LONG RANGE DETECTION AND MODELING OF SOUNDING ROCKET LAUNCHES

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Abstract

The Army Research Laboratory has been running an infrasonic array at its Blossom Point Research Facility since the summer of 1998. The infrasonic array monitors events in the 3 - 8 Hz window 24 hours a day/7 days a week. Interesting events are tracked down to determine the source of the infrasonic energy. This paper will discuss a series of detections that were determined to be sounding rocket launches from Wallops Island, Virginia. The paper will also discuss acoustic modeling efforts to determine reasons the launches were not always detected.

1 INTRODUCTION

Monitoring of rocket launches is a critical activity for the Army. Infrasound allows for the long range monitoring of these activities with the ability to determine characteristics of the rocket being tested. We use the Chaparral Physics Model 2 microphone as the sensor for the array. In order to span the widest available dynamic range, we used a 24-bit analog-to-digital converter. The computer used for data acquisition is a simple PC running the Unix like QNX operating system. ARL has operated an infrasonic array of microphones, with data collection, and signal processing operating as a server of infrasonic data since July 1998. The goal of this experiment has been the study of all aspects of infrasonic signals in the atmosphere. Our interest began with the detection of impulsive signals like artillery, mortars, and missiles, but due to the nature of infrasonic propagation, in the atmosphere we must also include other "background" signals that reach our sensors. By selecting array geometry with 20 m spacing, we have directivity in a frequency range that would be tactically useful to the Army (3 - 8 Hz). The study of the infrasonic energy available at these frequencies includes signatures of many natural events and man-made machines such as: thunderstorms, power stations, aircraft, and gas supply lines. Determination of the source of the signals detected by an infrasonic array has proven to be a time consuming process [1].

These "background" signals have ranged from signals of interest to Army operations such as explosive testing, artillery, power stations, rail traffic, and river traffic to "noise" signals such as passenger airliners, Concord, and thunderstorms. Due to the characteristics of infrasound propagation, unknown received signals can be from relatively close sources or extremely long-range

Figure 1: Chaparral Physics microphone with porous hose attached.

sources on the order of hundreds or thousands of kilometers. Due to the relatively short baseline, our two arrays can only triangulate on sources within 15km of our measurement facility [2]. If the unknown received signal repeats with a pattern or matches with a schedule, then the source can be tracked down. We have had very good success in tracking down and identifying signals from the Space Shuttle launches, Concord flights leaving Kennedy International Airport, rail traffic in Virginia, and passage jetliners flying into Reagan National and Dulles International Airports. In the spring of 2002, we tracked down one of these "background" signals that proved to be of high interest.

2 EXPERIMENTAL CONFIGURATION

The Globe microphone, now manufactured as the Chaparral Physics Model 2, has been used for this work. The major obstacle in the detection of infrasonic signals is wind. Turbulent motion of the air takes place as large eddies that propagate along with the wind causing low frequency noise. In order to reduce this effect pressure signals are averaged over an area that is a larger scale than the single point microphone thus reducing the apparent dynamics created by turbulence. A leader in the field of wind noise suppression at very low frequencies has been Dr. Al Bedard of NOAA's Environmental Sciences Laboratory [3]. Consultation with Dr. Bedard and Dr. Rod Whitaker of Los Alamos National Laboratory suggested the application of a radial arrangement of porous garden hose. A photograph with the Model 2 microphone attached to six 20-ft lengths of porous hose arranged radially is shown in figure 1.

We have been operating two arrays separated by 1 km. Array 1 is comprised of four Model 2 microphones forming a triangle with one microphone in the center. This array also contains a 3-axis seismometer for correlation of infrasonic events with corresponding seismic components. Array 2 has five Model 2 microphones forming a cross with one microphone in the middle. Figures

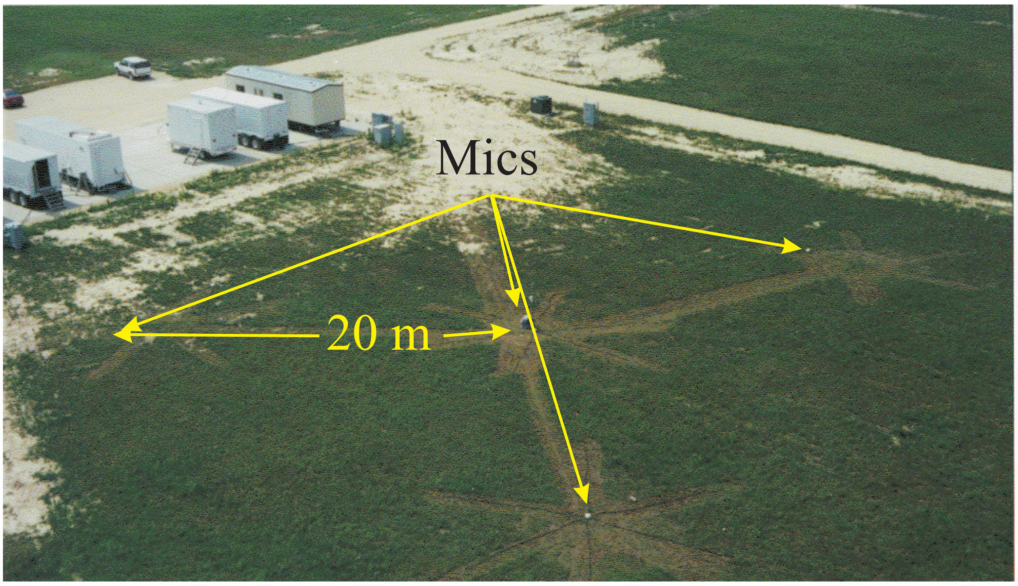


Figure 2: Layout of microphones at array 1.

2 and 3 shows the layout of the microphones for the two arrays. In the center of each array there is a met mast containing a Vaisala 425 Ultrasonic Wind Sensor and a thermister for measuring temperature, figure 4. The acoustic, seismic (array 1 only), and temperature data feeds to a Sigma-Delta analog-to-digital converter (ADC) produced by Symmetric Research Inc. The ADC unit is based on the Harris H17190 24-bit Sigma-Delta ADC. This device requires 4 times oversampling to assure non-aliased data rather than the normal 2 times Nyquist rate. As a result, we are sampling at 100 Hz to achieve a 25 Hz sample rate [4]. The ultrasonic wind sensor outputs its data serially to a control computer. The control computer for each array manages the ADC and wind sensor and stores the data into hourly binary files.

3 DATA PROCESSING

Data was collected at 100 Hz and filtered to 25 Hz, however, we only process data to 8 Hz to avoid grating lobes. The Average Spectral Coherence (ASC) across the array was employed as a signal detector [5]. An adaptive Minimum Variance Distortionless Response (MVDR) beamformer is used. The relationship used for the MVDR beamformer can be found in many references.

$$P_{\mathrm{MVDR}}\left(f,\vec{k}\right)=\frac{1}{\acute{A}^{T}R^{-1}\acute{A}} \tag{1}$$

$\acute{A}$ is the steering vector and R is the correlation matrix. Once ASC indicates that a signal is present, the beamformer creates 120 beams. Beamforming over the wavenumber range based on the measured ambient temperature and the frequency range of interest (3 to 8 Hz) the direction of arrival is selected by determining the maximum amplitude reaching the array. The direction of the maximum beam power is thus determined to be the direction of signal propagation. Once direction is established, the beamforming process is extended to consider the full wavenumber range and

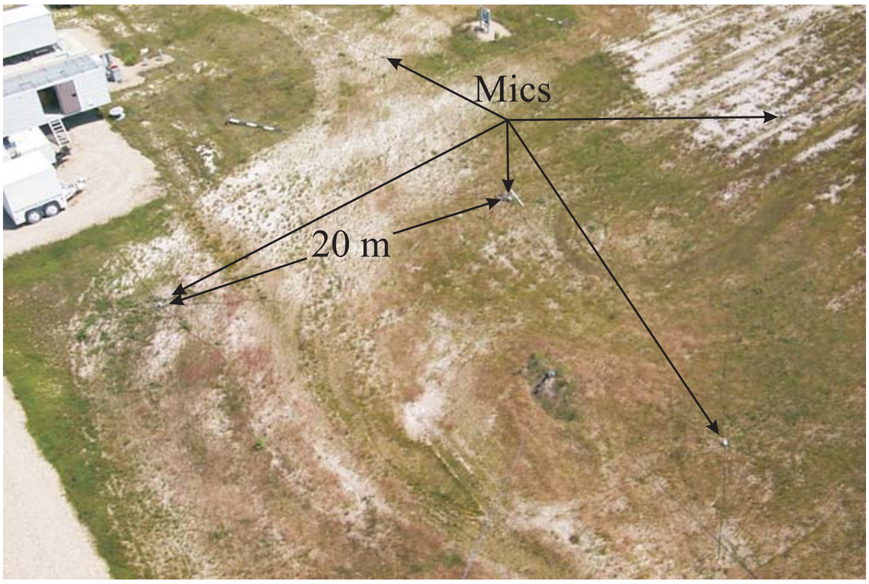


Figure 3: Layout of microphones at array2.

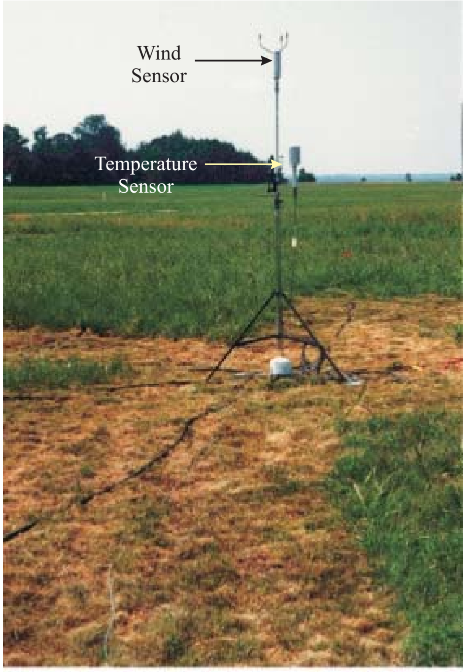


Figure 4: Meteorological mast with wind and temperature sensor.

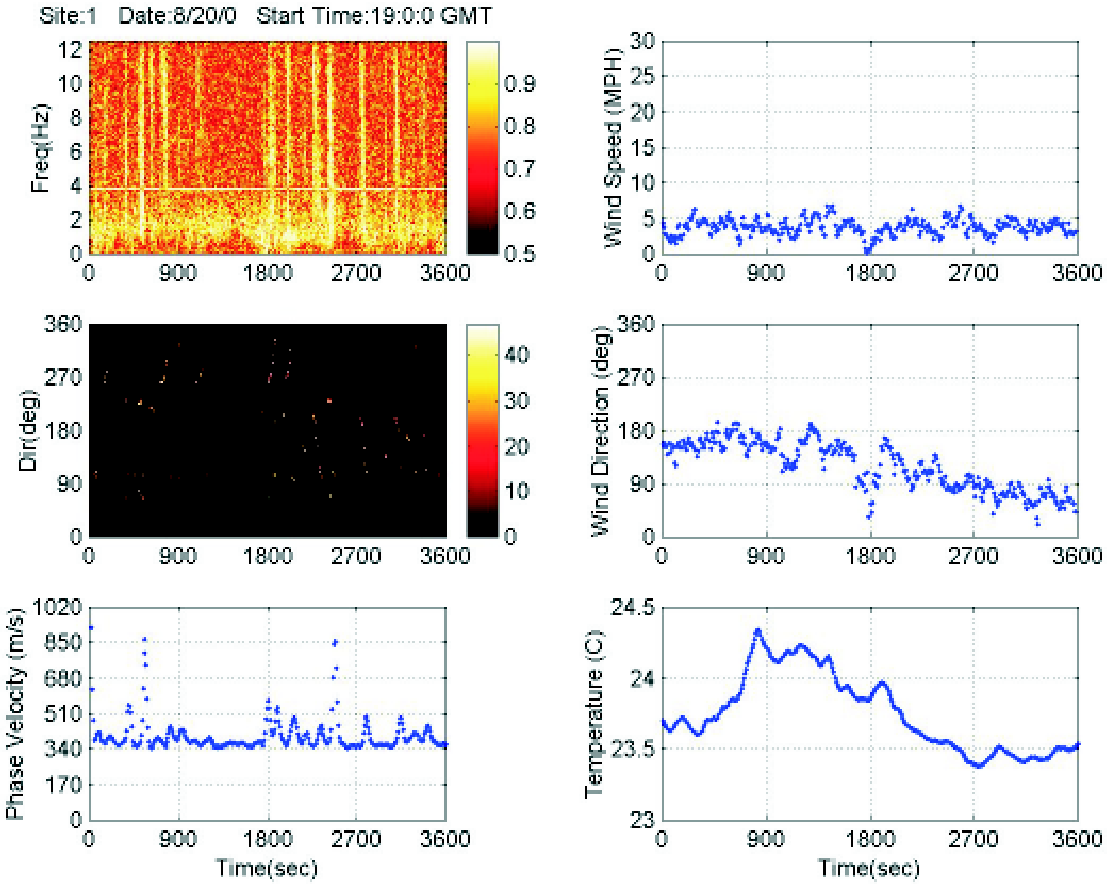


Figure 5: Typical output from data processor.

a range of apparent propagation speeds or slowness ($k/\omega = 1/c$). This slowness value is the apparent propagation speed, which infers the angle of elevation of the incoming signal [6].

MATLAB calculates the ASC, carries out the beamforming, and calculates phase velocity and elevation angle for each hour of data. These characteristics are presented in strip chart fashion so that the activity present during the hour is easy to visualize. Wind speed, wind direction, and temperature are plotted for the hour and all six parameters are shown on one graphic as a JPEG image. Each complete graphic image includes the site number, date, and start time for the file. Figure 5 is a typical plot from the MVDR beamformer where signals detected between 3 and 8 Hz are beamformed and the maximum amplitudes plotted. The figure shows arrivals from aircraft and possible rail traffic. Rail lines will create signals between 270 and 360 degrees azimuth and aircraft will show an elevated phase velocity.

4 PROPAGATION

Meteorological phenomena can have a significant effect on the received sound field. Some of the meteorological variables affecting propagation of sound in the atmosphere are pressure, temperature, wind velocity, and humidity. For infrasound, the primary atmospheric properties affecting propagation are temperature and wind velocity. For extremely long-range propagation of infrasound, pressure can also play a primary roll. In the atmosphere, the speed of sound (c) is [7]

$$c(T) = \sqrt{\frac{\gamma R T}{M}} \tag{2}$$

where γ is the ratio of specific heats, R is the universal gas constant equal to 8314.16 J/(kg K), T is the air temperature, and M is the molecular weight of air. The effect of the wind speed on the speed of sound is a vector relation. The effective sound speed is calculated by

$$c_{\text{eff}} = c(T) + u \cdot \hat{r} \tag{3}$$

where u is the magnitude of the horizontal wind speed and $\hat{r}$ is the unit vector in the direction of propagation. For long-range propagation of infrasound, there are a couple of naturally occurring wave guides in the atmosphere: stratospheric and thermospheric (figure 6). The stratospheric wave guide returns acoustic energy from 30-50 km in altitude while the thermospheric wave guide returns energy from 100-150 km [8]. This is illustrated by figure 7 of a raytrace showing rays turning over at the two altitudes.

These two other two effects that allow for infrasound to propagate extremely long distances are ground reflection and molecular attenuation. At infrasonic frequencies, the ground makes for a good reflecting surface allowing for most of the incoming energy to be reflected by the ground. Also at these frequencies, the molecular attenuation is approximately zero. This means that most of the energy in the signal is lost from refraction and diffraction.

5 DETECTION

Figure 8 shows the output from our data processor showing a short time broadband arrival from 128°. The arrays would periodically show this signal from the same bearing. Checking the various activities in the area did not show any correlation between ongoing activities and the received signal. Expanding the search out to an increasing distance, we finally found a match with the sounding rocket launch schedule from NASA's Wallops Island facility. Checking our historical data with that of the sounding rocket launches showed a very good correlation over several years. Table 1 shows the comparison between the sounding rocket launches and the detections.

For this paper, we will focus on the June 21, 2000 detection of a Nike-Orion launch. Wallops Island is located 153 km from our Blossom Point Research Facility arrays. Figure 9 shows the detection of the June 21st sounding rocket launch with the impulse at 10:52:30Z. Figure 10 is the time-series of the signal from the sounding rocket launch. For this detection, the peak amplitude is about 50 mPa (68dB). This signal is well above the background noise floor. Figure 11 shows the spectrogram of the time-series. The maximum energy in the spectrum for the sounding rocket launch is around 5 Hz and dies out about 12 Hz.

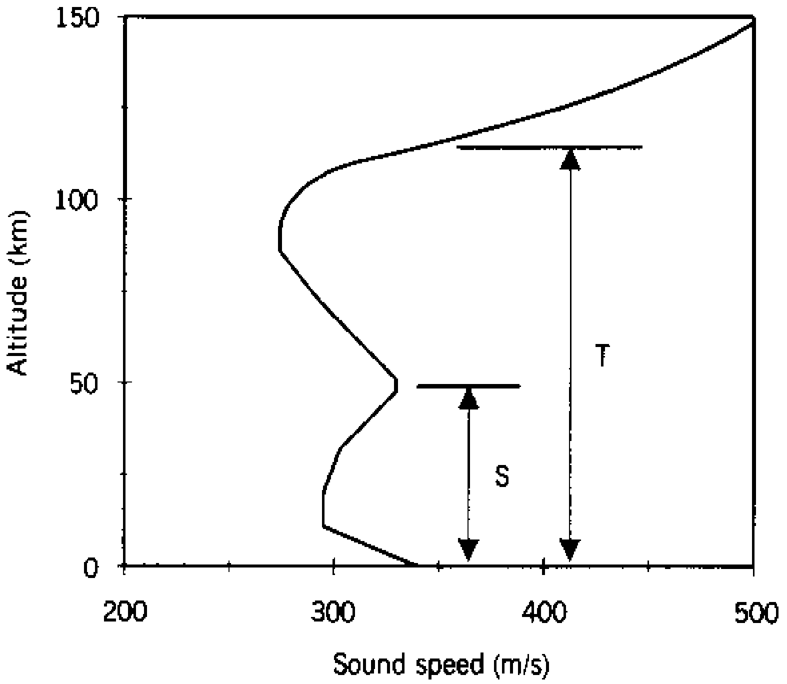


Figure 6: Example sound speed profile showing the stratospheric and thermospheric sound channels.

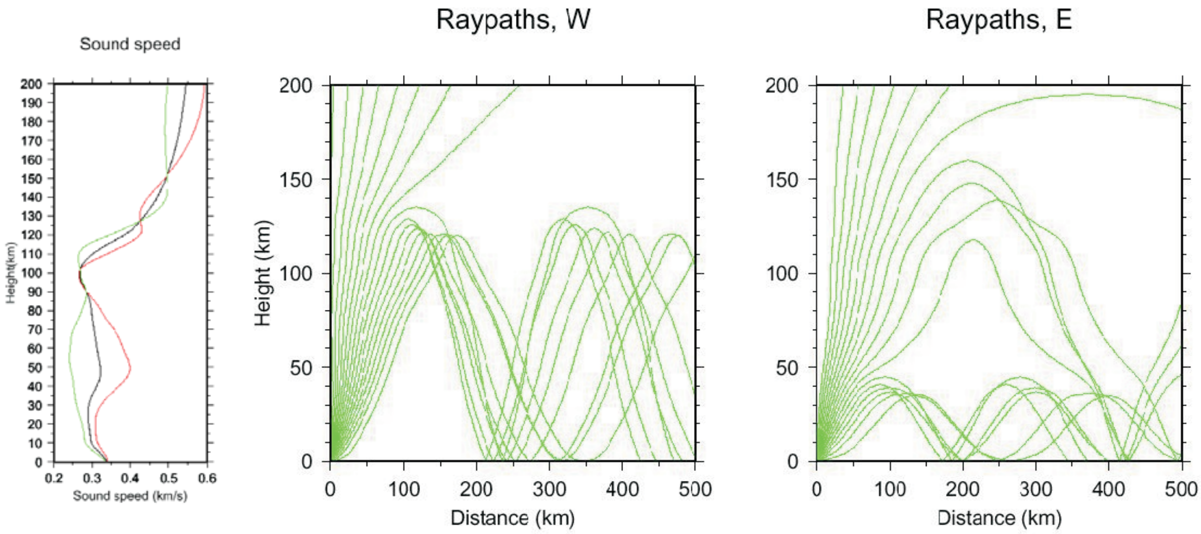


Figure 7: Raytrace showing the turning over of rays from the stratospheric and thermospheric wave guides.

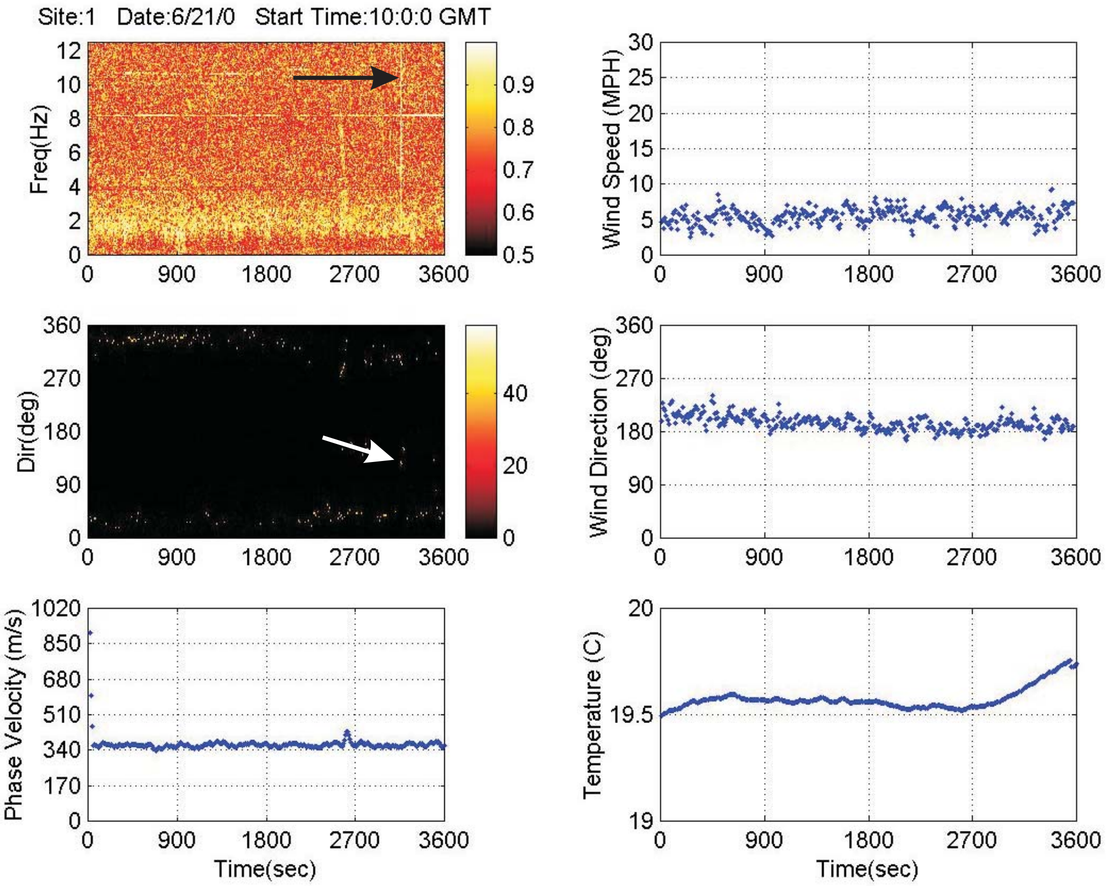
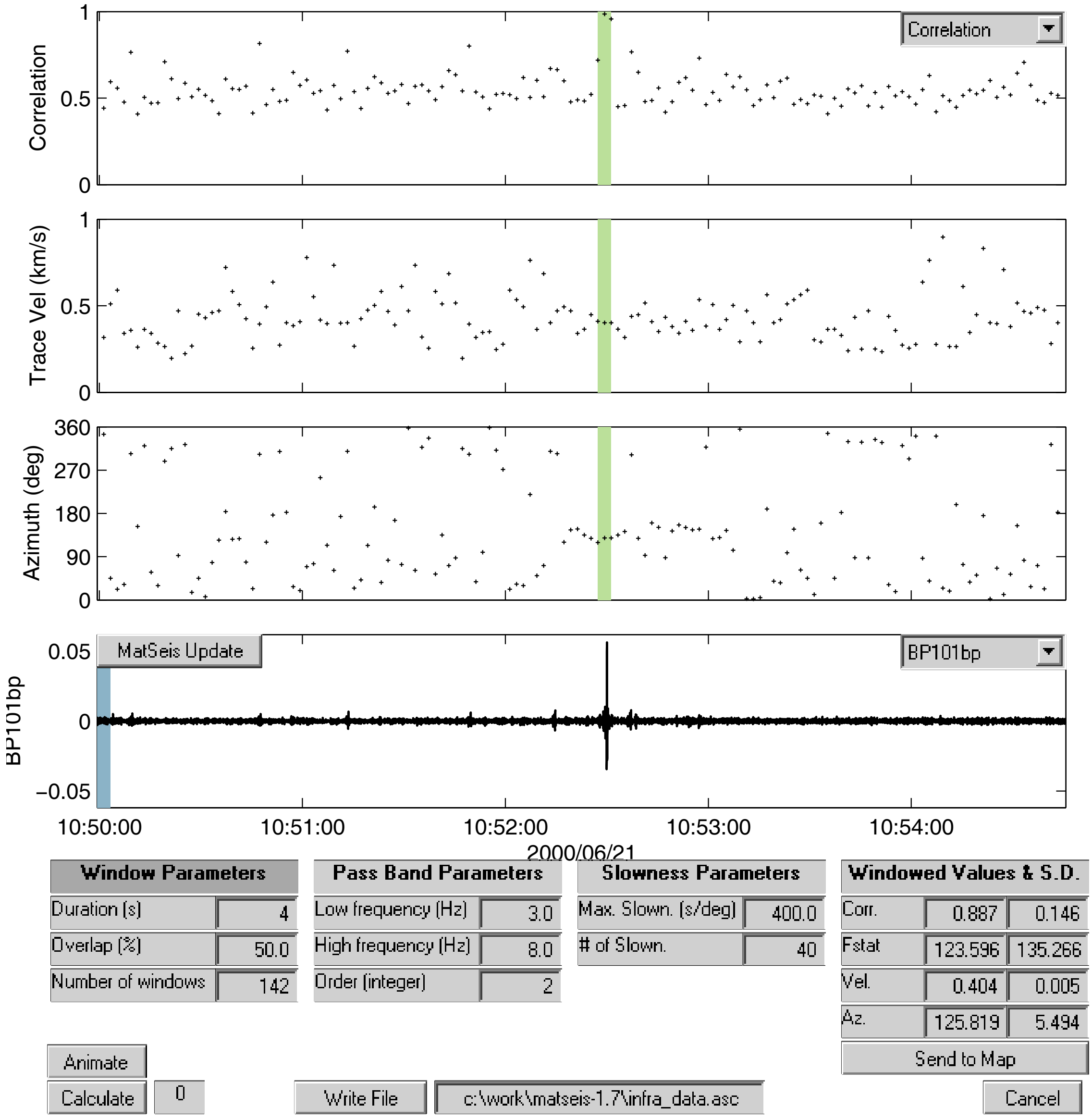


Figure 8: Array processor output showing the detection and bearing for a sounding rocket launch.



Window Parameters

Duration (s)	4
Overlap (%)	50.0
Number of windows	142

Pass Band Parameters

Low frequency (Hz)	3.0
High frequency (Hz)	8.0
Order (integer)	2

Slowness Parameters

Max. Slown. (s/deg)	400.0
# of Slown.	40

Windowed Values & S.D.

Corr.	0.887	0.146
Fstat	123.596	135.266
Vel.	0.404	0.005
Az.	125.819	5.494

Correlation

0

c:\work\matseis-1.7\infra_data.asc

Figure 9: Analysis of the June 21, 2000 sounding rocket detection.

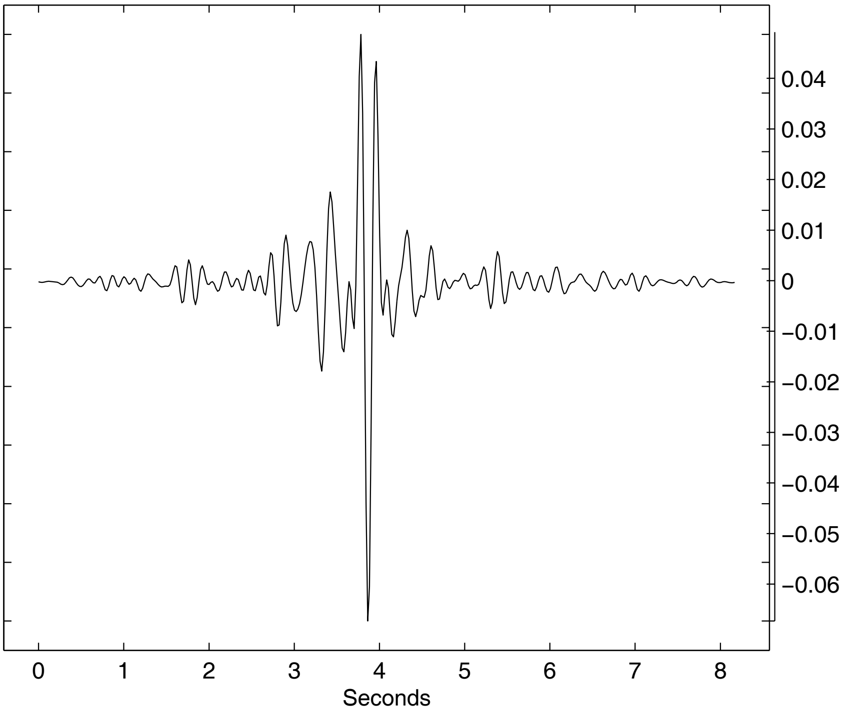


Figure 10: Time-series of the June 21, 2000 sounding rocket detection.

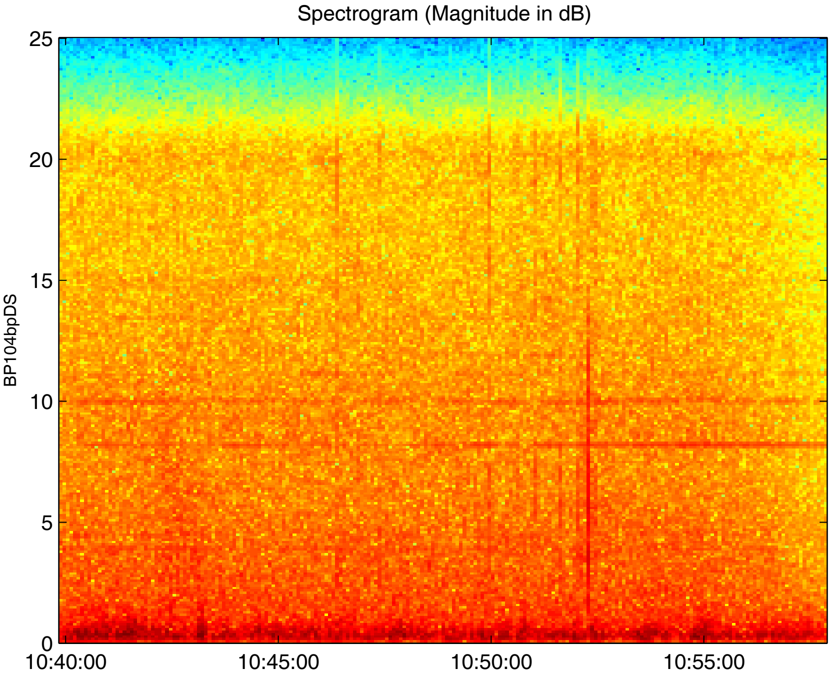


Figure 11: Spectrogram of the June 21, 2000 sounding rocket detection.

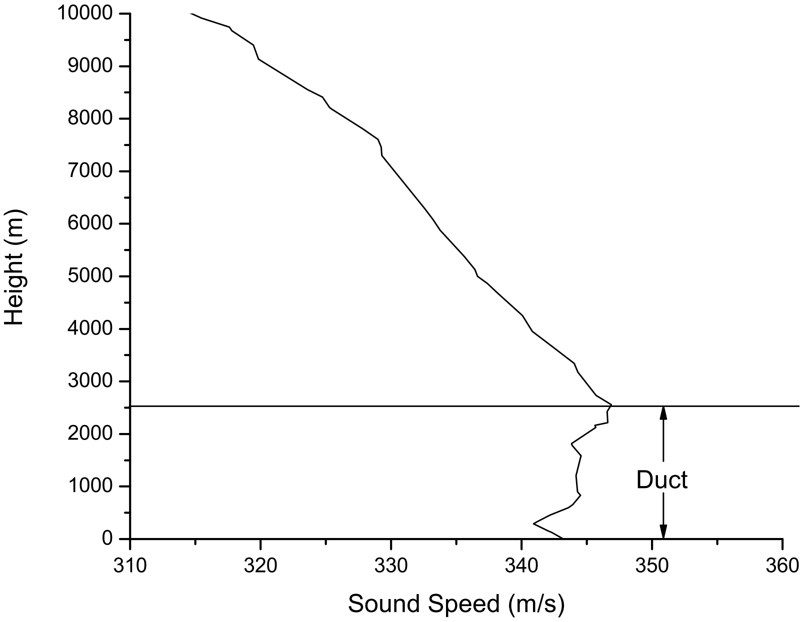


Figure 12: Sound speed profile of the June 21, 2000 sounding rocket showing a low level sound duct.

As Table 1 shows, we detect the sounding rocket launches about 50% of the time. The primary reason is the effect of the atmosphere on the sound propagation. As mentioned in the previous section, the temperature and vector wind are the primary factors in the atmosphere affecting propagation. We have obtained balloon launches from Wallops Island to look at the atmospheric effects on propagation. Figure 12 shows the sound speed profile for the June 21st launch. The profile shows a "low level" sound duct extending to 2500 m in height above the ground. The sound duct will allow for long range propagation of sound with little loss in amplitude [9].

6 SUMMARY AND FUTURE WORK

Infrasound arrays allow for the long range detection and tracking of sounding rockets. This is very important for the Army to monitor operations at a distance. The detection of these sounding rockets that are relatively small rockets at a distance of 150 km is very promising for the detection of larger more tactically important rockets at longer distance. We are beginning to study the atmospheric effects on these infrasound detections. We will be using the Acoustic Battlefield Aid (ABFA) [10] to perform atmospheric characterization for each of the sounding rocket launches to determine the reason why we did not detect a launch. ABFA will be used to perform this study because it incorporates Digital Terrain Elevation Data (DTED) allowing for effects of the terrain.

References

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Table 1: Comparison between launch schedule and detections

Vehicle	Date	Launch Time (Z)	Detection	Detection Time (Z)
Terrier-Orion	08/20/03	11:05:00	Yes	10:16:30
Test Vehicle	08/01/03	10:25:03	Yes	10:36:25
Terrier-Orion	06/30/03	07:07:00	Yes	07:19:10
Nike-Black Brant	06/30/03	06:50:00	Yes	07:02:20
Terrier-Orion	06/30/03	05:41:00	Yes	05:53:00
Terrier-Orion	06/29/03	03:19:00	No	–
Terrier-Malemute	06/10/03	06:31:00	System Down	–
Orion	06/06/03	10:01:00	Yes	10:13:30
Black Brant XI	06/02/03	09:28:00	Yes	09:40:30
Black Brant XI	05/30/03	09:35:00	Yes	09:47:30
Terrier-Orion	11/20/02	01:33:00	No	–
Viper	06/13/02	04:40:00	No	–
Orion	06/06/02	10:41:00	Yes	10:50:45
Viper	05/16/02	07:00:00	System Down	–
Nike-Orion	05/16/02	06:26:00	System Down	–
Viper	05/16/02	06:00:00	System Down	–
Nike-Orion	05/10/02	06:32:00	Yes	06:42:05
Viper	05/10/02	06:14:20	No	–
Black Brant V	06/29/01	00:44:01	No	–
Orion	06/06/01	10:50:00	No	–
Terrier-Lynx	12/19/00	11:58:00	No	–
Nike-Black Brant	07/17/00	06:17:00	Yes	02:26:30
Nike-Orion	06/21/00	10:43:00	Yes	10:52:30
Orion	06/18/00	11:03:00	Yes	11:12:30
Nike-Orion	06/13/00	16:06:00	Yes	16:15:30
Nike-Orion	05/17/00	10:18:39	Yes	10:28:30
Terrier-Improved Orion	12/17/99	17:00:00	No	–