.

Anthropogenic (man-made) noise is generally considered to dominate the seismic background over the frequency range of interest. This noise arises from a variety of sources including traffic, rail lines, aircraft, fixed machinery, and blasting. Spectral analysis of this noise does not completely characterize the potential problem that it would pose for the operation of a seismic mine detection system. Short duration transients such as those produced by blasting may not significantly contribute to background level measurements with long integration times. These can, however, produce apparent spatial anomalies in data generated with a synthetic array which could lead to false targets or mask real ones. Thus the temporal characteristics of the noise may also be significant.

Previous results have been reported from a laboratory experimental model that consisted of a sand-filled pit constructed in the foundation of a building on the Georgia Tech campus [1]. This was a particularly noisy environment. Ambient noise from the urban surroundings of the building as well as noise generated within the building was coupled to the model through the foundation. One of the adjoining laboratories was a clean room that contained several large pieces of rotating machinery. The effects of these were tactilely perceptible on the surface of the model and they were the dominant contributors to the noise floor over much of the band of interest. Figure 3 shows a comparison between a typical laboratory noise floor and the noise floor measured over a period of 100 seconds of relative quiet at a field site on the Georgia coast. Both measurements were made as 100 second records of the outputs of vertical 10 Hz geophones. The data have been converted to acceleration and plotted in 1/6th-decade bands for easy comparison with the USGS standard. Over most of the band of interest, the field site is 30 to 50 dB quieter than the laboratory. Only above 300 Hz, where the geophone becomes an unreliable measure of surface velocity due to spurious resonances, do the two noise floors begin to converge. Power line harmonics have been suppressed in this plot by interpolating a band of ±0.5 Hz at integer multiples of 60 Hz. There is still an obvious effect of the power line fundamental (60 Hz) in the bin centered at 53 Hz. For the field site, power lines are probably picked up electromagnetically from stray ground currents. In the laboratory, much of this energy may be received through the primary transduction mechanism as motion of the soil surface produced by transformer hum from florescent lighting. There are several strong tones in the laboratory noise (the strongest at 17 Hz) that have been obscured by the 1/6th-decade band analysis. These tones are the dominant low-frequency characteristic of data measured in the laboratory using the radar sensor. The mine-detection system's sensor currently has a self noise floor on the order of 1 nm measured in 1 Hz bands over the system's operating bandwidth in a laboratory environment. This noise results from a variety of sources including thermal noise in the mixers used for homodyne demodulation and phase noise in the 8 GHz source used to generated the radar interrogation signal. In the band of interest this corresponds to a monotonically increasing acceleration noise floor of -108 to -28 dB re 1 $ms^{-2}\,Hz^{-1/2}$ from 10 Hz to 1 KHz. Thus, in a quiescent field environment, motional noise is of little concern whereas it dominates the system's low-frequency noise floor in the laboratory.

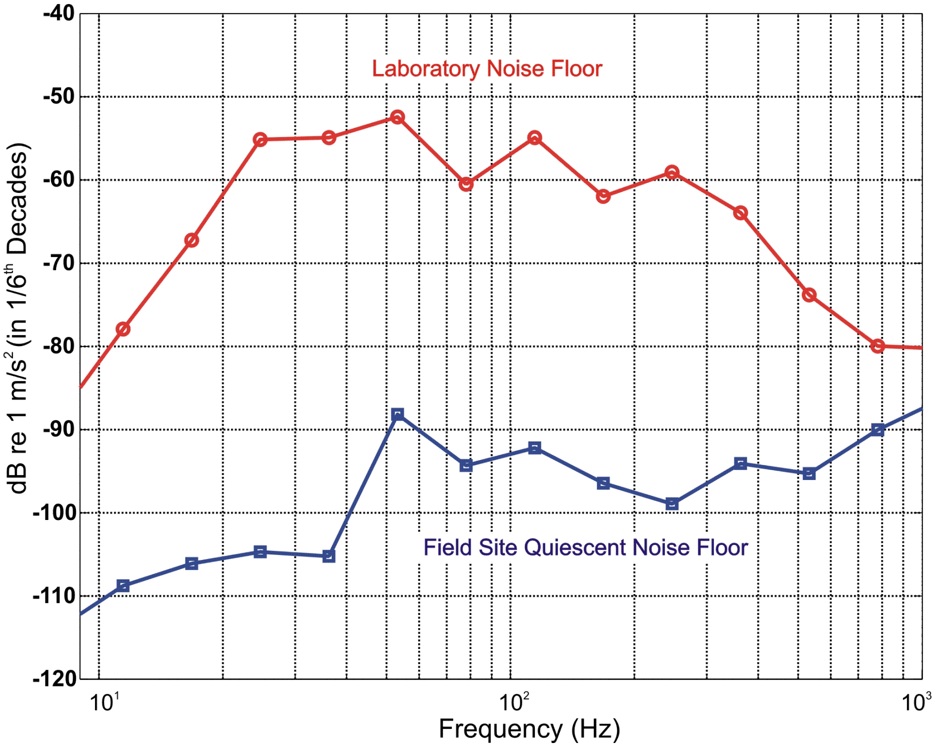

Figure 3: Comparison of the Apparent Background Acceleration Measured at Two Sites.

3. SYSTEM DEVELOPMENT

The measurement of ambient seismic noise revealed problems requiring hardware that was unique from that used for propagation and landmine detection studies. These data had been acquired using 16-channel, 12-bit analog-to-digital converters on PC cards (*National Instruments* PCIMIO16E-1). Data reported from a previous study (at a field site northwest of Atlanta) with ground contacting sensors [6] were acquired in this way and contain a strong tone at 2 KHz. This background component was believed to be electromagnetic in origin because of its spectral purity; however no source for it could be identified at the time. Later studies revealed that this tone was the result of aliasing and that the actual frequency was an AM radio station (1.55 MHz). The signal had been received electromagnetically on the output side of a set of antialiasing filters (*Frequency Devices* 9016) that were set about 3 decades below the AM radio band at 4 KHz. Several efforts at shielding the inputs of the digitizer failed to eliminate this, and a *Sony* digital-audio-tape (DAT) recorder with integral filters and 16-bit resolution had to be substituted for the PC cards in order to remedy the problem. With the aliasing problem fixed, a second radio-frequency (RF) pickup problem was discovered. This was that the geophone elements themselves were receiving the same AM radio signal and that they were constructed in such a way that they demodulated it. Thus a second RF pickup component was present that had been converted to an audio frequency signal prior to filtering and digitization. This problem does not appear to be documented in the literature nor was it familiar to the geophone manufacturer (*Sensor Nederland*). In order to remedy this, geophone elements were electrically shielded using copper foil over the non metallic ends of their cases. In this way, the RF signal was removed, and the audio-frequency signal that resulted from it was eliminated. This modification is depicted in Figure 4.

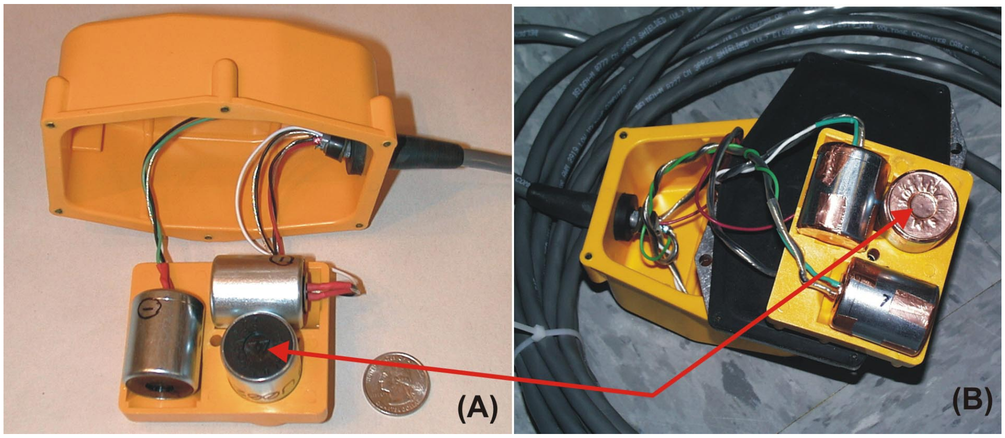

Figure 4: Shielding of Geophone Elements. Before Modification (A) and After Modification (B).

The amplification of received signals also posed several problems. Noise introduced by preamplifiers was found to vary dramatically between the various amplifiers that were readily available. Over the band of interest, the best among these proved to be a high quality microphone preamplifier (*TDT* MA2). Although this reduced the broadband noise in the measured data, it did not significantly reduce the levels of power line harmonics. This indicates that power line frequencies were received by magnetic pickup in the geophone and cabling prior to amplification. Currently several configurations of instrumentation amplifiers mounted very near the geophone elements are being studied to improve this situation.

4. ANTHROPOGENIC NOISE

It was difficult to attribute the background noise at the field sites to specific sources because it was relatively stationary and suspect sources could not be disconnected for purposes of diagnosis. Most of the available literature indicates that, for even the remote sites, man-made seismic noise should have dominated the background [7,9,11]. Certain transient events were much more easily attributed to specific human activity because all of the noise measurements were accompanied by simultaneous human observations and by a simultaneous recording of the output of a nearby microphone. This allowed for the later analysis of the specific contributions of aircraft over-flights, light traffic, large rotating machinery, and passing pedestrians within the noise records. These events were independently observed and accompanied by concurrent transients in the geophone data.

Aircraft Noise: At a field site northwest of Atlanta, measurements were made along the approach path to Dobbins AFB and the adjoining Naval Air Station. Several aircraft flew low overhead during the measurement of ambient noise. Unfortunately there is no available record of their altitudes, relative horizontal locations, or speeds beyond visual observations. Many of measurements associated with the more dramatic events were clipped due to the limited dynamic range of the data acquisition system. Among those that were not distorted were over-flights at a few hundred meters of altitude and less than a kilometer of horizontal separation by helicopters, large propeller aircraft, and jet fighter aircraft. Typical examples of these are depicted in the three spectragrams of Figure 5. Each event shows an interesting and somewhat unique signature. All of these correspond closely to the simultaneous microphone records. This is consistent with the primary air-to-ground coupling taking place in the vicinity of the sensor; however there is not sufficient information in the data to verify this supposition because of the limited physical extent of the 2-element array. Here the limitation was imposed by the number of channels available on the DAT recorder. In future studies, this will be increased to permit wave-number analysis of the noise field. Figure 5 clearly shows that the helicopter-generated noise was dominated by overtones of the engine and blade passing frequencies. In contrast, the large aircraft has a fairly broad signature with a concentration of energy below 50 Hz and no specific tones. The fighter plane signature is also broad although centered higher in frequency and shows a V-shaped feature center around 5 seconds and above 100 Hz. This corresponds to the observed Doppler shift as the plane passed overhead.

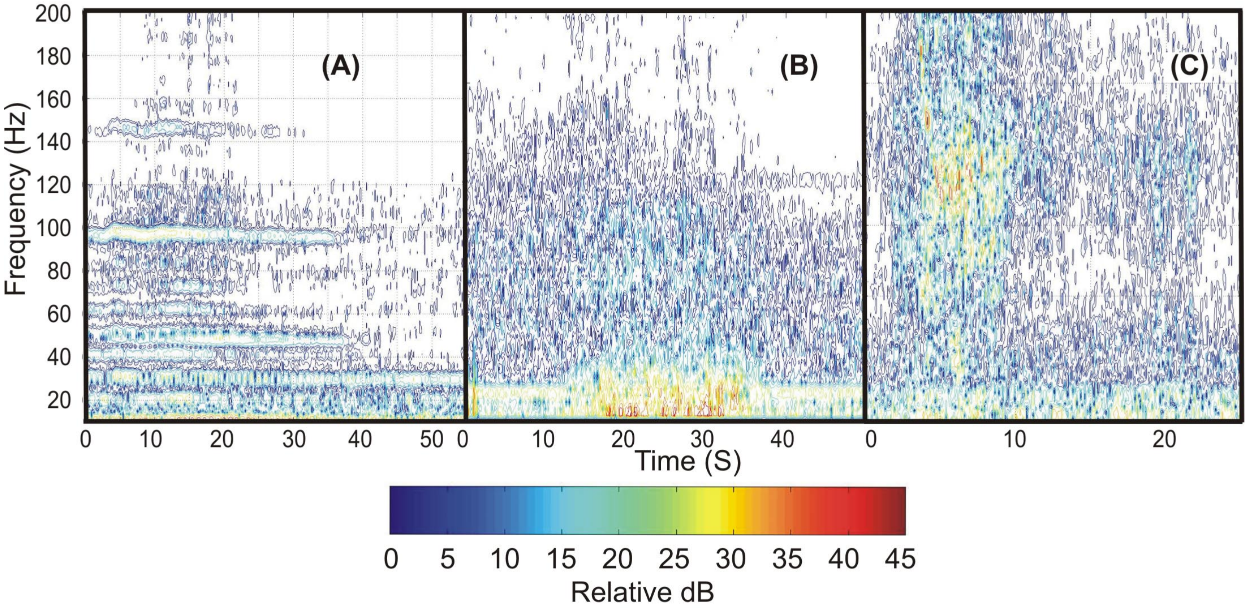

Figure 5: Spectragrams Depicting the Seismic Noise Introduced by the Over Flights of Three Different Aircraft: (A) Helicopter, (B) C-5 Transport, (C) F/A-18 Fighter.

Traffic Noise: All of the field test sites were located within a few hundred meters of lightly trafficked streets. Thus the passing of an individual car was usually easy to discern in the noise records. For the quieter sites, where these events were well above the background noise floor, there were clear differences in the airborne signals received by the microphones and the seismic signals received by the geophones. These included changes in relative amplitude and spectral content. At one of the field sites, where the ground was relatively soft and lossy, and the road was bordered by a drainage ditch, the airborne acoustic signal was much more discernable than the seismic signal at approximately 200 meters for vehicle speeds ranging from 30 to 60 km per hour. In contrast, when the ground was hard and the road shoulder flat the seismic signal dominated under similar source and range conditions. Figure 6 depicts a traffic simulation in which a car was intentionally driven past a vertical axis geophone with it nearest approach being about 3 meters. The record terminates when the car is about 60 meter away. The two spectragrams in the figure depict the outputs of the geophone and a nearby microphone. The car began from a stop and the initial impulse represents the car being placed into gear. The microphone record is obviously dominated by engine noise. The shift points for the automatic transmission are readily apparent. The geophone record is dominated by tire noise. The energy is concentrated much lower in frequency, there are no apparent engine overtones, and the event as a whole is noticeably further above the ambient noise floor. Thus it is reasonable to infer that, in terms of ground motion, the seismic path can dominate over the airborne path (coupled to the ground locally) in determining the noise produced by traffic. Power line harmonics are apparent in Figure 6 and several of the later figures whereas they were not visible in Figure 5. This is because the color scale has been set relative to the largest measured spectral component for each figure individually. The events depicted in Figure 6 are smaller in absolute terms than those depicted in Figure 5.

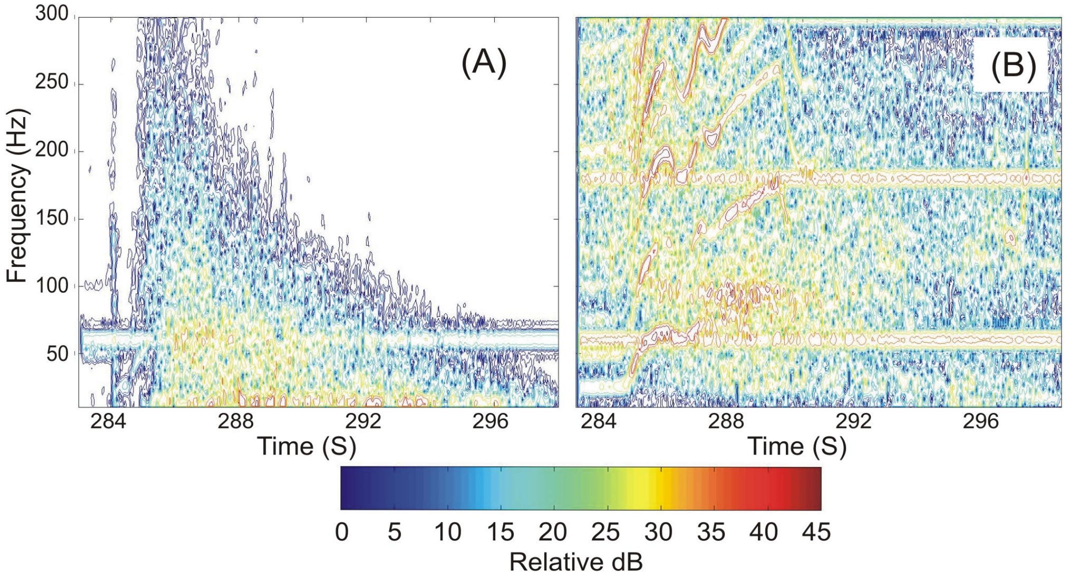

Figure 6: Spectragrams Generated When a Car is Driven Past a Geophone (A) and a Microphone (B).

Large Machinery: There were several pieces of large machinery that were anchored to the ground close to one of the field test sites. Unfortunately, these were being operated for unrelated purposes and could not be stopped and started during the noise measurements to determine their specific contributions to the ambient noise. At the field site northwest of Atlanta, one of these pieces of machinery was a wind tunnel powered by a 12 cylinder diesel engine that was anchored to a concrete slab. It was about 60 meters from the test site. This was running during one of the noise measurements and was shut down prior to the end of the record. The event of its shutdown is depicted in Figure 7 as both a time history and a spectragram. The overtones of the engine frequency can be seen to end at the moment that it is shut down and there is an obvious corresponding decrease in the ambient noise energy apparent in the time record. Following shutdown, other spectral components can be seen to shift in frequency. These are probably associated with the rotating turbine, and their shift is reflective of a transition to a compression-braking mode. There is sufficient inertia in the system that it is still spinning at nominally the same rate at the end of the record.

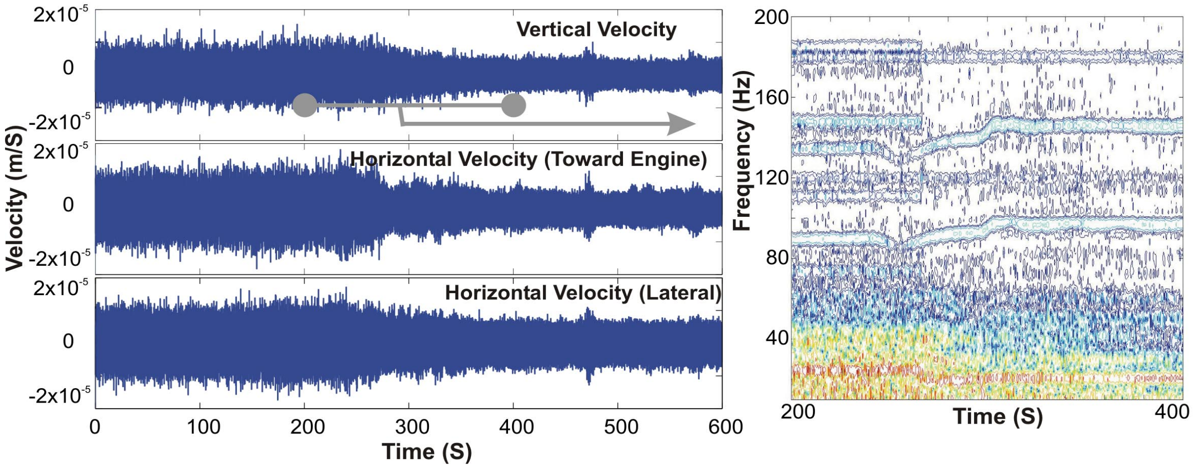

Figure 7: Wind Tunnel Shutdown, as a 3-Axis Time History and as a Vertical-Axis Spectragram on a 50 dB scale.

Pedestrians: A person walking quietly on open ground is very difficult to discern audibly at any significant distance. This is not the case for their seismic signatures. Each footfall constitutes a broadband impulsive seismic point source, and the regularity of a walker's gate is an excellent cue to the origin of these impulses. In tests conducted at all of the field sites, a walker could not be detected by either an audible reproduction or a visual inspection of data acquired with a microphone although he had passed with 2 meters of its location. In contrast the walker was readily apparent in a simultaneous geophone recording at ranges out to 20 meters through visual inspection of the time histories of recorded ground motion. Such a record is depicted in Figure 8 as both a time history and a spectragram. The regular impulsive nature of the footfalls is readily apparent in this figure. The diminution of the peaks in the time history as the pedestrian moves further from the sensor is accompanied by a loss of the high frequency components of the individual impulses that is consistent with attenuation in the ground over a longer propagation path.

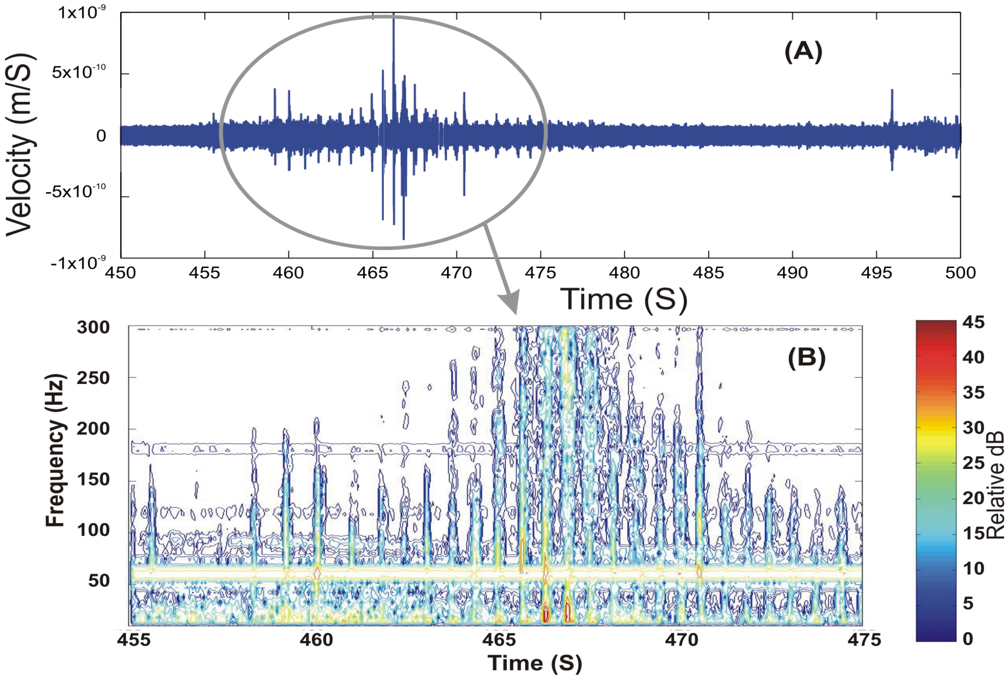

Figure 8: A Person Walking Past a Geophone as a Time History (A) and as a Spectragram (B).

5. NATURAL OR ANONYMOUS NOISE SOURCES

The dominant sources of natural noise observed in the microphone recordings were wind and biological noise (birds). Neither of these was manifest on the simultaneous geophone records. Wind has been documented as a source of seismic noise close to the earth's surface at frequencies up to 50 Hz, but the threshold for the observation of this effect has been reported to be a wind speed of 3 to 4 m/S [7,12]. Accurate wind speed observations were not made during the noise recordings at the field sites. Winds were noted as being very light in all the records reported here. Taken in conjunction with the relatively high background levels measure, this makes it unlikely that wind made a significant contribution to the seismic measurements.

Rain is expected to make a measurable natural contribution to seismic noise in the band of interest as it does to noise measured underwater [15,16]. The generation mechanism is likely to be quite different in the ground where bubble collapse should not play a role. Unfortunately, the weather has not yet cooperated in allowing this effect to be quantified in a field experiment. This measurement, which has many intrinsic complications, will be attempted in a future series of field experiments.

There were several features on the geophone records, other than those described in the previous sections, which did not have obvious analogs in either the microphone record or the written event log kept by an observer. These may have been events of natural origin. Two such events are depicted in Figure 9. These were recorded at the Georgia Tech Woodbury radio telescope facility in a rural area of central Georgia. The duration and spectral content of these two events is consistent with reports of seismic signals generated by thunder [10], however there are no simultaneous acoustic records in these reports to indicate whether or not the seismic path was the dominant path. The thunder explanation is consistent with the presence of thunder storms in the area of the experiment earlier that day. Alternatively, it is possible that wind coupling through nearby trees or the nearby radio telescope antenna could have produced an unusually large seismic signal without being perceived by the microphone or observer near the ground. Of course more mundane explanations involving man-made noise are possible too. These signals were recorded in an area where there is considerable quarry activity and individually they are consistent with quarry blasts recorded at distances of a few tens of kilometers.

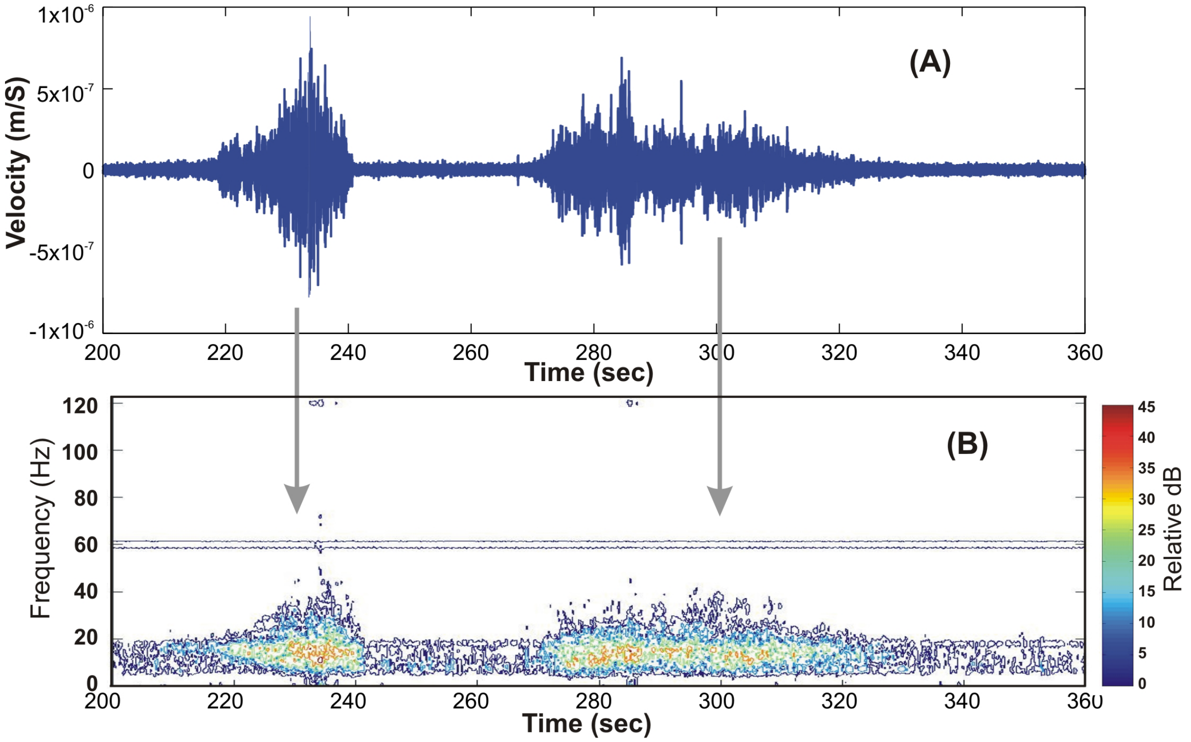

Figure 9: Anonymous Vertical Geophone Records. Time History (A) and Spectragram (B).

6. CONCLUSIONS

Observed seismic background noise at the four field sites was found to be considerably lower than levels measured in the laboratory. It is not believed to pose a serious limitation for the operation of the seismic mine detection system under similar conditions. Some interesting transients have been observed in the measured noise which will be useful in the design of future experiments in that they point to potentially problematic seismic noise scenarios. At present there is no evidence of sufficient seismic noise at any of the field sites to permit this to be exploited for the imaging of mines with the current system sensor.

7. ACKNOWLEDGEMENTS

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8. REFERENCES

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