Airframe Effects on Loran H-field Antenna Performance

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BIOGRAPHY

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ABSTRACT

The 2001 Volpe National Transportation Systems Center report on GPS vulnerabilities identified Loran-C as one possible backup system for GPS. The Federal Aviation Administration (FAA) observed in its recently completed Navigation and Landing Transition Study that Loran-C, as an independent radio navigation system, is theoretically the best backup for GPS; however, this study also observed that Loran-C's potential benefits hinge upon the level of position accuracy actually realized (as measured by the 2 drms error radius). For aviation applications this is the ability to support non-precision approach (NPA) at a Required Navigation Performance (RNP) of 0.3 which equates to a 2 drms error of 309 meters. The recently released report of the DOT Radionavigation Task Force recommended to "complete the evaluation of enhanced Loran to validate the expectation that it will provide the performance to support aviation NPA and maritime HEA operations." To meet this need, the FAA is currently leading a team consisting of members from industry, government, and academia to provide guidance to the policy makers in their evaluation of the future of enhanced Loran (eLoran) in the United States. Through FAA sponsoring, the U.S. Coast Guard Academy (USCGA) is responsible for conducting some of the tests and evaluations to help determine whether eLoran can provide the accuracy, availability, integrity, and continuity to meet these requirements.

One area of importance that has been under investigation has been the use of H-field antennas to receive the Loran signal (the times of arrivals of the signals, or TOAs, are used in the navigation position solution). H-field antennas provide better performance than E-field antennas (the usual maritime antenna) in the presence of precipitation static, which is a common problem on aircraft. However, in the past, our research has shown that H-field antennas suffered from loop coupling and other effects that led to variations, or errors, in the received TOAs as a function of bearing to the Loran station. New antennas are improved over older models; however, the installation of the antenna on the airframe changes the performance from that of the antenna alone.

A necessary task to certify Loran for NPA is bounding the effects of those error sources that cannot be eliminated. The USCG Academy and Alion in partnership with the FAA Technical Center have been conducting tests on H-field antennas both on and off the Convair 580 in order to characterize the impact the aircraft has on the antenna performance. This paper presents the results of this testing

and makes an assessment as to the error bounds required for H-field antennas on aircraft.

BACKGROUND / INTRODUCTION

Contrary to what some may believe, Loran-C is still alive and in use worldwide. The United States is served by the North American Loran-C system made up of 29 stations organized into 10 chains (see Figure 1). Loran coverage is available worldwide as seen in Figure 2.

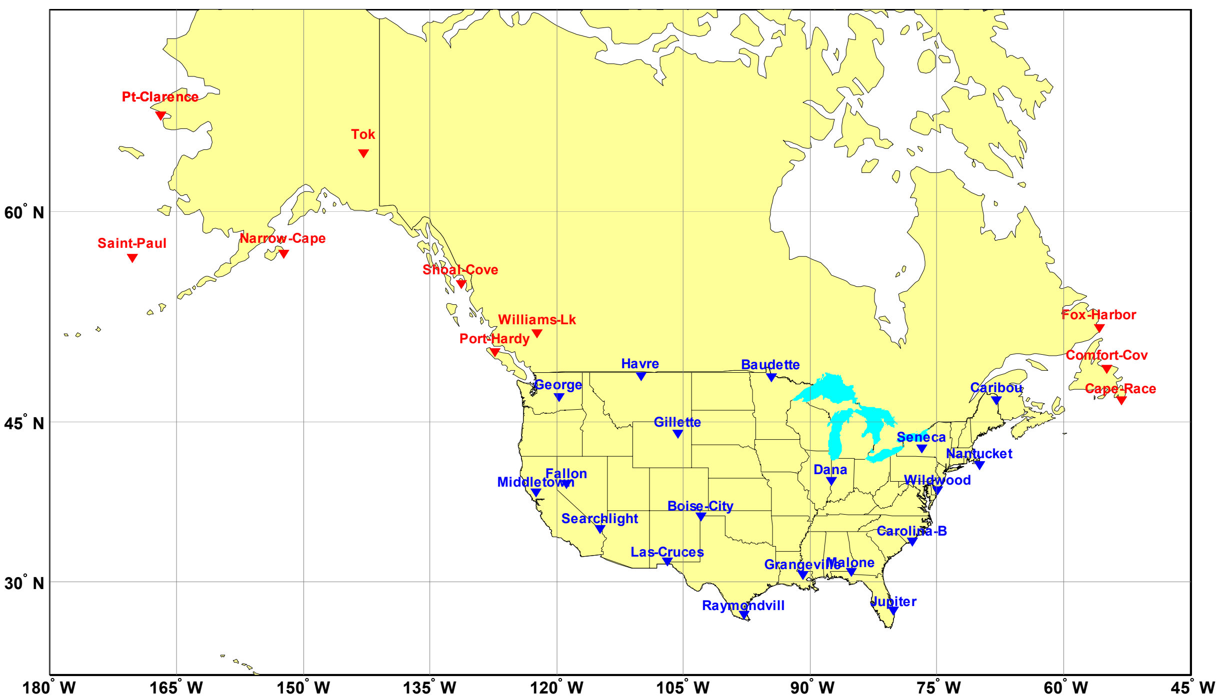

Figure 1 – North American Loran-C System

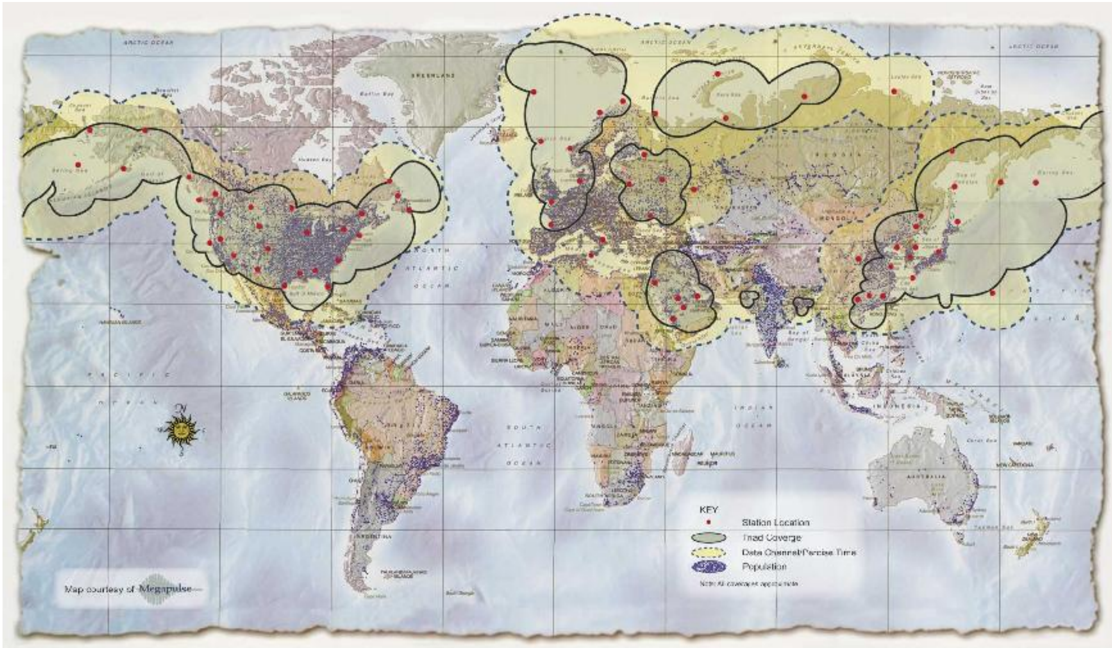

Figure 2 – Worldwide Loran Coverage

Given the ubiquity and quality of service available from the Global Positioning Service (GPS), one might wonder of what use is a system that has been operational since the 1970's? The answer is that Loran is an excellent backup system for GPS. As discussed in many sources, such as the Volpe vulnerability study [1], GPS is vulnerable to both intentional and unintentional jamming. Since Loran is a totally different system and subject to different failure modes than GPS, it can act as an independent backup system that functions when GPS does not. The Federal Aviation Administration (FAA) observed in its recently completed Navigation and Landing Transition Study [2] that Loran-C, as an independent radio navigation system, is theoretically the best backup for GPS; however, this study also observed that Loran-C's potential benefits hinge upon the level of position accuracy actually realized (as measured by the 2 drms error radius). For aviation applications this is the ability to support non-precision approach (NPA) at a Required Navigation Performance (RNP) of 0.3 which equates to a 2 drms position error of 307 meters and for marine applications this is the ability to support Harbor Entrance and Approach (HEA) with 8-20 m of accuracy.

There are several challenges to be overcome to enable Loran to meet the accuracy requirements. One of these challenges that has been under investigation has been the use of H-field antennas to receive the Loran signal (the times of arrivals of the signals, or TOAs, are used in the navigation position solution). H-field antennas provide better performance than E-field antennas (the usual maritime antenna) in the presence of precipitation static, which is a common problem on aircraft. However, in the past, our research has shown that H-field antennas suffered from loop coupling and other effects that led to variations, or errors, in the received TOAs as a function of bearing to the Loran station. New antennas are improved over older models; however, the installation of the antenna on the airframe changes the performance from that of the antenna alone.

A necessary task to certify Loran for NPA is bounding the effects of those error sources that cannot be eliminated. The USCG Academy and Alion in partnership with the FAA Technical Center have been conducting tests on H-field antennas both on and off the Convair 580 in order to characterize the impact the aircraft has on the antenna performance. This paper presents the results of this testing and makes an assessment as to the error bounds required for H-field antennas on aircraft.

H-FIELD ANTENNA DIRECTIONALITY

For a Loran receiver there are two choices for antenna types: a whip antenna that is responsive to the electric field (an E-field antenna) or a loop antenna that is responsive to the magnetic field (H-field antenna). A single loop antenna has a figure-8 antenna pattern; to achieve an omni-directional pattern, two loops are needed, oriented 90 degrees to each other. This is illustrated in Figure 3. The red line is the theoretical pattern from loop 1, the blue line is the theoretical pattern from loop 2 which is oriented at 90 degrees to loop 1. The green line is the resulting omni-directional pattern obtained by combining both loops.

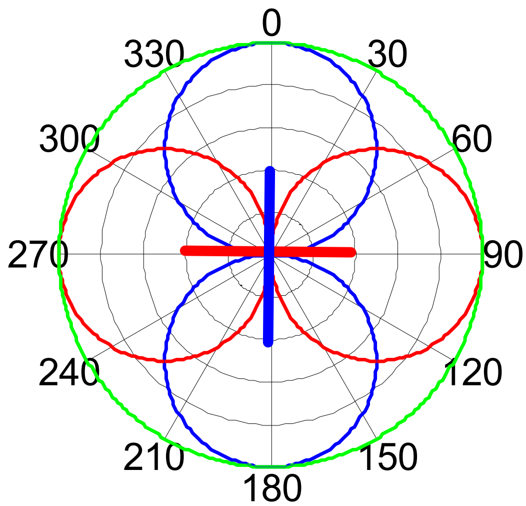

Figure 3 -- Loop Antenna Patterns: Loop 1 (blue), Loop 2 (red), Combined Loops (green)

Either antenna type can be used; however, the preference in the aviation community is to use the H-field antenna. The primary advantage of using an H-field antenna is that it is not vulnerable to precipitation static or P-static. This effect is described in detail in [3]. Another advantage is that the H-field antenna does not need a ground plane for good performance; E-field antennas are typically very sensitive to grounding.

The problem with H-field antennas is that they tend to induce a directional variance in the TOA measurement. Theoretically, two crossed loops should have a perfect omni-directional pattern and give consistent measurements regardless of the orientation of the antenna. However, real-world antennas tend to have phase and gain differences between the loops that cause the measured TOA for a given Loran station to vary as the antenna is rotated. This effect has been reported on in the past and most recently summarized in [4].

To put this error into context and explain why it is important, consider the following ASF noise model that we have proposed and are using in simulations to determine the maximum variation allowed in the spatial ASF component. We assume that the TOA can be broken up into the predicted TOA (all sea-water propagation) plus the predicted ASF (from the BALOR model) plus noise:

$$TOA_{actual} = TOA_{predicted} + ASF_{predicted} + Noise$$

The noise term (1σ) can be broken down into the following components, with estimated aviation values.

Receiver/channel: 25-100ns

Directional variation: 100ns

Altitude: 100ns

These values are used in a simulation to assess position error based on the noise, expected Loran signal power, and station geometry for a given area. Figure 4 shows the expected position error along the approach to Grand Junction airport (runway 29). At each position along the approach, the receiver is given the static airport values for the ASF to apply to the TOA (calculated as above) to use in the position solution. The blue line is the error due to the mismatch in ASF only, calculated at high resolution along the 10 NM approach. The red and green dots are the results of simulation including the noise components at 1 NM intervals along the approach path. The red dots are average error while the green dots are the 95% quantile. This is described more in our companion paper [5]. For this airport approach, the 95% quantile is very close to the 120m error bound (this is the amount of error allowed in the spatial domain, which when combined with other error terms must meet the RNP 0.3 requirement).

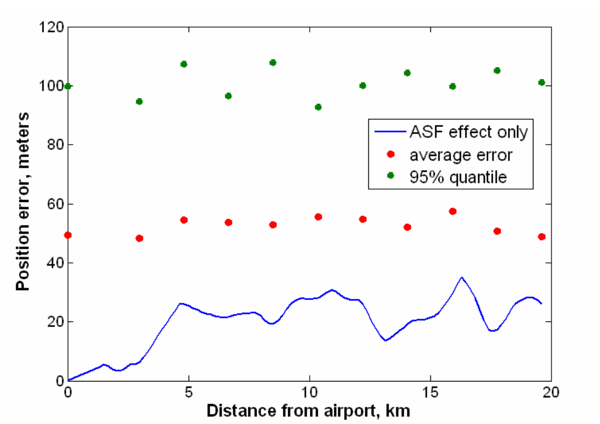

Figure 4 -- Typical Position Error, 100ns Directional Error

However, if we increase the directional error in the simulation to 200ns, then the 120m bound is exceeded (see Figure 5). This is the reason that this directional error is important; it has a direct impact on the amount of spatial ASF variation that can be tolerated.

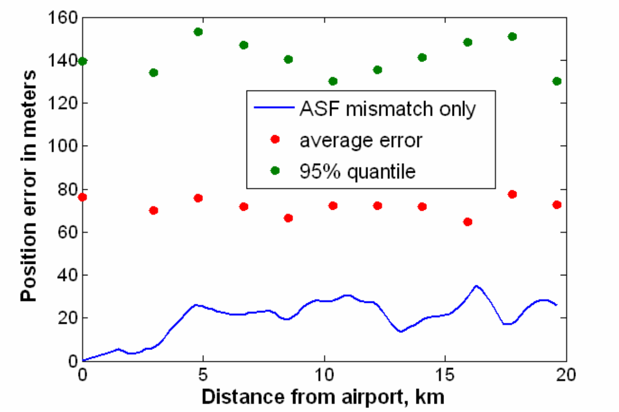

Figure 5 -- Typical Position Error -- 200ns Directional Error

INVESTIGATIONS TO DATE

The goal then is to try to isolate/identify the variation caused by the antenna being mounted on an aircraft and then to develop a calibration algorithm to compensate. In order to accommodate some spatial ASF variation without resorting to additional sets of ASF values we need to have antenna error less than perhaps 100ns, and this error term needs to be peak to peak or maximum error and not 1σ.

In our previous investigations [4] one of the limitations that we had noted was the lack of stability on the internal clock of the Loran receiver being used to estimate the TOAs, a Satmate 1030. Subsequent to that, we worked with the manufacturer to have them deliver a modified receiver that uses an external 10 MHz clock. This receiver was tested using a cesium frequency source for the 10 MHz reference to ensure that the receiver was sufficiently stable to measure the TOA variations due to antenna rotations. Typical results of this test for the 9960 Loran chain in New London CT are shown in Figure 6. The TOAs shown are all normalized to a zero mean so that all three stations under consideration (Seneca, Nantucket, and Carolina Beach) can be seen on the same scale. Each station has a range of about ±20ns with a standard deviation of about 10ns on each station. This is well within the range of acceptability for measuring the expected TOA variations.

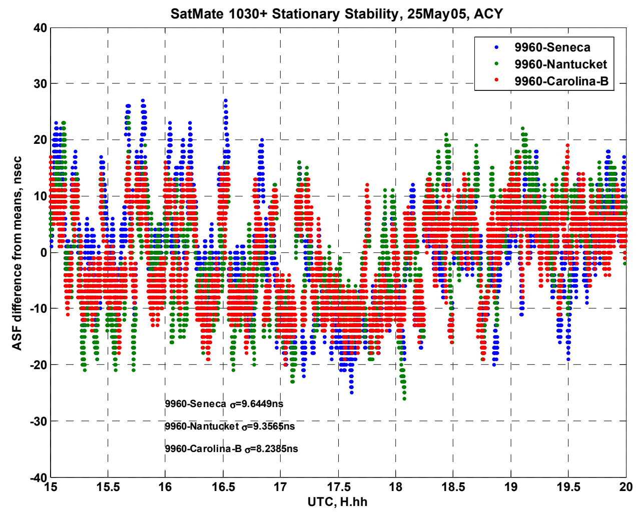

Figure 6 – SatMate 1030 Stability with 10 MHz External Reference.

With this more stable receiver, a number of investigations on antenna performance were conducted:

- Antenna alone (open field and on tarmac at FAATC).
- Antenna on aircraft (Convair, Cessna).
- Two different H-field antennas (marine antenna, aviation antenna).
- Different receivers (SatMate 1030, DDC).

The typical rotation test consisted of the following steps:

- Remain stationary for 10 minutes.
- Rotate antenna clockwise in 30 degree increments at 5 minute intervals.
- Perform 2 to 3 complete rotations (in other words, 12 points/rotation).
- Remain stationary for 10 minutes.
- Rotate antenna counter-clockwise in 30 degree increments at 5 minute intervals.
- Perform 1 to 2 complete rotations (again, a tota of 12 points/rotation).
- Remain stationary for 10 minutes.

When looking at the results of the antenna rotations, the normalized ASFs are typically plotted. ASFs are used and not TOAs in order to remove any variation in the TOA due to physical movement of the antenna. When rotating the antennas alone on the turntable, this is not an issue so normalized TOAs are equivalent to normalized ASFs; however, when rotating the plane, there is typically 20-30m of spatial movement during the rotation. Also, a ground reference station is used in order to remove any temporal changes in the TOAs/ASFs that occur during the course of the test.

ANTENNA ALONE

The initial test was the antenna (SatMate marine H-field) rotated in an open field. This was done to establish a baseline of the antenna performance under known conditions. A photo of the test rig in the field at the U.S. Coast Guard Academy is shown in Figure 7. This same antenna and receiver set-up was then taken to the FAA Technical Center (Figure 8) and rotated on the tarmac to verify that there were no local disturbances that would impact the antenna performance. Both tests had the same results; Figure 9 shows the normalized ASFs for three Loran stations showing the typical double frequency sinusoidal variation in ASF with heading over 5 rotations (3 clockwise and 2 counterclockwise). The range of variation is approximately 40-50ns with a standard deviation of about 13ns.

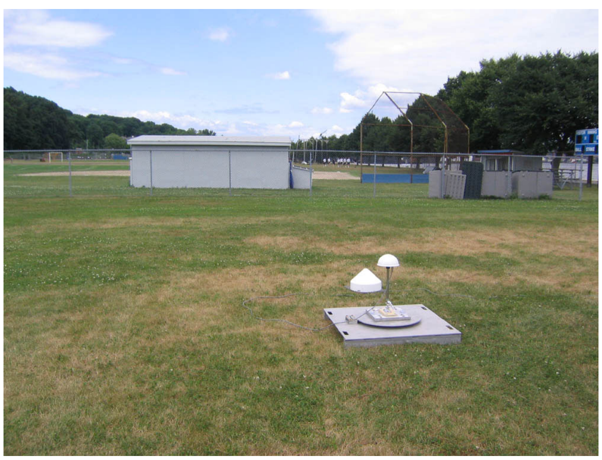

Figure 7 – Test Rig in Open Field at USCGA.

Figure 8 – Test Rig on Tarmac at FAATC.

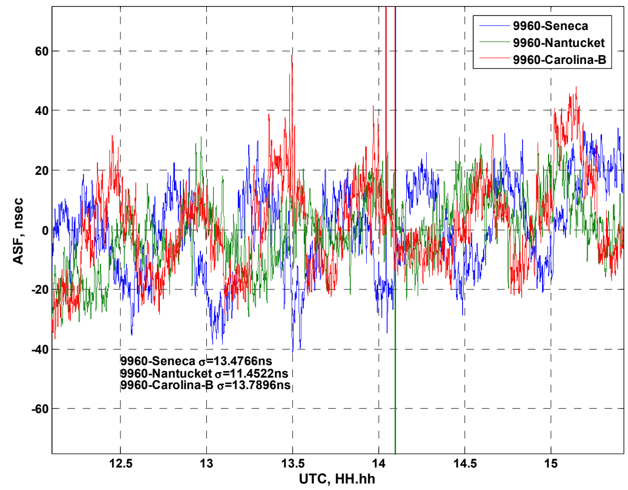

Figure 9 – Normalized ASFs for SatMate Antenna Rotated on Tarmac at FAATC.

Due to puzzling results obtained with later testing of the SatMate receiver/antenna combination, the USCG Academy DDC receiver was also tested. This is a research receiver that is used to capture raw Loran data for later software processing and analysis. The DDC receiver with a Megapulse H-field antenna was rotated on the lower field using the same test procedure as used for the SatMate marine antenna, to establish a baseline of performance for this receiver/antenna combination as well. The results for this receiver/antenna combination are shown in Figure 10. Again, normalized ASFs show the typical sinusoidal variation of ASF with heading, across all 5 rotations. Here the range of variation is larger (200ns), due to a larger mismatch between the gain and phase of the two antenna loops.

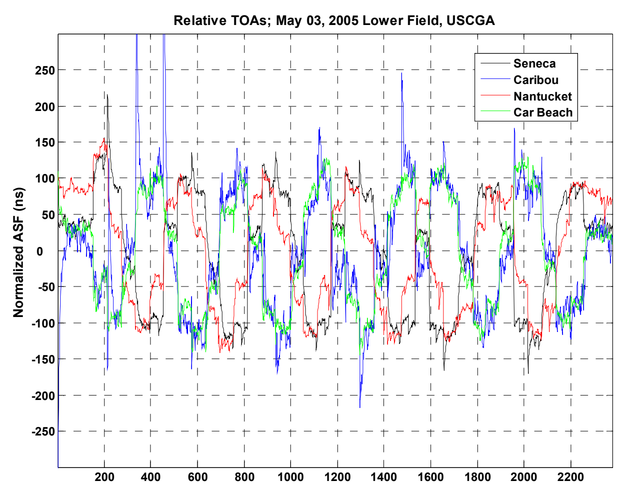

Figure 10 – Megapulse Antenna Rotated in Open Field at USCGA.

ANTENNAS ON CONVAIR

The next test was to put the exact same antenna on the Convair 580 (see Figure 11) and rotate the aircraft recording the TOAs with the exact same equipment. The results of this test are shown in Figure 12. In this case, the normalized ASFs for the same three stations are shown for the same rotation test (3 rotations CW and 2 CCW). In this test, the exact same antenna and receiver system were used as in the previous; the only difference was the antenna being mounted on the aircraft. However, in this case the range of TOA variation was now 300-400ns with standard deviations of 45-90ns. The range of variation was also not the same for each of the three stations.

Figure 11 – SatMate Marine Antenna Temporarily Mounted on the Convair.

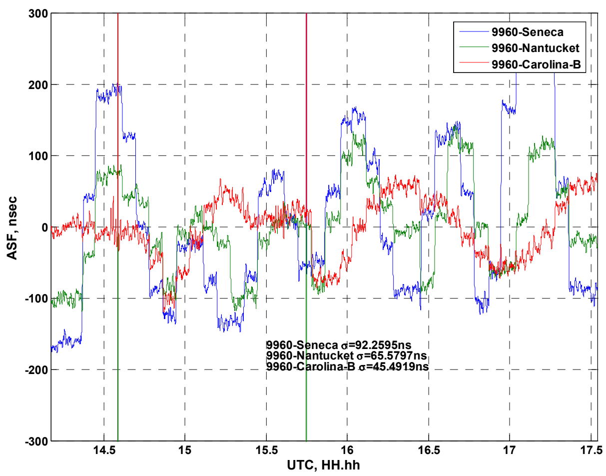

Figure 12 – SatMate Marine Antenna rotated on Convair.

The aviation antenna already installed on the aircraft was also tested in order to compare the performance of the aero antenna to the maritime antenna. These results are shown in Figure 13 and are consistent with the results from the maritime antenna.

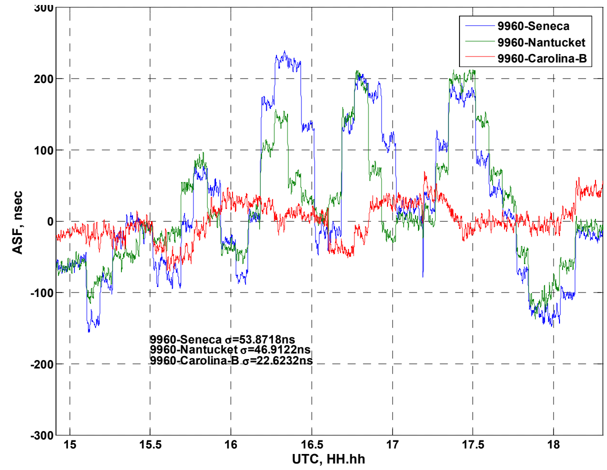

Figure 13 – SatMate Aviation Antenna Rotated on Convair.

ANTENNAS ON CESSNA

It was expected that there would be some difference in the results between rotating the antenna on the tarmac and the antenna on the aircraft; however, the results were very different, and were not entirely repeatable between rotations. Thus, it was decided to conduct additional aircraft testing and to use the USCGA DDC receiver to collect raw data along with the SatMate. Additional rotation testing was conducted with these two receivers and antennas using a Cessna 172 in Westerly, RI. In this case a shortened rotation test was conducted: the plane was rotated between three headings: -90, 0, and 90 degrees. The results of this are shown in Figure 14, where the normalized TOAs for Nantucket are shown from the DDC receiver in red and the SatMate in blue. Here, results are very consistent between the two receivers. When plotted as a function of heading (Figure 15), it is clear that the results are repeatable as well.

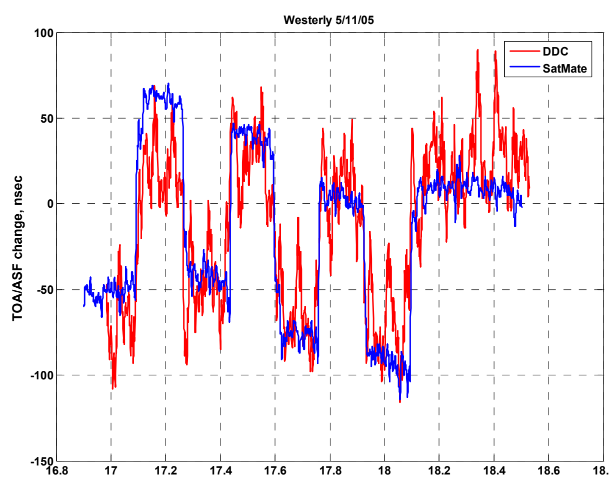

Figure 14 – TOA Variations Seen at Westerly, RI.

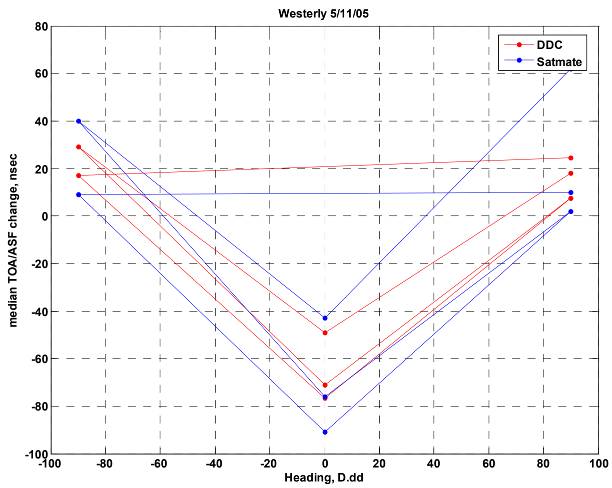

Figure 15 – Westerly TOA Variations vs. Heading.

SECOND CONVAIR TEST

A second set of tests was conducted using the Convair; this time using both the SatMate and the DDC receivers. The aircraft was rotated through the standard test while data was collected on both systems simultaneously. The normalized ASFs using the SatMate for the first three rotations (CW) are shown in Figure 16. The results are similar to that seen the first time; though this time the range of variation was only about 200ns with standard deviations of 20-50ns.

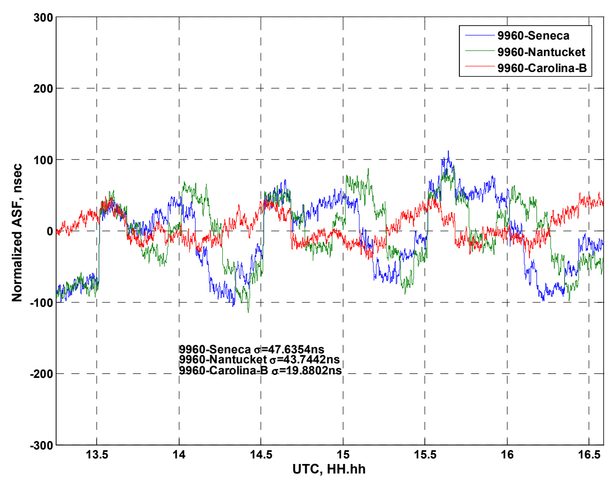

Figure 16 – SatMate Aero Antenna on Convair. Normalized ASFs for 3 CW Rotations.

The results are pretty repeatable as can be seen in Figure 17, where the normalized ASFs are plotted vs. heading. However, there are still different magnitudes of variation among the three stations. Also, and most troubling, is that the results are **not** repeatable between the CW and CCW rotations. In Figure 18 the normalized ASFs are plotted vs. heading for two rotations in the CCW direction and the results are very different than that seen when the aircraft was rotated in the CW direction. Heading dependence variation should not be a function of direction of rotation, so this is very puzzling and still under investigation at this time.

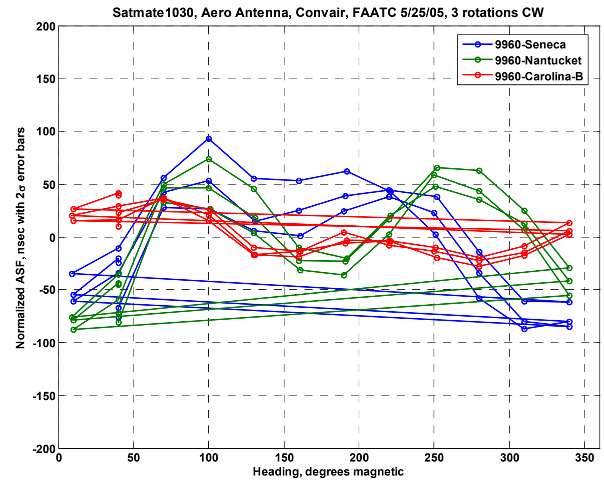

Figure 17 – SatMate Aero Antenna. Normalized ASFs for 3 CW Rotations, Plotted vs. Heading.

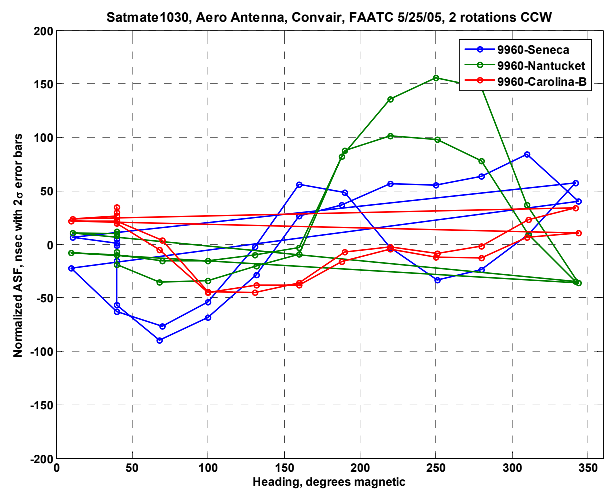

Figure 18 – SatMate Aero Antenna. Normalized ASFs vs. Heading for 2 CCW Rotations.

The data from the DDC receiver was more in line with what was expected. In Figure 19 the normalized ASFs for all five rotaations (3 CW and 2 CCW) are shown for three stations. The range of variation is 200-300ns with standard deviations of 75-85ns, but all three stations have about the same magnitude of variation and exhibit the typical sinusoidal variation with heading. The variations are also very repeatable with each rotation; across all 5 rotations (CW and CCW) as seen in Figure 20.

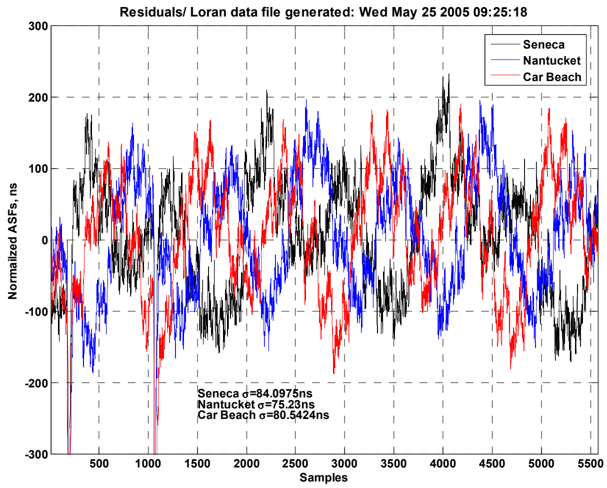

Figure 19 – Megapulse Antenna. Normalized ASFs for all 5 Rotations.

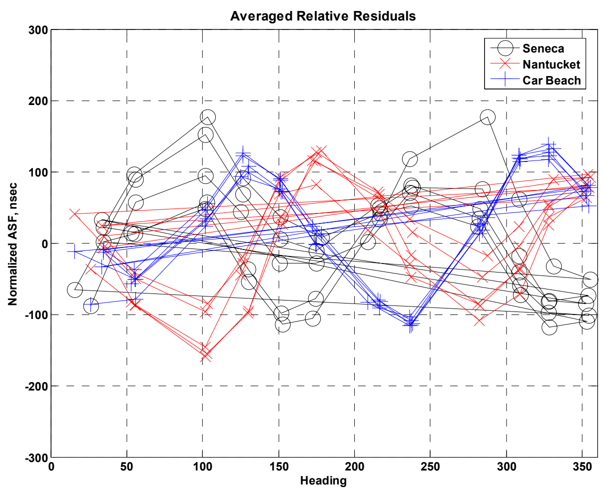

Figure 20 – Megapulse Antenna. Normalized ASFs Plotted vs. Heading for 5 Rotations.

This performance is not that much different from that seen from the antenna alone. Also, since the ASF variations as a function of heading are repeatable and regular, it should be possible to develop a calibration algorithm to compensate for the errors. A simple calibration algorithm of the form:

$$\alpha \cos(\theta + \phi) + \beta \cos(2\theta + \delta)$$

has been used. In this equation θ is the relative bearing to the Loran tower (antenna heading - bearing to tower). Using coefficients α, β, ϕ, and δ selected by trial and error (and definitely not optimized) and reprocessing the data with the calibration applied yields the results shown in Figure 21 where the range of variation is reduced to about 150ns with standard deviations of 30-50ns.

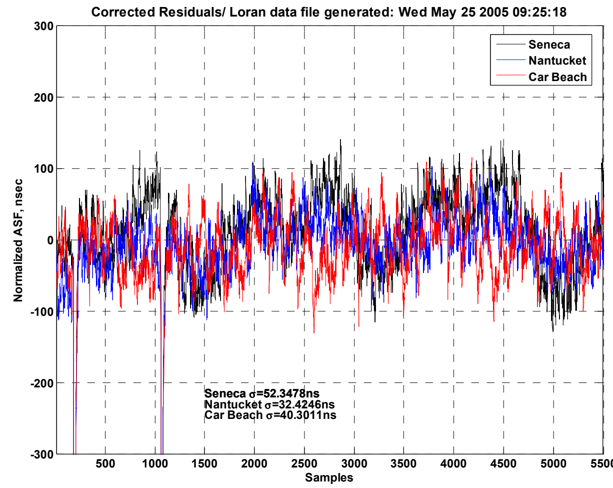

Figure 21 – Calibrated Megapulse Antenna Rotation Results.

CONCLUSIONS / FUTURE

The aircraft installation has a definite effect on the performance of the SatMate antenna and receiver. Tests were conducted to rule out location and antenna differences and show a definite airframe effect. Unfortunately and contrary to expectations, the effect is different depending upon which direction the antenna is rotated (CW vs. CCW). The reason for this is still under investigation.

The aircraft installation had much less of an impact on the DDC receiver/Megapulse antenna system. In this case the effect is repeatable and regular and calibration appears possible. Improved results were shown for a simple and non-optimized calibration algorithm.

In order for aircraft antenna systems to be certified to meet the RNP 0.3 requirements, the FAA will need to set antenna/receiver specifications for allowable antenna error (perhaps 100ns peak-to-peak). Manufacturers will then need to make antenna/receiver combinations that meet these specifications.

Future work will focus on investigating other antennas to determine if they have the same problems. We will also investigate fine-tuning the calibration of the Megapulse antenna as well as working to develop an auto-calibration algorithm.

ACKNOWLEDGMENTS

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