LORAN-C Atmospheric-Noise Flight-Test Results

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BIOGRAPHY

Curt Cutright is formerly a research engineer with the Avionics Engineering Center at Ohio University. He joined the Center in 2001. His work on LORAN-C involved research into atmospheric noise and P-static effects. In addition, he was responsible for integrated GPS/INS flight testing using the Center's Beechcraft C-90SE King Air twin-turboprop aircraft and the Aerovodochovy L-29 Delfin jet aircraft. He holds a B.S.E.E. degree from Ohio University.

Janet Blazyk is a software engineer with the Avionics Engineering Center at Ohio University. She joined the Center in 1990. Her work involves a variety of aviation-related computer applications, primarily in the areas of mathematical modeling and spectrum management. She received a B.S. degree from Brown University and an M.S. degree in Mathematics/Computer Science from Ohio University.

Frank van Graas holds a Fritz J. and Dolores H. Russ Professorship in Electrical Engineering and he is a Principal Investigator with the Avionics Engineering Center at Ohio University. He received the RTCA's *William E. Jackson Award* for his work on integrated GPS/LORAN, the *Johannes Kepler Award* for sustained and significant contributions to satellite navigation from the Satellite Division of the ION, and the *Thurlow Award* for outstanding contribution to the science of navigation for the ION. He has been involved with navigation research and flight-testing since 1984, Most recently, he has worked on fault detection, GPS attitude determination, GPS/INS integrated systems, GPS landing systems, and terrain-referenced navigation systems.

Dave Diggle is the Associate Director of the Avionics Engineering Center at Ohio University in Athens, Ohio. In addition to his duties as Associate Director, he leads the LORAN Support Team at the Avionics Engineering Center. Dave is a member of the Institute of Navigation and the International LORAN Association, and has received the RTCA's *William E. Jackson Award* for outstanding contributions in the field of avionics. He received his Ph.D. in Electrical Engineering from Ohio University and holds a private pilot certificate.

Mitch Narins is the Senior Systems Engineer with the FAA's Navigation and Landing Product Team who leads the FAA/USCG/Academic/Industry Team evaluating whether the LORAN-C system can provide benefits for the aviation, maritime, and timing and frequency communities. Mr. Narins has held a number of program-manager and lead-engineer positions at the Naval Electronic Systems Command and at the Federal Communications Commission. He holds a Bachelor of Engineering (B.E.) degree from the City College of New York and a Masters of Engineering Administration/Management degree from George Washington University.

ABSTRACT

The Federal Aviation Administration has been funding research to determine the feasibility of using LORAN 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 signals. Ohio University's Avionics Engineering Center (AEC) has been conducting flight tests for the past several years to collect data in the presence of these atmospheric noise conditions. This data will allow the effects of the atmospheric noise on the LORAN SNR to be characterized. Accurately characterizing these effects will play a major role in the accuracy, integrity, availability, and continuity analysis of the LORAN system.

Flight tests have been conducted at several locations under varying weather conditions. LORAN 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.

Characterizing the effect of aircraft charging and discharging is also important in studying the effects of noise on the LORAN signal. The charge built up on the aircraft during flight through inclement weather and the way that charge is dissipated by the aircraft introduces noise into the LORAN spectrum. In order to study these effects, the static dischargers on the Douglas DC-3 used during the flight testing conducted during July 2005 and July 2006 in southern Florida were instrumented. This allowed the charge being dissipated by the static wicks during flight to be measured and recorded. In addition, a field mill was installed on the aircraft to allow the level of the static charge on the aircraft to be recorded.

This paper will present the results from the July 2006 flight testing conducted in southern Florida near the Kendall-Tamiami Executive Airport (TMB), Kendall, Florida.

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 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. However, recent events have precipitated a change in thinking on the use of GPS as a sole source of positioning in the National Airspace System (NAS).

The LORAN Integrity and Performance Panel (LORIPP) was one of two panels formed by the Federal Aviation Administration (FAA) LORAN-C Program Office to evaluate the use of LORAN as a backup navigation system. The panels were formed to bring together people capable of determining the changes that would be required to permit LORAN to serve as a suitable backup. These changes will allow the new enhanced LORAN (E-LORAN) system to meet the Required Navigation Performance (RNP) used for non-precision approach (NPA) procedures.

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. 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. The results obtained from the data collected using this system have been shown in previous papers [1-3].

However, it has been determined from those results that additional information will be required to adequately identify the atmospheric processes that cause problems for the LORAN system. The additional data will allow for better analysis of the mechanisms which give rise to atmospheric interference with the LORAN signal. As a first step AEC, in 2004, added to its data collection system the capability to record aircraft static wick discharge currents and aircraft charging voltage. In addition, a rubidium clock was added to the airborne data collection system to increase the timing stability of the Reelektronika DataGrabber-based data collection system. The increase in timing stability also allows for better synchronization of the GPS-position and LORAN data files which are collected.

Included in this paper is an overview of the LORAN airborne data collection system and the atmospheric-charging instrumentation and data-collection equipment, all of which are on board AEC's DC-3 aircraft. A brief discussion of the ground data-collection system is also included. Results will be presented from the July 2006 flight testing at TMB which makes use of these systems.

2. Data Collection System

2.1. Overview

The primary goal of the LORAN data collection system designed at Ohio University by AEC is to collect RF data in the LORAN frequency band. The system was designed so that the data being collected provides an accurate representation of the data that would be seen by a typical LORAN receiver.

Data is collected during the flight testing using both airborne and ground-based data collection systems. The ground data is used as a baseline for the airborne data to help identify sources of interference that are not the result of atmospheric noise. The equipment that has been added to the airborne system is designed to collect data from instrumented static wicks installed on the aircraft as well as a field mill installed on the belly of the aircraft.

2.2. Airborne System

Figure 1 shows the data collection system installed on AEC's Douglas DC-3, 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. Unlike the King Air C-90SE on which the equipment has previously been installed, the DC-3 does not have a storm scope which would provide the capability to record lightning strike activity. Both E-field and H-field antennas are used in the data collection system. They are of the same type as the antennas used on the C-90SE setup, however the E-field antenna used during the DC-3 flight testing was the ship's antenna.

The data collection box contains the Reelektronika DataGrabber which is used to collect LORAN-C RF data, a Rubidium clock added recently for increased Data Grabber timing stability, and a GPS receiver from which position data is collected during flight.

Figure 1: Data Collection Equipment Rack

Figure 2: AEC's DC-3 Aircraft

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

The new data collection system consists of the previously fielded RF data collection system and the atmospheric-charging instrumentation equipment used to collect the aircraft charging data. This equipment includes the field mill, instrumented dischargers, and data collection system chassis. The front panel of the new data collection system chassis is shown in Figure 3.

Figure 3: Charging Data Collection System Chassis

The chassis contains the control head for the field mill and the instrumentation required to collect the aircraft charging data and transmit it to the data collection PC to be recorded. Figure 4 shows the internal components of the chassis.

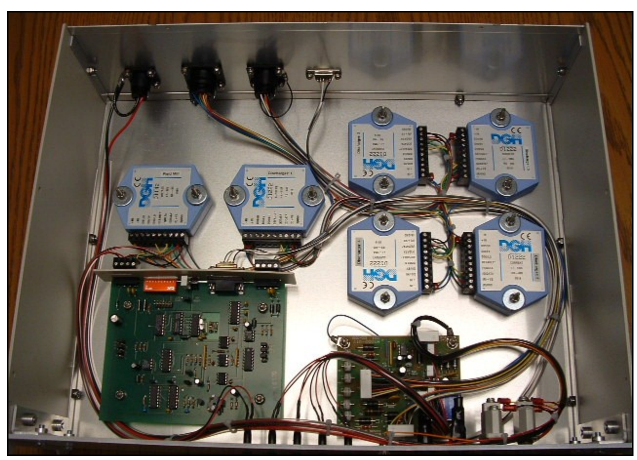

Figure 4: Charging Data Collection System Chassis Internal Components

The field mill used in the new data collection system setup is shown in Figure 5. It is used to measure the electrostatic field strength surrounding the aircraft. Since there is no ground plane under the field mill while the aircraft is in-flight all the measurements are relative to the charge on the aircraft. The field mill chosen was a Mission Instruments EFS-1001 Electrostatic Field Mill. This field mill was chosen primarily because it was the model used by the Federal Aviation Administration Technical Center (FAATC) in their equipment setup on their Aero Commander. This allows for easier data comparison between the two groups later.

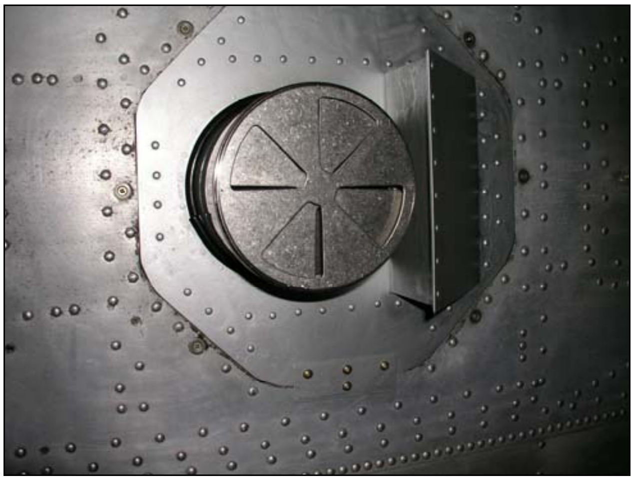

Figure 5: EFS-1001 Field Mill

The field mill has a range of ±100kV. The output of the field mill is sent to a digital voltmeter that is part of the aircraft charging data collection system. The module used is a DGH Corporation Model D1142 Voltage Input Module. The D1142 has an input voltage range of ±10V. The output of the field mill is scaled so that the full-scale deflection of the field mill causes a corresponding full-scale deflection of the D1142 module. The module converts the analog input to a digital output which is sent out over a serial connection the data collection PC.

Aircraft static wick discharge current data is collected from five of the aircraft static wicks which have been instrumented. The five instrumented static wicks are: left wing (LW), right wing (RW), left elevator (LE), right elevator (RE), and the rudder (RU).

An example of an instrumented static wick is shown in Figure 6. The static wicks are isolated from the discharger bases using a non-conductive barrel. A shielded wire is then run from the wick to the new data collection system chassis which contains the data collection modules. The shields of the wires from the static wicks are terminated on one end to help prevent the noise from various aircraft systems, or other sources, from affecting the current measurements.

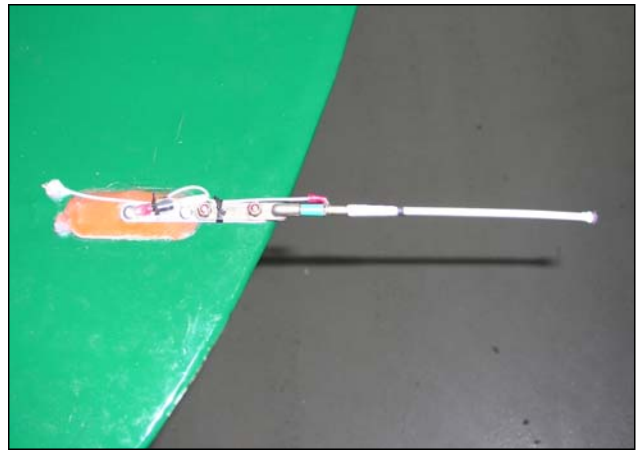

Figure 6: Instrumented Static Wick

The current data is collected using five DGH Model D1222 Current Input Modules. Like the module used for the field mill, these convert the analog current measurements to digital and transmit them to the data collection PC over a serial communication line. The D1222 modules have a range of ±1mA.

2.3 Ground System

Figure 7 shows the ground data collection system van used to collect data at TMB.

Figure 7: 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. A more detailed description of the ground data collection system can be found in reference 2.

3. Flight Test Overview

3.1 Location

Flight tests were conducted in southern Florida from July 11-20, 2005. As with all previous LORAN-C flight testing undertaken by AEC in southern Florida, the Kendall-Tamiami Executive Airport (TMB) was again used as the staging location for the flight tests. This allows for better comparison between the data, both air and ground, that has been previously collected.

3.2 Ground Equipment Setup

The ground data collection van (see Figure 7) was positioned near the glide slope shelter which is part of the National ILS Test Facility run by AEC. This is the location that was chosen in past years 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 Douglas DC-3 to be parked within 200 yards of the van so that baseline data could be collected on both systems under the same conditions.

Data was collected in the van using the ground data collection system during all of the flight tests. Battery power only was used to run the equipment as it has been determined from previous testing that ground power introduces additional noise into the data.

3.3 Flight-Test Description

Data from two flight test periods totaling approximately 4 and one-half hours is included in the following analysis. The two-plus hour flight conducted on July 14th provides an airborne baseline for nominal conditions when no atmospheric activity is present. The two hour flight on July 18th contains excellent examples of thunderstorm lightning activity which is then followed by significant P-static encounters.

As previously stated, ground data was also collected during all the flight testing. Results from the ground data collection are not shown in this paper. The presence of several additional noise sources not seen during previous testing will require additional data processing to be conducted to yield useful results. Once this is completed, this data will be used as a baseline for the airborne data collected, most significantly for the data collected near TMB during the flight conducted on July 18th where significant thunderstorm activity existed in the vicinity of the airport.

4. Results

4.1 Overview

Several five-minute periods of data from each of the flights were chosen to be processed. The data sets are representative of periods of quiet atmospheric conditions found in flight on July 14th and periods of significant lightning activity and severe P-static conditions found in flight on July 18th.

The flight path flown during each of the test periods is shown for each data set which is analyzed. The data was processed using the methods previously detailed in reference 2 and histograms of the atmospheric noise are generated from the results of the processing. Plots are shown to illustrate the impact of the noise on the RF signal. The ability of the data processing software to effectively locate and remove LORAN pulses and the measurements from the aircraft charging data collection equipment are also shown.

4.2 July 14, 2006 Flight Test Results -- Clear

The results shown here are from data that were collected during this two-plus hour flight test period. The skies were essentially clear and there was no atmospheric activity in the southern Florida region. This sequence of figures is representative of ambient background noise conditions for LORAN-C. The flight path is shown in Figure 8. The area in red shows the locale during the flight where the five minute sequence of data was collected.

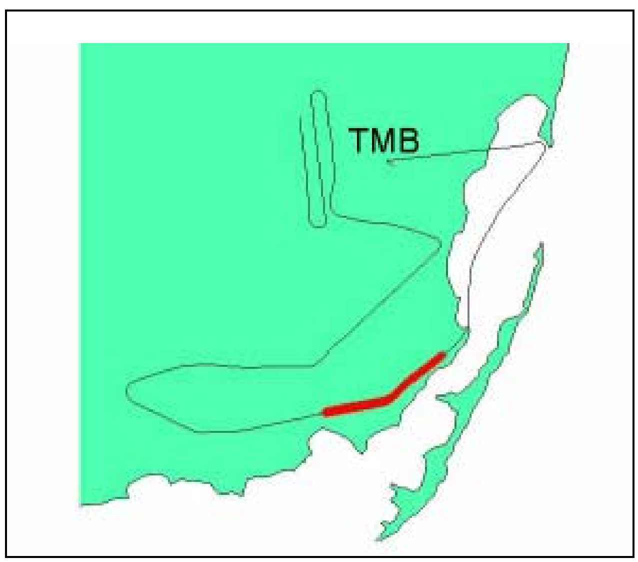

Figure 8: July 14 Flight Path

A two-second sample of the RF data collected during this period is shown in Figure 9. In the plot, the E-field signal (large amplitude) is blue and the H-field signal is red. Multiple groups of LORAN pulses are clearly visible above the noise floor on both the E-field and H-field antenna traces as would be expected during periods of minimal atmospheric activity. The difference in amplitude between the E-field and H-field antenna traces relates directly to the level of amplification associated with each antenna and not the DataGrabber sensitivity.

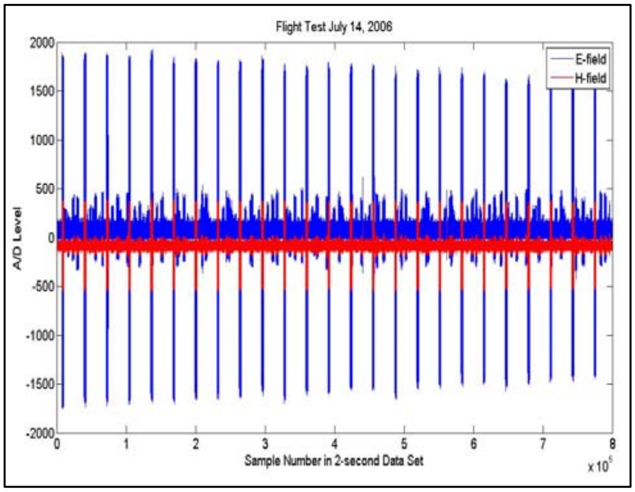

Figure 9: July 14 RF Data -- Clear

In Figure 10, which is a *zoomed* sample from Figure 9, individual LORAN pulses can be clearly identified above the noise floor on both the E-field and H-field antenna traces. The large-amplitude pulses are those of LorSta Jupiter (7980Y) which is approximately 100 nmi distant.

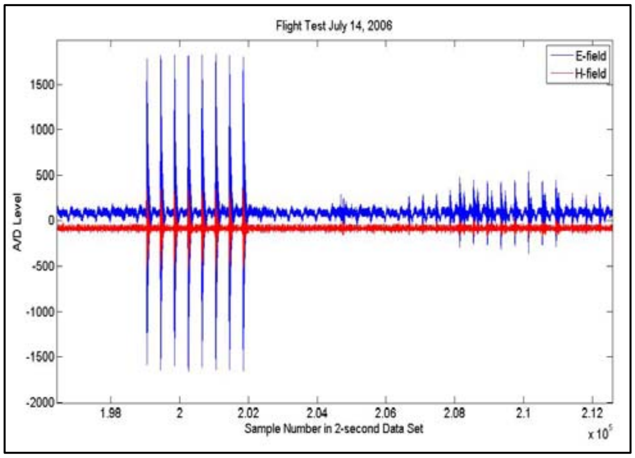

Figure 10: July 14 RF Data (Zoomed) -- Clear

Figure 11 shows the tracking performance (the ability to identify LORAN pulses within the data set) for both the E-field and H-field antennas. Virtually 100% of the pulses are identified. In Figure 12, all of the LORAN pulses identified in Figure 11 have been removed and a histogram of the noise which remains is shown for both E-field and H-field antennas. These histograms are indicative of the Gaussian distribution that would be expected from atmospheric noise. Once again, the differences in the histograms are indicative of the difference in amplification associated with each antenna. Figure 13 shows overall aircraft charging and associated discharging on the instrumented wicks on the left and right wings and elevators plus the rudder. The field mill recorded maximum field strength of about 600 V/m with minimal current discharge from the instrumented surfaces.

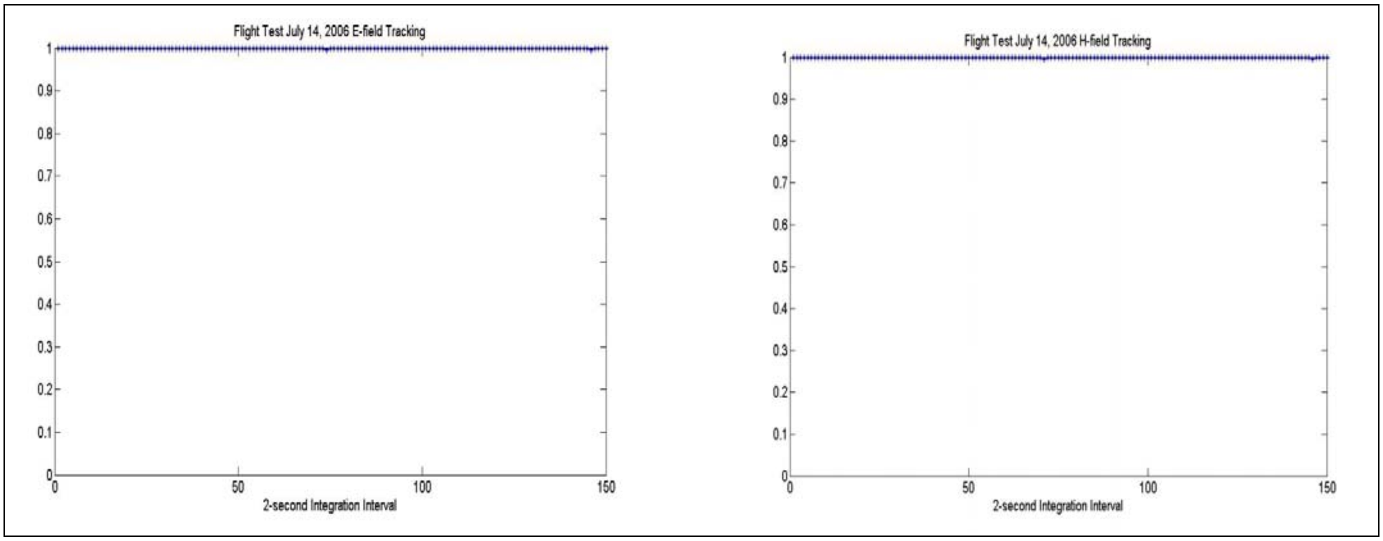

Figure 11: LORAN-C Tracking Performance -- Clear

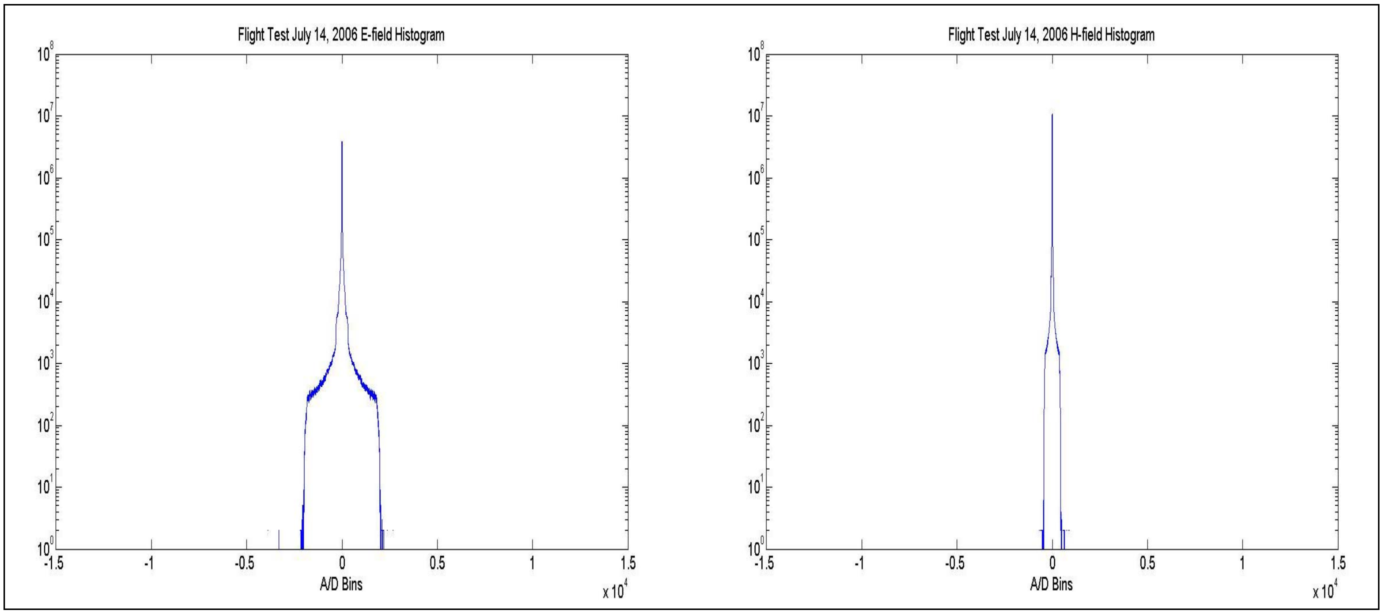

Figure 12: Noise Histograms — E-Field and H-Field Antennas -- Clear

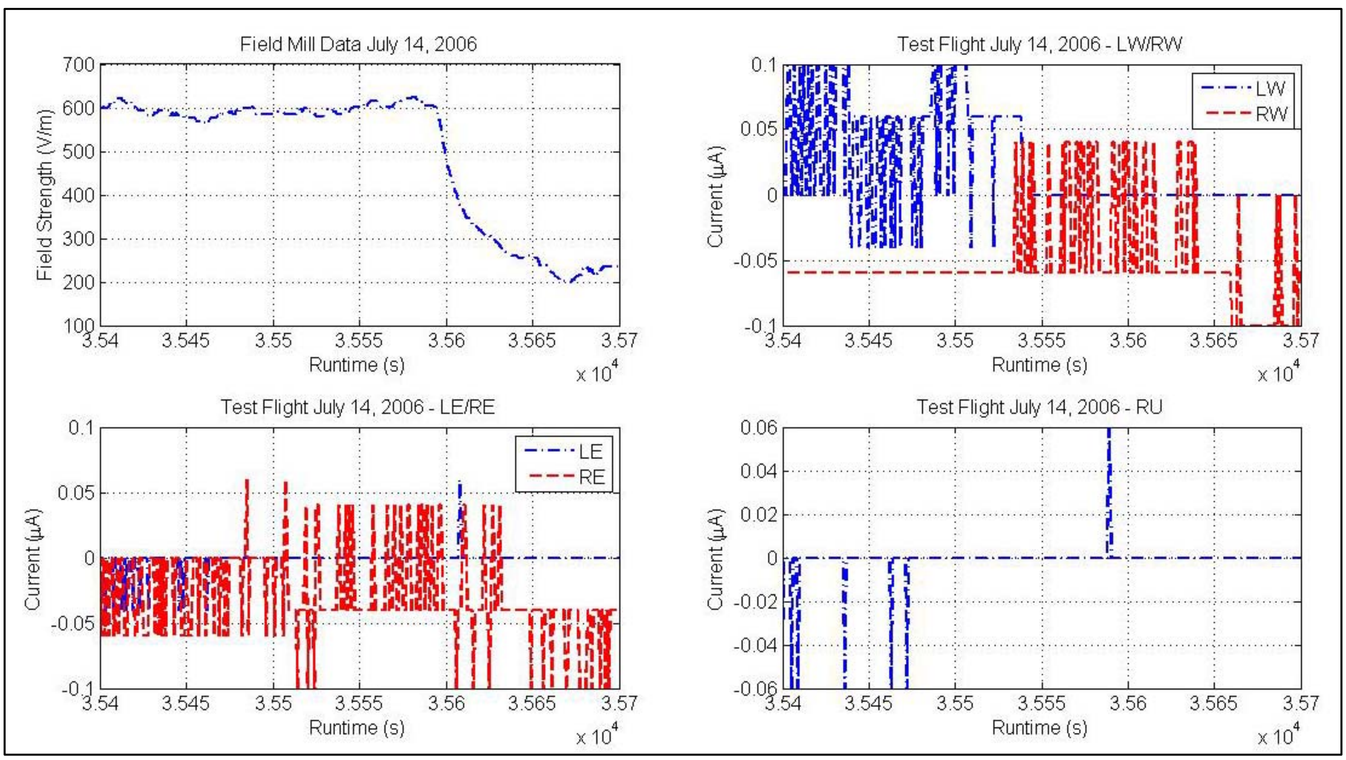

Figure 13: Aircraft Charging Activity -- Clear

4.3 July 18, 2006 Flight Test Results -- Lightning

The results that follow are from data that were collected during this two-hour flight test period. The weather at the time was overcast with moderate thunderstorms in the southern Florida region. This sequence of figures is representative of the LORAN-C signal in the presence of lightning effects. The flight path is shown in Figure 14. The area in red is the locale during the flight where the five minute sequence of data used in the analysis was collected.

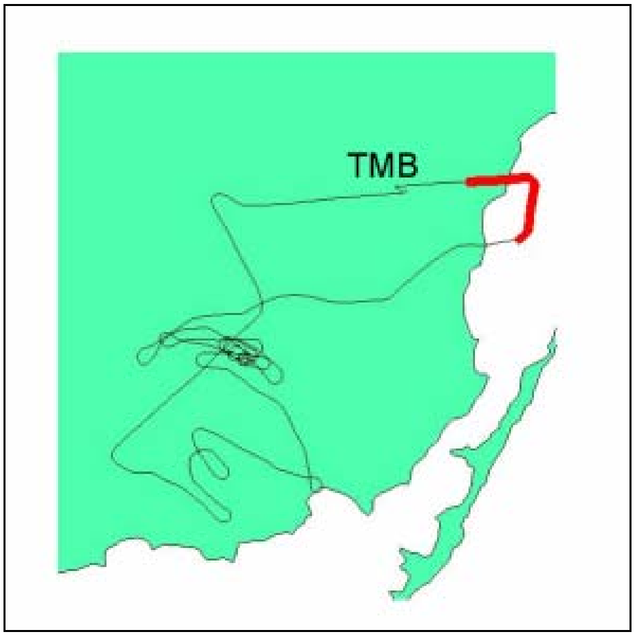

Figure 14: July 18 Flight Path

A two-second sample of the RF data collected during this period is shown in Figure 15. In the plot, the E-field signal (large amplitude) is blue and the H-field signal is red. Multiple groups of LORAN pulses are clearly visible above the noise floor on both the E-field and H-field antenna traces along with the noise caused by lightning strikes from the nearby thunderstorm cells. These strikes occur throughout the data set with varying frequency and power.

As bad as the lightning effect may look in Figure 15, the close-up detail in Figure 16 shows that LORAN pulses are still quite visible in the data. Also apparent is that the lightning strikes affect both the E-field and H-field signals in a similar manner as opposed to P-static effects which will be presented in the next section.

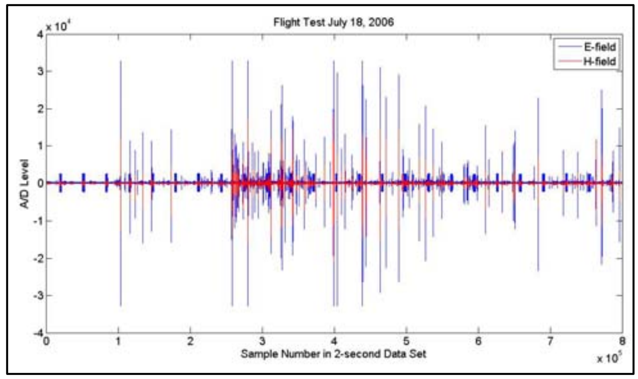

Figure 15: July 18 RF Data -- Lightning

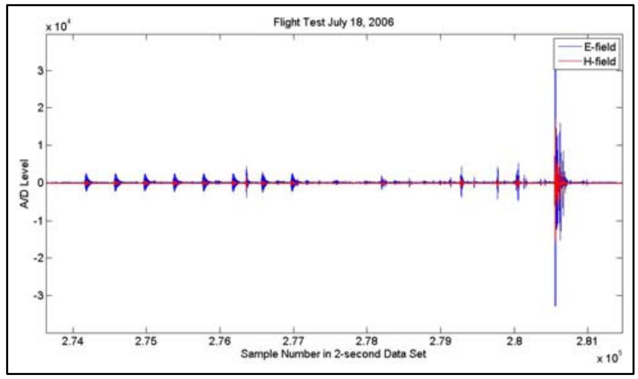

Figure 16: July 18 RF Data (Zoomed) -- Lightning

Figure 17 shows that both the E-field and H-field signals were tracked continuously throughout the five minute data set chosen. Performance is slightly degraded with the E-field antenna as compared to that of the H-field antenna. The histograms of the noise data with the LORAN signals removed (see Figure 18) show that both antennas were affected in similar ways, which one would expect based upon the RF data. Both of the E-field and H-field histograms in Figure 18 show that the noise, even when affected by the lightning strikes, is still generally Gaussian in nature. However, also apparent, is that the noise floor is increased due to the lightning activity in the region. The five-minute segment of charging data (see Figure 19) shows that the impulsive nature of lightning has very little, if any, effect on the aircraft. Any charge effects due to lightning are quickly bled off by the static wicks on the wings, elevators, and rudder. Further data analysis may show that the results seen during this period are almost completely due to normal aircraft charging that occurs even during flight through areas with no significant weather activity.

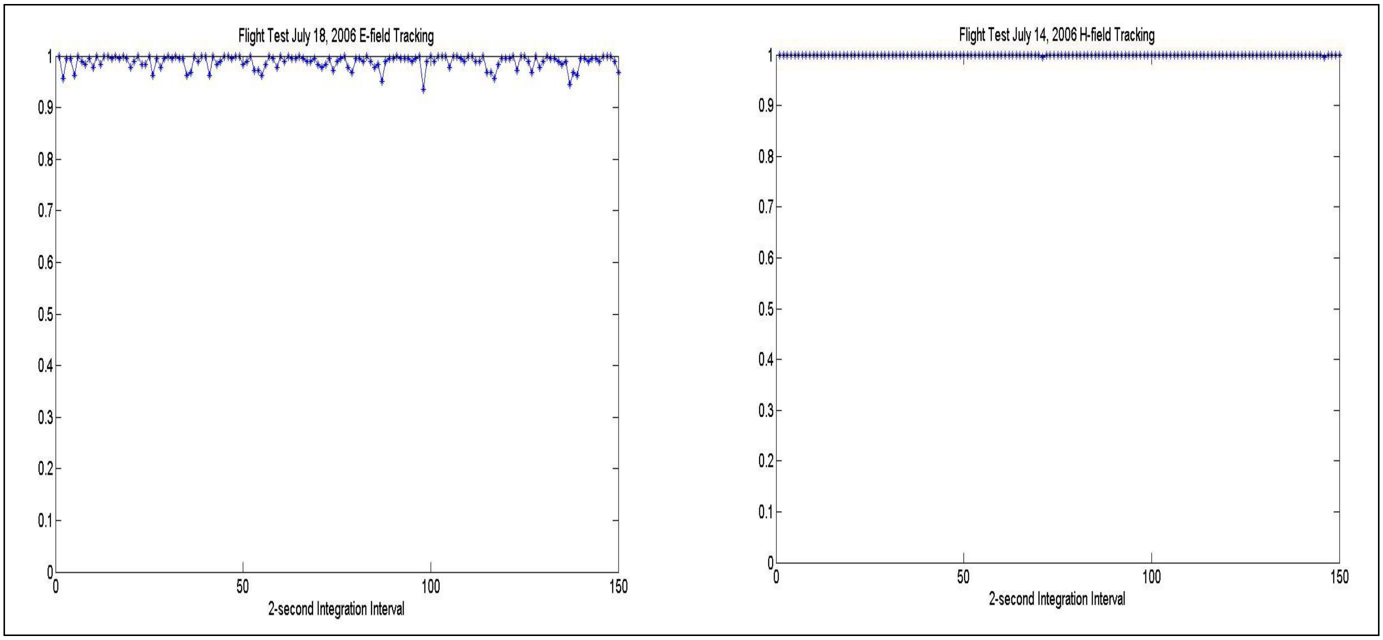

Figure 17: LORAN-C Tracking Performance -- Lightning

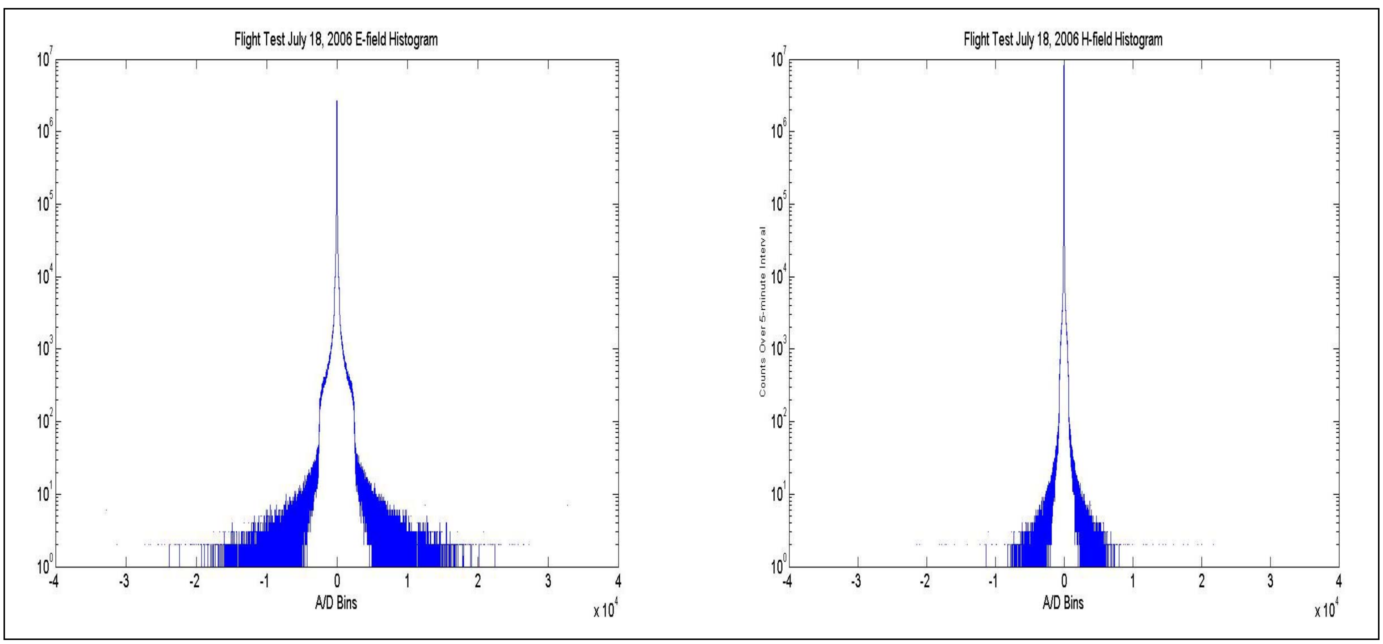

Figure 18: Noise Histograms — E-Field and H-Field Antennas -- Lightning

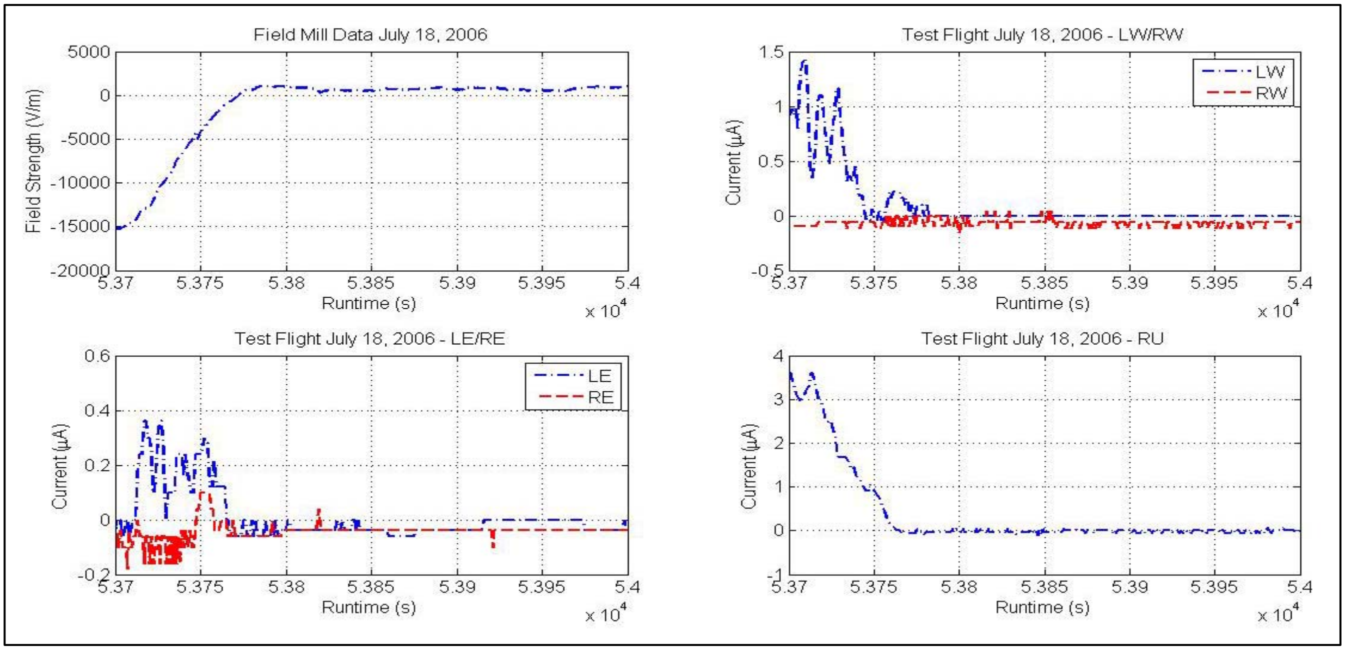

Figure 19: Aircraft Charging Activity -- Lightning

4.4 July 18, 2006 Flight Test Results -- P-Static

The results that follow are from data that were collected following the thunderstorm activity during this two-hour flight test period. The weather at the time was overcast and the moderate thunderstorms in the southern Florida region had mostly dissipated. This sequence of figures is representative of the LORAN-C signal in the presence of severe P-static effects. The flight path is shown in Figure 20. The flight path represents the search for an area of P-static activity. P-static effects to a greater-or-lesser degree are generally present in pockets following the passage of a thunderstorm. The area in red is the locale during the flight where the five minute sequence of data used in the analysis was collected.

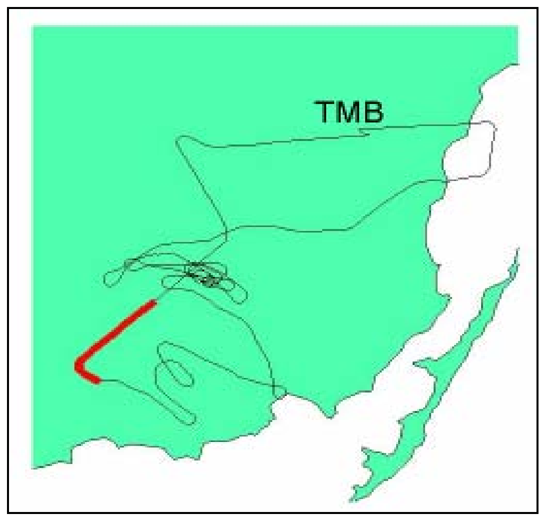

Figure 20: July 18 Flight Path -- P-Static

A two-second sample of the RF data collected during this period is shown in Figure 21. In the plot, the E-field signal (large amplitude) in blue is virtually swamped by the P-static noise. P-static noise is present to the extent that the entire dynamic range of the A/D converter in the DataGrabber has been saturated. At the same time, the H-field antenna channel remains unaffected and the H-field signal in red is clearly visible.

The close-up detail in Figure 22 shows even better that the H-field LORAN pulses are still quite visible in the data. Clearly, the H-field LORAN signal is essentially unaffected by the P-static interference.

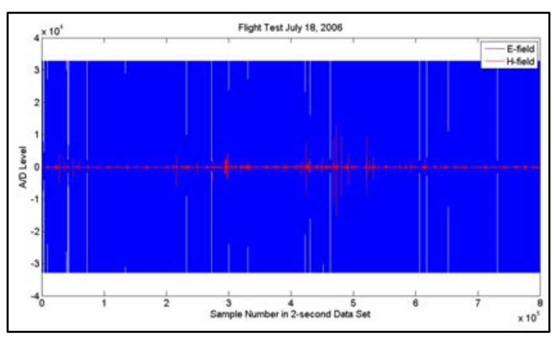

Figure 21: July 18 RF Data -- P-Static

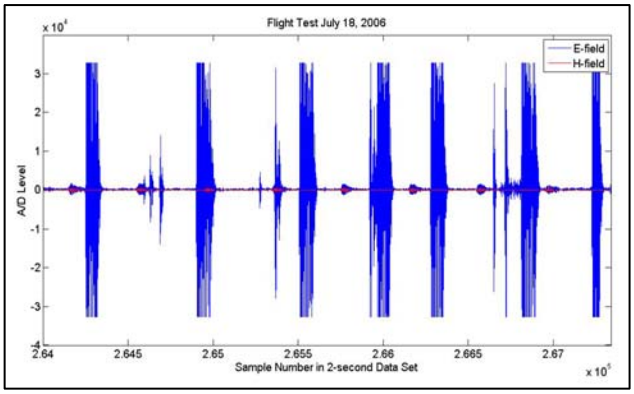

Figure 22: July 18 RF Data (Zoomed) -- P-Static

Figure 23 shows that the E-field tracking performance has suffered greatly throughout the five minute data set chosen. In fact, two Aviation-certified LORAN-C receivers sharing the DC-3 aircraft E-field antenna with the DataGrabber ceased navigating during this event. H-field tracking performance, which is slightly degraded, none-the-less was more than adequate for navigation using a LOCUS, Inc. SatMate 1030 all-in-view LORAN-C receiver. Little-to-no effect on receiver SNR was observed during the event. The histograms of the noise data with the LORAN signals removed (see Figure 24) are in complete agreement with the tracking performance. The E-field antenna histogram clearly shows the DataGrabber A/D-converter saturation evident in the RF data, as well as the high level of noise experienced with the E-field antenna. On the other hand, the noise levels on the H-field antenna are typical of those seen with lightning effects (see Figure 18). Thus, the H-field antenna histogram shows the Gaussian distribution that would be expected from simply increased atmospheric noise. The five-minute segment of charging data (see Figure 25) shows that during this period the aircraft charged and discharged. As the aircraft discharged the data recorded from the static wicks showed a corresponding increase in current flow. The field mill recorded maximum field strength of over 70K V/m and a sustained level of over 55K V/m during this time.

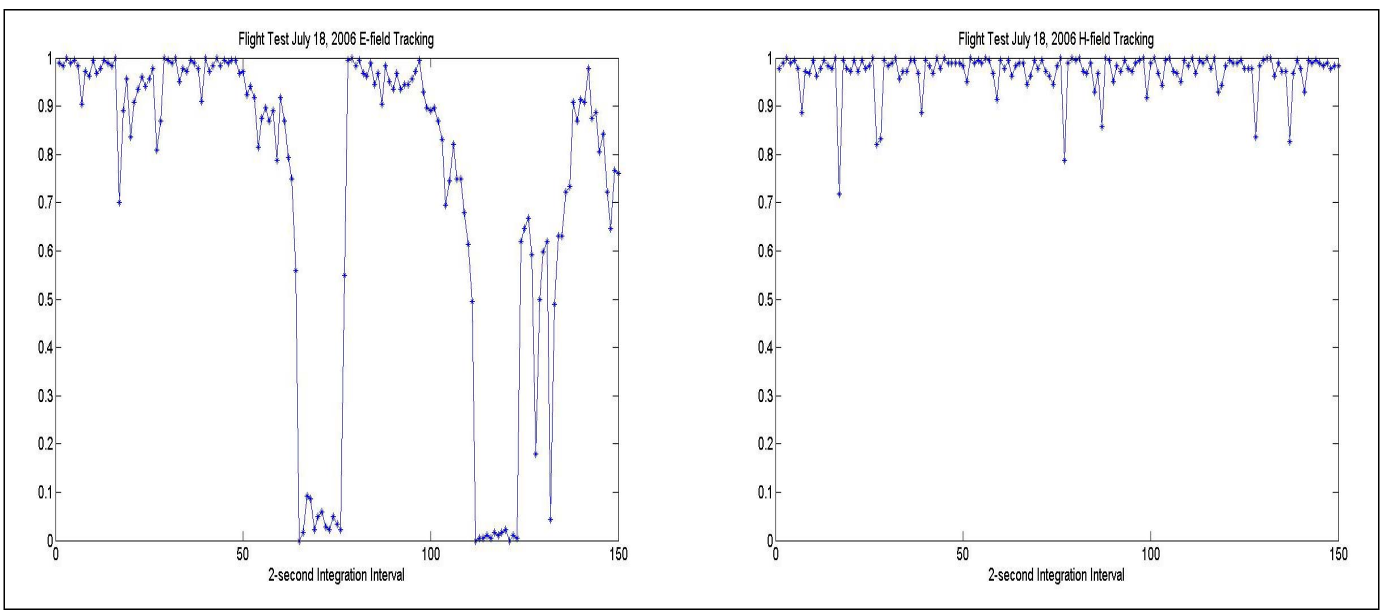

Figure 23: LORAN-C Tracking Performance -- P-Static

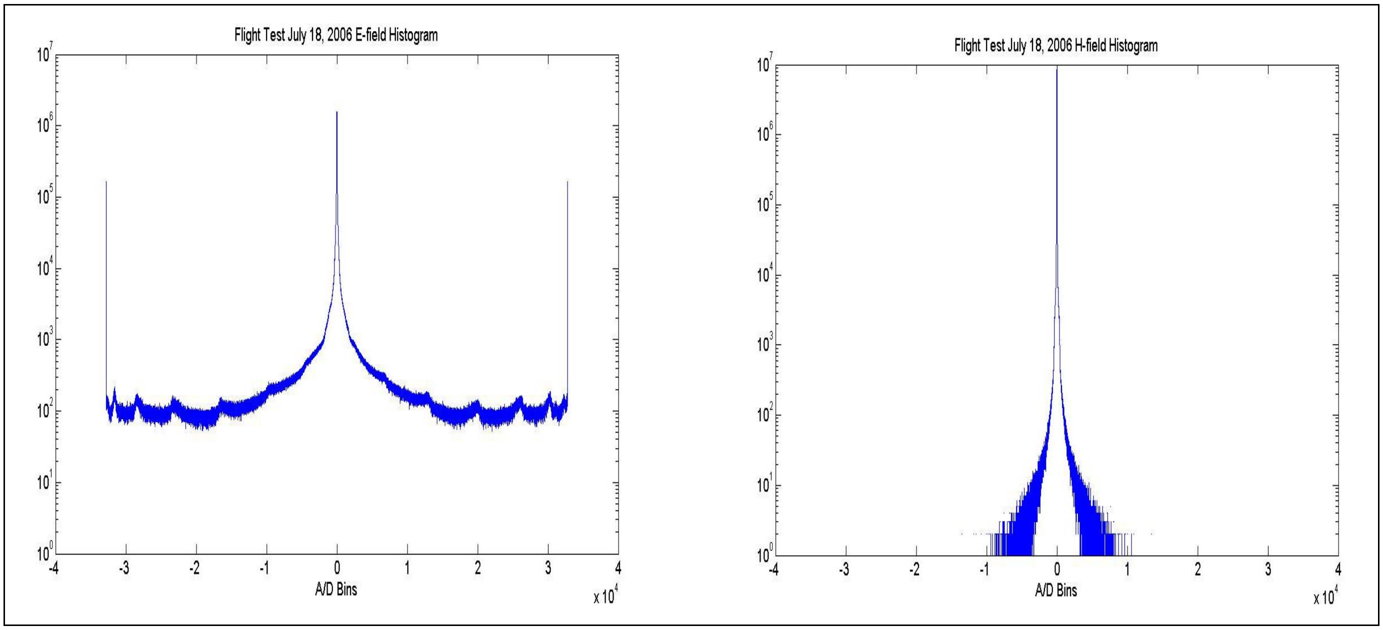

Figure 24: Noise Histograms — E-Field and H-Field Antennas -- P-Static

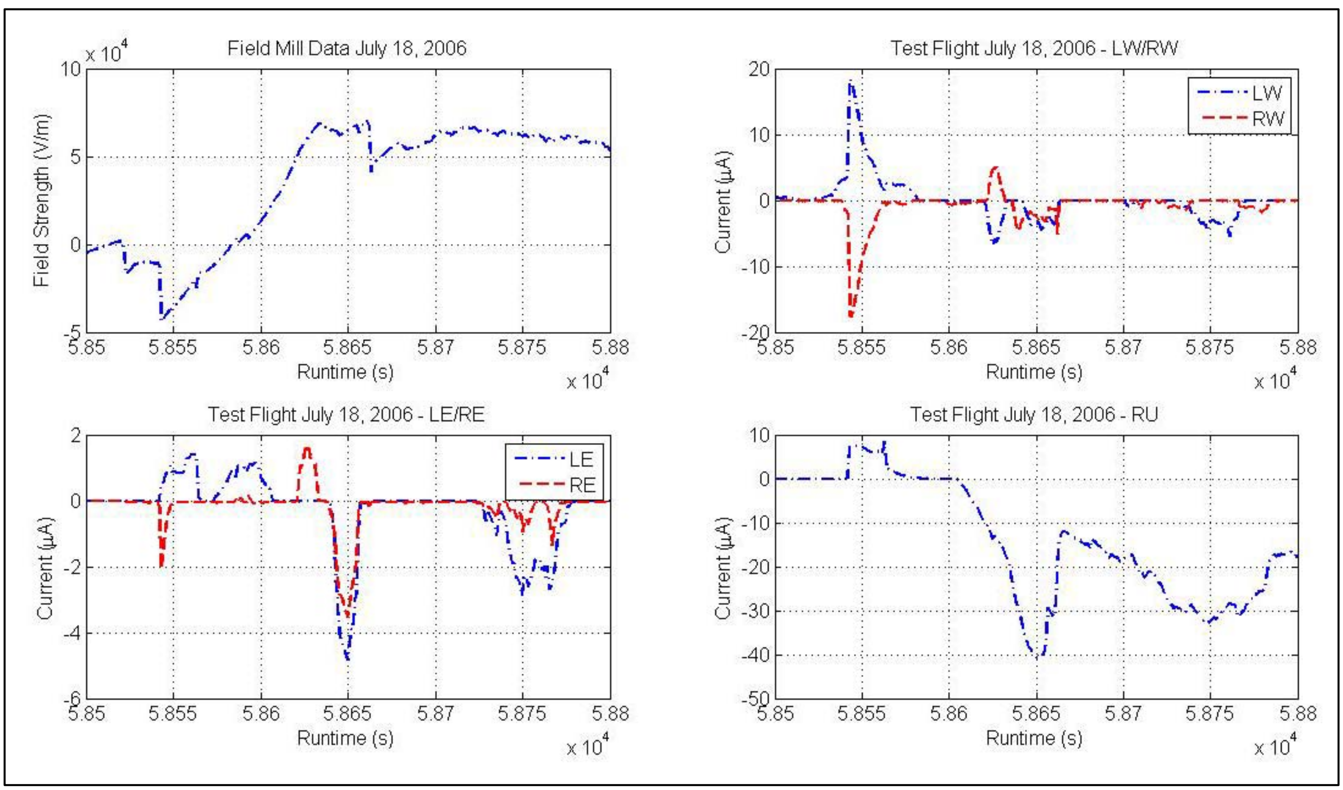

Figure 25: Aircraft Charging Activity -- P-Static

6. Conclusions

These results from the analysis of the flight-test data taken during July 2006 in southern Florida show that the primary source of atmospheric interference for LORAN-C is caused by P-static effects. The lightning effects seen during these flight tests have had a minimal impact on the noise seen by the data collection system which uses the Reelektonika DataGrabbers. This underscores the almost negligible effect of impulsive noise on LORAN receiver signal processing. The data also show that even the P-static effects are almost entirely mitigated by the use of an H-field antenna. H-field tracking performance is excellent overall and appears to suffer only slightly when there is a severe current discharge through the aircraft static wicks. After the discharge, signal tracking quickly recovers. A LORAN-C receiver onboard the Douglas DC-3 aircraft using an H-field antenna was unaffected during the P-static activity which caused two other LORAN-C aircraft-certified receivers using an E-field antenna to cease navigation.

These results, especially when put in the context of the upcoming E-LORAN system, indicate LORAN to be an extremely robust navigation system. With the use of a properly designed H-field antenna and with advanced data-processing techniques made possible by the increased computational power available today, technology not available when the original LORAN system was designed, the effects of atmospheric noise should not pose a serious threat to the ability to navigate using either the recapitalized LORAN-C available at the present time or the upcoming E-LORAN system.

7. Future Work

While the analysis presented in this paper appears to correlate well with all the past data which has been processed, that which remains still needs to be processed to determine if the results seen to date are found throughout all the data sets.

In addition, work will need to be done to develop a system capable of more accurately recording the in-flight lightning activity experienced so that a more thorough characterization of these lightning effects during the flight tests can be made. This will allow for a more accurate assessment of the effects of lightning based on strike amplitude, distance, and location.

The possibility of using modified E-field antennas should also be investigated. If an E-field antenna that is less susceptible to P-static effects can be developed, many known issues that arise from the use of H-field antennas can be avoided.

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