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ACOUSTIC ENERGY MEASURED FROM MESOCYCLONES AND TORNADOES IN JUNE 2003

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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 location 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 La Plata, Maryland tornado passed 13 km from the acoustic sensor and a time series showed a series of peaks in the spectrum. It was 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 three-week period including a small tornado on 9 June near Spearman, Texas, two strong supercells near Olney, Texas, and two supercells in north central Nebraska on 21 June. The highlight of the data collection was during the 24 June 2003 outbreak of tornadoes in South Dakota.

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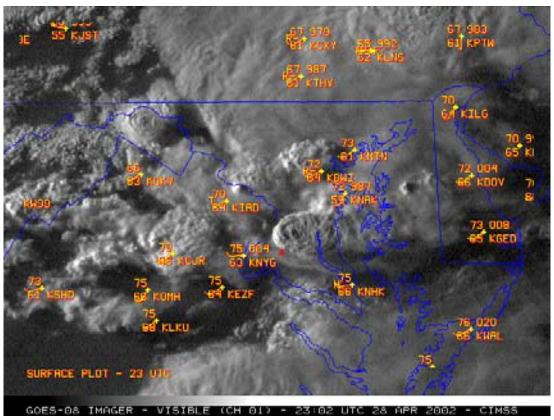
This paper will discuss the data collection methods, documentation of these data, and comparisons of the acoustic energy between the F4 La Plata tornado and the storms sampled in June 2003.

2. THE LA PLATA TORNADO

Since 1998, the ARL has operated an infrasonic array of microphones with data collection and signal processing to study all aspects of infrasonic signals in the atmosphere. With a geometry using 20-m spacing, there is an emphasis on low-frequency ranges of three to eight Hz. Data is collected at 100 Hz and filtered to 25 Hz, although these data are only processed to 8 Hz to avoid grating lobes (Noble and Tenney 2003). Numerous natural and 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, Maryland site where four microphones are set up in a triangle with an additional microphone in the center. It was discovered that thunderstorms were being processed by the equipment, and numerous storms were noted by the array system. 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 La Plata tornado was part of a large outbreak of severe storms ranging from the Midwest to the Atlantic Coast. The La Plata storm originated over the terrain of West Virginia, moving eastward as an isolated supercell and producing large hail and eventually tornadoes over Virginia and southern Maryland (Rogowski and Zubrick 2004). The main tornado that struck La Plata was on the ground for approximately 110 km and struck the city at 2302 UTC while moving at an estimated 50 knots. As seen in figure 1, the storm shows a distinct overshooting top as it approaches La Plata.

Figure 1. Satellite and observation composite from 2302 UTC 28 April 2002 as storm hit La Plata, Maryland.



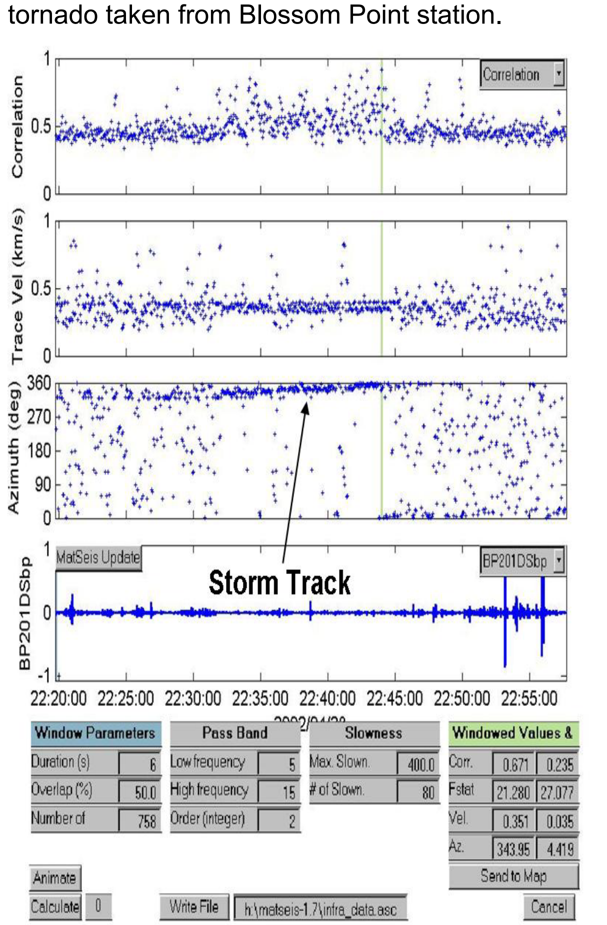
The La Plata tornado moved approximately 13 km north of the Blossom Point acoustic array and provided a detailed acoustic data set from the rotating storm as shown in figure 2. In figure 2, the four main data panels show the correlation, trace velocity (km/s), azimuth (deg) or storm location, and a time series of the acoustic data.

The correlation is a comparison with time between each channel of data. If these data are the same in each of the channels, then the correlation will be high. If each channel is different, then the correlation is low. The trace velocity is the speed at which the infrasonic wave moves across the array. The plot of the data from Blossom Point is from 2200 UTC to 2300 UTC and it indicates that the storm passed north of the station between 2230 and 2250 UTC, which makes sense since the tornado was first observed in La Plata at 2302 UTC. The fourth plot on the graph is a time series of the acoustic data.

According to information from the National Weather Service (NWS) at Sterling, Virginia and based on damage tracks and an average forward storm speed of 50 kn (Doppler radar), the first known tornado touchdown with the storm was between Rison and Marbury, Maryland at approximately 2256 UTC 28 April 2002 (Strong and Zubrick 2004). This location is 16 km west of La Plata, thus in the plots in figure 2 the final minutes of the hour are the only times with confirmed tornadic activity.

However, figure 2 does provide an excellent view of the pre-tornadic acoustic environment. It is uncertain what the cause of the higher correlations are between 2230 to 2245 UTC, which is only five to 20 minutes before the first confirmed report of a tornado. While there was no confirmation of a tornado in this time frame, and radar indicated that the low-level rotation had diminished, it is possible that the storm was exhibiting strong rotation aloft.

Figure 2. Output from the La Plata, Maryland tornado taken from Blossom Point station.



It also is not clear as to why the microphones are not showing high correlation at the time of the original tornado at 2256 UTC, but it is possible that wind noise from the storm may have made it difficult to record the tornado. According to Rogowski and Zubrick winds were gusting to 25 kn in the region (Rogowski 2004.)

The La Plata tornado and supercell were the first time that the Blossom Point array recorded such an event and it did raise many questions and provided insight into the infrasonic output of these storms. It also provided incentive to study more mesocyclones and tornadoes. To accomplish this goal, a mobile operation would be necessary rather than waiting for additional tornadoes near Blossom Point. Thus, a field study was conducted for three weeks in June 2003.

3. 2003 FIELD EXERCISE

For this experiment, the field study was conducted in the Plains of the United States during June 2003. June was selected since it is typical that severe storms move slower and their locations don't change as much from day to day as they do in early spring. Additionally, longer hours of daylight provide a better opportunity to verify and document storms. The field test lasted from 9 June to 24 June with ten days of active severe storms. The first five days were generally in Oklahoma and Texas while the final five days of the project took place in Nebraska and South Dakota.

To record the infrasonic nature of the storms, a portable collection system consisting of two Chaparral Physics Model 2 microphones were connected to a 24-bit A/D which controlled the single-board computer sampling at 100 Hz. This provided the portable system a bandwidth of 0.2 to 25 Hz (Noble et. al, 2004). It should be noted that due to a slight timing error in the GFS software system, the system time lagged the UTC by four hours. The microphones had six porous hoses connected to them to filter out wind noise. Figure 3 displays what the microphone looks like in the field. The electronics were enclosed in a weather-resistant case with a quarter-inch aluminum plate on top for protection from hail as seen in figure 4. A tarp was placed on top of the device to protect against water infiltration. The chase team consisted of three people, including two who had extensive experience chasing and documenting 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 five minutes, and this 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 microphones and equipment. To save time, data collection began even before storms formed to reduce the time needed to place the device in the field. On average it was decided, if possible, that seven to 10 km from the storm's rotation would be the ideal location to record the storm.

Figure 3: A view of one microphone in the array at Blossom Point, although two microphones were used in this field experiment

Figure 4. Photo of the case which protected the electronics from wind, dust, and hail. A scattering of hail is seen in this photo near Spearman, Texas 9 June 2003.

3.1 9 June 2003 case at Spearman, Texas

Ironically, the first day of the exercise provided the closest opportunity to measure a tornado. This day featured a weak dryline in northwest Texas with only moderate wind flow in the mid-levels. High-based storms developed in the northern Texas Panhandle at approximately 2230 UTC and moved slowly eastward. The equipment was deployed about eight km southeast of the main core where strong updrafts were noted along with cyclonic banding at cloud base (figure 5). At 2358 UTC a few gustnadoes were observed on the flanking line and about ten minutes later, at 0009 UTC, a tornado circulation was observed on the nose of the gustfront, under the most intense updraft of the storm. This tornado wrapped quickly 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.

Figure 5. A photo of the storm moments before tornado was observed on 9 June 2003.

Figure 6. Amarillo, Texas radar focused in on the Spearman, Texas storm at 0006 UTC, 10 June 2003, three minutes before the tornado was observed.

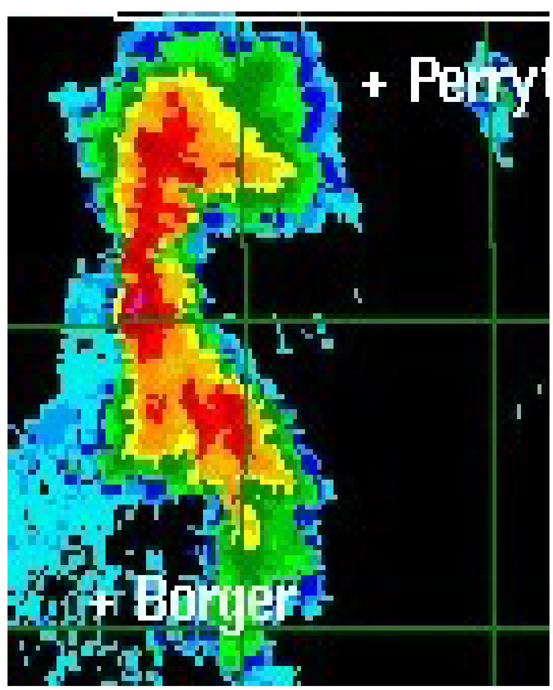
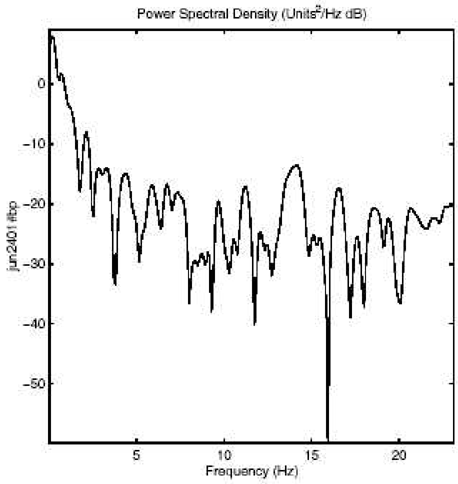


Figure 7. A power spectral density plot just before Spearman tornado, 9 June 2003



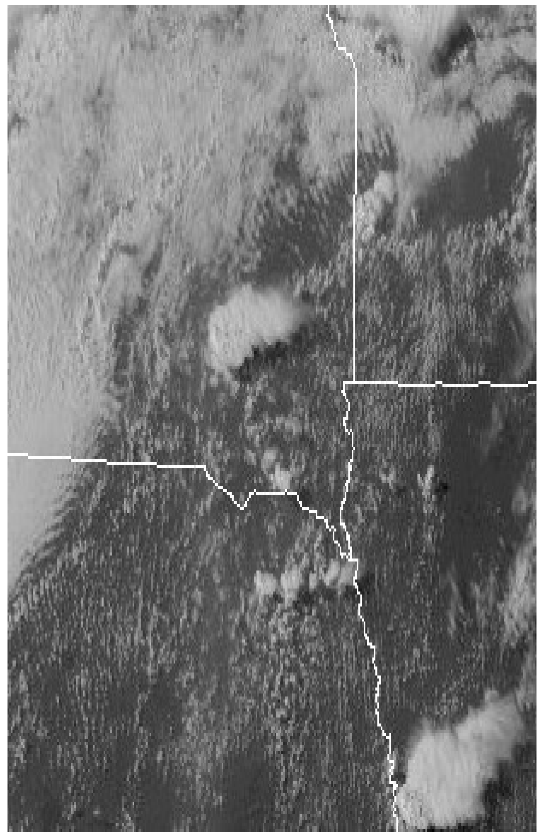
In this plot (figure 7), at the beginning of the Spearman tornado there are a number of peaks from 2 Hz to 18 Hz. The largest peak is a 13 Hz peak with a variety of low-frequency peaks between two and six Hz. These peaks are apparently related to the dynamics of the source in the storm generating the acoustic signal.

3.2 24 June 2003 case in South Dakota

This day featured a major outbreak of tornadoes in South Dakota. The morning data analysis indicated a warm front on the Nebraska- South Dakota state line which was gradually moving northward. However, there was also an outflow boundary intersecting the warm front with a mesolow noted in the surface analysis under a very concentrated area of upper diffluence. Figure 8 shows the imitation of the first South Dakota supercell at 2145 UTC.

Storms developed near Mitchell, SD, and the equipment was deployed at 2225 UTC when the Mount Vernon, SD tornado was in progress. The acoustic array was located on the south edge of Mitchell in an isolated area off Highway 37. Over the next three hours there were numerous tornadoes observed and reported in the area.

Figure 8 Satellite view at 2145 UTC 24 June 2003. Storm forms on the intersection of the warm front and outflow boundary.



Large tornadoes near Woonsocket and Manchester, SD, were within 80 km of the array but numerous smaller tornadoes were also sampled closer to the array. It is uncertain how much range the equipment truly has and how strong a signal is received from that distance. Additionally, at the time of the Manchester tornado another tornado was being reported slightly to the west so there might be interference from more than one supercell. In figure 9, a radar image is shown from the FSD (Sioux Falls) site at 0003 UTC which would be 30 minutes before the start of the F4 Manchester tornado. At the time of this radar display there were wall clouds and funnels being observed at ground level and a large tornado began 12 minutes later (Moore 2003)

Figure 9. Radar image from 0003 UTC 25 June 2003 FSD, Sioux Falls, SD. Copied from http://www.rap.ucar.edu

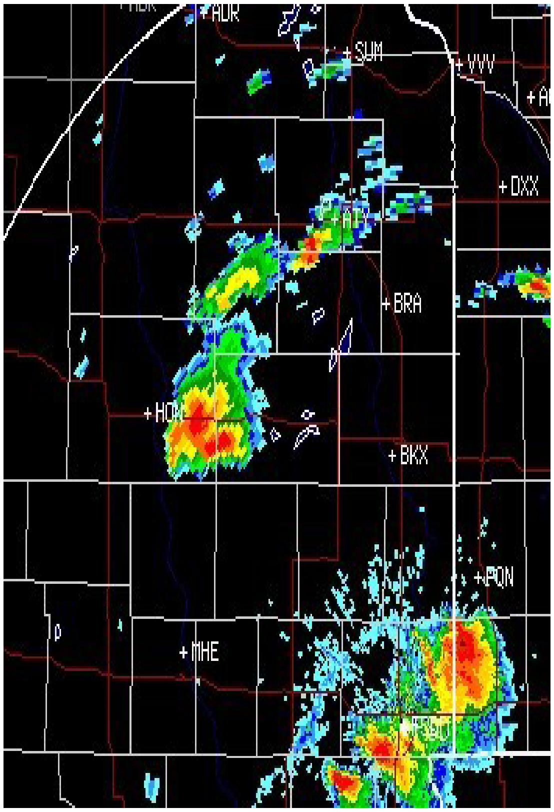
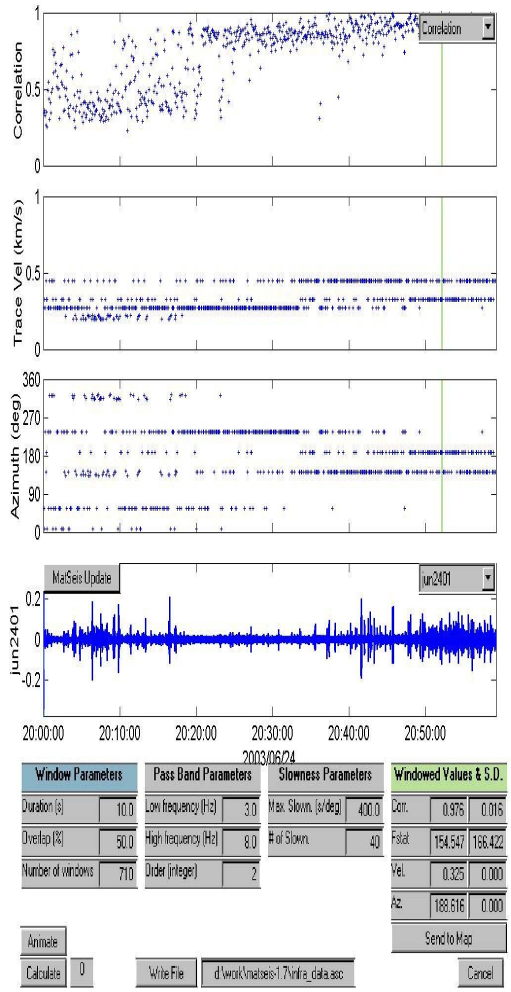


Figure 10 shows the plot from the acoustic array south of Mitchell; approximately 80 km from the Manchester tornado and mesocyclone. The plot is from 0000 UTC to 0100 UTC 25 June, covering a 60-minute span which includes the lifecycle of the Manchester tornado (0032-0053 UCT).

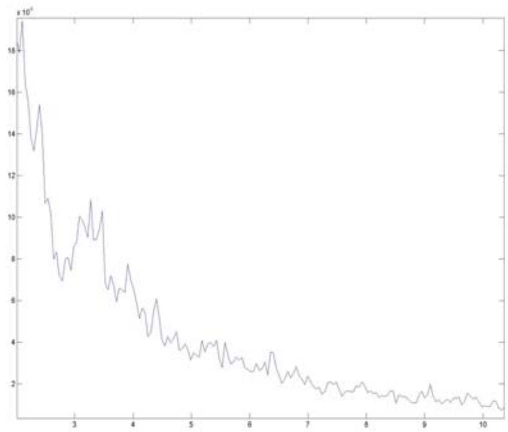
In this plot the travel velocity and azimuth are not available; however, the correlation plot shows high correlation of the signal and the time-series of the acoustic data also show many peaks. In figure 10, the correlation increases at 0021 UTC and increases to approximately 0.90 during the entire Manchester tornado. This is an indication that the system was detecting a very coherent signal in the three to eight Hz band.

Figure 10. Correlation and acoustic time series from 0000 UTC to 0100 UTC 25 June 2003.



In figure 11, the peaks of the power spectral density plot are shown. Unfortunately, the frequency units are difficult to see in this plot but range from two Hz to 10 Hz along the X-axis of the plot. The most interesting feature of figure 11 is a weak peak at about 3.25 Hz. It was also noted that there were no peaks above 10 Hz in this case, unlike the Spearman tornado shown in figure 7.

Figure 11. The power spectral density of the Manchester, SD tornado between 0000 and 0100 UTC 25 June 2003.



4. DISCUSSION AND CONCLUSIONS

Most of the previous work in recording acoustic waves from severe storms has been conducted in research efforts by the National Oceanic Atmospheric Administration's (NOAA) Environmental Technology Laboratory (ETL) in Boulder, Colorado. According to Bedard (2000), NOAA began to study infrasonic data in the 1970s to investigate if they could improve tornado warnings. In the following decades, they monitored severe storms and found a relationship between funnel diameter and infrared frequency. There is apparently a connection between pressure fluctuations in the frequency range 0.5 to 10 Hz and the occurrence of tornadoes.

Bedard (1998) explains many of the cases studied at the Boulder, Colorado site and notes that a funnel from three km away provided evidence that rotation aloft was a source of infrasonic energy. Later cases, such as the 15 June 1997 Boulder F1 tornado, indicated that signals arrived from different angles and that sound was generated from the entire length of the vortex column. Additionally, Bedard notes on 31 May 1998 there is evidence of being able to receive wave energy from the Spencer, SD tornado 800 km away. His work indicates that potential sound generation can come from many sources but it appears that the radial vibration model is most consistent with the infrasonic data.

Another interesting approach to the infrasound problem was mentioned by (Nicholls et al. 2004), who ran a two-way interactive nested-grid version of the Colorado State University Regional Atmospheric Modeling System (RAMS). The model was initialized with a low-level vortex in cyclostrophic and hydrostatic balance in an ambient environment of large convective available potential energy (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.

In this project, much of these data collected still need to be investigated, although data from the 24 June 2003 case indicate some interesting results when compared to the La Plata case and cases studied earlier by NOAA ETL. The La Plata storm from 28 April 2002, displayed in Figure 2, shows many similarities to the Manchester tornado of 24 June 2003. It is interesting to note that these two tornadic storms were in different mesoscale environments. The La Plata tornado evolved from a long-track supercell that had signs of rotation for hours and had not produced a tornado in over one hour. The mesoscale environment was one of moderate CAPE and high shear with some localized wind enhancement from the low-level jet and backed winds from the Potomac River Valley as suggested by Rogowski (Rogowski and Zubrick 2004). The higher correlation moments before the La Plata storm may be a sign that the mesocyclone is intensifying aloft which would be very useful information to operational meteorologists monitoring the storm. Based on work from Bedard and data from Noble (Noble et al. 2003) it appears that the sound waves are emanating from a source aloft.

The Manchester plot, in figure 10, shows wave energy being received in a distinct pattern and period. The Manchester tornado was one of many in a family of tornadoes from the same supercell traveling to the north in a high CAPE environment on the intersection of the outflow boundary and warm front. Observations and documentation of the Manchester tornado (Moore, 2003) indicate that in the early stages of the tornado (approximately 0032 UTC) the tornado was clearly multivortex and remained this way for several minutes before forming one larger half-mile wide tornado. There are some indications that La Plata may also have been a multivortex tornado in its first ten minutes. Of course the La Plata tornado had a narrow width as it was first being observed by the acoustic array while the Manchester tornado was a half-mile wide before becoming a narrower tornado later in its lifecycle. It will be interesting to compare the video of the Manchester tornado with the output of the array data but it is encouraging to see distinct patterns similar to some of the patterns that Bedard has noted in his work.

There are still many unanswered question about the acoustic data accumulated in this study. How much of the wave energy is degraded using only two microphones in the field rather than five at Blossom Point.? Is there any chance that there is interference in the signal from the supercell storms in far south eastern South Dakota? Does it matter that La Plata was only 13 km from the Blossom Point receiver, while Manchester was 80 km from the device?

These questions can not be easily answered in this study, but they do provide the motivation to study future cases and pave a path for future research in this area.

5. ACKNOWLEDGEMENTS

The authors would like acknowledge Mr. Gene Moore for his immense contributions to this project. Gene provided outstanding forecast skills and chase experience that made data gathering possible. Special thanks to Steve Rogowski of the National Weather Service in Sterling, Virginia for his insight to the La Plata tornado and Robert E. Dumais Jr. for reading and critiquing this paper.

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