FAA Tests E- and H-field Antennas to Characterize Improved Loran-C Availability During P-Static Events

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BIOGRAPHY

BACKGROUND

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Robert Erikson was 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. Currently he is the Test Director for Loran-C and Transponder Landing System projects at the Technical Center.

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ABSTRACT

Loss of Loran-C guidance during flight in instrument meteorological conditions can be traced in some cases to electrical charging of the aircraft in flight and the radio noise generated by the subsequent electrical discharges. The FAA is conducting ground and flight tests to document Loran-C h-field (loop) antenna performance during p-static events. This paper describes in summary how the aircraft is charged during a p-static event, results of electrostatic ground testing, and results of flight measurements using an FAA aircraft.

Comparisons among three dissimilar airplanes show consistency in corona noise amplitude and in noise reduction of greater than 20 dB using standard airframe discharger devices. With the additional performance benefit of h-field antennas, "open installation" standards may be possible, without the need for installationspecific tests on each airplane.

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Throughout the history of U.S. Federal Aviation Administration (FAA) consideration of Loran-C as a navigational system for use in the National Airspace System (NAS), concern has been voiced over the effects of precipitation-static (p-static) interference. P-static is the term used to describe electrical noise which can be generated by the transport of electrical charge from the airframe to the surrounding atmosphere. The airframe can become electrically charged during flight; the equalization of this charge can cause arcs between airframe segments, streamer discharges across dielectric surfaces and corona discharges from airframe elements with relatively small diameters (trailing edges, antenna tips, relief tube ends, and other devices).

The first aviation Loran-C receivers in the 1980s were generally intended for use in visual flight conditions. However, the system proved to be a popular and low-cost area-navigation solution and there was a move to extend its use into instrument flight, including non-precision (lateral-guidance-only) instrument approaches. During instrument flight, some pilots reported loss of Loran-C guidance due to low signal-to-noise ratio (SNR) in conditions which could cause p-static interference. Remembering experience with the even-lower-frequency Omega Navigation System, the electric-field (e-field) or "whip" antennas installed with the early receivers became suspect. For Omega users, the switch to magnetic-field (hfield) or "loop" antennas improved performance substantially.

Continued use of medium-frequency automatic direction finding (ADF) equipment to the contrary, the general movement toward the higher frequencies for communications and navigation has tended to reduce the occurrences of p-static interference. It is therefore understandable that somewhat reduced attention has been given to antenna and airframe bonding maintenance, provision of resistive coatings on exposed non-conductive surfaces and regular inspection and maintenance of airframe discharge devices. We consider the low frequencies used by Loran-C to be advantageous, especially when the system is called upon as a dissimilar partner or back-up system for the Global Positioning System (GPS). Since p-static effects can be at their most troublesome at the lower frequencies, the FAA has supported initiated a series of tests and analyses during consideration of Loran-C for use in the National Airspace System (NAS).

It has become evident through test and analysis that h-field antennas are desirable for aviation Loran-C use, despite the added computational load required to account for antenna orientation relative to the transmitters, particularly during aircraft maneuvers. The electrical environment for p-static consists of high-voltage, low-current events which approximate electrostatic conditions in the near field. This fact alone appears from past work and from physics to favor the h-field antenna. The directional qualities of each antenna loop may also provide advantages by reducing the atmospheric noise "seen" by its receiver channel compared to an omni-azimuth antenna.

ELECTRICAL NOISE GENERATED IN FLIGHT

A difference in electrical potential between the airframe and its surroundings may occur for several reasons:

- flight in regions of atmospheric charge separation (e.g. near thunderstorms or in turbulence)
- triboelectric charging, involving impact ionization of dust, ice or water particles
- engine charging, especially in turbines, in high power - low altitude climb operations

In flight, the charge stored on the airframe increases with time when charged particles are encountered, when particleimpact ionization occurs, or when engine-air friction causes charge separation. In general, increased airspeed results in a higher rate of charge accumulation. The faster aircraft simply encounters more particles. Also, the faster slipstream moves the ion products of impact charging away from the airframe before local recombination can take place.

A good example of this process is the van de Graaff generator, in which ions are liberated by a power supply and transported by insulated belt to an isolated conductor, often a sphere. So long as the ion deposition continues and no discharge occurs, the voltage on the conductor continues to grow.

Typical aircraft charging rates are quoted from experience as about 400 μ A for general-aviation single-engine aircraft, 750 μ A for cabin-class twins, and as high as 1.5 mA for airliners. Currents of 5 mA have been recorded in extreme cases. [1]

As for the van de Graaff generator, continuing encounters with charged or impact-ionized particles will cause the

potential on an isolated airframe to rise until one of the charge equalization mechanisms becomes active. There is a natural tendency for potential difference (charge separation) to decrease with time, either gradually through recombination with atmospheric ions, or suddenly due to an ion avalanche (a discharge, or breakdown).

We consider three mechanisms for equalization of potential among airframe components and between the airframe and the surrounding space. Each can be troublesome for radio systems in its own way, and each requires separate design and maintenance attention to achieve an electrically "quiet" airframe.

Arcs: Arcs can occur when elements of the airframe become charged to different potentials. Such differences occur due to non-conductive gaps, which can be the result of corrosion or loose components. They can also occur for other, more obscure reasons (a metallic emblem arcing through its adhesive was the culprit in one case).

Arcs cause broadband noise and are relatively energetic. It is important to maintain aircraft structures and surfaces free of corrosion, de-bonding, or loose rivets. Severe arcing can affect any radio-based navigation system regardless of the antenna type.

Streamers: Streamers are low-current arcs which form across dielectric surfaces such as windscreens, radomes and composite components. Special conductive treatments are required on aircraft where composite skin or structural materials are used, to avoid streamer noise or the potentially destructive effects of lightning.

The effects of streamers are similar to arcs. Coatings or resistive strips may be used to drain accumulated charge and minimize the tendency to form energetic arcs. Optically clear coatings for windscreens and RF-transparent coatings or loading methods for radomes are available. For the windscreen case, the glue often used to seat the glass or plastic window can act as an insulator, and must be resistively bypassed.

Corona: Of the three discharge mechanisms, corona can be most troublesome due to its frequency-selective nature. When the airframe is charged, the equalization of this charge occurs at the trailing edges (and antenna tips and other convenient spots), as ions of opposite polarity are attracted to the points on the aircraft with minimum radius of curvature (the points where maximum electric field intensity exists). Above the corona threshold, atmospheric breakdown (ion avalanche) occurs as free atmospheric ions are accelerated to the point where they in turn ionize neutral air atoms (largely oxygen atoms for negative field and nitrogen atoms for positive field values). The resulting chain reaction causes the air to change almost instantly from an insulator into a conductor, and "breakdown" occurs. The *amplitude* of these discharge events is approximately constant, determined by the characteristics of the surrounding air – temperature, pressure (altitude), humidity, and the aircraft's velocity, all of which affect the air ionization process. Therefore, as airframe charge rate and resulting electric field increase, the *repetition rate* of the corona discharges also increases, as the corona-point field value returns more quickly to the critical field value needed to cause the next ion avalanche. A *corona current* thus flows, made up of the individual charge-equalizing equalizing pulses which reduce the corona-point momentarily to a field below the threshold of air breakdown.

Once the critical ionization point is reached, the ion avalanche occurs within a few nanoseconds; the effect then decays (See Figure 1) as ions in the region near the discharge point use charge from the airframe to recombine into neutral atoms.



Figure 1: Individual corona pulse [2].

This repetition rate can easily reach 100 kHz and higher. (In fact, the rate can also occur at 30, 90, 150, 9960 Hz, and other audio or RF frequencies of great interest to communications and navigation avionics designers.)

Assuming an airframe which is generally corrosion-free and where attention has been given to quieting dielectric surfaces through resistive coatings or other means, the basic mechanism for reducing electrical noise is the "discharger." Airframe dischargers are often 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 resistance are design parameters which can be varied by the manufacturer to enhance performance in selected frequency ranges.

The discharger needs to be long enough to place the departing charge far enough from the airframe trailing edge that recombination does not take place on the aircraft. A resistive discharger forms a low-pass filter with the airframe capacitance, reducing radio noise during corona events. The FAA tests described below use a Model DD-2 discharger from TCO Manufacturing Co. (Figure 2) which has a semi-flexible resistive body approximately 6.5 inches long, and is tipped with four thousand 4-micron wires.[3] These wires are the actual corona points, with minimal radius for low corona threshold and a large number of wires for current-carrying capacity.

The three charge and discharge processes may all be occurring simultaneously from multiple points on an



Figure 2: TCO DD-2 discharger [3].

airframe, particularly during severe charging encounters. Inflight separation of the electrical noise observations into the elements discussed above is difficult. As shown in Figure 3 [4], the three processes are most energetic at the lower frequencies, but corona and arcing can cause interference well into the high-frequency (HF) and very-high frequency (VHF) bands and beyond.



Figure 3: Noise caused by electrostatic charging [4]

How to Reduce Noise: As the test results show, relatively straightforward airframe installations and maintenance measures can dramatically reduce p-static noise. The goal is to keep the airframe parts at equal potential, and the entire airframe at as low a potential as possible with respect to the surroundings. In particular, it is necessary to keep the airframe potential low enough that the antennas *themselves* do not become corona discharge points. Even then, since at least some noise is inevitable from corona, owners/operators should do the following (See also [5]):

- install discharge devices at trailing edge extremities and discontinuities,
- see that the discharge devices provide small-radius corona points and sufficient current-carrying capacity to maintain airframe potential at the lowest practical value,
- decouple corona discharges from the airframe by using resistive discharger devices which low-pass-filter the discharge currents in combination with the airframe capacitance,
- and **maintain the airframe and its dischargers** to preserve the electrically- quiet environment.
- *Then* for use in instrument conditions, install a Loran-C h-field antenna for even more protection.

Past work shows that reduction of noise on the airframe results in improved operation of onboard systems in general, and low-frequency systems in particular. The p-static processes can produce wideband noise over nearly the entire spectrum used for communications, navigation and surveillance. It should be evident that all three discharge mechanisms are factors when optimizing avionics performance.

ELECTROSTATIC TESTING

Studies, experiments and developments have been carried out over many years to characterize airframe electrical activity in flight and to minimize effects of electric fields and stored charge on airframe structures, avionics, and personnel. At the beginning of one experimental project at Ohio University, a literature search and summary of thencurrent knowledge was prepared.[6] This report includes a bibliography with citations from the mid-1940s and later.

Ohio University Avionics Engineering Center (1981-1982 and 2000):

Testing was conducted using a University DC-3 and a Beechcraft Bonanza. The DC-3 tests included electrostatic ground calibrations and test flights. In one test, the DC-3 aircraft was artificially charged with onboard equipment while in flight. Loran-C receivers using both electric- and magnetic-field antennas were installed on the aircraft to determine comparative performance.

The Beech Bonanza test in 2000 [7] showed a 14-dB SNR reduction during flight in snow for a Loran-C receiver with an e-field antenna, while the SNR for a receiver with an h-field antenna remained largely unchanged. This test is revealing in that the effect was significant even on an aircraft which is well-maintained. No p-static instrumentation was available during this weather-of-opportunity occurrence, however. It was reported that in more than 50 hours of flight, only one significant p-static event was recorded.

The DC-3 tests included installation of discharger devices instrumented so that discharge currents could be measured, a field mill for determination of the electric field and potential associated with the airframe, and a data collection package. See Figure 4.



Figure 4: Ohio University DC-3 N7AP, 1982

In association with high-voltage consultant Robert Truax, president of TCO Mfg., a manufacturer of low-noise airframe discharger devices, a complete ground electrostatic survey was carried out [8, 9] followed by flight tests using natural charging and artificial charging using an onboard high-voltage power supply. This series of tests was quite similar to the March, 2004 test plan at the FAA WJ Hughes Technical Center (FAATC), reported below.



Figure 5: DC-3 (1982) with and without dischargers in simulated p-static.

Figure 5 gives relevant results for the DC-3 ground test. The "bare" airplane was simulated with 1/8" brass rods replacing dischargers, to produce corona discharges which were not decoupled from airframe trailing edges. This configuration provided data typical of a craft which may have had broken discharger units, or none at all. Figure 5 (upper panel) shows clearly that the aircraft experienced over 30 dB of noise increase in the Loran-C band almost immediately when corona discharges began. When resistive dischargers designed for low-frequency quieting were installed (lower panel), a 24-dB reduction in noise was evident up through 100 μ A of discharge current. Even at discharge rates considered "severe" or "unusual" in practice, fully 17 dB of quieting was noted.

The dischargers, by acting somewhat like Zener diodes to keep airframe potential lower, and by providing a decoupled path for equalization of charge with the atmosphere at lower electric field strength, significantly "quieted" this airframe. Loran-C would perform better, even with a well-designed efield antenna! The flight tests are reported [8] to have confirmed the ground test results, but the traditional difficulty of locating natural-charging conditions on demand was noted. Onboard static charging of the airframe was successful, and airframe-quieting results similar to those above were reported. It was pointed out that onboard charging is convenient and controlled; minimized flight-time and stable electric-field conditions were pointed out as advantages.

Illgen Simulation Technologies (1999):

Concern over p-static interference to Loran-C persisted in some quarters, and in 1999 a second ground electrostatic survey was carried out with FAA support, to assess the potential for p-static impact on Loran-C availability. By this time, the h-field or "loop" antenna was being used in some tests and was being considered for wider application. These antennas were successful in reducing p-static interference for earlier Omega receivers, operating at even lower frequencies than Loran-C (10-13 kHz). Onboard computational power and new "steering" techniques were reducing the projected costs of h-field antenna equipage to reasonable levels.

Within the FAA Loran-C evaluation program, Illgen Simulation Technologies performed a study [10] including modeled Loran-C availability-of-accuracy estimates for allin-view receivers and a ground electrostatic survey of a Piper Saratoga aircraft, N8238C. The airplane is owned by the Ohio University Avionics Engineering Center, and the tests were carried out in Ohio with the cooperation of the Center. Figure 6 shows the electrostatic test underway.



Figure 6: Ground Electrostatic Survey underway on Piper Saratoga N8238C, 1999 [10]

Figure 7 shows results of the ground charging test on the Piper Saratoga. The data clearly showed a 16-dB rise in p-static noise even at very low discharge currents (26 μ A). A Loran-C receiver operating on this aircraft could experience this 16-dB SNR reduction upon entry into almost any cloud formation.



Figure 7: Saratoga N8238C (1999) with and without dischargers in simulated p-static.

With a set of dischargers designed to reduce low-frequency p-static noise, the 1999 tests showed airframe quieting of approximately 24 dB at 100 μ A, and projected low noise out to 250 μ A discharge current. This represents a major improvement in airframe noise performance.

The author's experience flying this very aircraft bears these data out in flight. With dischargers removed, the Loran-C (using e-field antenna) simply ceased upon entry into cloud, whether stratus or cumulus. When the dischargers were re-installed, no such problem occurred.

There was no field mill installed on N8238C, so no airframe electric field data were collected.

A paper on p-static performance comparing e-field and h-field antennas would not be complete without reference to the often-quoted Loran-C data collected during the 1999 tests. Figure 8 shows this comparison, which is typical across receivers and across airplanes. More than 20 dB separated the relatively unaffected h-field traces and the simultaneous e-field traces, much of the difference occurring prior to reaching 50 μ A of discharge current (without dischargers). Once again, with dischargers, even hundreds of μ A would be expected to cause less noise and not to affect the h-field antenna noticeably.



Figure 8: E-field and H-field comparison, Piper Saratoga N8238C (1999); no dischargers

FAA TECHNICAL CENTER TESTS (2004)

FAA initiated a follow-up series of ground and flight verification tests at the W.J. Hughes Technical Center. Preliminary information was presented by the authors in 2003. [11, 12]

The FAA test program replicated the earlier work conducted by Illgen Simulation Technologies and Ohio University, but used a significantly different airframe. The FAA test program consists of the following sections:

- ground based measurements with electrostatic charging,
- flight tests with naturally occurring charging in weather,
- and flight tests with artificial charging, using an onboard high-voltage system.

As of the date of this report, the ground measurements are completed and the flight tests with natural charging are underway. Flight tests with artificial charging will likely become a necessary follow-on activity, due to the difficulty of finding p-static conditions on demand. The test team has planned for this, and the FAA has purchased the necessary equipment for the later tests.

Ground-Based Measurements - Electrostatic Charging:

The goal of the testing program was to obtain definitive information on:

- the degree to which p-static interference reduces Loran-C availability,
- Loran-C-specific maintenance that is required, if any,
- whether there is a requirement for installation-specific Loran-C approval,
- and the extent to which the magnetic loop, or h-field antenna offers performance benefits.



Figure 9: N50, the Rockwell Commander 680

The FAATC test conductor (co-author Robert Erikson) and his team worked with the safety representatives and maintenance personnel at the FAA Technical Center to obtain the necessary approvals and modifications. The FAA's aircraft N50, an Aero Commander 680, was made available for the tests. See Figure 9. In brief, the test was required to simulate flight conditions where the aircraft motion ionizes particles which encounter the leading edges, and where the airframe liberates charge to the slipstream once a discharge threshold has been reached. The ground test therefore required that the airframe be isolated from all surroundings and then subjected to stored electrical charge. The airframe potential was expected to reach values approaching 100 kilovolts. It was required that several different configurations of discharger devices be placed on the aircraft, either temporarily for ground testing or in a flight-worthy manner for airborne evaluation. There was a requirement that the electric field resulting from stored charge on the airframe be measured from 0 to +/-100 kV, and that the discharge currents from at least three discharger devices be measured from 100 nA to 1 mA.

Two modern-design Loran-C receivers were installed aboard the aircraft for simultaneous e-field and h-field measurements of performance during aircraft charging and discharging. A "legacy" Loran-C receiver was made available for recording, to give some data on avionics presently in the fleet.

Finally, the position of the airplane in flight was instrumented, for later flight data-collection missions. All data is time-tagged to permit synchronization with the ground-system data stream.

On-Aircraft Data Collection

The aircraft instrumentation was made self-contained, with no umbilical connections outside the aircraft, due to the airframe isolation requirement and the safety issues related to the high voltages employed.

The aircraft was modified to permit flight-worthy exchange of dischargers at the wingtips and the tip of the vertical stabilizer. The discharger bases at these locations were "instrumented" by isolating them from the airframe and adding a current monitoring wire to cabin instruments. These "instrumented dischargers" permitted sampling of the total discharge current on the aircraft, and they were calibrated during the ground test so that flight measurements may be normalized.

A field mill was installed to measure the electric field due to airframe charging. A flight data package was installed to permit operator control and data collection from the field mill plus the Loran-C receivers and to record instrumented discharger currents. Figure 10 shows the field mill and discharger configuration and Figure 11 shows the receiver package diagram.



Figure 10: Field mill and instrumented dischargers recording configuration.



Figure 11: Loran receivers aboard N50 for ground and airborne testing.

Two Locus SatMateTM Model 1020 receivers were installed, one with e-field and one with h-field antenna. A II-Morrow ApolloTM 2010 legacy (hard-limited) receiver was installed, with its e-field antenna, and the Apollo 2101 Navigation Management Computer to provide serial-port output of necessary data for the tests.

The details for aircraft-installed equipment are given in [13], "Equipment on Test Aircraft.doc", originally released by the Test Director on August 30, 2004.

The aircraft was skin-mapped [14] to establish appropriate locations for the antennas. Figure 12 shows the final installation, just aft of the wing, on top of the fuselage.



Figure 12: Test antennas on N50

Ground Charging System

The isolated airframe leading edges are "flooded" with ions without direct contact, and the products of corona discharges are collected at the trailing edges, so that the accumulation of charge via impact ionization and eventual equalization via the slipstream are as representative of the flight environment as possible. Applied voltage and the charging current which is applied to the aircraft must be recorded and time-stamped. All collected corona currents from airframe discharges at the trailing edges must be recorded separately (left and right wing, left and right elevator and vertical stabilizer). Additionally, "current accountability" must be maintained, to prevent inaccurate data, but also to document that free ions are not being allowed to escape the experiment and cause potential danger by charging the hangar environment.[15]

These requirements are met by unique equipment and procedures developed by consultant Robert Truax, who was employed to provide the ground system. His technique is illustrated in Figure 13 and is the same as that employed for the Ohio 1982 and Illgen 1999 tests. The high-voltage



Figure 13: Ion flood and collection fixtures

power-supply shown in Figure 13 liberates ions using standard airframe dischargers placed near the leading edges, with applied voltages up to 50 kV, a sufficient drive voltage determined from long experience. The charge-pumping characteristic of this arrangement allows the airframe to achieve the necessary voltage to begin discharge activity. The photographs in Figure 14 show part of this system in use at FAATC.

Figure 15 shows the combination analog and digital panel fabricated by TCO Mfg. to meet the ground system control and data collection requirements.



Figure 14: Flood power supply, nose flood fixture and collector fixtures near N50



Figure 15: Ground system high voltage and current monitor panel

Isolation of the airplane

For the Aero Commander it was necessary to elevate the airplane on jacks to raise the belly and the various antennas and a laser reflector mirror cluster far enough above the hangar floor that electrical leakage would not interfere with the measurements. The jacks and tail-stand were placed on acrylic sheets for insulation, as shown in Figure 16.



618: Acrylic sheets isolate the aircraft from ground.

Conductive tape was placed around the periphery of each sheet to "catch" any stray currents escaping from the aircraft. The tape was connected to the metering panel to account for any currents which flowed across the acrylic sheets as streamers. The aircraft body was also protected from ground with the same acrylic-sheet treatment.

Before each high-voltage test the acrylic was cleaned with denatured alcohol to remove any dust or debris which could cause arcing and leakage from the high field strength generated during testing.

Simulated Loran-C Signals

Conducting the test inside an aircraft hangar provided a stable environment which allowed all ions to be placed on and collected from the aircraft. Outside, wind and moisture would have provided additional paths for leakage current flow, making current accountability difficult. Unfortunately, charging the aircraft in the hangar also made receiving on-air Loran-C stations more difficult. It was decided to use a Loran-C simulator to radiate Loran-C signals.[16] 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, so preparatory tests were carried out to establish that the near-field signals from the simulator suitably represented the far-field on-air signals.[17] For the tests, the distant 9940 west-coast chain was simulated, to avoid interference from the "real" stations.

Fuel System Nitrogen Purge

The fuel system was pressurized with nitrogen to insure the replacement of all fuel vapors with a non-flammable mixture. See [18] for a detailed description of the pre-test preparation and operation of the purge system.

An Industrial Scientific Corporation Multi-Gas Monitor was used to measure both percent oxygen and lower explosive limit (LEL) by placing a tee in the outflow tube. This method allowed the fuel vapor to be vented outside the hangar while providing a sampling port inside the hangar to connect the TMX412 Monitor. See Figure 17.



Figure 17: The team assembles the nitrogen purge equipment to maintain fuel system safety during charging.

Field Mill Calibration

A custom field-mill was procured by FAATC to permit calibration of the aircraft electric field strength. As shown in Figure 18, a ground-plane plate was affixed to the field mill housing, and a second plate was placed 10 cm from the first, with insulating standoffs for support. The high-voltage power supply negative terminal from the ion flood system was attached to the outer plate and the airframe and positive high-voltage terminal were grounded.

The field mill was calibrated to 100 kV/m by applying 0 to - 5 kV to the outer plate in steps, and then multiplying by 10 to account for the close plate spacing. A calibration curve was drawn for the field mill.[19]



Figure 18: Field Mill calibration fixture in use

Ground Electrostatic Survey:

Figure 19 shows an overall view of the test area at the FAA Technical Center as high-voltage tests began. See [20] for a more detailed explanation of the survey by the Test Director.



Figure 19: Overview of the Ground Electrostatic Survey at the FAATC hangar

The primary purpose of this test was to calibrate the measurements of aircraft potential and discharge currents as well as to determine the field strength on the airframe. In addition, the SNR for various simulated Loran-C stations was recorded as a function of aircraft field strength and discharge current.

Baseline Aircraft Discharger Configuration

The Baseline test was run to establish the condition of the aircraft with the only modification being the installation of the instrumented dischargers on the wingtips and the top of the tail. Ground data collected included ion flood voltage and current, current collected from the dischargers on left and right wing, left and right elevator, from the vertical stabilizer/rudder assembly, and currents collected from the acrylic isolation pads, plus time. In the aircraft cabin, data recorded included the airframe electric field, the currents from wingtip and tail-tip instrumented dischargers, the complete data output from the Loran-C receivers for all stations received (signal strength, signal-to-noise ratio, navigation data), and time.

Additionally, during this and all other tests, a continuous check was made for arcs, streamer currents, or strong corona discharge from non-instrumented points on the airframe (importantly, points such as the ends of whip antennas). The method was to use a simple AM pocket radio to listen to the corona (which at low currents starts as a series of clicks and becomes a whine or scream at higher currents – a reflection of the corona repetition rate variations). Arcs are immediately identifiable as loud clicks, and streamers appear as lower-energy arcs when the radio is placed near an affected dielectric component such as a windscreen.

For a well-designed and maintained aircraft (such as N-50) arcs and streamers are not expected, and none were detected during these tests. Also, using this technique to detect noise on the acrylic isolation pads and in the flood system acted as a control, insuring that noise detected by the Loran-C receivers was produced by the airframe dischargers and not the instrumentation.

In the Baseline test as for the others, flood voltage was increased and all ground-system currents were monitored and recorded. Radio contact with the crew in the cabin provided a check on aircraft field values, which were manually restricted to less than -100 kV/m by limiting the flood voltage. Baseline-test data are not presented here in

detail, as post-test analysis revealed some unanswered questions about data system operations during this test. Once these are resolved, the results will be released at a later date.

Bare Aircraft Discharger Configuration

The "bare" aircraft test simulated an aircraft without discharger units, or one on which the dischargers had not been well maintained. The dischargers are often broken due to hangar accidents or have had their tip wires fused together by nearby lightning strikes or very severe current flow. On some aircraft, simple wires are installed as dischargers which does provide a corona point but no decoupling of the noise from the airframe. To test the aircraft safely, the normal dischargers were replaced by 1/8" brass rods, which allowed control over the collection of corona currents.

The aircraft is again flooded with ions to store charge, and the ground and air data are collected as in the Baseline test.. With the larger-radius discharge points, the expectation was that the airframe would rise to a high value before corona current flowed, and that noise values (reduction in Loran-C SNR) would be relatively high. The flood voltage was brought to a maximum of -27.2 kV in steps, while continuous checks was made for arcs or streamer currents as described earlier.

For the Bare aircraft test, flood voltage of -11 kV to -27.2 kV produced airframe electric fields from -30.6 kV/m to - 63.2 kV/m and total discharge current from all brass rods of -125 μ A. A Loran-C-band noise increase of 24 dB and an airframe electric field of -59.7 kV/m were observed at -100 μ A discharge current.

Optimized Aircraft Discharger Configuration

For this test, the three instrumented discharger locations were equipped with TCO DD-2 dischargers, and DD-2s were also placed at TCO-recommended locations on wings, elevator and vertical stabilizer. The wingtip and tail-tip dischargers are instrumented for current observations

For the Optimized aircraft test, flood voltage of -5.5 kV to -40.9 kV produced airframe electric fields from -9.5 kV/m to -80.4 kV/m and total discharge current from the DD-2s of 756 μ A. The airframe field was measured at -31.4 kV/m, roughly half of the bare-aircraft value. The Loran-C-band noise increase was only 1 dB at 100 μ A! The airframe has indeed been significantly "quieted" through decoupled liberation of stored charge.

Figure 20 gives a brief digest of some of the data recorded during the ground test sequence, in the same format used for the earlier tests, for comparison. By now it should come as no surprise that the addition of well-designed dischargers limits the airframe electric field and significantly reduces the p-static noise output.



Figure 20: Aero Commander N50 (2004) with and without dischargers in simulated p-static.

A large quantity of detailed data was collected during these tests; individual instrumented discharger currents, Loran-C SNR data for all stations in the simulated 9940 chain for all receivers, applied ion-flood potential and current, and also the currents which "escaped" the airplane and returned via the dielectric isolation pads. These data are being analyzed as of this writing, but the "bottom line" is certainly the amount of Loran-C SNR reduction due to the additional noise caused by corona discharges. This SNR reduction was consistently greater on the legacy e-field receiver than any other receiver. There was a large reduction of SNR in every test for the SatMate with e-field antenna. SNR loss was not significant in any test for the SatMate with the h-field antenna.

Since the noise level is fairly consistent between the Saratoga and the N50 tests, we should expect similar Loran-C behavior on the two aircraft at similar total discharge current values. From the FAATC test data, 21 shows the effect on simulated 9940 Loran-C signals with increasing airframe field strength (and thus increasing discharger activity). Its similarity to Figure 8 from the Saratoga test should be evident.

The legacy receiver (black) was clearly having difficulty dealing with the increased noise as discharge current increased. The SatMate e-field receiver showed the familiar pattern: more discharge noise caused reduced SNR until navigation finally stops. The SatMate h-field receiver continued essentially unaffected. The momentary change in h-field SNR somewhat above -50 μ A of discharge current is not yet explained, but is coincident with loss of the e-field trace for 9940Y. There is no clear reason why the two events should be related.



Figure 21: N50 SNR data for simulated 9940M signals vs. airframe electric field and discharge current; no dischargers.

Ground Test Summary

We have discussed three recent p-static studies, on three different airplanes, at different times and places. It is instructive to look at the similarities and differences among these somewhat independent tests, and to think back on what is really the noise mechanism. Comparing the three airplanes at -100 μ A discharge current, for example:

Noise @ 100 µA	DC-3	Saratoga	N50	
Bare aircraft	33.9 dB	28.1 dB	24.0 dB	
With dischargers	4.5 dB	2.6 dB	1.0 dB	
Difference	29.4dB	25.5 dB	23.0 dB	

Table 1: Comparison of Ground Test p-static noise at Loran-C frequencies: $-100 \ \mu A$ current

The similarities in Table 1 are noticeable when one considers the different airframe size, shape, and different percentage of aluminum and non-conductive skin and structure among the aircraft tested over the years. Such data should be considered carefully during the development of

approval and certification paths for Loran-C and other avionics.

We are encouraged to conclude that the presence of discharger devices designed to quiet the airframe at low frequencies provides large benefits even *before* we consider using h-field antennas to optimize Loran-C performance. The consistency shown here also permits consideration of a standard which does not include a model-specific or aircraft-specific test before approval of Loran-C for flight in instrument conditions.

A review of SatMate configuration parameters revealed that some parameters should be modified prior to future testing, to be certain tracking loop and other parameters are correct.[21]

Flight Tests with Natural Charging in Weather:

From October 2003 to the present, using the airborne data collection package summarized earlier and described in detail in "Equipment On Test Aircraft .doc"[13], flight missions have been carried out in the vicinity of the New Jersey-based FAA Technical Center. All flights are documented in memoranda authored by Robert Erikson and issued by the test team at the FAA Technical Center. The work continues, and as questions are resolved these memoranda may be revised. Further test plans and experiments may be performed.

Two of the twelve flights were chosen for presentation here, as they exhibit important characteristics we seek to analyze. The other flights either did not encounter any p-static conditions or were equipment checkout flights.

A benefit to using the natural-charging 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. The disadvantage is the hit-ormiss nature of finding p-static on any given flight.

Our hypotheses were the following, based on past work discussed earlier in this report and on the FAA Technical Center ground electrostatic survey of March, 2004.[22]

- During flight, changes will be observed in the relative field strength (field mill output) between the airframe and its surroundings. In cloud, these measurements will likely be more variable than in clear air.
- The airframe may become charged (most often negatively) in cloud or precipitation, and upon achieving some threshold value the airframe will begin to deliver charge to the slipstream through the corona process. We will be able to observe this corona current using the wingtip and tail-tip instrumented dischargers.

- We expect that p-static will not always occur when flying in cloud or precipitation, and that it may in fact be relatively rare.
- Once corona begins, we expect to see a reduction in Loran-C signal-to-noise ratio (SNR) due to the addition of local corona-generated noise to a more or less constant Loran-C signal strength. This reduction will principally affect the avionics units using antennas sensitive to the electric-field component of the radiated signal. Further, we expect that older radio designs will be more sensitive to the SNR reduction than more modern receivers. We expect minimal effect on avionics using magnetic-field antennas.
- During a p-static event of given intensity, the presence of well-designed resistive discharger units on the airframe will result in a lower level of stored charge and will produce less noise, even though more discharge current may be flowing.
- We expect to be able to compare meaningfully the flight data with the data collected during the ground electrostatic test.
- Based on past experience, we expect to observe some data characteristics which are difficult to explain immediately. The difficulty may arise because we have not instrumented to observe that quantity, or because of imperfect understanding of all the interactions which can take place between the airframe and an externally-charged environment.

Flight March 25, 2004

Figure 22 shows an overview of results of the March 25, 2004 flight test [25], which followed the ground electrostatic calibration. For this flight, all dischargers were removed from the airframe except for three TCO DD-2 units, one at each wingtip and one at the top of the vertical stabilizer. These dischargers were instrumented so that current flow could be observed.

Takeoff occurred at t=34853 and the field mill showed a high positive reading beginning immediately at wheels-up, followed by a more typical negative field values enroute. There were four negative-charging features, three of which were not specifically called out in the flight log but which may have been cloud encounters. It is clear that the fourth encounter with airframe charging produced the maximum field strength for this flight, and it was coincident with a 3-dB reduction in SNR for the Apollo legacy Loran-C receiver, on the 9960W (Caribou) station. Otherwise, aside from a curious increase in SNR during taxi, the Apollo Caribou data variations seem not to be correlated with flight conditions.



Figure 22: Flight 3/25/04 – P-static encounter; effect on legacy receiver

The two Locus Satmate[™] Loran-C receivers showed no correlated effect with the high electric-field condition on the airframe, and for the stronger stations Seneca and Nantucket (not shown) there was no visible effect from any of the receivers. All 9960-chain stations were recorded by the SatMate receivers.



Figure 23: Flight 3/25/04 – Discharge Currents and Field Mill Data

Figure 23 adds the dimension of discharger current to the 3/25/04 flight data. The top trace is the same as the lower trace of Figure 22, and the bottom trace shows the currents observed at each of the three instrumented dischargers. It appears from the chart that the corona threshold for this discharger installation is ~ -9,500 V/m at 7,800 MSL on this day. We see individual currents from the left (magenta) and right (red) wingtips and from the tail-tip (black) which are proportional to the field when it is in excess of this threshold. It is instructive to compare the flight data with ground data. There is also (in green) the sum of all discharge currents, which is of importance in SNR effects prediction.

Earlier in the flight there is one isolated instance of a small current from the left wing discharger only, in response to a momentary charge event which produced an airframe field slightly greater than -9,500 V/m.

Figure 24 relates the flight observations to ground electrostatic calibration data. The flight data plot is the cumulative discharger current observed on 3/25/04. The



Figure 24: Flight 3/25/04 Compared with ground calibration data

other plots are from the three ground calibration tests already discussed. The "bare aircraft" test showed that for a given discharger current to flow, a relatively high field strength was required. We know that this effect reflects a high corona threshold and a potentially noisy airplane, possibly due to suboptimum discharger design or placement. The flight data in this case more closely resembled the "optimized" airplane on which modern-day dischargers were placed in optimum locations.

At these low discharge currents, it is reasonable that the airplane compared well with the "optimized" ground data. The airplane in flight was equipped with a total of three dischargers, all of modern design. The discharge current is low. In the ground test, it is highly probable that at such low currents, only one or a very few dischargers were conducting. Therefore in effect, the ground and airborne configurations were similar, and the data reflect this fact.

The significance of this flight is that an effect on Loran-C SNR for existing hard-limited avionics is shown at a very low discharge current, and that no apparent SNR effect appears on a "modern" linear-processing receiver, either with an e-field or h-field antenna. Also, the correspondence between flight and ground data is encouraging.

Flight August 16, 2004

The August 16, 2004 flight [26] is one of a series for which the TCO instrumented dischargers were removed and a set of 1/8" diameter brass rods were installed at the wingtips and the tip of the vertical tail. The rods were used here, as they were in the ground tests, to simulate an airplane with no dischargers; one with no resistance between the airframe and the corona point to decouple noise, and with a relatively large diameter at the corona points. We expected to see a higher corona threshold due to the increased trailing-edge radius, and higher stored charge (higher field-mill outputs) on the airframe prior to corona onset. See Figure 25.



Figure 25: Flight 08/16/04 – Showing p-static effect on efield receivers, Loran-C signal strength, discharger currents, and field mill activity.

The flight was conducted in conditions of low ceilings with rain, and temperatures well above freezing. The "takeoff effect" of apparent positive charging is less visible here due to the much larger chart scale, but it is present. Immediately after takeoff, the aircraft field increased to about 100 kV/m. (This is the limit of the field-mill sensor output.)

This flight was a case where it was evident that there are fields outside of, and independent of, the aircraft. The aircraft apparently encountered an area of charge separation which created a field transverse to the aircraft for a short time. The external field shifted the charge on the airframe such that negative-point corona occured at the right wingtip (red) and simultaneously positive-point corona fired at the left wingtip (magenta). At other times during the flight, there was selective discharge from each of the three instrumented dischargers one at a time, also indicating that external fields were keeping one or more of the dischargers below corona threshold by causing migration of the stored charge to other parts of the airframe. Note that the totalcurrent trace (green) is arithmetically added as plotted in Figure 25. To determine SNR effects, the currents were added as absolute values. See Table 2, below.

It is also good to recognize that positive-point corona generally produces more noise than negative. This is due to the preferential ionization of nitrogen atoms by positive corona and oxygen atoms by the negative corona. Nitrogen has a slightly higher ionization potential than oxygen. This is another area for further measurement.

In such conditions the field mill was seen to be less useful in numerical terms, but the Loran-C receiver data could be compared to the effects measured in ground tests with the "bare" (brass-rod-equipped) airplane and simulated Loran-C signals. The table below gives a summary of the variations noted, and a comparison with "bare" airplane ground data at the same discharge current. Loran-C signal strength remained essentially constant throughout the encounter. The first entry, at t=39764 is chosen as the baseline for this flight – a period where p-static is not occurring.

		Flight SNR data for station Nantucket (9960W), and simulated ground data						
Graph time tick	Sum of discharge currents	SatMate (e-field) dB		Apollo (e-field) dB		SatMate (h-field) dB		
(seconds)	μΑ	Flt	Gnd	Flt	Gnd	Flt	Gnd	
39764 no discharge	0	23	13	3.0	1.5	26	20	
38817 both wings	32	2	-4	- 2.3	No track	26	21	
39093 right wing	6	7	7	1.9	-7.1	26	20	
40064 tail tip	3	14	10	3.0	-3.4	26	21	

Table 2: Flight 08/16/04, Summary p-static comparison with "bare aircraft" ground data

Figure 26 presents a graph of these same data. In general, the trends were similar for flight and ground data for each receiver. Exceptions may be due to the nature of the simulated signals used in the ground tests. During experiment set-up there were some concerns over the near-field effects which might be encountered in the hangar. This area remains under investigation. Notice the constant, high-SNR condition for the SatMate with the h-field antenna typical of all flights.



Figure 26: Flight 8/16/04, receiver SNR vs. discharge current. Nantucket (9960W) flight; simulated 9940M ground

Figure 30 illustrates an apparently impressive charge / discharge encounter compared to the other flights, but it is not at all "severe". The 32 μ A maximum discharge current is rather routine, relative to experience,[27] where discharge currents of hundreds or even thousands of microAmps are encountered. Nevertheless, a significant SNR effect is seen here in both e-field receivers, with no observable effect in the h-field. Loran-C signal strength is generally high for the stations shown, so none of the receivers actually failed to produce navigation data during this event.

CONCLUSIONS

The FAATC ground electrostatic survey and flight tests to date confirm and replicate the similar work elsewhere in 1982 and 1999.

- The survey data also agree broadly with many uncontrolled or anecdotal observations of p-static interference reported by pilots and others.

The three different instrumented aircraft tested in the FAA programs since 1982 exhibit consistency in the quantity of p-static noise generated by a given flow of discharger current, in both ground and flight measurements.

- Discharge noise consistency prompts a general standard rather than installation-specific approvals for avionics including Loran-C functions.

For all three aircraft tested, it is possible to "quiet" the airframe greater than 20 dB using careful maintenance and purpose-built dischargers.

- Well-designed e-field antennas will likely work well in these quieted circumstances. The airframe and discharger maintenance program must be followed carefully however, to avoid degradation over time.

Loran-C receivers using e-field antennas are generally more susceptible to p-static noise; typically a reduction in SNR of greater than 20 dB is observed in mid-severity charging scenarios. - The h-field antenna offers another >20 dB performance margin against a maintenance-related rise in p-static noise over time.

The "legacy" Loran-C receiver used at FAATC was affected at lower noise levels than the "modern-design" receiver, with both receivers using e-field antennas. A retrofit h-field antenna is desirable.

- In another test, a legacy receiver with an h-field antenna performed normally in "severe" p-static conditions.

The modern receiver using an h-field antenna shows greater than 20 dB more "protection" from p-static noise than does the same receiver using an e-field antenna.

- Even at levels of charge/discharge considered "severe" in practice, there was little or no reduction in SNR from receivers with h-field antennas.

RECOMMENDATIONS

"P-static on demand" is necessary in order to gather the flight data needed to resolve the basic questions:

- Does use of Loran-C in aviation require extraordinary airframe maintenance?
- Is specialized equipment required? (e.g. h-field antennas)
- Are unique approval processes required? (Must every *installation* be inspected?)

Continue and complete the data analysis of the FAATC ground electrostatic survey.

The analysis to date has provided good insight into the operation of p-static, of airframe dischargers, and of Loran-C receivers and antennas in electrically charged conditions. The analysis continues to support the flight program which is underway.

Continue and complete the FAATC flight testing program.

The present series of flights provides the data needed to confirm quantitatively in flight the ground tests at FAATC and elsewhere. These preliminary tests can be conducted with the airplane in the "normal" category. The artificial charging system will be installed on aircraft N-50, necessitating an "experimental" label and the restrictions which follow.

The flights with artificial charging will determine whether we must test-*fly* dischargers, receivers and antennas, or whether we can use the program's flight data to build a knowledge base for bench testing which is representative of flight conditions.

Bring the knowledge down to Earth.

Assemble the necessary tools to establish a laboratory for the testing and approval of avionics components under electric-field stresses such as those found in instrument flight. Examples of such capabilities are:

- high-field-strength testing of anti-corona coatings
- accurately-simulated p-static noise spectra at the full range of corona repetition rates
- high-voltage arc and streamer bench tests

An FAA laboratory capable of such tests and analysis would support the development of a Loran-C certification/commissioning path and its FAA orders, RTCA documents and proponent qualification of equipment. Benefits to manufacturers and users of non-Loran-C avionics and to non-aviation users of Loran-C and other systems can be envisioned.

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