

FAA Tests An H-Field Antenna To Increase Loran-C Availability During P-Static Events

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ABSTRACT

Reported loss of Loran-C guidance during approaches in bad weather has led some to say “Loran-C fails just when you need it the most.” Loss of guidance can be traced to triboelectric charging of the aircraft during flight through particles of water or ice, and the subsequent radio noise generated by the electrical discharge from the aircraft. The phenomenon is known as "precipitation static". The high-voltage, low-current discharge produces a noisy electric field which affects Loran-C receivers equipped with E-field, or "whip" antennas. Various studies have shown that use of a magnetic-loop, or H-field antenna, improves Loran-C reception during P-static events. The FAA is conducting a series of formal ground and flight tests to document the improvement produced by using an H-field antenna during P-static events.

This paper presents a brief description of how the aircraft is charged during a P-static event, types of discharge, previous H-field antenna tests and results, the ongoing FAA test program, and results of preliminary testing using the FAA aircraft.

1.0 BACKGROUND

During FAA efforts in the late 1980s to implement Loran-C as a system for instrument approach guidance, criticism was leveled at the system concerning precipitation-static interference. "P-static" was said by some to deny Loran-C guidance just when the user needed it most; that is, when the flight encountered instrument meteorological conditions. P-static is the triboelectric charging of the aircraft during flight through particles (water, ice, dust etc.), and the subsequent radio noise generated by the electrical discharge from the aircraft.

Loss of signal due to P-static may have been true for some users at that time because inexpensive electric-field “whip” antennas were included with aviation receivers. Antennas were often installed without detailed guidance on preparation of the antenna mounting and grounding requirements. At that time, the solution for reducing P-static was to make sure the aircraft was properly bonded, and that the static dischargers were properly installed and maintained. While guidance did exist, there was evidence that aircraft owners and operators were not careful to provide and maintain airframe static discharger devices. To be fair to these owners and operators, it was natural that emphasis on dischargers had decreased over time, as most aircraft radio services have moved away from the low frequencies where P-static is often most energetic.

When it became obvious that Loran-C would be a popular system among aviators, offering “free” distance measurement and new flight-management information even for low-end aircraft, FAA's interest in P-static and its minimization increased. Ohio University was tasked to perform several studies to demonstrate the effectiveness of various types of discharge devices.

Now that Loran-C is once again being considered by some as a continuing part of the aviation navigational suite, the subject of P-static is again prominent. This is particularly true after the release of the recent Volpe study on GPS vulnerability [1]. Developments in digital signal processing techniques and increased computer processing power since the 1980's has enhanced Loran-C receiver performance. One such improvement is the use of a magnetic loop or "H-field" antenna to improve signal availability during periods of P-static. Based on experience from the Omega Navigation System, it is expected that H-field

antennas will be less sensitive to electrical interference caused by the high-voltage, low-current discharges encountered during flights into precipitation or clouds. The antennas are quite similar to those used for automatic direction finders (ADF) or Stormscope™ - type devices. In these devices, loop antennas are used to permit measurement of the angle of arrival of the signal. For Loran-C, this angle is not important for position measurement, but the desirable properties of the loop antenna are needed. (In fact, the angle-of-arrival feature must be defeated for Loran-C through receiver processing, to avoid undesirable phase-reversal effects.)

2.0 ELECTRICAL NOISE GENERATED IN FLIGHT

Airframe charging occurs when electrons are knocked free from particles of ice or water which strike the aircraft during flight. As might be expected, more speed means more such collisions and thus a higher rate of charging. A highly-charged airframe can give rise to visible glow ("St. Elmo's fire") during corona discharges and to noticeable discharge to fingers when placed near the windscreen. Essentially, the whole process can be compared (loosely) to the arc drawn when touching a doorknob after shuffling across a carpet.

Once the charge is transferred to the airframe through this "triboelectric" process, there are three main mechanisms for equalization of charge among airframe components and between the airframe and the surrounding space. Each can be troublesome in its own way and each requires separate attention by maintenance personnel to achieve an electrically "quiet" airframe.

2.1 ARCS

Arcs occur when different elements of the airframe are charged to different voltages. Such differences can occur due to corrosion or loose components, but can also occur for other reasons. One noise case was solved when it was discovered that a metallic emblem was glued to the aircraft's painted surface, rather than being screwed or riveted. The non-conductive paint and glue acted as a dielectric in a capacitor, which then arced when the potential difference between the emblem and the airframe reached high values.

Arcs cause broadband noise, and are relatively energetic. It is important to maintain aircraft surfaces free of corrosion, de-bonding, or loose rivets (as much for structural integrity as for electrical reasons). Severe arcing can affect any radio-based navigation system regardless of the antenna type.

2.2 STREAMERS

Streamers are low-current arcs which form across dielectric surfaces such as windscreens and radomes. (Special coatings are required on aircraft where composite skin or structural materials are used, to avoid noise or more serious effects of lightning.)

The effects of streamers are similar to arcs, but conductive coatings or strips may be used to minimize their energy. Much effort has been expended to develop optically clear coatings for windscreens and RF-transparent coatings or loading methods for radomes. The coating must obviously be connected to the airframe; in the windscreen case, the glue often used to seat the plastic window can act as an insulator. A method must be found for conducting the surface charge across this barrier, so as to maintain as low a potential on the dielectric as possible.

2.3 CORONA

Of the three discharge mechanisms, corona is perhaps lowest in instantaneous energy, but can be most troublesome due to its frequency-selective nature. When the airframe is charged, packets of charge leave the trailing edges (antenna tips and other convenient spots), and these ions are carried away by the slipstream. The amplitude of each of these events is approximately constant, determined by the trailing-edge geometry. (Ions can escape at lower potential levels from points with very small radius of curvature.)

Discharger wicks are made up of bundles of very fine wire in an attempt to provide a low-energy discharge path for accumulated charge on the airframe. Discharger length and resistivity are design parameters which can be varied by the manufacturer to enhance performance in selected frequency ranges.

If the charging rate (the input of charge from collisions with precipitation particles) increases, the corona mechanism must liberate ions more frequently to equalize the charge. Therefore, the corona current consists of more-or-less constant amplitude events with a varying repetition rate proportional to the airframe charging rate. This repetition rate can easily reach 100 KHz. (In fact, the rate can also occur at 30, 90, 150, 9960 Hz, or other audio frequencies of great interest to navigation-aid designers.) Also troublesome is the fact that the corona pulses look just like digital pulses, and when they get into digital systems through corroded joints or poor ground connections, data errors can result intermittently and thus in a stealthy manner.

Corona currents can be in the nano-ampere range, but when originating from an airframe charged to 50,000 volts, noticeable noise may result. It is in this environment that our navigation equipment must operate. As encouraging background, it is in this environment that the Omega Navigation System operated successfully on aircraft large and small, generally using H-field antennas.

2.4 MAINTAINING THE AIRFRAME

It is possible to “quiet” a particular model of aircraft by designing the discharge wick installation appropriately, given the airframe shape. However, once those aircraft are in service, variations in maintenance frequency and technique can cause individual differences. Each owner and operator needs to be alert to methods for minimizing airframe-charging/discharging noise. The foregoing description of the noise mechanisms gives hints for successful maintenance. Eliminate corrosion and maintain bonding to avoid arcs, maintain and test discharger wicks to keep the corona discharge energy low, replace wicks when burnt or after a close encounter with lightning, and maintain appropriate conductive coatings on radomes and windscreens to prevent streamers.

There are test sets which can be used to detect “hot spots” on particular aircraft. Trouble with Loran-C or other avionics may signal airframe-noise as a cause.

3.0 WHY DO WE EXPECT H-FIELD ANTENNAS WILL INCREASE AVAILABILITY

3.1 STUDIES AT OHIO UNIVERSITY

Various tests to study the effect of and elimination of P-static have been conducted at Ohio University [2, 3, 4, 5, 6, 7]. Testing has been conducted on several University aircraft: DC-3, Piper Saratoga, and Bonanza. These tests have included electrostatic ground calibrations as well as actual flights. In one test, the aircraft was artificially charged in flight. Loran-C receivers using both E and H field antennas were installed on the aircraft to determine comparative performance. Wide band recordings of the electrical noise generated by the electric discharge were also made.

Figure 1 shows the effects on Loran-C signal-to-noise-ratio (SNR) during a severe P-static event (snow). Data is for Northeast US Chain (9960) station Y (Carolina Beach). The red trace is the SNR as reported by the receiver with an E-field antenna while the green trace is for the H-field antenna. This figure shows that the SNR for the receiver with the E-field antenna dropped approximately 14 dB while the SNR with the H-field antenna remained unchanged. This data was captured during actual flight. Potential on aircraft and discharge currents were not recorded during these tests. These tests were weather targets of opportunity.

Figure 2 shows the results of a test lead by Illgen Simulation Technologies Inc. using an Ohio University aircraft. In this test, the aircraft was artificially charged while sitting on the ground. The technique is also known as electrostatic charging. Data is presented for Loran-C Station Seneca, NY. The left half of the chart shows the SNR and time differences for the Loran-C receiver using an E-field antenna while the right half shows data for the same event but from the receiver using an H-field antenna. Before 20:15 the aircraft had no charge. Over the next 10 minutes the charge on the aircraft was increased to 27 kV with

51 μ A of current. During this time the SNR for the receiver with the E-field antenna decreased by approximately 30 dB while the SNR for the receiver with the H-field antenna remained constant.

Figure 3 shows the data from the same test but presents a whole series of results. In this case, the figure shows the SNR as a function of aircraft potential and discharge current for various conditions. Data is from II Morrow 612 Loran-C receivers. The legend on the side of the figure shows the line type for each of the three Loran-C stations (M – Seneca, NY; Y – Carolina Beach, NC; & Z – Dana, IN). What is important to note from the figure is that the SNR for the Loran-C receiver with the loop (H-field) antennas remained almost constant while the SNR for Loran-C receiver with the whip (E-field) antennas decreased as the charge increased. The SNR decreased approximately 18 dB.

In each case (figures 1 to 3), the SNR for a Loran-C receiver with an H-field antenna remained constant while the SNR dropped for a receiver with an E-field antenna, to the point where the receiver failed to track Loran-C signals.

3.2 OMEGA

Omega provided world wide navigation capability for many years until it was finally turned off in 1997. During that time it was used by both the maritime and aviation community. P-static interference was a common problem on aircraft using Omega, and H-field antennas became the solution. Omega equipment required external airspeed and heading inputs, to select the correct loop antenna element for reception. Omega operated at 10.2, 11.3, and 13.6 kHz and shared many of the same noise problems as Loran-C.

4.0 FAA TEST PROGRAM

The FAA test program will replicate some of the work previously conducted by Ohio University and Illgen Simulation Technologies Inc. The test program has been on the books for sometime and has changed in scope. It was assumed that electrostatic charging of the aircraft while on the ground and artificial charging of the aircraft in flight would not be a problem since similar tests had previously been conducted. Lack of previous experience with this type of testing by local aircraft approval officials has required a slight change in direction. Previously it was expected that all equipment would be installed on the project aircraft, ground electrostatic calibration conducted, and then flight test with artificial charging would be conducted. It was decided that by adding a few more steps, the experience level could be increased and the project would go forward.

The test has now been broken into the following sections:

1. Ground based with electrostatic charging
2. Flight test with naturally occurring charging
3. Flight test with artificial charging.

4.1 GROUND BASED WITH ELECTROSTATIC CHARGING

The primary purpose of this test is to calibrate the measurement of aircraft potential and discharge currents as well as determine the corona discharge voltage. In addition, the SNR for various Loran-C stations will be recorded as a function of aircraft potential and discharge current. Location of the test is still being negotiated. Conducting the test inside an aircraft hangar provides a stable environment which will allow all ions to be placed on and collected from the aircraft. Wind and moisture provide additional paths for leakage current flow making accounting for all currents difficult and is therefore undesirable.

Unfortunately charging the aircraft in the hangar also makes receiving on-air Loran-C stations more difficult. Use of a Loran-C simulator to radiate Loran-C signals is being explored. Limited tests have shown it is difficult to radiate a test signal in close proximity to the aircraft which gives realistic results from both E-field and H-field antennas. Obtaining a non-metallic shelter which can house the aircraft and provide protection from the wind and moisture is also being explored.

In many tests of this type, tanks are topped off to eliminate vapor during charging. In our tests, the precaution of inerting the fuel system with pressurized nitrogen will be taken, to insure the replacement of all fuel vapors with a non-flammable mixture.

The technique used to electrostatically charge the aircraft was developed by Robert Truax of TCO, Inc. TCO is a manufacturer of aircraft static discharge wicks and works with various aircraft manufacturers to determine the location and type of discharger required for a specific aircraft. The test method is designed to place no unique electrostatic stresses on the aircraft or its systems which are not experienced in normal flight.

Figure 4 shows a simplified layout of the electrostatic calibration process. A variable high voltage power supply is used to provide the potential needed for the test. Output of the power supply is directed to ion flood fixtures, which simulate the deposition of ions on the airframe through collision with particles which are ionized as a result of the encounter. Each flood fixture contains a corona ball to avoid stray ions in the test area, and fixtures are placed along the leading edge of the aircraft. Three flood fixtures are typically used for a single-engine aircraft, with one in front of each wing and one facing the propeller cone. A picture of this setup can be seen in figure 5. This picture is of a test conducted at Ohio University using the Piper Saratoga.

Ion collection fixtures (simulating the removal of ions by the slipstream) are placed along the trailing edges of the wings and tail. All fixtures are connected using high voltage automotive ignition cable. This is a non-contact test -- therefore no flood fixture or collector will contact the aircraft. Accidental contact causes energetic arcing, which does not occur in nature. The aircraft is electrically isolated from ground by placing the aircraft on sheets of acrylic. Foil tape is placed along the edge of each sheet of acrylic to capture leakage currents occurring through landing gear and tires. As can be seen in the figure 5 diagram, all current in and out is accounted for, to be certain the airframe potential / discharge current relationship is measured accurately.

As ions are pumped onto the airframe, the potential rises. Until the corona threshold potential is reached, little current will flow. Once the corona voltage is reached, increasing the output voltage from the power supply increases the aircraft potential and the discharge current as a function of the airframe impedance -- its ability to "store" charge at a particular potential.

4.2 FLIGHT TEST IN NATURALLY OCCURRING CHARGING

In the previous test, the instrumentation to measure aircraft potential and discharge current will have been calibrated. This series of tests will record the SNR from Loran-C receivers using both E and H field antennas under naturally occurring P-static. In addition, aircraft potential and discharge currents will be measured. As will be shown later, aircraft potential varies greatly if left to naturally occurring charging and is not always present. A benefit to using this approach is that the aircraft can remain in standard category and confidence is gained that the values planned for use during artificial charging flights are realistic.

4.3 FLIGHT TEST WITH ARTIFICIAL CHARGING

During this test, a high voltage power supply will be mounted inside the aircraft with one output terminal connected to the aircraft frame and the other to a tail boom. The boom will extend from the aircraft about three feet and be constructed of polycarbonate. A high voltage automotive ignition cable placed inside latex tubing will connect the power supply to the tail boom. The tail boom will also contain a static discharger which will operate "backwards", liberating ions into the air stream and leaving the airframe charged. The boom length moves this process far enough from the airframe that it does not affect the normal discharge process, because the tail-boom ions are neutralized through recombination in the free-space slipstream, completely separated from the aircraft.

During ground checkout of the high voltage power supply and tail boom, the aircraft fuel system may once again be inerted with nitrogen to reduce the risk of fire. Once check out is complete flights will be conducted using various potentials and discharge currents. In the previous test (naturally occurring charge) the test program will be looking for clouds; in this test we will be trying to avoid clouds so that controlled charges may be induced and maintained on the aircraft.

4.4 EQUIPMENT SUITE

Various equipment will be installed on the aircraft as well as on a data collection rack installed inside. A Missions Instruments EF-1001 field mill will be installed through the aircraft skin, to measure the potential on the aircraft. This device is capable of measuring maximum potentials of 10 kV and 100 kV depending on choice of scales, switch-selectable by project personnel. Three instrumented static dischargers will also be installed. Each discharger is electrically isolated from its base mount with a wire running to the data collection rack to record the current flow. The wire is then grounded to the aircraft frame. One discharger will be installed on each wing tip and one on the top of the tail. Three Loran-C receivers will be used to measure SNR. One receiver will be an Apollo Multi Chain Loran Sensor (MCLS). This is a legacy receiver using hardlimited technology and an E-field antenna. The other two Loran-C receivers will be Locus SatMate 1020s. One receiver will be connected to an E-field antenna while the second will be connected to an H-field antenna. The SatMate 1020 receivers are state-of-the-art employing digital signal processing techniques and have been designed to use an H-field antenna. Aircraft truth data will be recorded from a post flight differentially corrected GPS receiver.

Figure 6 shows pictures of some of the equipment. The aircraft data collection rack is shown in the upper left. The unit on the very top of the rack contains the field mill control head and display on the left. On its right is the control head and display for the high voltage power supply to be used to charge the aircraft in flight. Also included in this unit are the analog-to-digital converters used to record aircraft potential, discharge currents, and high voltage power supply output voltage and current. Middle shelf contains the control head for the Apollo Loran-C receiver. Located under this are the two Locus SatMate Loran-C receivers. On the very bottom of the rack is a remote display unit.

The photos on the right show the field mill installation. The field mill is the white “coffee can” located on the bottom of the aircraft under “N-50”. The lower left photo shows the two E-field antennas and the H-field antenna. These antennas are located on the top of the aircraft above “N-50”.

4.5 WORK TO DATE

A safety plan has been written and submitted for approval. Work is in progress to resolve several outstanding issues. A skin map was conducted on the project aircraft to determine a location for the H-field antenna, in much the same way an antenna location would be determined for a Stormscope™ or ADF receiver. Antennas, field mill, and data collection rack have been installed on the aircraft. Hangar tests have been performed to determine if Loran-C signals could be received inside the hangar and if a Loran-C simulator could be used.

Figure 7 shows the aircraft potential measured during a check-out flight on October 22, 2003. The flight was approximately 50 minutes in length. The x-axis is time while the y-axis is measured potential. At times the potential went as high as 10 kV with three periods of approximately 8 kV. Polarity also varied during flight. Due to a data collection problem, occasional data points with 0 V potential are also present. Since the flight, the source of the problem has been identified and corrected.

Figure 8 shows additional data from the same flight. In this figure, SNR from Seneca, NY; Caribou, ME; and Dana, IN are displayed as well the measured potential (same as figure 7). The SNR plots show values for each of the three Loran-C receivers (blue = SatMate with E-field, red = SatMate with H-field, and black = Apollo with E-field). SNRs for the SatMate are properly scale in dB while Apollo SNRs are displayed

using in internal quality number between 0 and 99. The Apollo data will also be scaled to SNR in future plots. For the plot of Seneca it is expected the values in the 90's likely represent an SNR of +8 dB. No clear drops in SNR coincide with peaks in aircraft potential. Since discharge current was not being measured it is unclear if the corona discharge voltage has been exceeded. Variations in potential may be due to variations in potential of the clouds being penetrated.

5.0 REFERENCES

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- [3] Nickum, J. D., "The Effects of Precipitation Static and Lightning on the Airborne Reception of Loran-C (Volume 1 - Analysis)" Ohio University, DOT/FAA/RD-82/45-1, 1982.
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6.0 Biographies

Robert Erikson (Robert.Erikson@faa.gov)

Robert Erikson graduated from Drexel University with a BS in Electrical Engineering in 1973. Since graduation he has worked for the Federal Aviation Administration at the William J Hughes Technical Center in Atlantic City, NJ. Work assignments have included testing of various radio navigation and landing systems for aviation. Currently he is the Test Director for Loran-C and Transponder Landing System projects at the Technical Center.

Robert has been involved with the evaluation of the Loran-C system for aviation use since the early 1980's. The evaluations have included both ground and airborne data collections efforts. Results of the evaluations were presented at various ILA conferences and were used in the development of a Minimum Operational Performance Standard For Airborne Loran Receivers by RTCA. He is a member of the ILA.

Robert Lilley (rlilley@illgen.com)

Dr. Robert Lilley is Vice President of Illgen Simulation Technologies, with day-to-day responsibilities for the company's navigation-related activities in Santa Barbara, CA, and at Illgen's field operations in Washington, DC. He leads the company's Loran-C related projects, currently emphasizing all-in-view receiver designs and low-frequency antenna characterization, as a part of the FAA Loran-C program. Bob also participates in various of Illgen's DoD contract efforts.

Bob has been a member of the ILA Board of Directors since 1989 and served as President in 1992-93, during the time the Association was beginning to emphasize the value of a multiple-system world including

Loran-C. He has been Newsletter Editor, Bylaws Committee Chair, Convention Chair (1996) and Technical Co-Chair (1998). In 1995, he was awarded the Association's Medal of Merit. He assists with the activities of the ILA Operations Center on a continuing basis.

Dr. Lilley is Director Emeritus of the Avionics Engineering Center, Ohio University, earned his Ph.D. at Ohio University and is an instrument-rated commercial pilot. As part of the FAA/NASA Joint University Program team, he was awarded the FAA's first Excellence in Aviation Award in 1997.

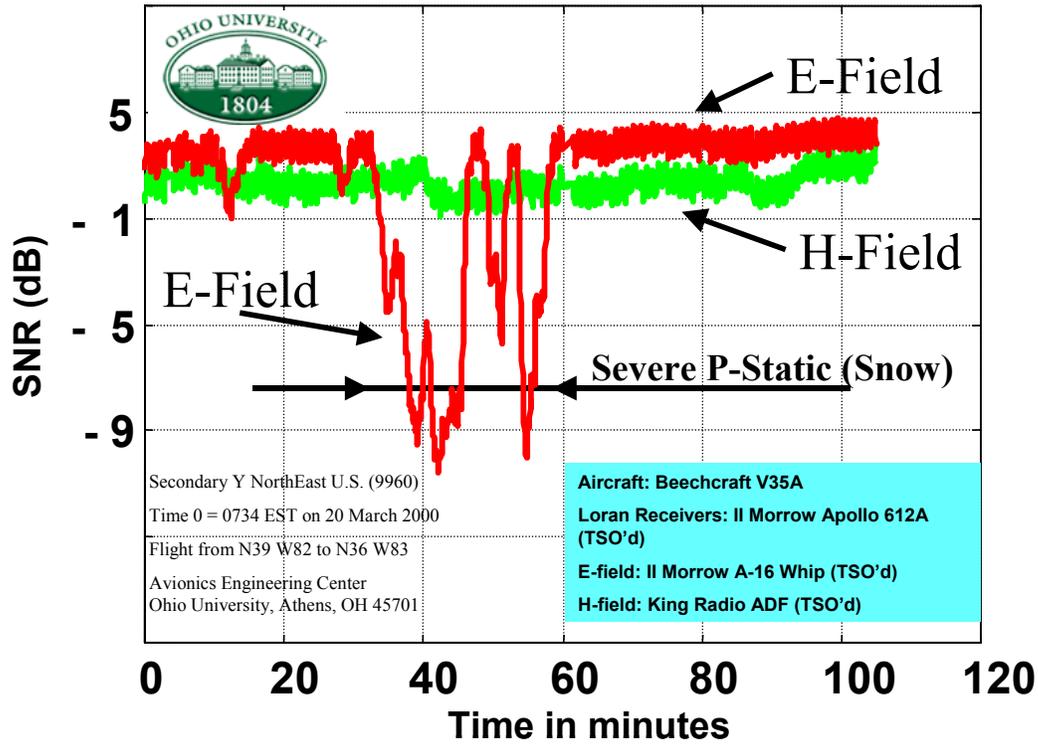


Figure 1 Ohio University - E-Field – H-Field Comparison

Test performed by Illgen Simulation Technologies, Inc. with support of the Avionics Center, Ohio University. November 1998, using equipment provided by Locus (e-field) and Megapulse (h-field)

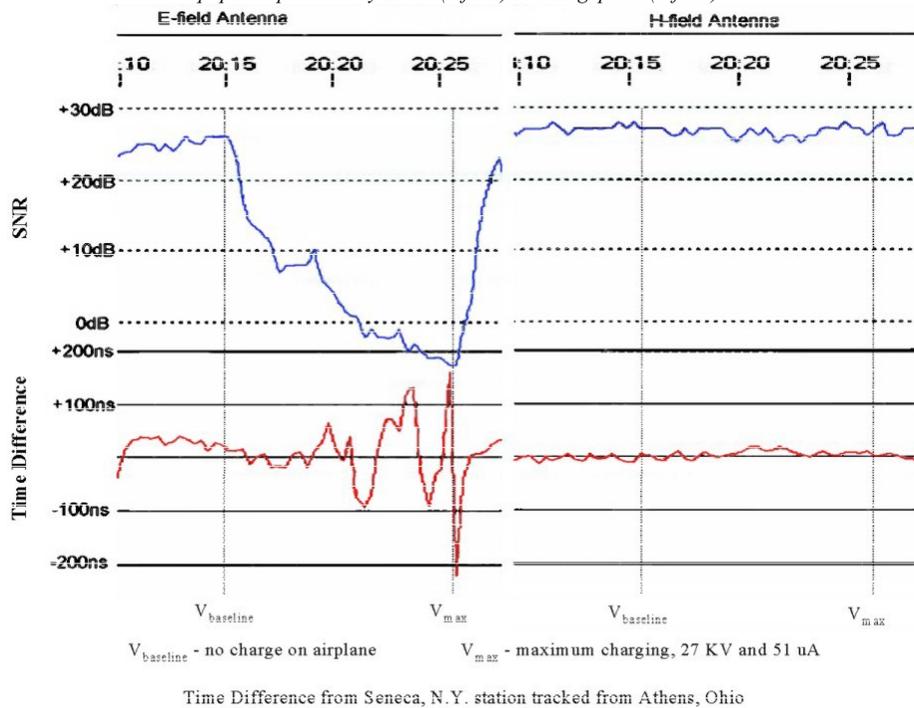


Figure 2 Illgen/ Ohio University – E-Field – H-Field Comparison (single station)

Test performed by Illgen Simulation Technologies, Inc. with support of the Avionics Center, Ohio University. November 1998, using equipment provided by Locus (e-field) and Megapulse (h-field)

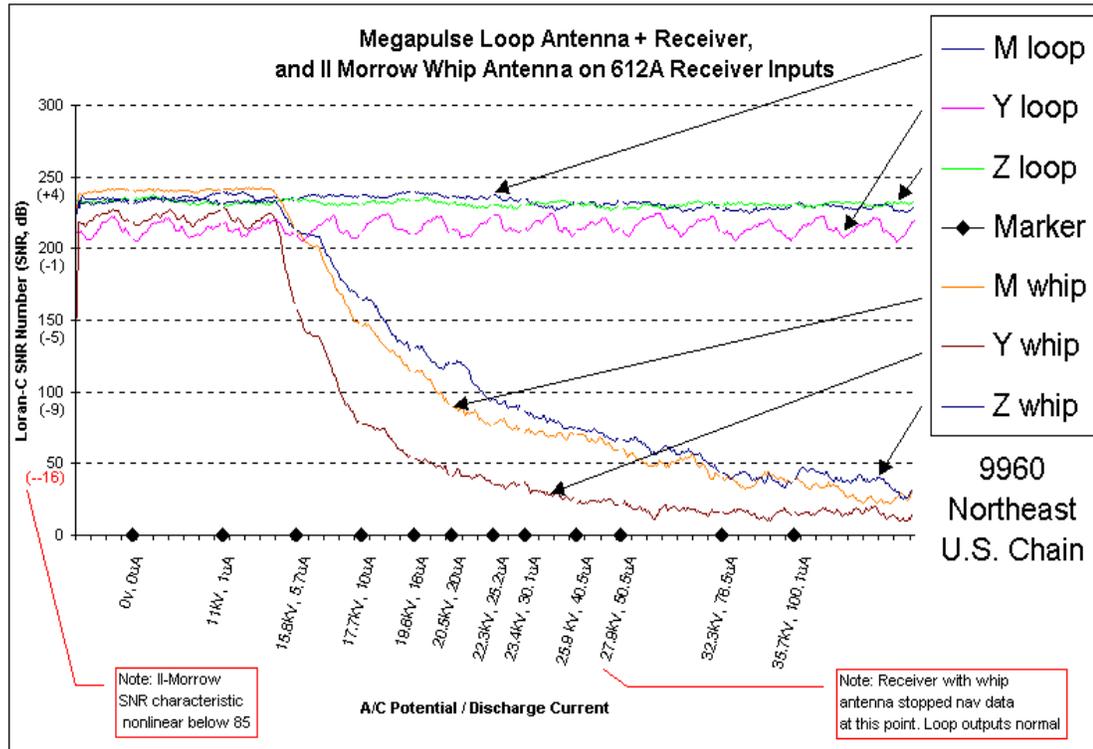


Figure 3 Illgen/ Ohio University – E-Field – H-Field Comparison (multiple stations)

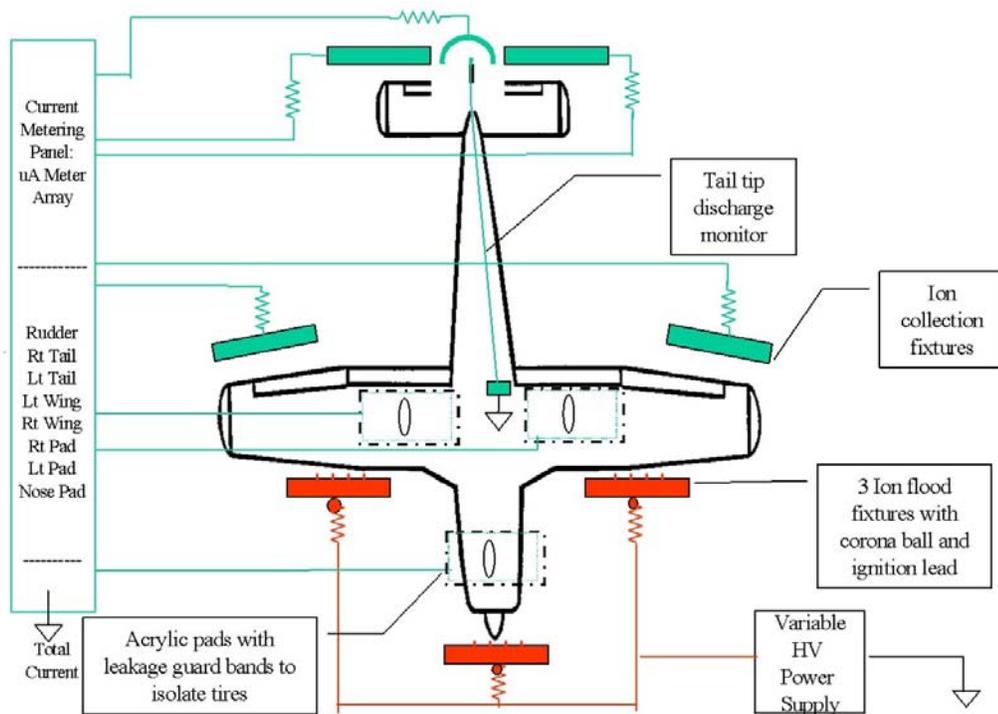


Figure 4 Simplified Schematic Of Ground Based Artificial Charging



Figure 5 Illgen / Ohio University Electrostatic Tests



Figure 6 FAA Equipment

Check-out of field mill data collection (Raw data. Rogue zeros are now gone!)

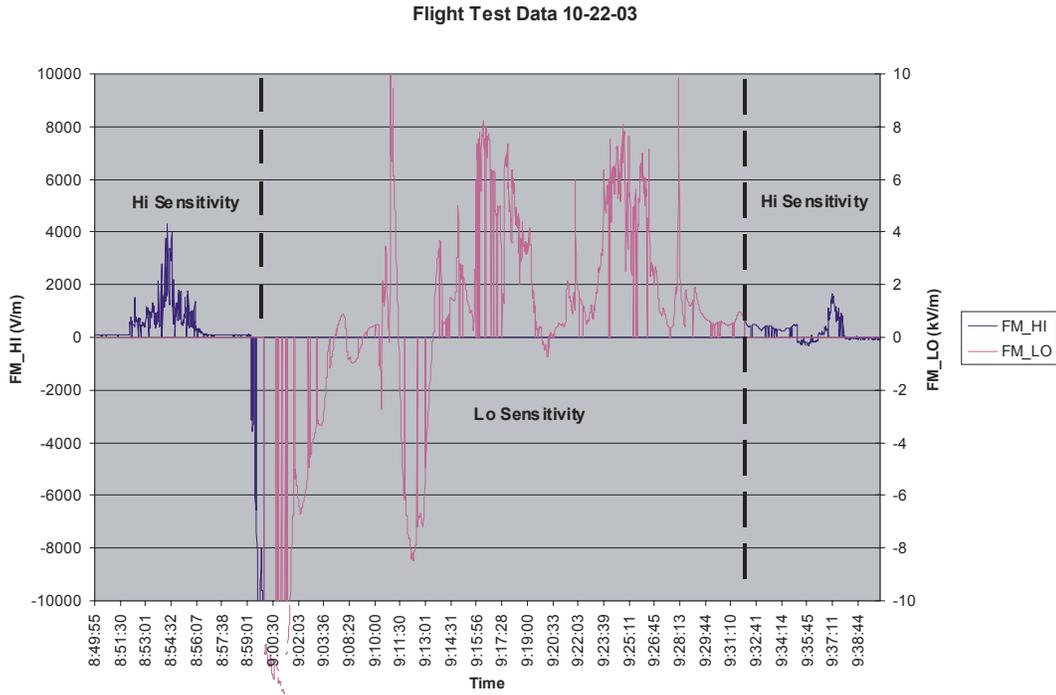


Figure 7 Check-out Flight N-50 10-22-03

Check-out receiver data collection equipment and observe airframe potential in clouds.

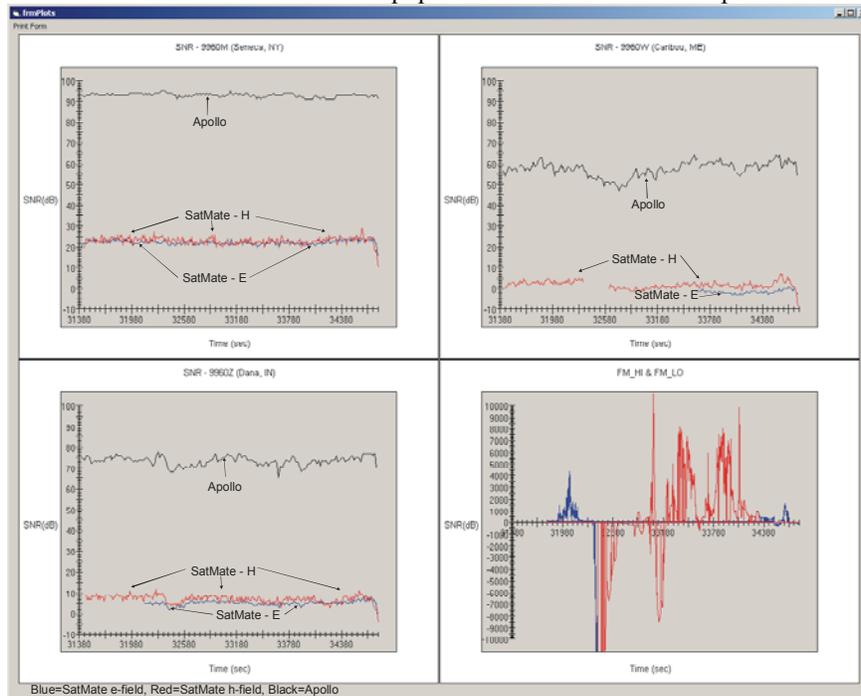


Figure 8 FAA N-50 Flight 10-22-03