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Acoustic Energy Measured in Severe Storms During a Field Study in June 2003

by Jeffrey E. Passner and John M. Noble

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14. ABSTRACT
The U.S. Army Research Laboratory (ARL) has developed a low-cost, mobile, rugged, non-line-of-sight acoustic sensor for surveillance, detection, identification, and locations of targets using unattended microphone sensors to measure infrasonic (<10 Hz) energy. However, it was discovered that the acoustic sensor is capable of measuring background noise sources such as thunderstorms and severe weather. On 28 April 2002, the F4 La Platta, Maryland tornado passed 13 km from the acoustic sensor and a time series showed a series of peaks in the spectrum. ARL decided to investigate the infrasonic spectrum in a variety of storm environments in a field study in June 2003. During the 3-week study in the Central Plains of the United States several severe storms, mesocyclones, and tornadoes were sampled. This report discusses the data collection, documentation, and structure of these storms. Based on the observations and data collected there is apparently a correlation between tornadic storms and storms that record less than 10 Hz signals in this study.

15. SUBJECT TERMS
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Summary

The U.S. Army Research Laboratory (ARL) has operated an infrasonic array of microphones, with data collection and signal processing since July 1998. The goal of this array was to study various infrasonic signals found in the atmosphere. Originally the object was to record signals such as artillery, mortars, and missiles, but due to the nature of infrasonic propagation in the atmosphere it was possible to investigate background noise such as thunderstorms and severe weather.

On 28 April 2002, the F4 LaPlata, Maryland tornado passed 13 km from the acoustic sensor and a time series showed a series of peaks in the spectrum. ARL decided to investigate the infrasonic spectrum in a variety of storm environments in a field study in June 2003. Much of the work in recording acoustic waves from severe weather has been done by the National Oceanic Atmospheric Administration's Environmental Technology Laboratory in Boulder, Colorado (ETL). ETL discovered a connection between pressure fluctuations in the frequency range 0.5 to 10 Hz and the occurrence of tornadoes. In this study a mobile acoustic sensor was deployed in the Central Plains of the United States where several severe storms, mesocyclones, and tornadoes were sampled. Results indicate that many of the features discovered by ETL in their data also appeared in these data samples, while many differences were also noted.

1. Introduction

The U.S. Army Research Laboratory (ARL) has developed a low-cost, mobile, rugged, non-line-of-sight acoustic sensor for surveillance, detection, identification, and locations of targets using unattended microphone sensors to measure infrasonic (<10 Hz) energy. However, it was discovered that the acoustic sensor is capable of measuring background noise sources such as thunderstorms and severe weather. On 28 April 2002, the F4 LaPlata, Maryland tornado passed 13 km from the acoustic sensor and a time series showed a series of peaks in the spectrum. ARL decided to investigate the infrasonic spectrum of a variety of storm types and environments during a field exercise in June 2003. The exercise was designed to collect data from severe thunderstorms, supercells, and tornadic storms, investigating the low-frequency sound generated from these atmospheric phenomena. Numerous storms were sampled and documented during a 3-week period; these storms included a small tornado on 9 June 2003 near Spearman, TX; two strong supercells near Olney, TX; and two supercells in north central Nebraska on 21 June 2003. The highlight of the data collection was during the 24 June 2003 outbreak of tornadoes in South Dakota.

2. The Acoustic Array at Blossom Point, Maryland

Since 1998, the ARL has operated two infrasonic arrays of microphones with data collection and signal processing to study all aspects of infrasonic signals in the atmosphere at Blossom Point, MD. Typically human hearing extends from 20 to 20,000 Hz with frequencies below 20 Hz classified as near infrasound. Of most importance to ARL is the range between 3 and 8 Hz which includes many sources such as rockets, planes, explosions, and power plants in this frequency band. Additionally, infrasonic sound in the 3 to 8 Hz range can be detected at long ranges and this is advantageous because the size of the array can be smaller and even portable. Infrasonic data for many man-made events such as Space Shuttle launches, Concorde flights leaving Kennedy International airport, rail traffic in Virginia, and aircraft at local airports have been recorded at the Blossom Point site (*1*,*2*).

2.1 Configuration of Acoustic Array at Blossom Point

Array 1 is comprised of four Chaparral model 2 microphones which form a triangle with one microphone in the center. The array site also has a three-axis seismometer to monitor for correlations between acoustic and seismic signals. Figure 1 shows the configuration of Array 1 at Blossom Point.

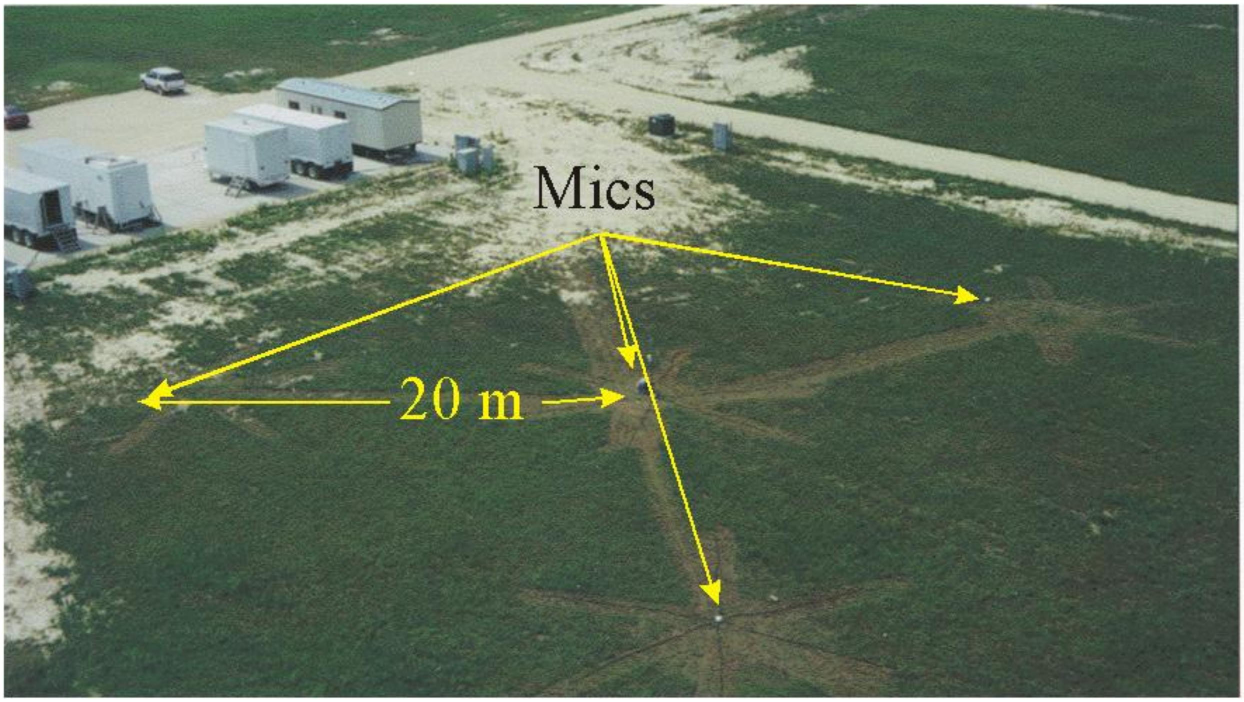

Figure 1. Configuration of Array 1 at Blossom Point, MD.

NOTE: The arrows are pointing to position of the microphones.

Array 2 has five microphones forming a "cross" with one microphone in the middle. At the center of each array is a small meteorological mast containing a temperature sensor and a Vaisala 425 ultrasonic wind sensor. The acoustic, seismic (array 1 only), and temperature data feeds to a Sigma-Delta analog-to-digital converter (ADC) produced by Symmetric Research Inc. This device requires four-times oversampling to assure non-aliased data rather than the normal two times Nyquist rate. As a result, data are sampled at 100 Hz to achieve 25 Hz sample rate. The ultrasonic wind sensor outputs data serially to a control computer which are stored into hourly binary files. At the completion of each hour, a Matrix Laboratory (MATLAB) based quick-look algorithm runs to provide a graphical display. [*](*3,4,5*).

[*] MATLAB is a commercial product produced by Mathworks Inc. that is a high-level computing language used in this study for data visualization, data analysis, and signal and image processing.

A major obstacle in the detection of infrasonic signal is the 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 larger scale than the single-point microphone, thus reducing the apparent dynamics caused by turbulence. It was suggested to place a radial arrangement of six porous 20-ft garden hoses around the microphone as seen in figure 2.

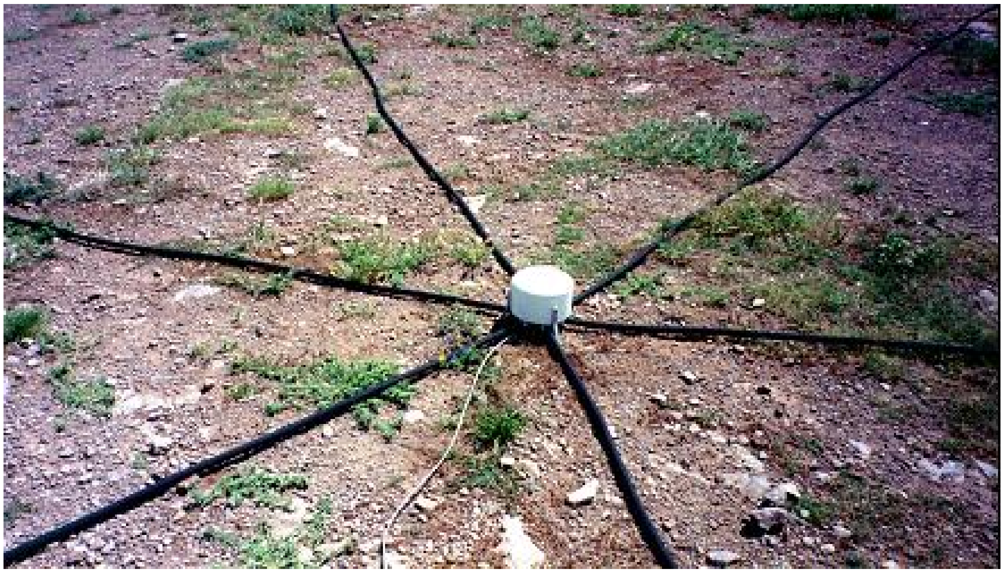

Figure 2. Chaparral Physics Model 2 microphone is used as the sensor for the array with six garden hoses used to filter and reduce wind noise.

2.2 Data Processing

Data were collected at 100 Hz and filtered to 25 Hz, however only data to 8 Hz were processed to avoid grating lobes. The Average Spectral Coherence (ASC) across the array was employed as a signal detector and an adaptive Minimum Variance Distortionless Response (MVDR) beamformer was applied. The direction of maximum beam power is determined to be the direction of signal propagation. Once the direction was established, the beamforming process was extended to consider the full wavenumber range and a range of apparent propagation speeds. This value was the apparent propagation speed, which infers the angle of elevation of the incoming signal (*3*).

The MATLAB program calculated the ASC, carried out the beamforming, and calculated phase velocity and elevation angle for each hour of data. These characteristics are presented in strip-chart fashion such that wind speed, wind direction, and temperature are plotted for the hour and all six parameters are shown on one graphic as a JPEG image. Figure 3 is a plot from the MVDR beamformer where signals detected between 3 and 8 Hz are beamformed and maximum amplitudes plotted.

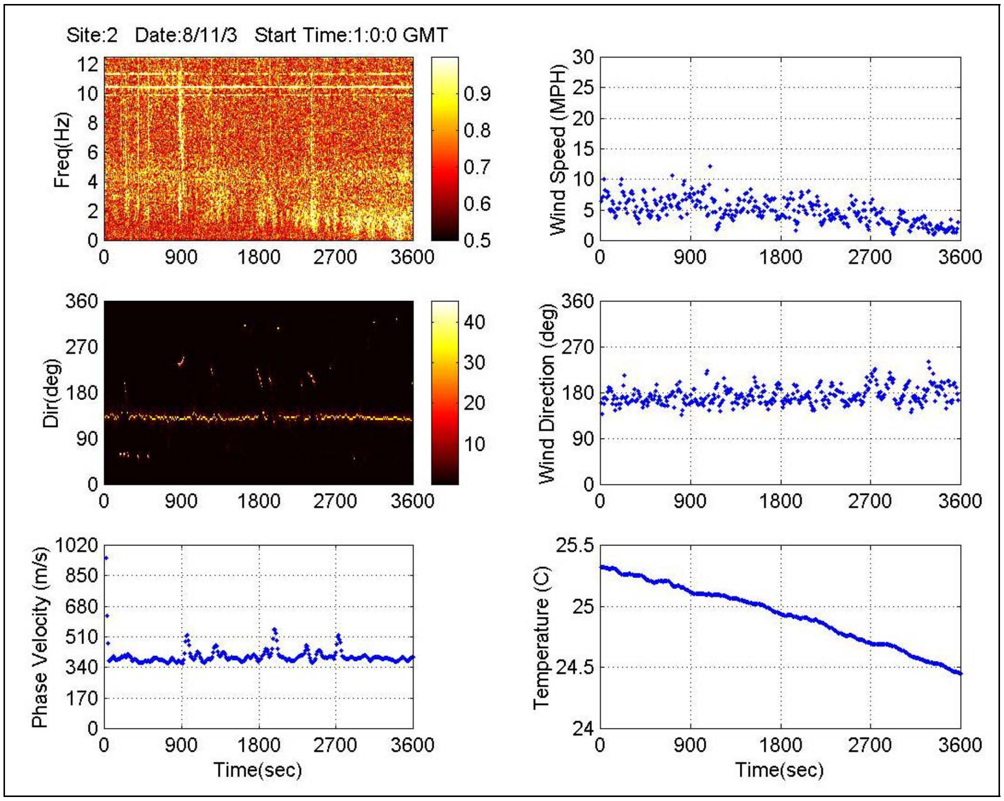

Figure 3. Output from data processor on 11 August 2003 between 0100 to 0200 Coordinated Universal Time (UTC).

The upper left image in figure 3 is the average signal coherence or the correlation between the pressure signals with time across the array. In this plot the x-axis is given in seconds for the 1-h plot while the y-axis is the frequency in Hertz. The plot shows low correlation of the signal for most of the hour; however, there is a more coherent signal or higher correlation coefficient in the final 15 min of the hour, centered at a low frequency between 1 and 2 Hz. The left middle image is the bearing to the source with time and in this case the array is finding the strongest or dominant signal coming from about 120° (east to southeast direction). The bottom left plot is the horizontal phase velocity across the array. This is a general way of estimating the elevation of the sound source since the acoustic wave traveling along the ground will pass the array at the speed of sound, and elevated signals will pass the array at higher speeds. On average the phase velocity will be near 344 m/s at 20 °C; however, there are three higher peaks noted, which may indicate that the sound is being observed from an elevated source.

During this hour, based on radar (not shown), there were non-severe thunderstorms noted to the west of Blossom Point and the array. The wind speed is less than 10 mph while the wind direction is steady between 160° to 200°. There is little temperature change during the hour plotted, with only a 1° drop which is most likely due to normal diurnal fluctuations and not approaching thunderstorms. It is uncertain as to what the true source of the signal is during this hour; however, it is not due to the any known weather-related systems.

2.3 The LaPlata, Maryland Tornadic Thunderstorm

Since 1999, numerous thunderstorms have passed over the two arrays at Blossom Point and have displayed infrasonic signals that were vastly different than many of the man-made signals. On 28 April 2002, a strong severe weather and tornadic event occurred in the vicinity of Blossom Point and was well documented by the infrasound arrays.

The LaPlata tornado was rated as an F4 tornado on the Fujita scale, which indicated destructive winds from 207–260 mph, and was part of a large outbreak of severe storms ranging from the Midwest to the Atlantic Coast. The tornadic storm originated over the higher terrain of West Virginia and moved eastward as an isolated supercell which produced large hail and eventually tornadoes over Virginia and southern Maryland. The tornado that struck LaPlata was on the ground for approximately 110 km and reached the city at 2302 UTC while moving at an estimated 50 kn (*6*).

Apparently, tornadogenesis followed the classic sequence with a rear-flank downdraft displayed on radar at 2235 UTC. A hook echo, as shown in figure 4, was noted at 2251 UTC and finally a confirmed tornado was observed at 2256 UTC 16 km west of LaPlata.

Figure 4. Doppler radar image of approaching tornadic thunderstorm.[†]

[†] From WJLA in Washington, DC, 28 April 2002 approximately at 2300 UTC.

The tornado moved approximately 13 km north of the Blossom Point acoustic array and provided a detailed acoustic data set from the rotating storm as shown in figure 5 and figure 6 (*7*,*8*).

In figure 5, in the upper-left plot there is correlation in the signal between 2232 and 2245 UTC, although the direction of the sound source is not plotted in this case. There are a few peaks in the horizontal phase velocity with the most pronounced occurrence after 2255 UTC, which coincides with the time of tornado touchdown. The wind speed averages about 15 mph; however in the last 10 min of the trace there is an increase of wind speed to over 20 mph which may also cause significant problems with wind noise at the array site.

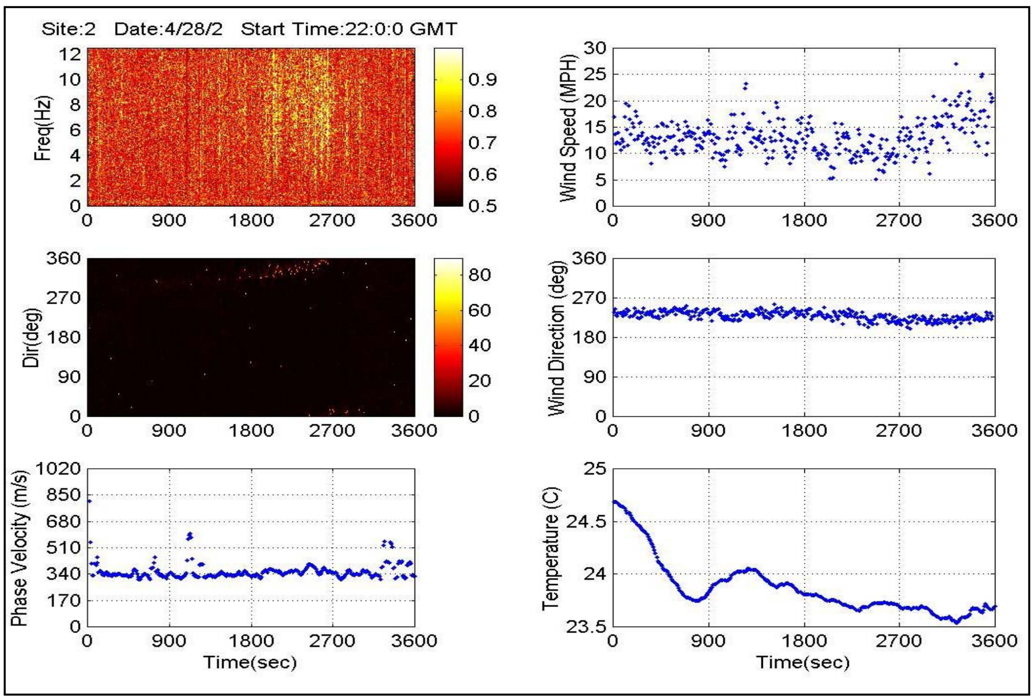

Figure 5. Output from data processor on 28 April 2002 at Blossom Point, MD as tornado approaches LaPlata, MD.

The plot in figure 6 is another way of interpreting the data output. In the upper panel, the correlation that is shown is a comparison with time between each channel of data. Typically, the higher correlation coefficient of the signal, the higher the value is plotted on the chart. The second panel is the trace velocity as a function of time which is the speed at which the infrasonic wave moves across the array in kilometers per/seconds. The plots in figure 6 are from 2200 to 2300 UTC and based on the azimuth plot, it indicates that the source of the sound (the storm) passed north of the station between 2230 and 2245 UTC which agrees with radar and surface observations; however, it appears that there might be some interference from wind noise after 2245 UTC as the azimuth plot is more cluttered. The fourth panel in figure 6 is a time series of the acoustic data or the amplitude of the signal calibrated to pressure with respect to time. In this panel there is an intriguing peak in the signal starting at 2250 UTC which is just a few minutes before the initial tornado observation.

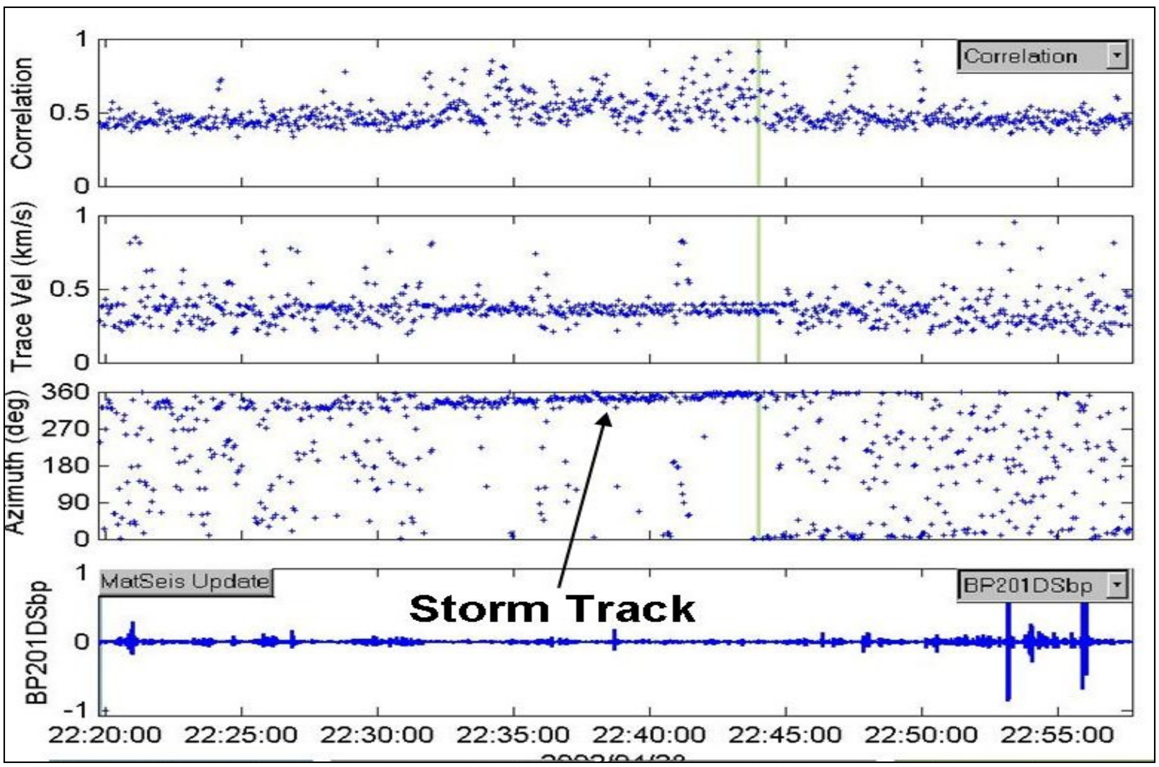

Figure 6. Acoustic output from the LaPlata, Maryland tornado taken from Blossom Point, MD on 28 April 2002.

Figure 7 shows a Power Spectral Density (PSD) plot of the time series as the tornado approached LaPlata. A PSD is the average power of a sound during a time range in a given sound frequency and provides the relative contribution to the overall time signal (acoustic pressure fluctuations) of given frequency intervals.

Another item to investigate is: Does the sound source contain any harmonic structure to the signal? In figure 7, the units shown are decibels versus Hertz. The plot shows the peaks in the spectrum and in figure 7 there are a number of recorded peaks from 7 to 15 Hz. Based on experience, the lower-frequency noise appears to be related to the general wind noise associated with the stronger winds observed at this time; however, the peaks in the 7 to 15 Hz range are of more interest and may be related to some feature in the severe thunderstorm.

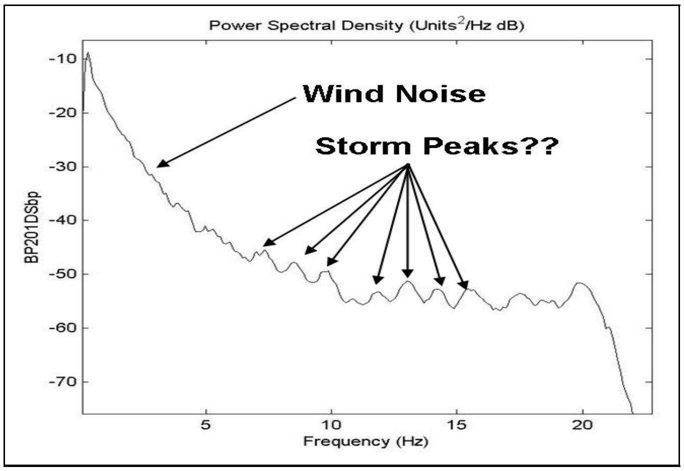

Figure 7. PSD as the tornado approaches LaPlata, MD on 28 April 2002.

While the sequence of plots in figures 4 to 7 only include a short time frame of the actual LaPlata tornado, they do provide a fascinating view of the pre-tornadic acoustic environment. It is uncertain what the cause of the higher correlation, between 2230 to 2245 UTC, is related to, or if the peaks between 7 and 15 Hz represent anything related to acoustic signals from the developing tornado.

The F4 tornadic storm at La Plata was a local “surprise” because tornadoes are not frequent in the Maryland region and rarely of this extreme intensity. However, it did raise interest in the interpretation of the acoustic output. It is not possible to make general conclusions about tornadic signals based on this one storm and far more data are needed to understand these output.

Given that the probabilities of the tornadic event ever occurring near Blossom Point again were so low, it was determined that best way to gain more insight on the topic was to find the storms that produced severe weather and tornadoes. It became logical to take a measuring device or array to the Plains of the United States and “chase” storms to get more data and learn more about the acoustic signals they create.

3. Goals of the June 2003 Field Exercise

In addition to the goal of learning more about the acoustic signals produced by severe storms, there were several other objectives in the project. It was an opportunity to

- prove that small, low-cost, transportable arrays can detect targets and provide data
- show that mobile arrays in the field can function under extreme weather conditions
- enhance the "library" of signals detected in the 3 to 8 Hz range which is vital to ARL infrasonic research.

From a meteorological angle, acoustic data can assist in detection of destructive storms, particularly in remote areas where radar or weather data can not be applied.

June was selected as an ideal time of year to conduct the field study. During this time thunderstorms tend to move slower and the area of severe storms does not change as much; thus, providing the chase team more time to document and observe the storms and less time needed to drive from area to area. Additionally, longer hours of daylight provide a better opportunity to observe the storms and verify any severe weather activity. The field study lasted from 9 June to 24 June 2003 with 10 days of severe storms during that period. The first 5 storm days were generally in Texas and the final 5 storm days took place in Nebraska and South Dakota.

To record the infrasonic nature of the storms, a portable collection system was used in the field study with two microphones which were connected to a 24-bit ADC which controlled the single-board computer sampling at 100 Hz. This provided the portable system with a bandwidth of 0.2 to 25 Hz. To filter out the wind noise, each microphone, like the Blossom Point array, had six porous garden hoses connected to them. The electronics were enclosed in a weather-resistant case with a .25 in. aluminum plate on top for protection from hail as seen in figure 8.

Figure 8. The portable acoustic device as seen on 9 June 2003 in operation near Spearman, TX.

A tarp was placed on top of the device to protect against water infiltration. The chase team consisted of three people, two from ARL and a contractor who had extensive experience chasing severe storms.

Each morning a “target” area was determined using conventional upper-air, surface, satellite data, and numerical model output. A cell phone connected to a laptop was utilized to download data during the day so adjustments could be made to the target area if necessary. Once severe weather began, the device could be deployed in under 5 min; the quick deployment was necessary for safety reasons. An effort was made to place the receiver in a “compromise” position; close enough to record the acoustic nature of the storm, away from traffic, but at a safe distance to avoid wind noise as well as damage to the microphone and equipment. To save time, data collection began even before storms formed to reduce the time needed to place the device in the field. If possible, the device was placed 7 to 10 km from the storm’s rotation area. At the conclusion of the chase, the team went back to the acoustic device and placed it back into the van (*9*).

As mentioned, there were 10 chase days. A review of these days is provided below; more detail is provided in later sections.

Chase Days	Storm Details
9 June	Small tornado spotted near Spearman, TX. Data were collected.
10 June	Central Oklahoma gust front, no data collected due to strong outflow winds.
11 June	Mesocylone north of San Angelo, TX. No data were collected: although near dark, a brief, small tornado was observed by the chase team.
12 June	Two mesocyclones near Olney, TX (W-NW of Fort Worth and SE of Wichita Falls). Brief tornado before deployment; however, 3 h of data were collected on this day.
13 June	Supercell near Ozona, TX. Rotation aloft, no data collected.
14 June	No storms formed. Drove back to Norman, OK to prepare for an anticipated 6-day break in storm activity
20 June	Supercells and tornado on a squall line near Colorado-Nebraska border. No deployment.
21 June	Two supercells in north central Nebraska. Deployment near Wood Lake, NE. Funnels observed, possible tornado. Data collected.
22 June	Numerous tornadoes in Nebraska and Kansas. Record hail event. Deployment and data collection north of the storm.
23 June	Supercells in southwest Nebraska. There was no deployment of the acoustic device as storms were in a rain-cooled environment.
24 June	Southeastern South Dakota tornado outbreak. Deployment near Mitchell, SD. Several hours of tornado and mesocyclone data recorded.

4. Overview of Four Days in the Field Study

Four of the storm days will be discussed in more detail in this section. These 4 days are unique because of the environment in which the storms were formed in and the way that the storms were generated. The 4 days selected are 9 June 2003 near Spearman, TX; 11 June near Olney, TX; 21 June 2003 near Wood Lake, NE; and the 24 June 2003 tornado outbreak in South Dakota.

4.1 9 June 2003, Spearman, Texas Tornado

This day was the first day of operations and ironically provided the closest opportunity to measure a tornado. The main weather feature for this day was a dryline in northwest Texas with only moderate wind flow in the mid-levels of the atmosphere. Figure 9 displays an overview of the synoptic and mesoscale environment in the northeast Texas Panhandle at 2345 UTC while the chase team was observing the storm. An area of thunderstorms was noted south and west of Spearman while winds were backed to 150° at PYX (Perryton, TX). Very moist surface air was advecting northward as noted by the 69 dewpoint at Childress, TX while Dalhart in the western Panhandle had westerly winds behind the dryline.

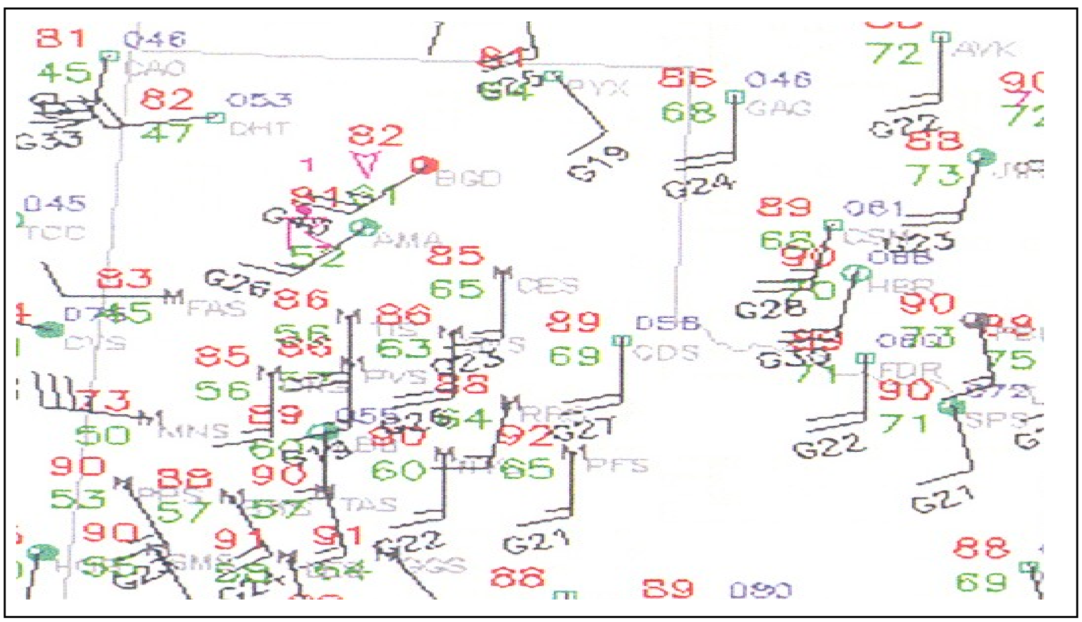

Figure 9. Surface plot at 2345 UTC 9 June 2003, from http://www.rap.ucar.edu/weather/ (*10*).

While the conditions were not initially favorable to sample a tornado, high-based storms developed along the dryline at approximately 2230 UTC and moved slowly eastward. The acoustic device was deployed 8 km southeast of the main rain core where strong updrafts were noted along with cyclonic banding at cloud base. At 2358 UTC gustnadoes were observed on the flanking line and about 10 min later, at 0007 UTC, a tornadic circulation was observed on the nose of the gustfront under the most intense updraft of the storm as seen in figure 10. This tornado quickly wrapped into the rain core and apparently dissipated. The National Severe Storms Laboratory Doppler on Wheels vehicle was nearby and recorded a cyclonic circulation within the cell of 45 m/s (*11*).

Figure 10. Tornado circulation near Spearman, TX at 0009 UTC, 10 June 2003.

The plot in figure 11 shows a number of peaks from 2 to 18 Hz at the beginning of the Spearman tornado. The largest peak is a 13 Hz peak with a variety of low-frequency peaks from 2 and 6 Hz.

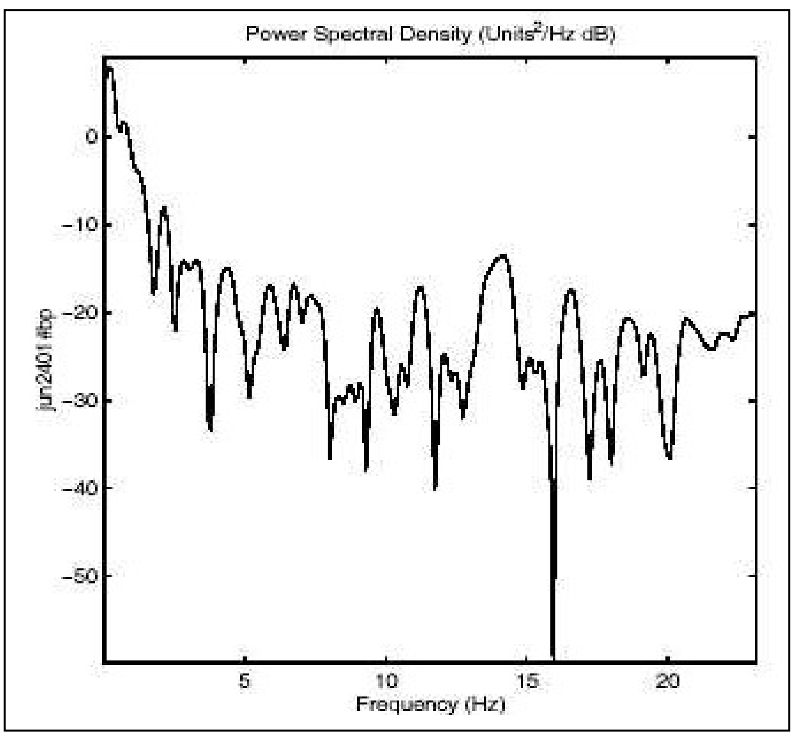

Figure 11. A PSD plot at 0004 UTC 10 June 2003, 3 min before the Spearman tornado.

4.2 12 June 2003, Onley, Texas Mesocyclones

On the fourth day of the field test an outflow boundary from earlier convection stretched across north Texas to a position about 80 km northwest of Fort Worth, TX. At the same time a significant dryline was pushing into the region from the southwest, thus providing excellent convergence despite being in a rain-cooled area. Surface temperatures were only in the low 70s (°F) in the Fort Worth area but warmer to the northwest, with Wichita Falls reporting 82 °F at 2300 UTC. There was excellent directional and speed shear of the wind at 0000 UTC on the Fort Worth sounding (not shown) with low-level easterly flow in the boundary layer and moderate westerly flow to 40 kn in the mid-levels. Other than the cool, low-level air near the surface and a modest inversion near 500 hPa, this day did provide a favorable environment for severe storms and possibly tornadoes.

Unfortunately, the updrafts along the dryline were unable to sustain themselves due to shallow moisture, a result of the earlier storms veering the local winds and reducing the depth of the moisture. However, two storms did form along the outflow boundary as shown in figure 12.

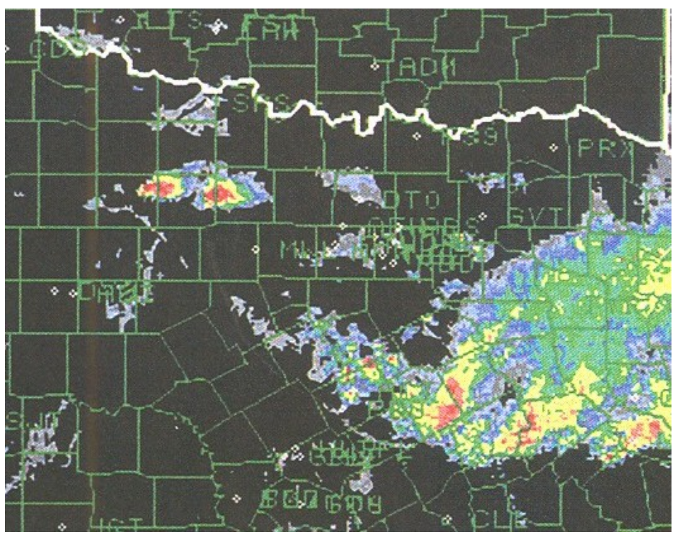

Figure 12. The radar at 0000 UTC 13 June 2003. [‡]

The chase team approached the eastern cell because it briefly had a hook echo on radar and also looked stronger. The National Weather Service Office at Fort Worth put out a tornado warning on this particular mesocyclone and, while there was a tornado reported at 2257 UTC, the chase team did not see this tornado and had not deployed the acoustic device. Finally, at a safe location along Highway 114, just east of Olney, TX, the acoustic recorder was deployed and sampled both mesocyclones over the next 3 h.

[‡] The plot shows two distinct supercells just off the intersection of the outflow boundary and the dryline about 30 km south of Wichita Falls, TX (SPS) and 80 km northwest of Fort Worth, TX.

Initially, the storm was within 10 km of the device and did pass over the acoustic instrument with heavy rain, which unfortunately corrupted the data due to wind noise. However, there were several minutes of quality data during the stage of the storm when rotation was observed both on radar and in the field along Highway 114. Figure 13 shows the PSD from the acoustic output at 2316 UTC, or about 7 min after the device was deployed near Olney, TX. There are several peaks in the data between 2 and 6 Hz which become less frequent above 6 Hz. Figure 14 is a photo of the mesocyclone at approximately 2316 UTC as it moves east, just south of Highway 114.

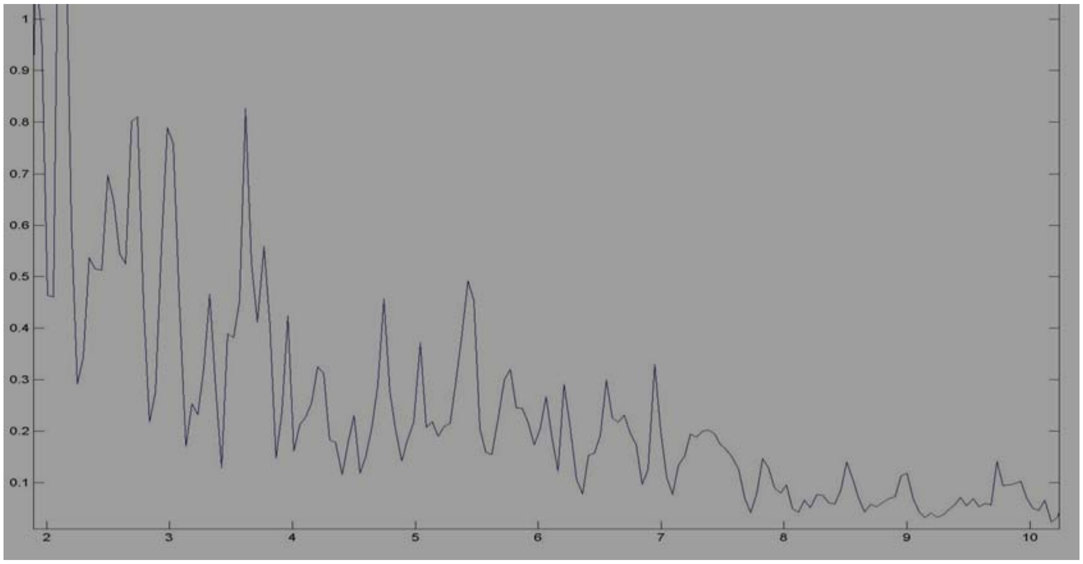

Figure 13. PSD plot from 2 to 10 Hz at 2316 UTC, 12 June 2003 near Olney, TX.

Figure 14. Mesocyclone with wall cloud observed by chase team at approximately 2316 UTC, 12 June 2003.

In figure 15, the plot is different than the one displayed in figure 6, the LaPlata tornadic day. In this field exercise it was impossible to place any meteorological sensors in the field, thus there is no wind or temperature data available. Additionally, with just two microphones it was not possible to get an accurate reading of the trace velocity or azimuth data on the storm. In the 1-min plot below, there is evidence of very high correlation in the signal at the start of the time frame and then a more harmonic display of the data during the remainder of the sample. Meanwhile, the bottom panel of figure 15 indicates a variety of peaks in the amplitude of the signal. There are several increases in the amplitude of the received sound, especially during the last 10 s of the plot.

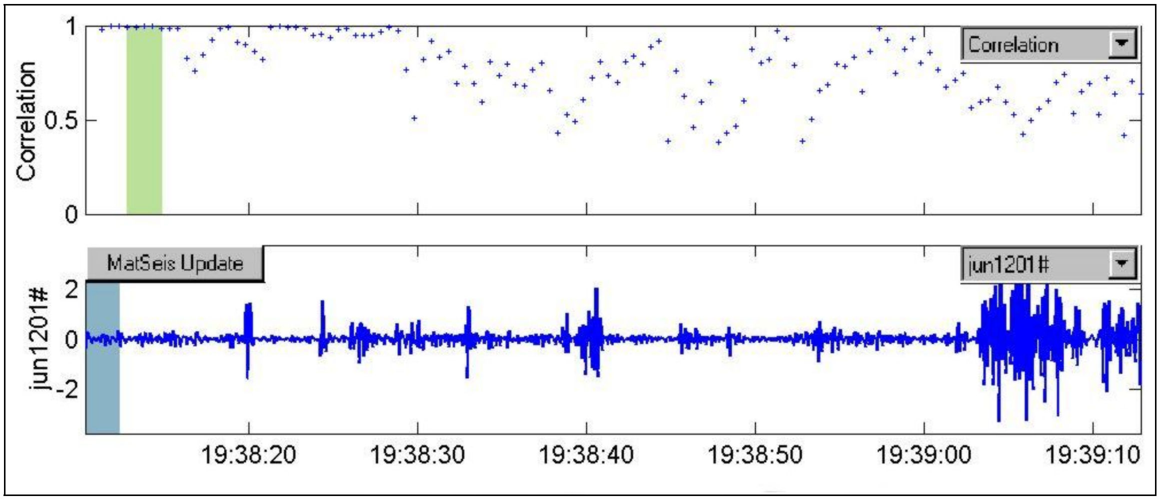

Figure 15. Correlation of signal and time series of acoustic data during a 1-min plot at 2338 UTC, 12 June 2003.

The results from the Olney storm are interesting since there was no tornadic activity noted by the chase team and other crews following the storm. However, the patterns noted in figures 13 and 15 are very similar to storms such as the LaPlata storm. The PSD at 2316 UTC does show a more traditional plot for tornadic storms than the 9 June 2003 Spearman storm, with higher peaks at the low frequencies. It was decided to take a corresponding look at the PSD at 2338 UTC and this appears in figure 16.

The acoustic display in figure 16 is still showing low-frequency peaks even 20 min after the initial data plots. The chase crew was still observing and documenting the storm at this time and noted less cloud-base rotation and a slow trend toward an outflow-dominated storm with little chance of producing a tornado.

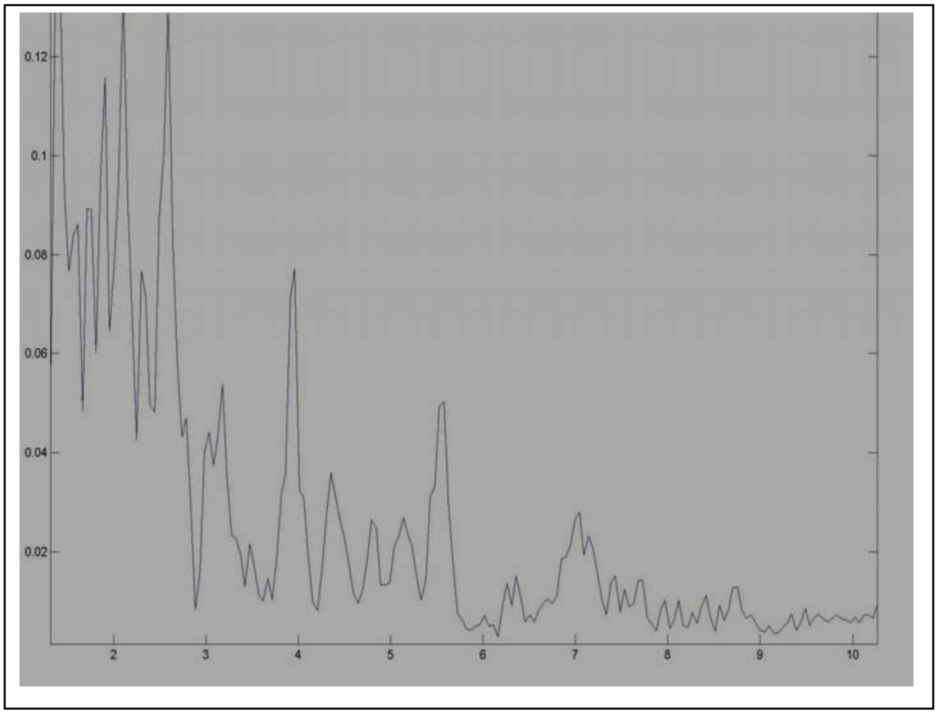

Figure 16. PSD at 2338 UTC, 12 June 2003 as storm moves southeast from Olney, TX.

4.3   21June 2003 Supercells in North Central Nebraska

On 21 June, a conventional June storm-chase day, storms formed further north and later in day. An area of convection in the Dakotas early in the day carried much of the deeper boundary-layer moisture to the east, leaving limited moisture in the areas of central and western Nebraska. The initial cloud bases in South Dakota in the late afternoon were high based, an indication of limitations in the mixing ratio in the lower levels of the atmosphere. The chase team headed south into Nebraska in search of a better environment for rotating storms and a situation more favorable to collect additional acoustic data.

The overall wind profile on this day was favorable, as a moderate low-level jet of about 20 kn observed at 0000 UTC 22 June (not shown). The mid-level winds were about 40 kn while the atmosphere was unstable with the Convective Available Potential Energy (CAPE) noted to be near 1700 J/kg. These were favorable conditions for rotating storms with the only missing ingredients being the limited deep moisture and slightly warm layer between 500 and 400 hPa. Still, the chase team saw towering cumulus along a northeast to southwest dryline in Nebraska. There were initially three isolated cells in northern Nebraska. The first storm was small and was struggling with the limited moisture; however, the second storm in the line was ingesting some deeper moisture as the low-level jet to the south advected moisture northward. This second storm was located near Highway 20 and it was decided to deploy the acoustic equipment in advance of the storm near Wood Lake, NE. Figure 17 is a radar image of the storms at 0158 UTC. The Wood Lake storm is the more isolated storm behind the main line in eastern Cherry County, NE.

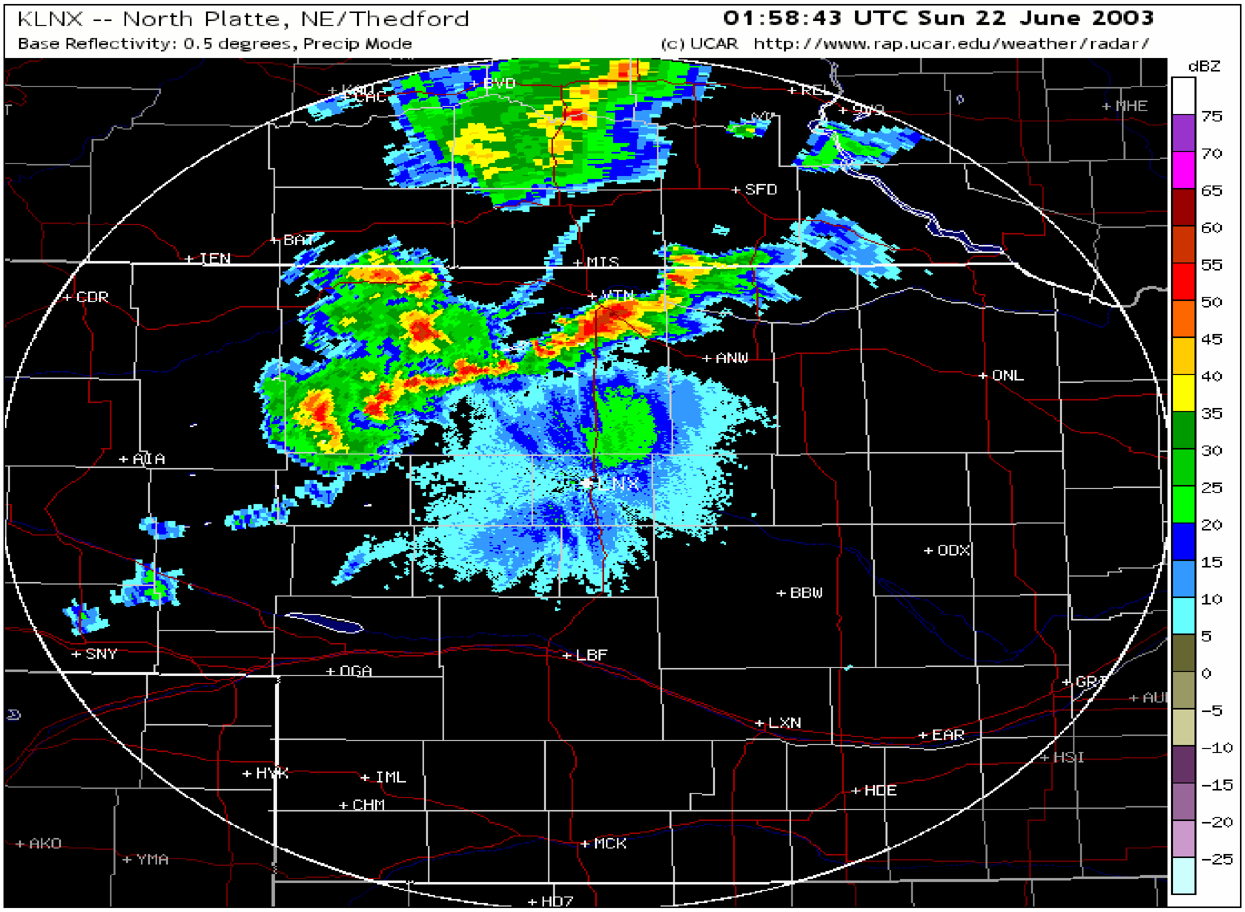

Figure 17. Radar image of north central Nebraska on 22 June 2003 at 0158 UTC.

The Wood Lake storm developed a rotating wall cloud and funnel under the flanking line of the storm. There was no persistent tornadic circulation noted, however the storm was observed to be rotating. This storm became outflow-dominated but another isolated supercell was observed moving northeast. This new storm merged with the outflow boundary of the first storm and the cell intensified dramatically over the next few minutes.

Figure 18 shows the appearance of the storm as observed by the chase team.

Figure 18. Photo of the rotating wall cloud near Wood Lake, NE.

Fortunately, the strong winds associated with this storm system did not corrupt the output data from the acoustic array. In figure 19, at 0226 UTC on 22 June, the plot shows some peaks in the correlation and a harmonic motion that might be associated with a few of the peaks in the acoustic time series.

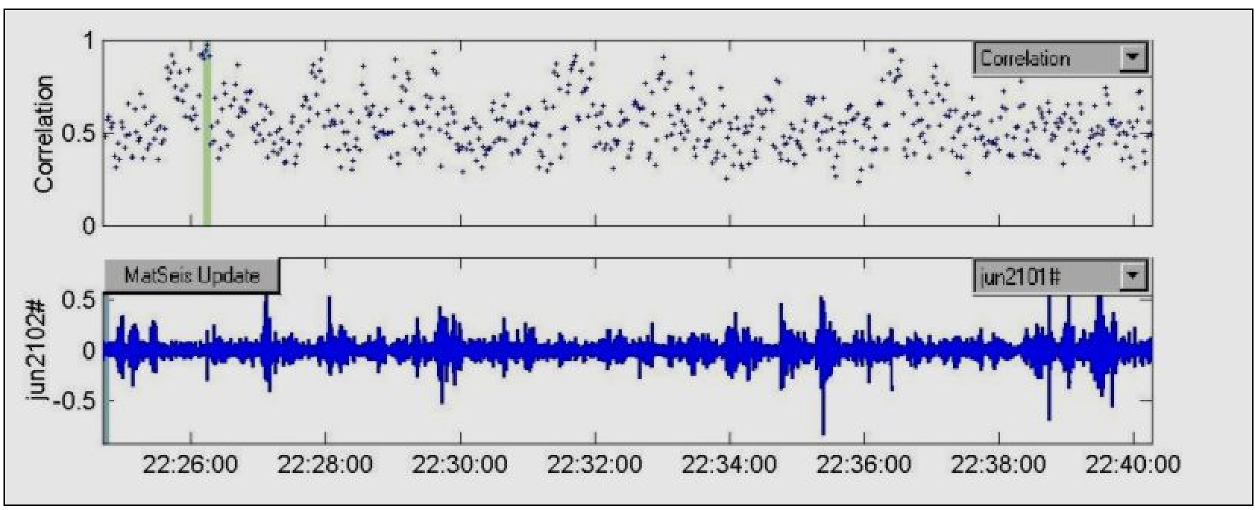

Figure 19. Correlation plot and time series of the acoustic data from Wood Lake, NE at from 0224 to 0240 UTC, 22 June 2003.

In figure 20, the PSD taken from the 4-min period between 0226–0230 UTC, shows many peaks below 4 Hz. The trends seen in these two plots resemble the ones found with the Olney, Texas storm of 12 June. While no tornado was confirmed, these two mesocyclones provide another excellent set of data which closely parallel other storms in this study.

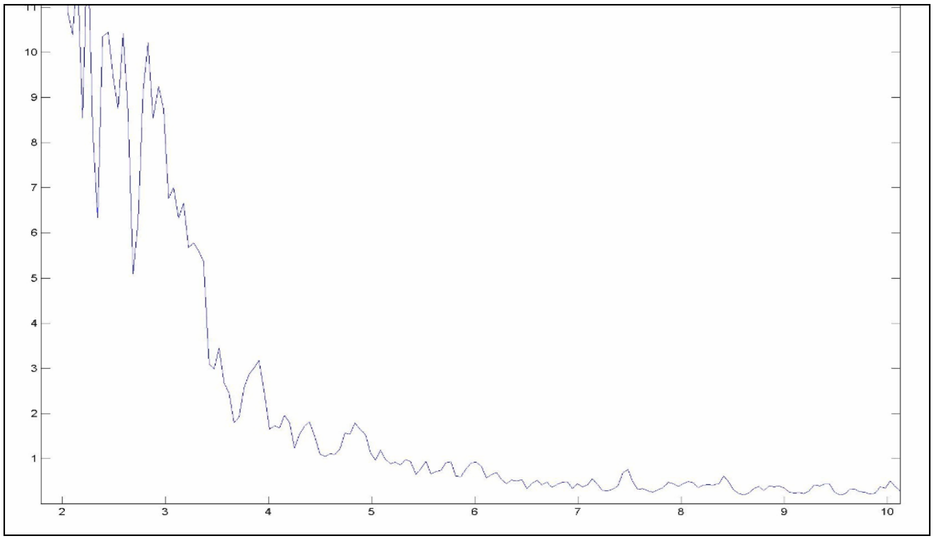

Figure 20. PSD of Wood Lake storm between 0226 and 0230 UTC, 22 June 2003.

4.4   24 June 2003 South Dakota Tornado Outbreak

On 24 June 2003, an outbreak of record-breaking, tornadic storms occurred in SD. This event was well forecasted and documented by the chase team. Furthermore, these storms were sampled by the acoustic device which was deployed near Mitchell, South Dakota. The morning weather maps indicated a classic setup, with an intersecting outflow boundary, a developing warm front, and a mesolow. While there was no upper-air observation near this region, the sounding at Omaha, NE (not shown) displayed excellent directional shear of the wind while profiler data further to the north indicated a 40 kn low-level jet at 2200 UTC as well as 45 kn of winds from 240° at 18,000 ft above ground level. The flow at 300 hPa was diffluent with wind speeds of 70 kn observed in southwestern South Dakota. Surface temperatures warmed into the mid-80s while surface dew points ranged from 72° to 77° by mid-afternoon in southeastern South Dakota which provided an environment where cloud bases would be lower under intense updrafts. While only the initial storms were close to the array, several of the storms provided dramatic infrasonic signals.

Figure 21 shows the initial storm development on satellite at 2145 UTC.

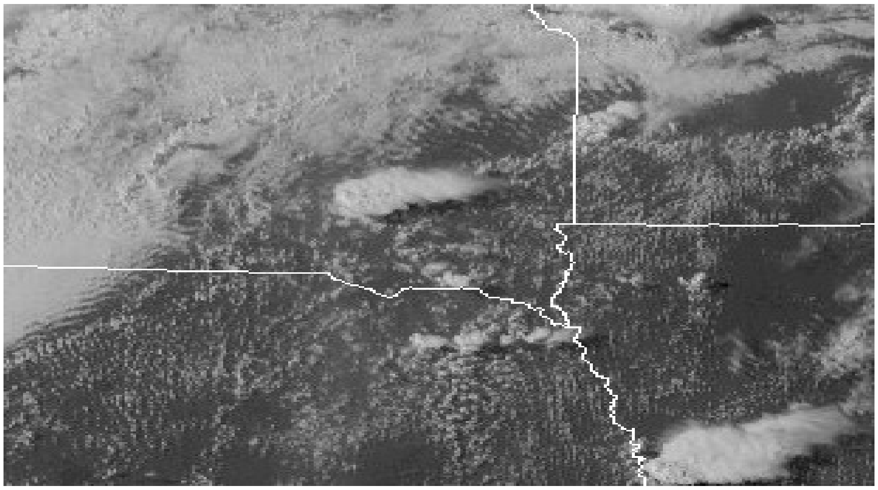

Figure 21. Initial storm formation at 2145 UTC, 24 June 2003 on the intersection of the warm front and outflow boundary.

The storm had an impressive updraft and the Omaha sounding (not shown) at 0000 UTC, 25 June 2003 showed a lifted index of -8.2 and the CAPE value at 3279 J/kg. Early in the lifecycle of the storm a wall cloud, funnel, and tornado formed and the acoustic array had to be deployed as quickly as possible. This was done south of Mitchell, SD to avoid the interference of the city and to place the device in a safe place.

The first tornado was near Mount Vernon, SD and was verified by the chase team at 2217 UTC with the final sighting at 2236 UTC. Fortunately, data was being collected at this time and is shown in figure 22.

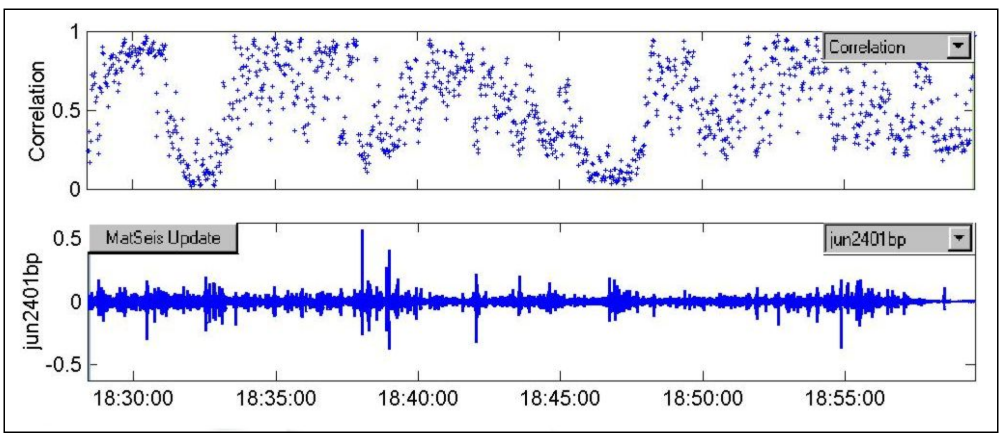

Figure 22. Display of the signal correlation and time series between 2230 and 2300 UTC, 24 June 2003 during the Mount Vernon, South Dakota tornadic event.

The plot in figure 22 shows a variety of peaks in the correlation. The storm was about 29 km from the array at this point and only the first 6 min of the plot are associated with an actual confirmed tornado on the Mount Vernon storm. However, the storm itself may have continued to rotate.

About an hour later, a more dramatic event occurred. Near Woonsocket, SD, a tornado began dissipating at about 0015 UTC, 25 June and the wall cloud began to spin violently and two large vortices formed from this storm. At about 0032 UTC a large and destructive tornado was observed in the community of Manchester, SD. This tornadic storm is shown on radar in figure 23 and has a well-defined hook echo southeast of Huron (HON), SD at 0038 UTC while the tornado reached F4 on the Fujita scale.

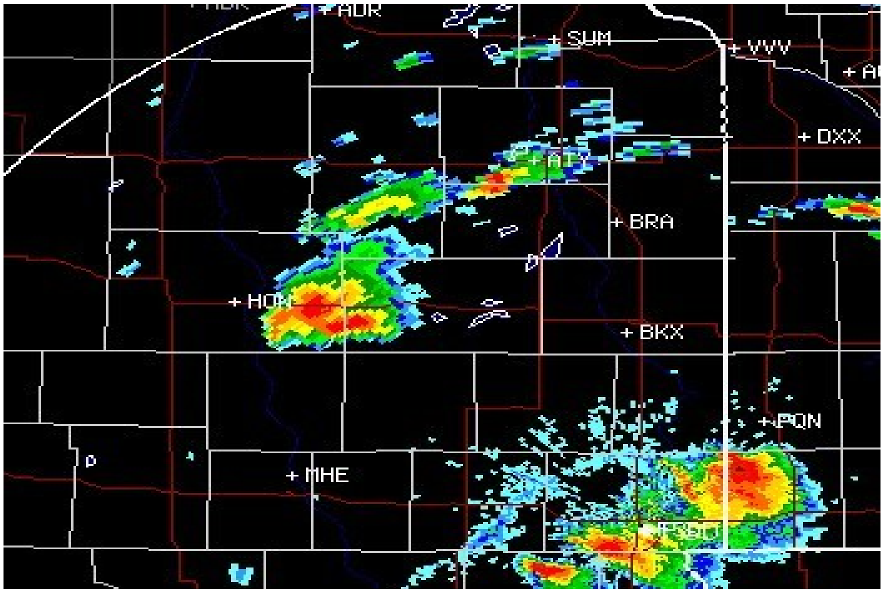

Figure 23. The radar image southeast of Huron, SD (HON) at 0038 UTC, 25 June 2003.

The photo of the Manchester, South Dakota tornado appears in figure 24.

Figure 24. The F4 Manchester, South Dakota tornado at approximately 0049 UTC, 25 June 2003.

The infrasonic data for the period 0000 to 0100 UTC are shown in figure 25. The Manchester, South Dakota tornado began at 0032 UTC and continued until 0053 UTC, thus the entire lifecycle of the tornado is documented in this plot. It is interested to note that even at nearly 80 km for the acoustic recorder, there is an extremely high correlation of the signal from 0020 UTC to the end of the hourly data along with very dramatic changes in the intensity of the signal received.

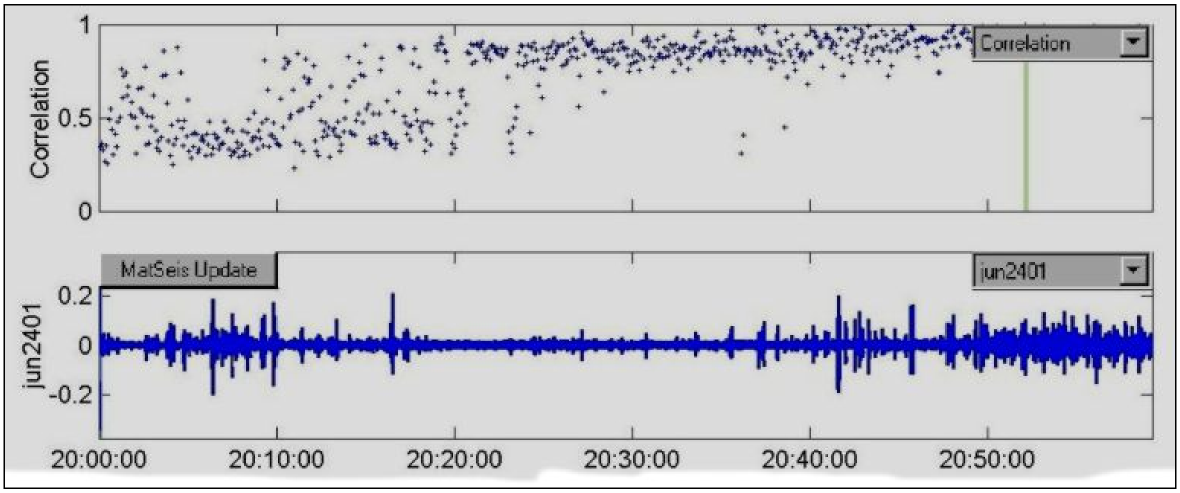

Figure 25. The infrasonic output showing the correlation and time plot of the signal during the Manchester, South Dakota tornadic thunderstorm 0100 to 0200 UTC 25 June 2003.

In figure 26, the PSD shows the peaks in energy received below 10 Hz. Like many of the other storms, there are a few peaks in the lower ranges from 2–4 Hz and then many smaller peaks in higher frequencies.

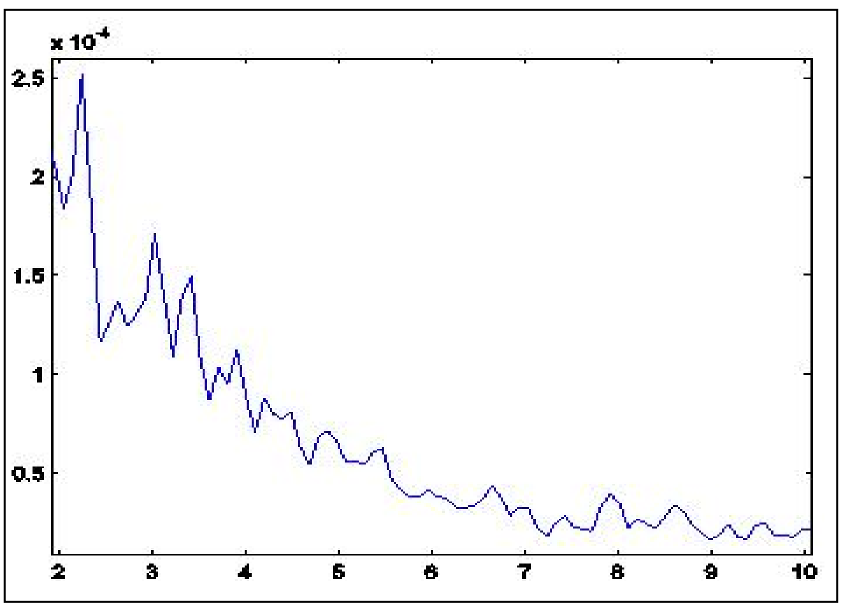

Figure 26. PSD during the Manchester, South Dakota F4 tornado at 0040 UTC 25 June 2003

5. Evaluation and Discussion of the Acoustic Results

5.1 Previous Work on Acoustic Signals in Severe Storms

Much of the work in recording acoustic waves from severe storms has been conducted in research efforts by the National Oceanic Atmospheric Administration (NOAA) Environmental Technology Laboratory in Boulder, CO. According to Bedard, NOAA began to study infrasonic data in the 1970s to investigate if they could improve tornado warning capability. In the following decades, they monitored severe storms and found a relationship between funnel diameter and infrasonic frequency. There is apparently a connection between pressure fluctuations in the frequency range 0.5 to 10 Hz and the occurrence of tornadoes (*1*).

Bedard discusses many of the cases studied at the Boulder, Colorado site and noted that a funnel from 3 km away provided evidence that rotation aloft was a source of infrasonic energy. Other cases such as the 15 June 1997 Boulder, Colorado F1 tornado indicated that signals arrived from different angles and that the sound was generated from the entire length of the vortex column. His work indicates that potential sound generation can come from many sources but it appears that the radial vibration model is the most consistent with the infrasonic data (*12*).

Another interesting approach to the infrasound problem was mentioned by Nichols, et al., who ran a two-way interactive nested grid version of the Colorado State University Regional Atmospheric Modeling System. The model was initialized with a low-level vortex in cyclostrophic and hydrostatic balance in an ambient environment of large CAPE. This simulation of a non-supercell tornado and the subsequent analysis of the model results show possibilities that the main mechanism responsible for generating the infrasound was small-scale latent heating fluctuations. As an air parcel is heated and it expands, the adjacent air is compressed, which generates the infrasonic wave. However, it appears that the main mechanism may have been from the radial vibration mechanism and their study does not find any significant contribution of latent heat release.

In figure 27, the time series of the pressure perturbation is plotted between 600 and 630 s after model initiation at a distance of 1.5 km from the center of the storm. The ranges shown on the left are from -279 to -298 Pa (*13*).

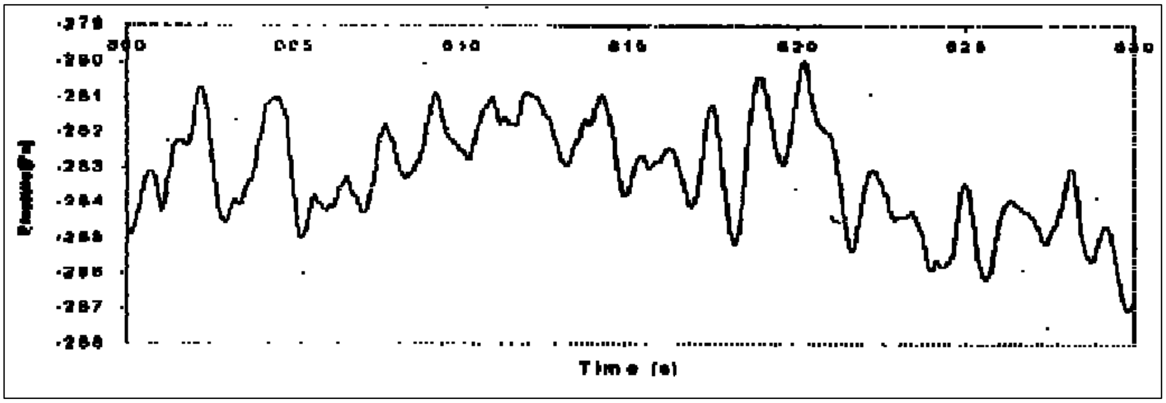

Figure 27. The time series of the surface pressure perturbation at 1.5 km from the center of the storm at t = 600-630 s (*12*).

Nichols' results show the amplitude of the waves to be about 2–3 Pa and a period of about 1.5 s. He conducted a second simulation with an initial vortex of 60 m/s^{-1} which produced waves of about 1 Hz.

Al Bedard's group at NOAA in Boulder, Colorado has developed the Infrasound Network (ISNet) which includes three acoustic arrays. One is located at the Boulder Atmospheric Observatory in Erie, CO while the other two are located at National Weather Service offices at Goodland, KS and Pueblo, CO. These arrays are in continuous operation, require no storm chasing to record data and are located in regions where tornado and severe storm frequency is high enough to collect significant data sets. Over 100 cases have been documented, with a variety of signal types. These cases are compared to Doppler radar as part of the verification study. Bedard sampled storms with both mesocyclones and storms without mesocyclones on Doppler and found no cases where the non-mesocyclones reported sound less than 20 Hz (*14*).

Figure 28 is an example of data captured by the ISNet. This plot shows a 1-h sequence of a storm near Sterling, CO. The storm did produce an F1 tornado in Sterling at 0125 UTC 10 June 2004. The correlation coefficient does increase to about 70 (on this scale) a few minutes before tornado touchdown, but again it should be noted that the distance between the array and tornado location is significant enough that the arrival of the sound will be delayed slightly before it arrives at the Boulder array site. This delay is one of the disadvantages of not being able to chase the storms and record data from longer distances (*15*).

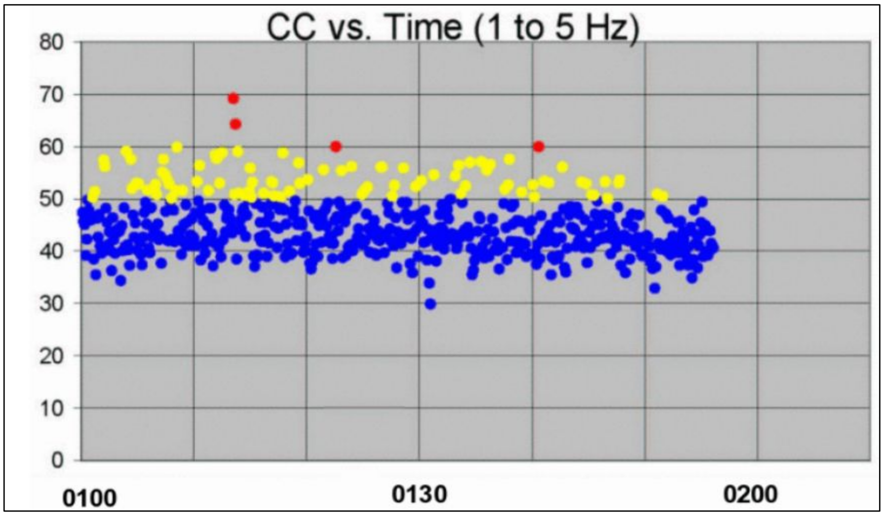

Figure 28. A time series of correlation coefficient from a tornadic storm in Colorado.

5.2 Interpretation and Results of the 2003 ARL Field Study

In the ARL project, six major severe weather events are documented and each day has its own unique characteristics.

- Two days are dryline days (Spearman and Wood Lake events),
- One day featured storms that formed in a rain-cooled environment along an outflow boundary (Olney),
- One day displayed a classic tornadic environment of high CAPE and shear (South Dakota outbreak), and
- One day involved a long-track single storm in the Eastern United States (LaPlata).

However, all six storms generated the same general time series plots and PSD plots. In this study, it appears that all the storms have their major peaks in sound waves from 2–5 Hz, although the Spearman tornadic storm is not as detailed in that range and the LaPlata pre-tornadic plot shows a slightly higher range from 7–15 Hz. Still, these results agree with many of the storms sampled by Bedard's group and provide some clues to the origin of the sound waves. It does not appear to matter how large the mesocyclone is, as both the Olney mesocyclone and Manchester tornado display very similar patterns in the PSD (*14*).

The correlation plots are more ambiguous. In some cases such as the Olney, LaPlata, and Wood Lake storms the correlation is harmonic, varying from about 0.5–1.0 in many intervals. However, the Mount Vernon tornadic storm shows dramatic changes in correlation in a pattern that makes it unlikely that wind noise is influencing the results. It becomes an interesting and difficult question if the correlation change over a 2-min period is due to a true change in the dynamics of the pressure and sound waves, the source of the waves, interference in the wind speed or temperature along the propagation path, or even the equipment. Of most interest is the Manchester tornado which was rated as an F4 tornado and displays a correlation of the acoustic waves of about 0.9 for almost the entire life cycle of the storm.

One of the more interesting aspects of the Manchester data is that other data sources are available since the storm was well sampled. Tim Samaras and his associates from Applied Research Associates Inc. placed one of their Hardened In-Situ Tornado Pressure Recorders (HITPR) directly in the path of the Manchester, South Dakota tornado.[§] The instrument noted approximately a 100-mbar pressure drop in a matter of seconds as seen in figure 29. The plot starts at 0045:32 UTC and runs for 225 s (*16*).

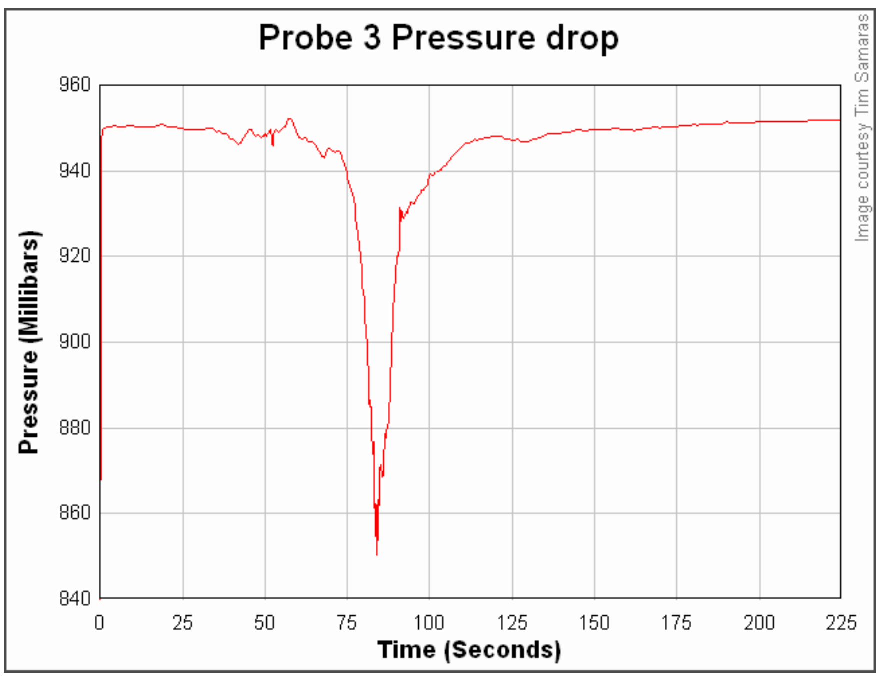

Figure 29. Pressure plot recorded by HITPR starting at 0045 UTC during the Manchester, South Dakota tornado.

[§] The HITPR is a small device that measures the temperature, moisture, pressure, and wind data in and near a tornado.

Based on this location and time, the sound of this F-4 tornado would have arrived at the ARL portable acoustic array at 0051 UTC. Investigating figure 25, there are a series of pressure fluctuations that start at about 0042 UTC and continue until the end of the hour. It is not logical that the acoustic array would respond to a 100-hPa drop in pressure, but it is an indication that a tornado this large and with this rotational speed has huge pressure differences across its core and is capable of generating sound waves.

A.J. Bedard mentions four accepted theories of the sound-source mechanisms in his 2005 work. He mentions A.J.Abdullah's work with radial vibrations as well as T.M. Georges and his studies with flow instabilities around the vortex. Bedard also notes that B.E. Mitchell proposes co-rotating multiple vortices as a source of the low-frequency sound, while F.B. Tatom theorizes that boundary-layer pressure fluctuations may produce the acoustic waves heard (*17*).

One of the difficulties of this research effort is to make conclusions about the source of the sound. Unfortunately, there is evidence that any of these four methods could be responsible for the sound. Video of a tornado near DeSmet, SD shows evidence of a tornado within another tornado, perhaps giving scientists a view of vorticity forming within a larger region of vorticity. Each of the tornadoes studied in this report are different and while the basics of tornado formation are known, the true details are not yet well documented and understood. Thus, it becomes almost impossible at this time to declare one method or another as the source of the acoustic sound being made by a storm.

However, based on data collected, some conclusions can be made from this study and others like it. There is evidence that the acoustic sound from non-tornadic mesocyclones such as the Olney, Texas storm provide similar infrasonic sound to tornadic storms like the Manchester, South Dakota storm. Perhaps, all rotating storms do have the ability to produce sound of less than 10 Hz. Additionally, the array appears to be able to differentiate between rotating and non-rotating storms as was seen by investigating some of the acoustic signals from non-severe storms near Blossom Point, MD.

Despite the difficulties in making precise conclusions about the source of the infrasonic sound, there is still much optimism in this research effort. The acoustic array handled the conditions well and continued to provide data in most of the storms with only some data loss due to high wind speeds. The chase crew had several opportunities to witness storm structure and document storm features and compare these to infrasonic output. Infrasonic sound of less than 10 Hz was observed in all the storms sampled, possibly proving that all rotating storms provide this signal. This would give high confidence that thunderstorms with less than 10 Hz recordings are rotating and could provide some useful information in areas devoid of radar or in complex terrain where radar is not as effective.

Overall, this field study exceeded the initial goals set and led to many fascinating scientific questions and investigations in mesoscale meteorology, storm-scale studies, and infrasonic studies.

- Is the array hearing vortices?
- Is the array picking up vortices that we as humans can not see or document?
- Does the storm itself influence what the array is “hearing?”
- Are the oscillations seen on the plot of the Mount Vernon, South Dakota tornado (figure 22) due to core busting, downward vertical motion in the core, or radial velocities or is the source of sound shifting from one part of the storm to another?

These are questions that might not be answered immediately but are clearly worth investigating in the future.

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List of Acronyms

ADC	Analog-to-Digital Converter
ARL	U.S. Army Research Laboratory
ASC	Average Spectral Coherence
CAPE	Convective Available Potential Energy
ETL	Environmental Technology Laboratory
HITPR	Hardened IN-Situ Tornado Pressure Recorder
Inset	Infrasonics Network
MATLAB	Matrix Laboratory
MVDR	Minimum Variance Distortionless Response
NOAA	National Oceanic Atmospheric Administration
PSD	Power Spectral Density
UTC	universal time coordinated

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