# Analysis of the Effects of Atmospheric Noise on LORAN-C

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## ABSTRACT

The Federal Aviation Administration is currently funding research to determine the feasibility of using LORAN-C for enroute and non-precision approach guidance as a backup to the Global Positioning System (GPS). The signal-to-noise ratio (SNR) of the received LORAN-C signal is one of the key factors in determining the usefulness of LORAN-C signals for navigation. The effects of atmospheric noise, such as precipitation static and thunderstorms can have a significant impact on the SNR of LORAN-C signals. Ohio University's Avionics Engineering Center (AEC) has been conducting flight tests for the past year to collect data in the presence of these atmospheric noise conditions. This data will allow the effects of the atmospheric noise on the LORAN-C SNR to be characterized. Accurately characterizing these effects will play a major role in the accuracy, integrity, availability, and continuity analysis of the LORAN-C system.

Flight tests have been conducted at several locations under varying weather conditions. LORAN-C data was collected using a two-channel data collection device to simultaneously collect radio frequency (RF) data from two independent antennas. Both e-field and h-field antennas are used to allow for comparison of the data so analysis of the performance of each antenna in varying environments can be accomplished. An identical data collection system is used to simultaneously collect ground data to be used as a baseline reference.

This paper will describe the data collection system used by AEC. Examples of the data collected by both the in-flight and ground-based systems will be presented. Preliminary results of the data analysis and comparisons between the ground and airborne data will be presented.

## 1. INTRODUCTION

The Long Range Navigation (LORAN) system has been in use since World War II as a position, navigation, and timing system. However, LORAN-C has typically had fairly large (100-500 meter) errors in its position solution performance. In addition, its use as an airborne navigation system has been hampered by problems of integrity, availability, continuity, and accuracy caused by climatic (changes in propagation path), aircraft induced (precipitation static), and atmospheric (lightning) effects.

The introduction of new navigation systems has gradually reduced the use of LORAN-C as a primary means of point-to-point navigation, especially for aviation. Most notably, the Global Positioning System (GPS) has provided the capability for worldwide navigation using a single system with accuracy, integrity, availability, and continuity performance far exceeding that typical of LORAN-C.

Recent events have precipitated a change in thinking on the use of GPS as the source of positioning in the NAS. In addition, the timing and frequency communities began to realize their need for a backup system to reduce their dependence on GPS. In order to facilitate the evaluation of LORAN-C as a backup, two panels were formed to bring together people capable of determining the current capabilities of the system and of suggesting changes that would be required to allow LORAN-C to serve as a suitable backup. One of these panels was the LORAN-C Integrity and Performance Panel (LORIPP) formed by the Federal Aviation Administration (FAA) LORAN-C Program Office.

As part of this panel, the Avionics Engineering Center (AEC) at Ohio University was tasked to evaluate the effects of atmospheric noise and precipitation static (p-static) on LORAN-C performance. This task was to be accomplished by collecting data under varying weather conditions, determining the effects those weather conditions had on the LORAN-C signal, and mitigating those effects when and where possible. Collecting data that would allow these weather-related effects to be observed required that a data collection system capable of capturing radio frequency (RF) signals in the LORAN-C frequency band be fielded.

AEC has put together such a system and has been using it to collect data for the last one-and-one-half years. Both airborne and ground data collection systems are used during the data collection missions. Collecting ground data provides a stable reference data set to which the airborne data can be compared and allows the effects of the atmospheric conditions to be more readily identified.

This paper will provide an initial report on AEC's data collection mission conducted in July of 2004 at the Kendall-Tamiami Executive Airport in Miami, FL.

# 2. Data Collection System

## 2.1. Overview

The primary goal of the LORAN-C data collection system being designed at Ohio University is to collect RF data in the LORAN-C frequency band. However, it is also important that the data being collected provide an accurate representation of the data that would be seen by a typical LORAN-C receiver. Therefore, it is important to use equipment that is designed to work in the LORAN-C frequency range as well as possess the proper bandwidth to capture the entire LORAN-C spectrum.

## 2.2. Airborne System

Figure 1 shows the data collection system installed on AEC's King Air C-90SE, which is shown in Figure 2.

The data collection PC and the box containing the data collection equipment are mounted in a 19-inch rack which is installed on the seat rails of the aircraft. A WX-500 StormScope is part of the aircraft avionics package. Both the e-field and h-field LORAN-C antennas and GPS antenna on the King Air are used exclusively by the data collection equipment.

**Figure 1: Data collection equipment rack**

The Apollo 618 LORAN-C receiver is mounted in a 19-inch rack mount chassis and is used only to power the e-field antenna preamplifier. The signal going to the data collection equipment is split from that antenna and sent to the data collection box.

The data collection box contains the Reelektronika DataGrabber, which is used to collect LORAN-C RF data, and a GPS receiver from which position data is collected during flight.

**Figure 2: Ohio University's King Air C-90A**

A complete description of the airborne data collection system is available in the paper presented at the 32nd International LORAN Association Conference [1].

### 2.3 Ground System

Figure 3 shows the ground data collection system van used to collect data at the Kendall-Tamiami Executive Airport in Florida.

**Figure 3: Ground Data Collection System**

The ground data collection system uses the same LORAN-C equipment as is used in the airborne system. This provides the capability to collect baseline data during flight testing for comparison with the airborne data.

The ground data collection system has two deep cycle batteries and an inverter to provide power to the LORAN-C equipment. This eliminates the interference found when using the ground power grid when thunderstorms are in the vicinity of the data collection area. Ground power from the grid can be used to run the equipment so that the effects of the thunderstorms on the power grid can be studied and compared to the data collected using the batteries.

The ground based data collection system does not have a StormScope or other independent lightning detection system. Data from the National Lightning Detection Network (NLDN) is used to determine the lightning activity in the area. The NLDN data is also used as a comparison for the airborne lightning data collected using the StormScope.

## 3. Flight Test Overview

### 3.1 Location

Flight tests were conducted in southern Florida from July 13-17, 2004. The Kendall-Tamiami Executive Airport (TMB) was used as the staging location for the flight tests. This location was chosen due to the frequent thunderstorm activity that occurs during the summer months. It's location near the Florida Everglades also provides an area where flight testing can be conducted with a minimum of interference to or from local air traffic. The southern Florida peninsula also provides an area where there is an almost all seawater path to three LORAN-C transmitters.

### 3.2 Equipment Setup

The ground data collection van was positioned near the glideslope shelter which is part of the National ILS Test Facility run by AEC. This location was chosen due to the ready availability of ground power and lack of overhead power lines or large buildings in the surrounding area. In addition, this location allowed the King Air to be parked within 200 yards of the van so baseline data could be collected on both systems under the same conditions.

### 3.3 Description

Approximately 10 hours were flown during the week of flight testing. The flight tests were all conducted in the vicinity of the TMB airport. The weather conditions during the flight testing varied from clear to moderate-to-severe thunderstorms.

Ground data was collected during all the flight testing. Baseline data was also collected with the aircraft positioned as close as possible to the van. The ground data collection system was powered using both the van batteries and ground power during the flight tests and collection of the baseline data sets.

## 4. Data Processing

The Reelektronika DataGrabbers collect data at a rate of 400ksamples/second. Only minimal filtering, to reject out-of-band noise and prevent aliasing, is performed in the front-end. This allows the complete LORAN-C band to be captured by the DataGrabbers. It also allows the noise in the LORAN-C band, which is the primary focus of this research, to be completely captured.

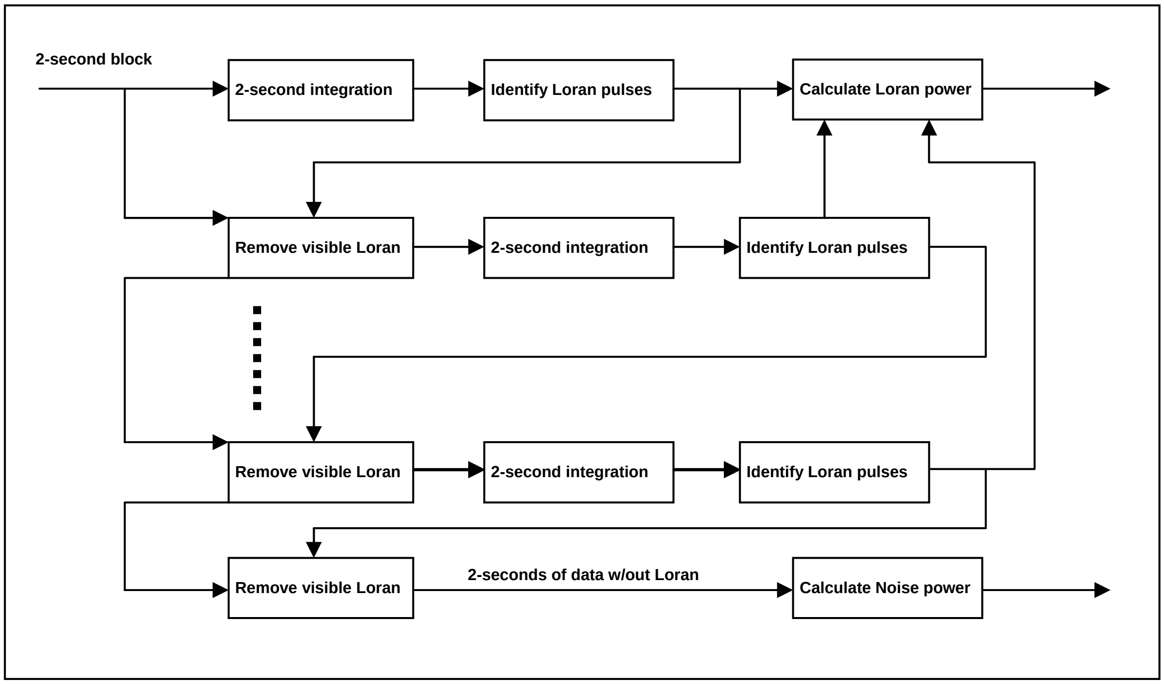


**Figure 4: Data Processing Block Diagram**

The data is processed in 2-second blocks. A block diagram of the data processing scheme is shown in Figure 4.

Each 2-second block is initially processed to remove any continuous wave (CW) interference that is present. The 2-second block of data is then integrated over the phase code interval (PCI) for the group repetition interval (GRI) being processed in this iteration. The LORAN-C pulses are then identified and the SIGNAL power is calculated. The software calculates power in terms of analog-to-digital converter (A/D) levels, not watts or volts per meter. The identified LORAN-C pulses are then removed by blanking the corresponding samples.

The process is repeated for all the visible LORAN-C chains. Once all of the visible LORAN-C signals have been removed the noise power of the remaining signal is then calculated.

# 5. Results

### 5.1 Overview

Six sets of data representative of the varying conditions encountered during the flight testing were chosen to be processed for the initial data analysis. Both the airborne and ground data for each set were processed. Plots were then generated to illustrate the results for each set and show the comparison between the airborne and ground data.

The results of five of those sets will be shown in this paper. Set Two results are presented in this section. The results of the remaining sets are contained in appendices at the end of the paper.

### 5.2 Data Collections Conditions and Equipment Configuration

Set Two contains airborne data during takeoff. The weather at TMB was clear and no significant weather activity was noted in the area. The aircraft had been positioned at the runway end nearest the data collection van for baseline data collection prior to takeoff and the same runway was used for departure. The ground data collection system was being powered using AC power from the glideslope shelter.

### 5.2 Correlation Results

Figures 5 thru 8 show the results of the correlation process used to identify the LORAN-C pulses in each 2-second block. Only the correlation results for the southeast U.S. chain (GRI 7980) are shown. The correlations are performed using an array of ones and zeroes representing the LORAN-C pulses. Pulse locations are determined using the GPS position recorded for the corresponding 2-second data block. The y-axis is an arbitrary number representing the correlation strength. The x-axis shows which 2-second block in the approximately 5-minute data set for which the correlation was performed.

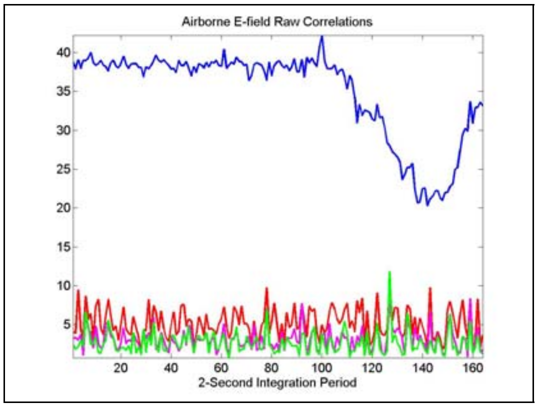


**Figure 5: Airborne E-field Correlation**

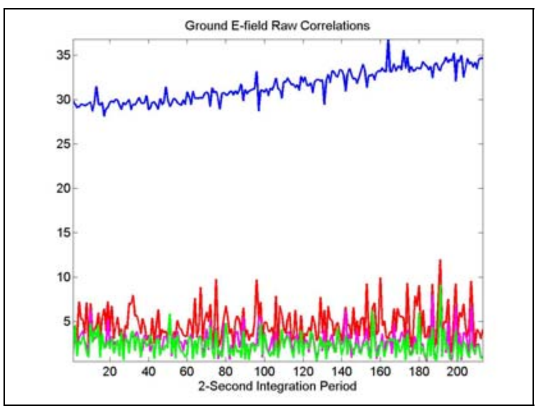


**Figure 6: Ground E-field Correlation**

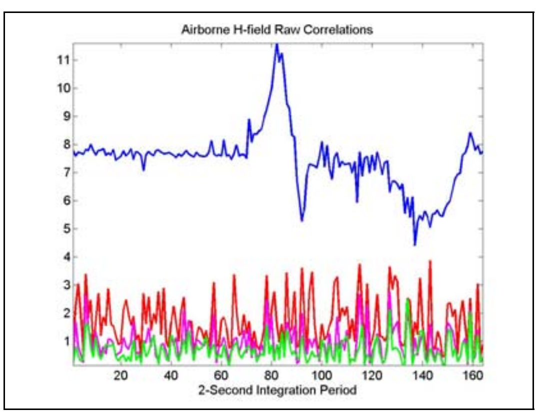


**Figure 7: Airborne H-field Correlation**

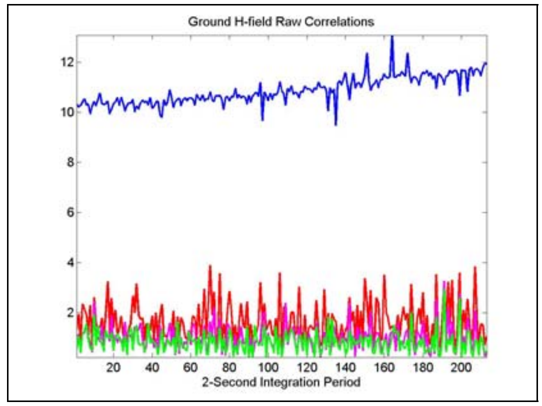


**Figure 8: Ground H-field Correlation**

### 5.3 Probability Density Function Results

The plots in Figures 9 and 10 show the probability density function (PDF) results for the airborne and ground noise data. The results for the e-field and h-field are shown together for comparison.

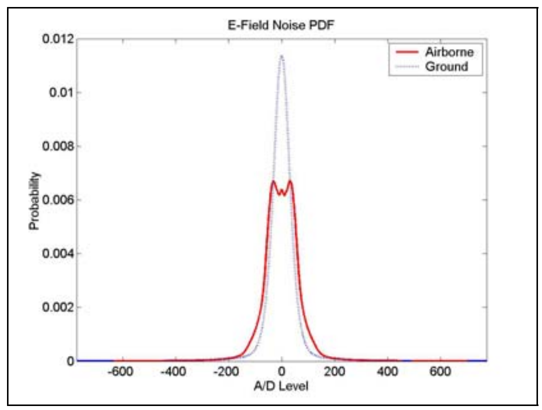


**Figure 9: E-field Noise PDF**

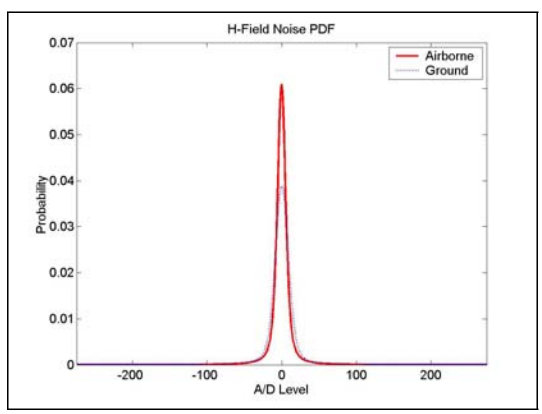


**Figure 10: H-field Noise PDF**

### 5.4 Cumulative Density Function Results

The following plots show the cumulative density function (CDF) results for the noise data. The CDF tails represent the likelihood that a data set will contain a particular A/D level. The lower the tails, the less noise was found in a particular data set.

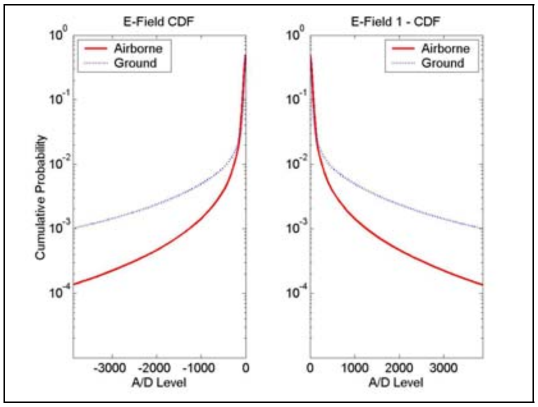


**Figure 11: E-field Noise CDF**

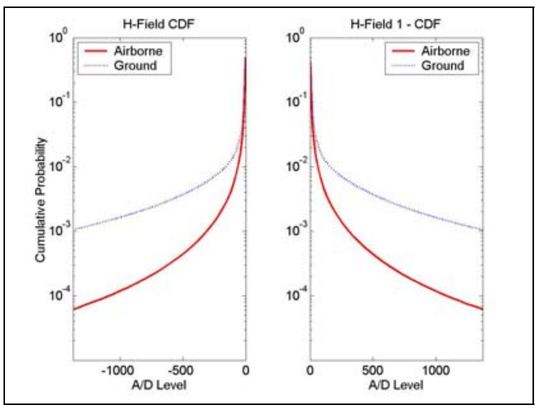


**Figure 12: H-field Noise CDF**

### 5.5 Signal to Noise Energy Ratio Results

The plots in Figures 13 and 15 show the e-field and h-field LORAN-C signal energy-to-noise ratio for the airborne and ground data. Figures 14 and 16 show the ratio of the airborne to ground results. If one assumes that the signal strength is the same in the airborne and ground data, then this represents a ratio of the airborne-to-ground noise energy.

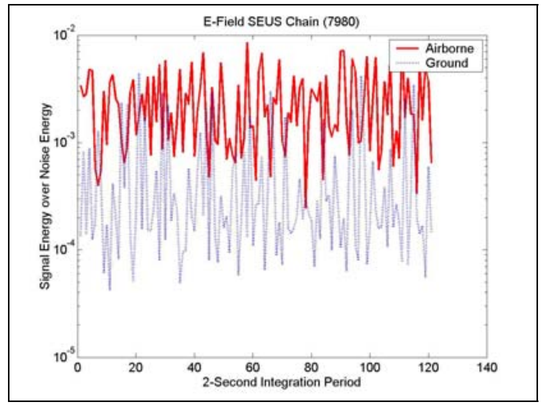


**Figure 13: E-field Signal to Noise Energy**

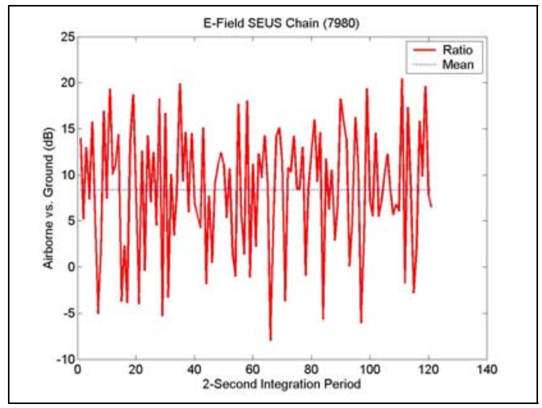


**Figure 14: E-field Airborne vs. Ground**

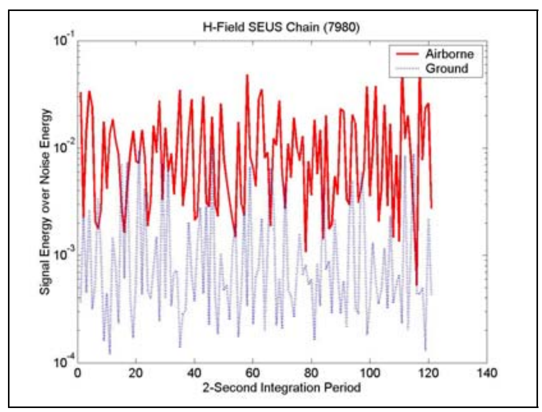


**Figure 15: H-field Signal to Noise Energy**

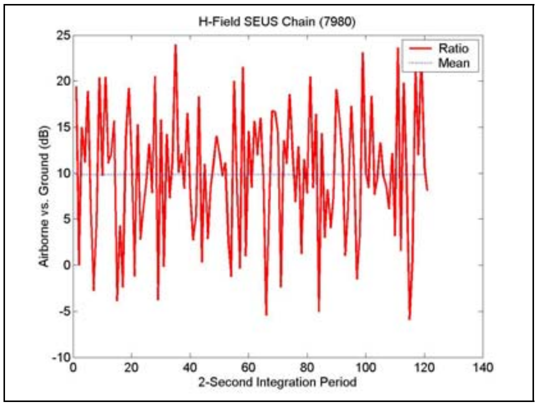


**Figure 16: H-field Airborne vs. Ground**

The dashed line in Figures 14 and 16 shows the average ratio for the airborne vs. ground signal energy to noise energy comparison.

## 6. Conclusions

Although these results are preliminary, they tend to show that the airborne data has less noise than the ground data. This is not the case, however, with all the data. The data sets where the ground data shows less noise are the sets where the aircraft was flying in close proximity to moderate or severe thunderstorms. In these cases, it is to be expected that the airborne data would show more significant noise than the ground data.

The data also show that in cases where the ground data was collected with the system powered by AC from the glideslope shelter, the noise in the ground data increases. Based on previous data collected in the lab, this result was expected. It is likely that the power lines act as antennas and pick up the noise generated by the thunderstorms. This emphasizes the need to have data collection systems isolated from this effect, as the airborne systems are in the aircraft.

## 7. Future Work

The remaining data needs to be processed to determine if the results seen in the initial data analysis are found in all the data sets. Analysis of the lightning data will also have to be conducted to determine the impact of lightning strikes of varying strengths and proximity on the noise in the LORAN-C band.

## Acknowledgements

This work was performed under Federal Aviation Administration contract DTFA01-01-C-0071 Technical Task Directive 2.1 – LORAN-C Analysis and Support. The authors would like to thank the Program Office manager, Mr. Mitchell J. Narins, for his assistance in making this research possible. In addition, we would like to thank Bryan Branham and Jeff Rambadt, our King Air pilots, and the Mr. Michael Handrahan, the Kendall-Tamiami Executive Airport manager. The help of Dave Diggle and Frank van Graas at AEC has also been invaluable throughout this project.

### References

[1] Cutright, C., et al., “LORAN-C Band Data Collection Efforts at Ohio University”, Proceedings of the International LORAN Association (ILA-32) Convention and Technical Symposium, Boulder, Colorado, November 3-7, 2003

# Appendix A

### A.1 Data Collections Conditions and Equipment Configuration

Set Three was collected while the aircraft was parked at the fixed base operator (FBO) building at TMB. A thunderstorm was directly over the field and delayed the takeoff for the flight test. The van was operating on AC power from the glideslope shelter.

### A.2 Plots

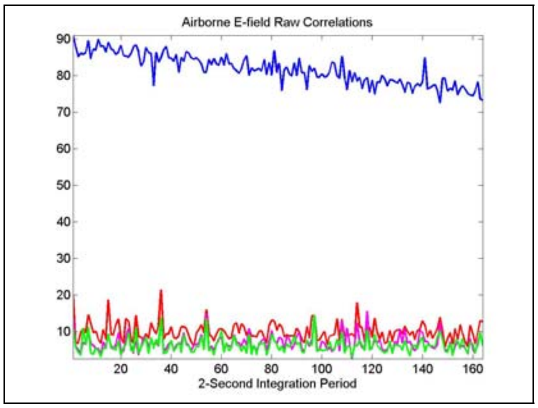


**Figure A1: Airborne E-field Correlation**

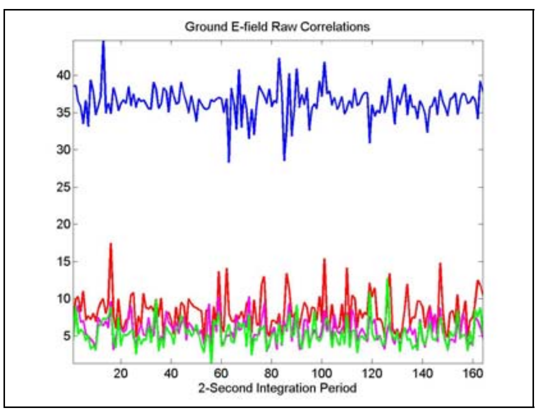


**Figure A2: Ground E-field Correlation**

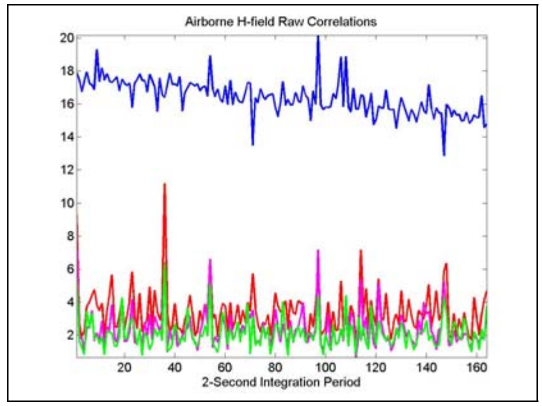


**Figure A3: Airborne H-field Correlation**

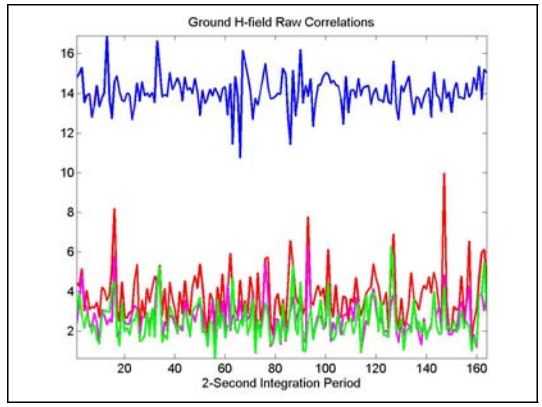


**Figure A4: Ground H-field Correlation**

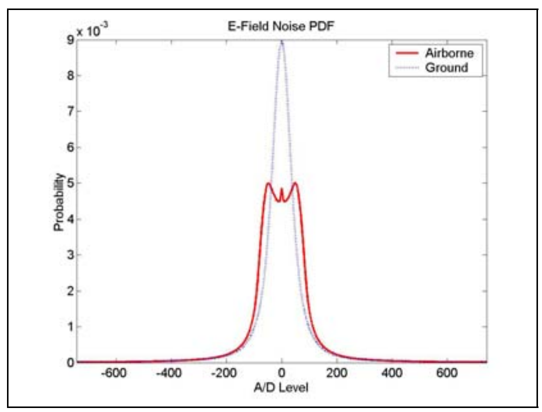


**Figure A5: E-field Noise PDF**

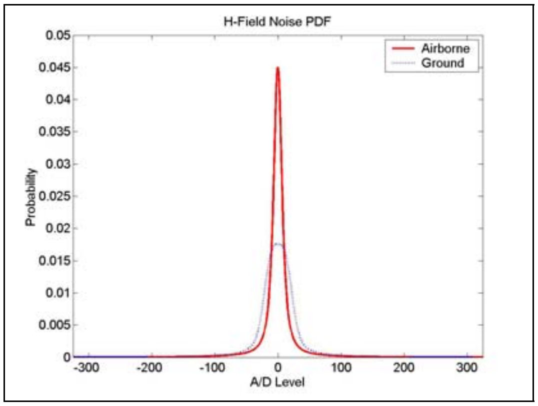


**Figure A6: H-field Noise PDF**

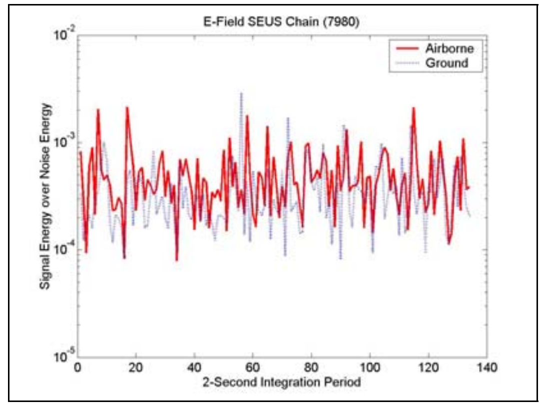


**Figure A9: E-field Signal to Noise Energy**

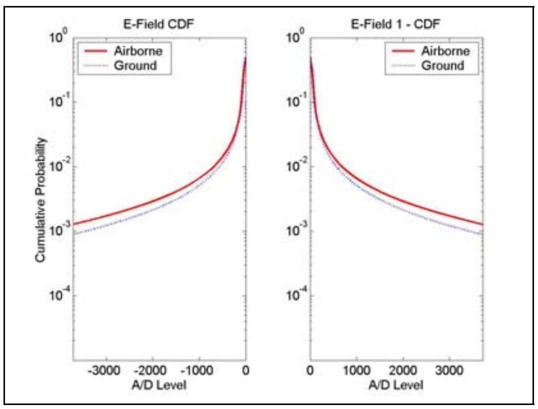


**Figure A7: E-field Noise CDF**

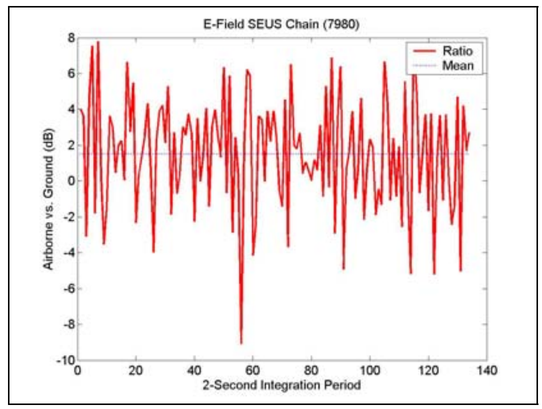


**Figure A10: E-field Airborne vs. Ground**

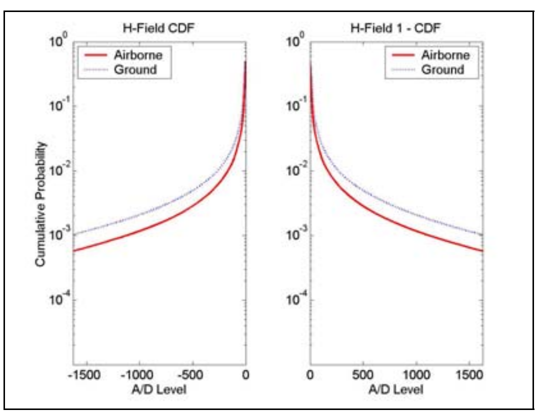


**Figure A8: H-field Noise CDF**

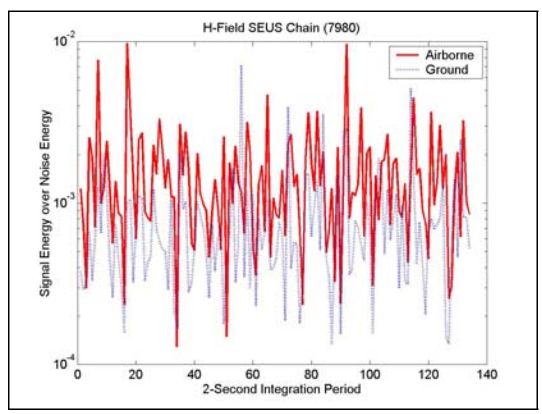


**Figure A11: H-field Signal to Noise Energy**

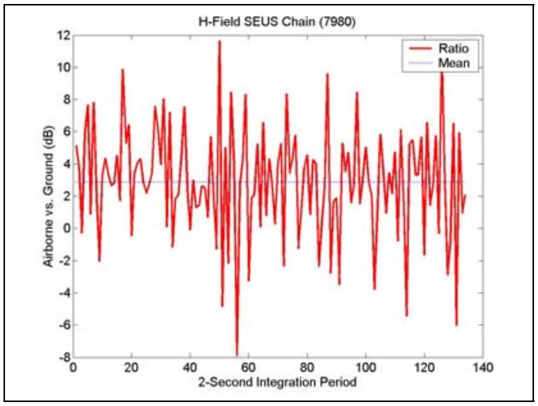


**Figure A12: H-field Airborne vs. Ground**

## A.3 Results

The plots show that the airborne system performed better than the ground based system during the storm. Both systems were on the ground and located approximately 1 mile apart.

# Appendix B

### B.1 Data Collections Conditions and Equipment Configuration

Set Four was collected while the aircraft was flying near moderate thunderstorms. Light-to-moderate lightning activity was observed from the storm. No significant weather was present over TMB during the data collection. The van was operating on battery power during this flight test.

### B.2 Plots

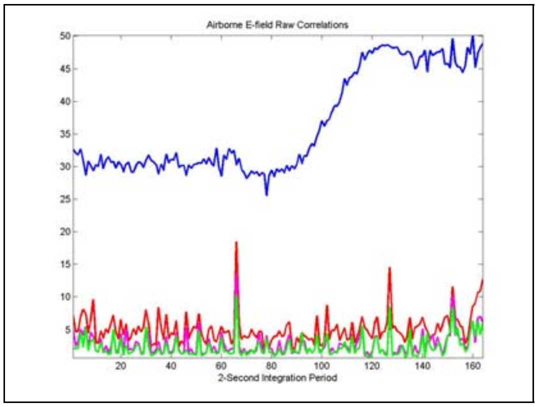


**Figure B1: Airborne E-field Correlation**

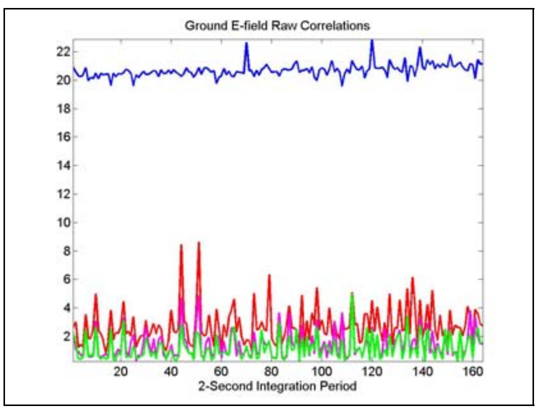


**Figure B2: Ground E-field Correlation**

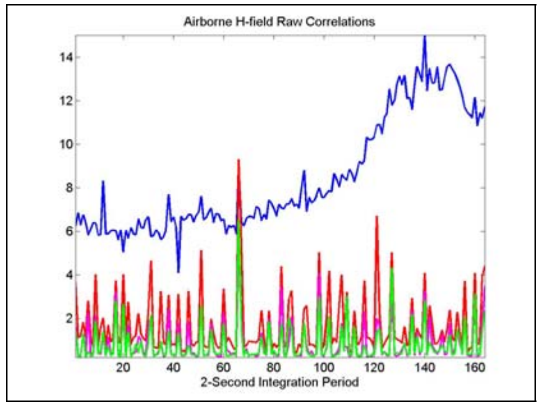


**Figure B3: Airborne H-field Correlation**

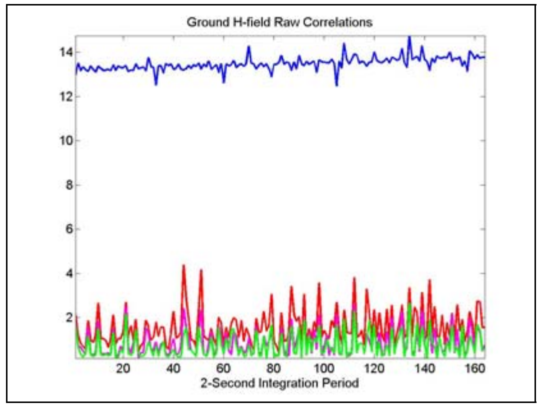


**Figure B4: Ground H-field Correlation**

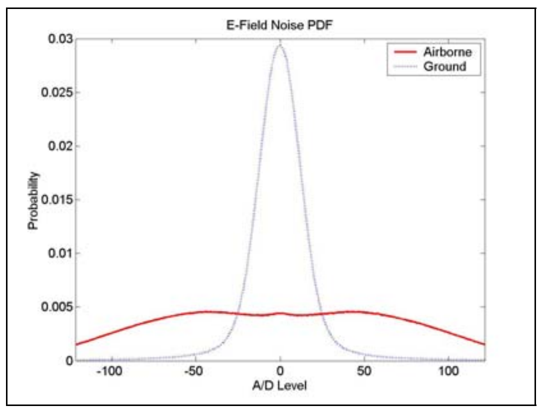


**Figure B5: E-field Noise PDF**

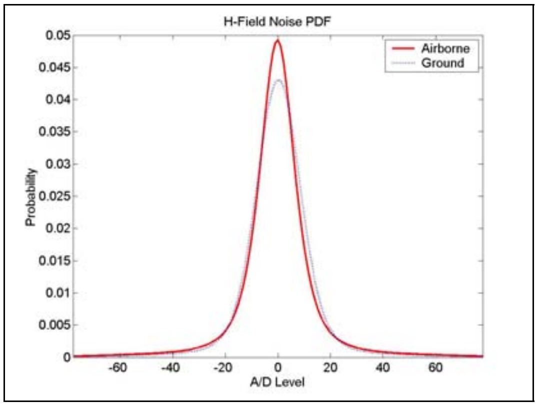


**Figure B6: H-field Noise PDF**

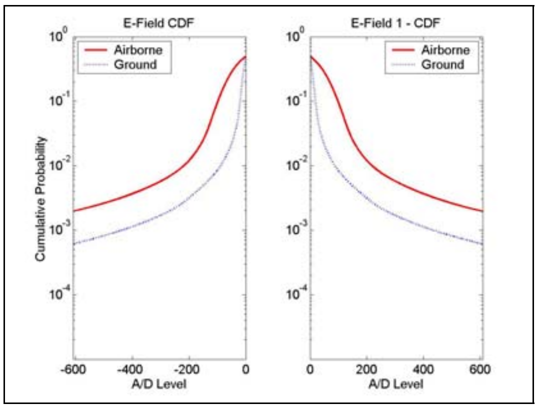


**Figure B7: E-field Noise CDF**

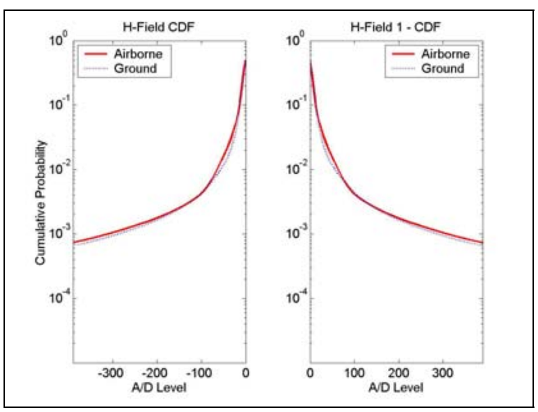


**Figure B8: H-field Noise CDF**

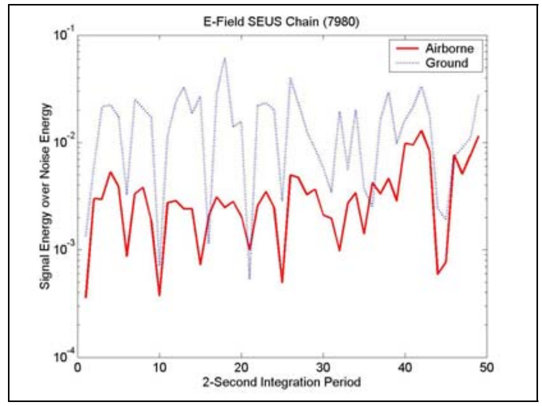


**Figure B9: E-field Signal to Noise Energy**

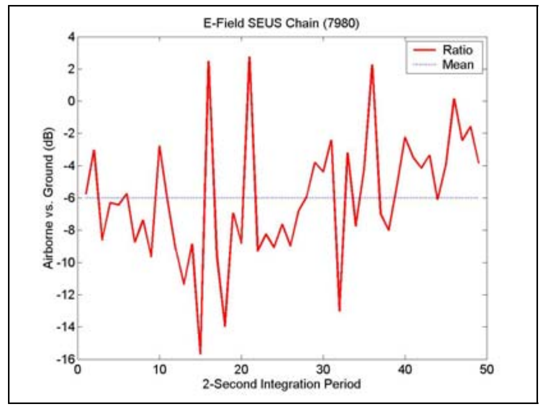


**Figure B10: E-field Airborne vs. Ground**

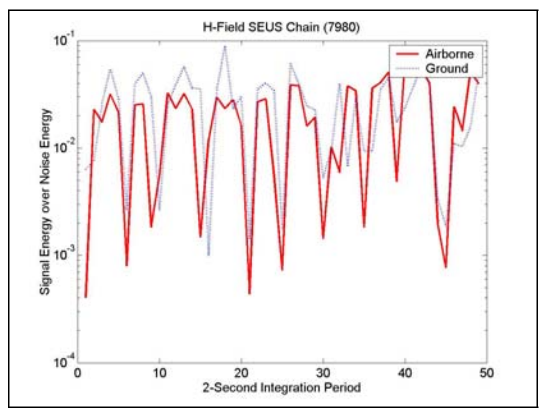


**Figure B11: H-field Signal to Noise Energy**

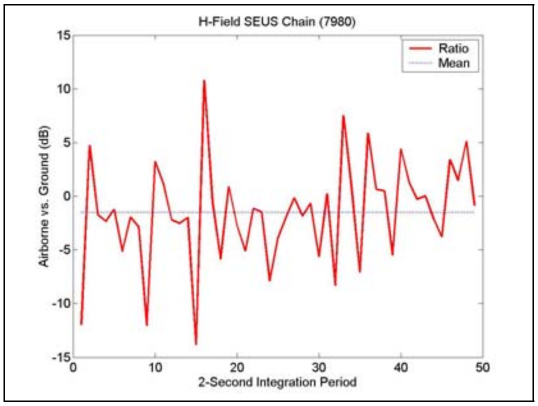


**Figure B12: H-field Airborne vs. Ground**

## B.3 Results

The plots show that the airborne system performed slightly worse than the ground based system during the flight in the vicinity of the storm. This is not entirely unexpected due to the proximity of the storm to the aircraft and its distance from the ground based data collection system. The results also show that the airborne h-field performance, while not better than the ground based data, is better than the e-field airborne data relative to the ground based e-field results.

Figure B13 shows the number of lightning strikes in each 2-second block as recorded by the aircraft WX-500 StormScope during the flight test.

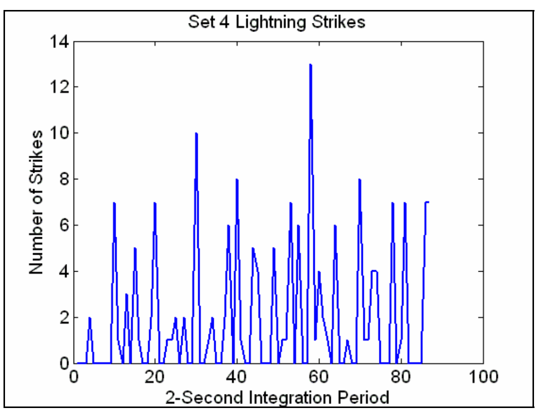


**Figure C13: WX-500 Lightning Strike Data**

# Appendix C

## C.1 Data Collections Conditions and Equipment Configuration

Set Five was collected while the aircraft was flying near moderate-to-severe thunderstorms. Moderate-to-heavy lightning activity was observed from the storm. No significant weather was present over TMB during the data collection. The van was operating on AC power during this flight test.

## C.2 Plots

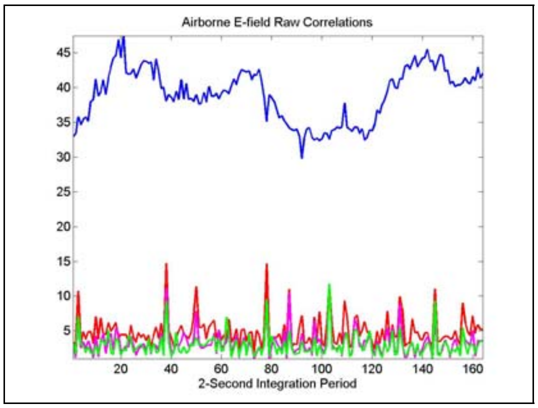


**Figure C1: Airborne E-field Correlation**

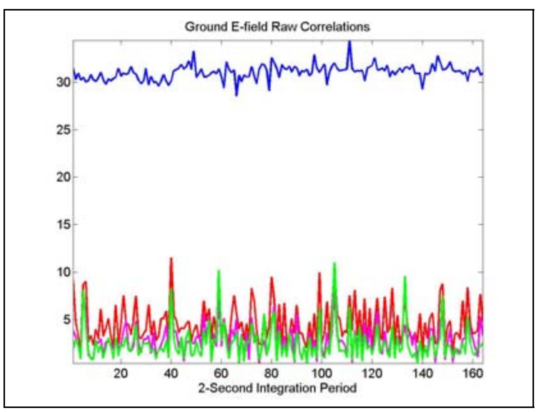


**Figure C2: Ground E-field Correlation**

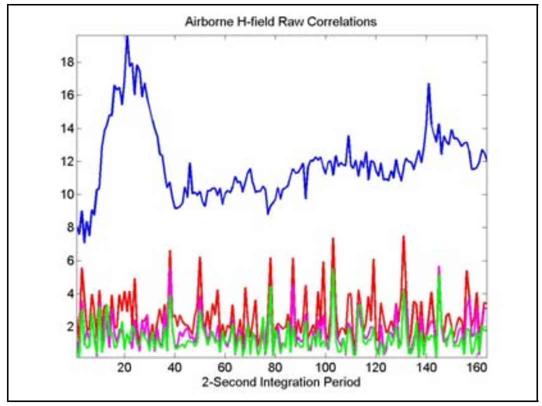


**Figure C3: Airborne H-field Correlation**

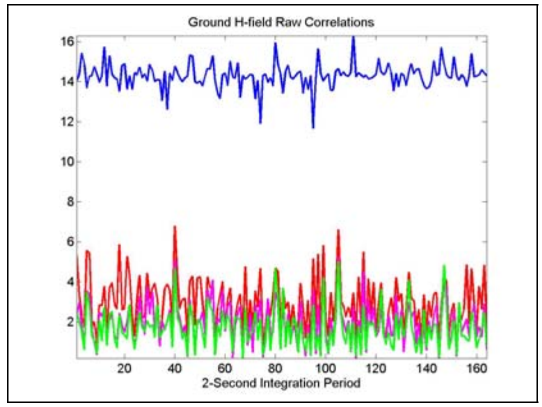


**Figure C4: Ground H-field Correlation**

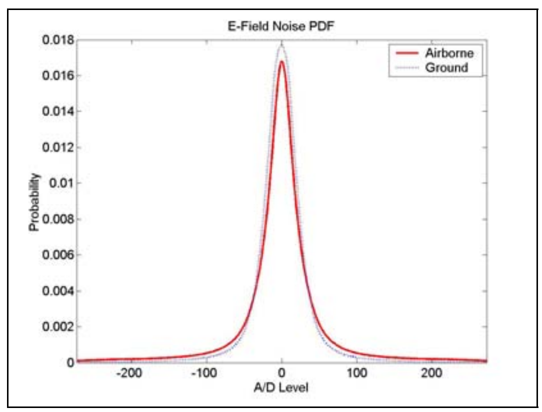


**Figure C5: E-field Noise PDF**

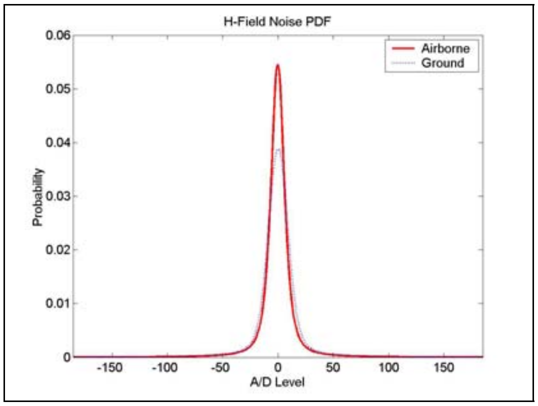


Figure C6: H-field Noise PDF

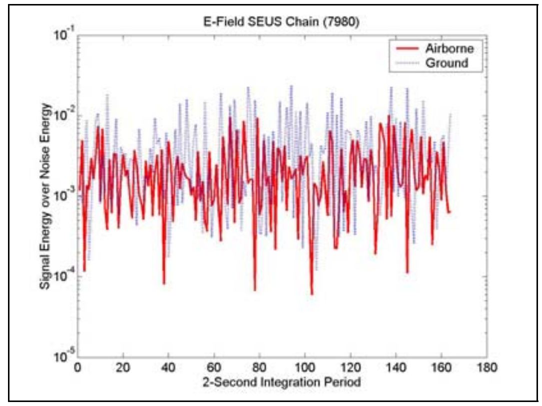


Figure C9: E-field Signal to Noise Energy

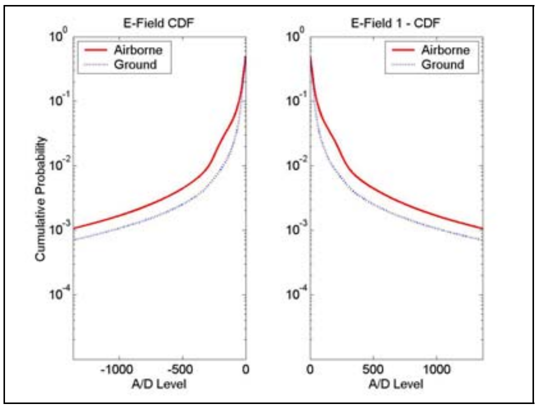


Figure C7: E-field Noise CDF

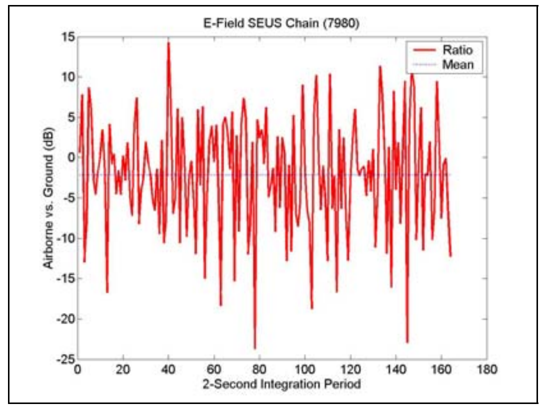


Figure C10: E-field Airborne vs. Ground

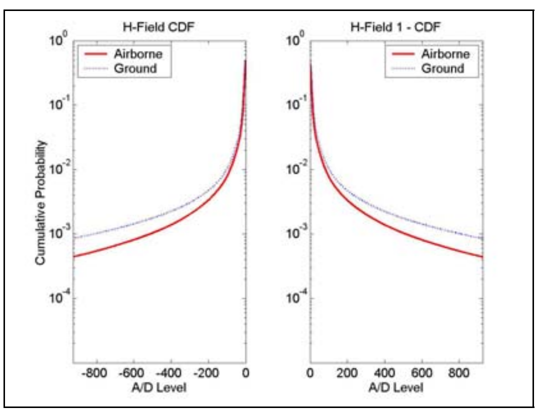


Figure C8: H-field Noise CDF

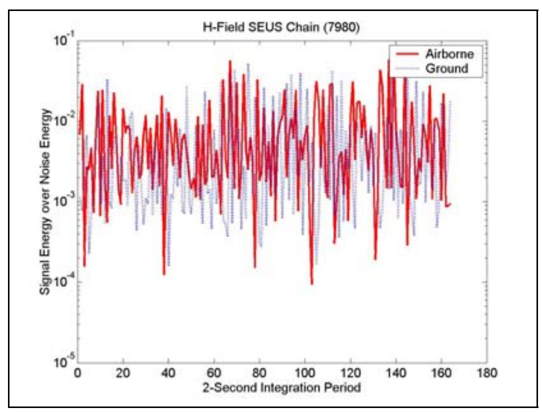


Figure C11: H-field Signal to Noise Energy

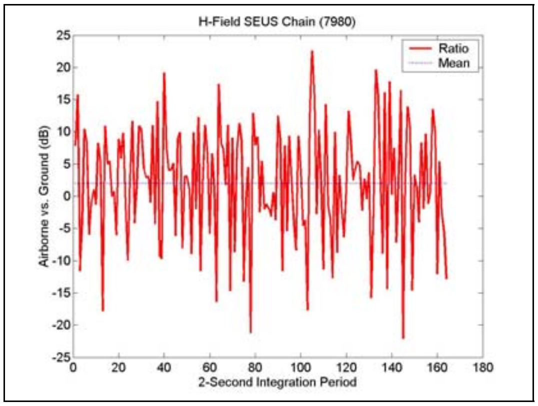


**Figure C12: H-field Airborne vs. Ground**

## C.3 Results

The plots show that the airborne e-field results are still slightly worse than the ground based system during the flight in the vicinity of the storm. However, they are better than the Set Four results, despite the more severe nature of the thunderstorms encountered during this flight. The h-field data shows that in this case the airborne data is better than the ground based data. This is attributed to the van being powered by the glideslope shelter AC power.

Figure C13 shows the number of lightning strikes in each 2-second block as recorded by the aircraft StormScope. This is not a complete depiction of the number lightning strikes, since the StormScope does not capture all the strikes that occur. However, it does provide a basis for comparison between different sets of data collected during thunderstorms until a more complete analysis of the lightning activity is completed.

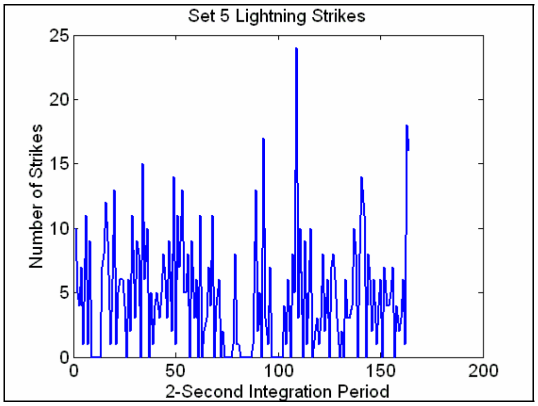


**Figure C13: WX-500 Lightning Strike Data**

# Appendix D

### D.1 Data Collections Conditions and Equipment Configuration

Set Six was collected as a baseline data set. The aircraft was parked approximately 200m from the ground based data collection system. The van was operating on battery power during this flight test. The weather at TMB was sunny and no thunderstorms were in the area.

### D.2 Plots

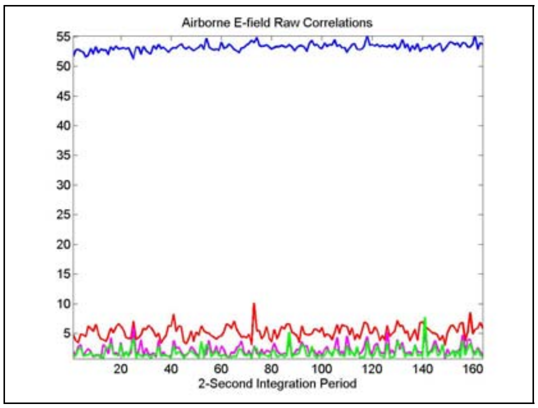


**Figure D1: Airborne E-field Correlation**

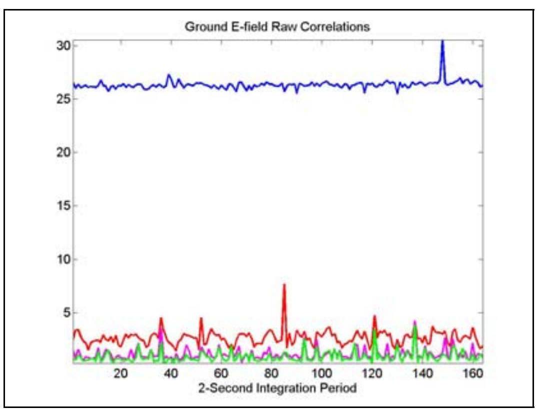


**Figure D2: Ground E-field Correlation**

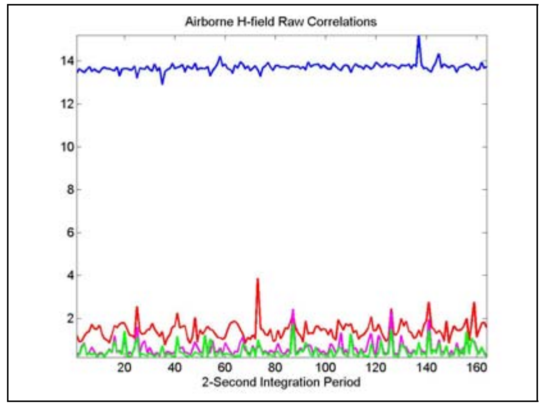


**Figure D3: Airborne H-field Correlation**

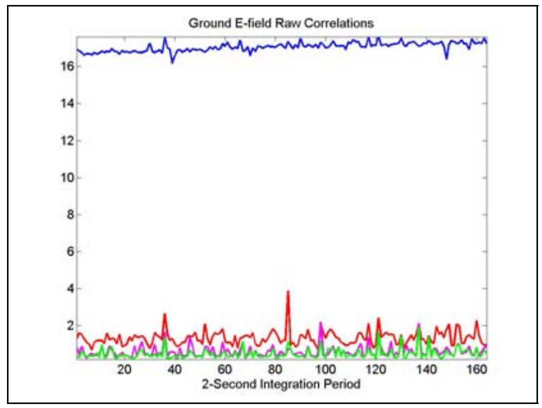


**Figure D4: Ground H-field Correlation**

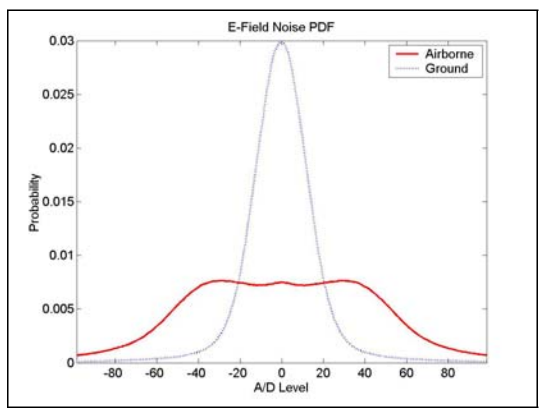


**Figure D5: E-field Noise PDF**

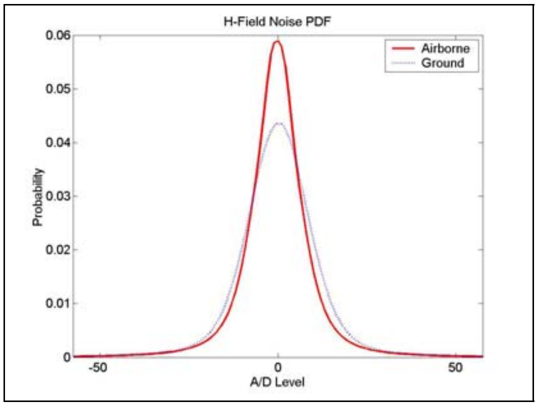


**Figure D6: H-field Noise PDF**

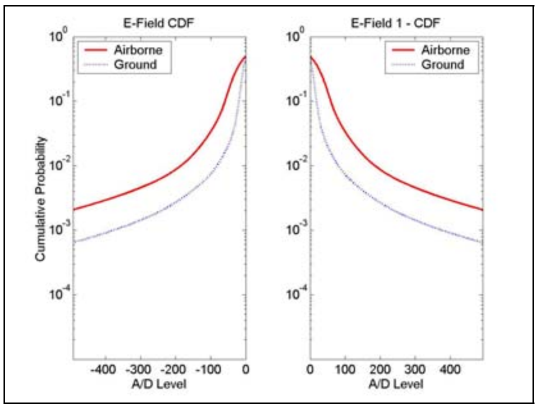


**Figure D7: E-field Noise CDF**

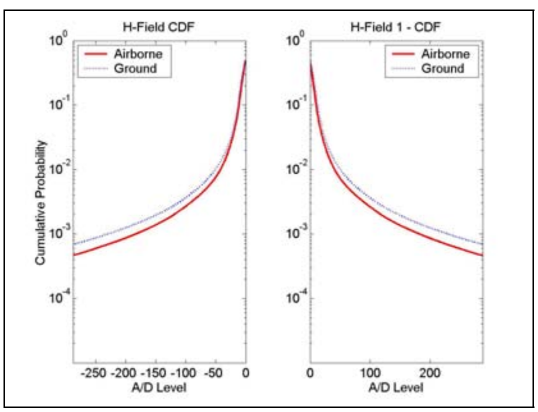


**Figure D8: H-field Noise CDF**

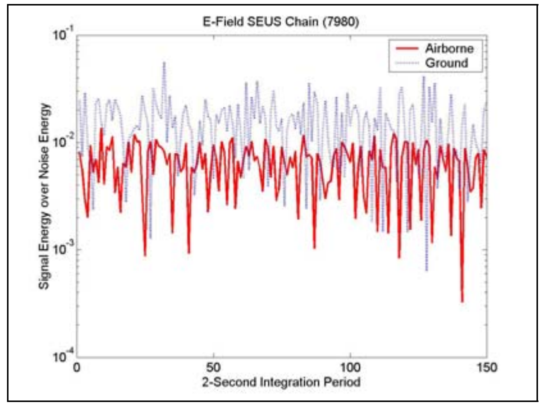


**Figure D9: E-field Signal to Noise Energy**

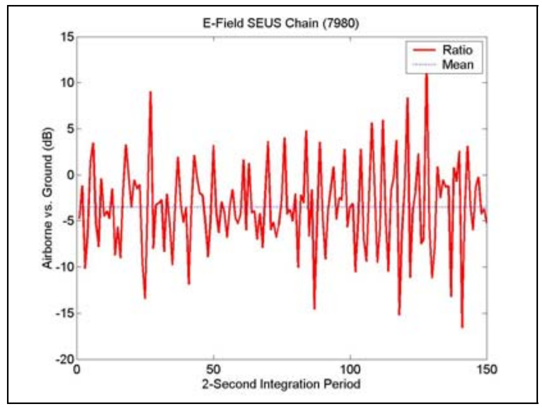


**Figure D10: E-field Airborne vs. Ground**

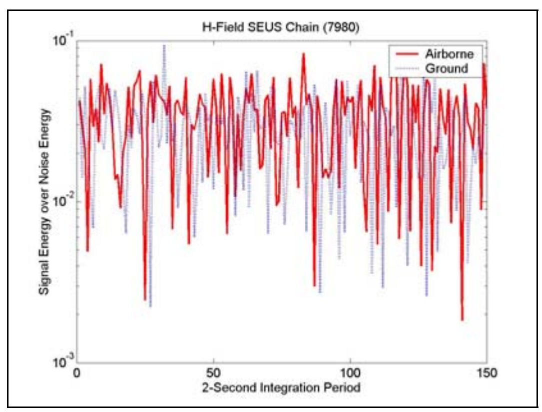


**Figure D11: H-field Signal to Noise Energy**

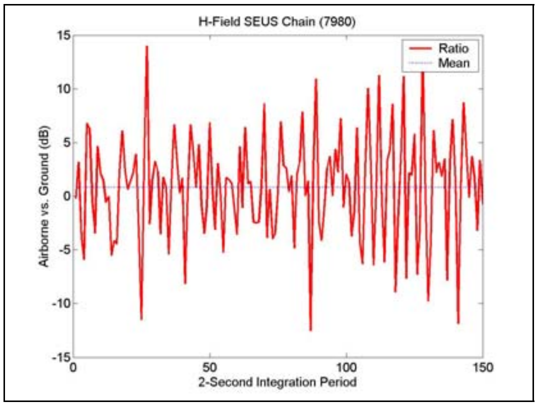


**Figure D12: H-field Airborne vs. Ground**

## D.3 Results

The results show that while the airborne e-field data is slightly worse than the ground data, the h-field data shows that the airborne system is performing as well or better than the ground system.

When these results are compared to Set Two, the beginning of which was taken near the same location, it shows that when the ground system was using AC power the airborne data showed significantly better results.  This supports the results seen in Sets Four and Five where the ground system shows relatively better results when using the van battery power versus ground AC power.