BALOR Model Validity for the Airport ASF Mapping Methodology

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ABSTRACT

In 2001, the Volpe National Transportation Systems Center completed an evaluation of the Global Positioning System (GPS) vulnerabilities and the potential impacts to transportation systems in the United States. One of the recommendations of this study was for the operation of backup system(s) to GPS; Loran C was identified as one possible backup system. The Federal Aviation Administration (FAA) has been leading a team consisting of members from industry, government, and academia to evaluate the future of Loran-C in the United States. In a recently completed Navigation Transition Study, the FAA concluded that Loran-C, as an independent radionavigation system, is theoretically the best backup for the GPS; however, in order for Loran-C to be considered a viable back-up system to GPS, it must be able to meet the requirements for non-precision approaches (NPA's) for the aviation community and the Harbor Entrance and Approach (HEA) requirements for the maritime community.

A significant factor limiting the accuracy of a Loran system is the spatial and temporal variation in the times of arrival (TOAs) observed by the receiver. A significant portion of these variations is due to the signals propagating over paths of varying conductivity; these TOA corrections which compensate for propagating over non-seawater paths are called additional secondary factors (ASFs). Hence, a key component in evaluating the utility of Loran as a GPS backup is a better understanding of ASFs and a key goal is deciding how to mitigate the effects of ASFs to achieve more accurate Loran-C positions while ensuring that the possibility of providing hazardous and misleading information (HMI) will be no greater than $1x10^{-7}$. For an aviation receiver, the approach to mitigate propagation issues under study is to use a single set of ASF values (one for each Loran tower) for a given airport. This value may have seasonal adjustments applied to it. The Loran receiver will use this set of static ASF values to improve position accuracy when conducting a non-precision approach (NPA).

A Working Group is currently developing the procedures to be used to "map" the ASF values for an airport. The output of the Working Group will be a set of tested and documented procedures for conducting an airport survey; these procedures can then be followed to survey airports nationwide. The draft procedure has been tested during data collection efforts at airports in Maine, Ohio, and New Jersey. A key component of the proposed procedure is the use of the BALOR ASF prediction software to reduce the number of field measurements. ASF

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14. ABSTRACT

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measurements made on the ground along the airport approaches and in the air on long baselines to and from several Loran towers are used to compare to the BALOR predictions to determine the validity of the BALOR model. This paper discusses the results of this data collection: how well the measured spatial variations match the BALOR model predictions, how well the proposed mapping procedure works, and results of the position accuracy obtained by the aircraft flying approaches when using the airport ASF values.

BACKGROUND / INTRODUCTION

Loran-C has been operational in the United States since the 1970's and is currently available in many parts of the world. For details on the Loran system in general see [1-3]. Given the ubiquity and quality of service available from the Global Positioning Service (GPS), one might wonder of what use is a 35 year old system? The answer is that Loran-C is an excellent backup system for GPS. As discussed in many sources, such as the Volpe study from 2001 [4], GPS is known to be vulnerable to both intentional and unintentional jamming. Since Loran is a totally different navigation 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 2002 Navigation and Landing Transition Study [5] that Loran-C, as an independent radio navigation system, is theoretically the best backup for GPS; however, Loran-C's potential benefits hinge upon the level of position accuracy actually realized. 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.

A significant factor limiting the accuracy of Loran is the spatial and temporal variation in the times of arrival (TOAs) observed by the receiver. These variations are mostly due to the signals propagating over paths of varying conductivity (different from seawater).The TOA corrections which compensate for non-seawater paths are called additional secondary factors (ASFs); hence, a key component in the future utility of Loran as a GPS backup is a better understanding of ASFs. Further, a key goal is deciding how to mitigate the effects of ASFs to achieve more accurate Loran-C positions while ensuring that the possibility of providing hazardous and misleading information (HMI) will be no greater than $1x10^{-7}$.

The future of Loran for aviation is based on a multi-station, multi-chain, all-in-view, DSP-based receiver observing TOA measurements with an H-field antenna. For such a receiver, the approach under consideration to mitigate the effects of propagation issues on accuracy is to use a single set of ASF values (or corrections, one for each Loran tower) for a given airport. (In the event that local ASF variations are too large to meet the accuracy targets with a single set of ASF values, it is envisioned that an additional set of ASF values will be used with the user's receiver interpolating between them.) While ASFs also exhibit seasonal variation, the current approach is to choose the ASF value for each station in the middle of the seasonal range and to absorb the variation within the navigation system's error budget. The Loran Evaluation Panel Working Group on ASFs is currently developing the procedures to be used to "map" the ASF Correction Estimates (ACE) for an airport. The output of the Working Group will be a set of tested and documented procedures for conducting an airport survey; these procedures can then be followed to survey airports nationwide.

In a presentation at the 2005 ION June meeting, we proposed a preliminary set of procedures and a testing methodology to validate those procedures [6]. One of the runways at Walker Field in Grand Junction, CO, was used as an example in that presentation. Equipment to be used in the testing, the error budgets for that equipment, as well as the ASF methodology itself, were also discussed. This paper reviews and updates our proposed methodology and then presents results for airports in Maine and Ohio, focusing on the validity of the BALOR model.

PROPOSED METHODOLOGY

The goal for certifying Loran for use in Non-Precision Approaches (NPA) at an airport is to publish a single set of static ASF values for each airport (or for each runway approach). If the ASF variations along an approach are too large (pushing the position solution error outside the bounds) then two sets of ASF values could be used, with the user receiver interpolating between the two values. No temporal correction would be used; the ASF values would be chosen in the middle of the seasonal range and the error introduced by the seasonal variation included in the overall system error bounds. As such, there needs to be a standard, validated procedure for establishing these airport values, the ASF Correction Estimates (ACEs) that would be published for use.

The currently proposed methodology for surveying airports is summarized as follows. Once an airport and its specific runways have been identified, the methodology consists of two parts:

1. **Computational and simulation work to establish locations for field measurements.** Run BALOR predictions to estimate ASFs along the airport approach paths. Identify the locations with the largest ASF differences for field measurements. Using simulation for positions along the entire approach path, determine

whether one set of ASFs is sufficient based on the worst case of ASF differences, station geometries, and expected signal levels – aiming for a maximum error in the position domain of 120m.

2. **Field measurements.** Use a static monitor at the airport to remove temporal variations during testing. Make static measurements at each of the locations identified above, collecting sufficient data at each measurement point so that the error in the ASF measurement is less than perhaps 25-50ns, 1 sigma. Since differencing between the TOAs of the mobile unit and the ground reference adds the observation noise present in each receiver, this limit is on total error for both measurements. After the field measurements, adjust each measured ASF to a true ASF using system timing data from the timing equipment at the Loran stations. Assign ASF Correction Estimates (ACE).

For further details on this ASF Methodology see [6, 7]. Note that we have the working assumption that the BALOR ASF prediction software (described in [8]) provides a reasonable assessment of the real world conditions. One of the goals of the field measurement work of the working group is to validate this assumption. This is the subject of this paper.

FIELD TESTS

A series of field tests have been conducted by Alion, USCGA, and the FAATC during July, August, and September of 2005. The goal of these (and future) tests has been to collect ASF data in order to assess the validity of the BALOR model and to evaluate/prove the proposed methodology, with the aim of modifying the methodology as necessary based on the results of the tests. The test plan consists of four components:

- Ground measurements of ASFs at selected locations along the approach paths (to validate data used for the simulations of Loran performance along the entire approach)
- Flight verification of the simulated RNP 0.3 performance (to validate the results of the simulations)
- Long baseline flights (to directly assess BALOR accuracy)
- Measuring ASFs versus altitude (to bound any variation present in the 4000 ft altitude range)

During July-September 2005, data was collected for airports in Maine and Ohio to achieve the first two goals; additional data collection is planned for the latter two goals (see our ILA paper on altitude effects for further information [9]). Table 1 lists the airports used, runways at eacah airport, and the number of ground points measured at each airport. The number of ground points is less than expected at PWM due to the runway approaches being over the water in some cases.

Table 1: Airport Data

State	Airport	Runways	# Ground Points
Maine	Auburn-Lewiston (LEW)	4, 22, 17 and 35	20
Maine	Portland International (PWM)	11, 29, 18, and 36	16
Ohio	Lorain County (LPR)	7 and 25	10
Ohio	Toledo Express (TOL)	7, 25, 16 and 34	20

GROUND MEASUREMENTS

The procedure for the ground measurements is to collect static data at multiple points along each approach path, to 10 NM out. A nominal spacing of 2NM between points was chosen. A ground reference station that collects data at a single point during the entire field test is used to remove temporal variation. An average value for the ASF at each point, called ASF*, is calculated for each test point. These values can then be converted to true ASF values by correcting for any system time errors. The field data collection system is shown in Figure 1.

Figure 1: The FAATC test van employed for ground data collection.

FLIGHT VERIFICATION

Flight verifications of all airport approaches were conducted using the FAATC Convair 580 (Figure 2). The procedure is to fly all approaches available at the airport, five times each. Each approach is flown along the extended runway centerline from 10NM out until the threshold. The approach starts at 4000ft AGL at 10NM out, and ends at the threshold at ~200ft above the runway. These values were chosen to capture the limits of variation; 10NM out and 4000ft AGL are the maximums for runway approaches; most approaches are actually less than this. During the flights TOAs are measured and recorded. ASF* values are also calculated real-time and recorded. To verify the approach, the TOA data is post-processed with the ACE values for the approach and position error calculated.

Figure 2: The FAATC Convair 580 employed for flight verification.

FIELD TEST RESULTS

In order to be sure of the results we needed to be sure of our field test equipment. The equipment has been described in the past [6, 7, 9, 10]. All of the pieces of equipment were tested individually to ensure the manufacturers' specifications were met prior to being assembled into the test sets. To ensure the validity of the test sets, a series of tests was conducted to examine the repeatability of the data measurements. Results include aircraft data from one year apart and ground data on the same day and several days apart.

AIRCRAFT DATA

The ground tracks for flights along the southern New Jersey shore conducted with the FAATC in October 2004 (Figure 3) and November 2005 (Figure 4) are shown. As can be seen, the aircraft flew pretty much the same path in both tests.

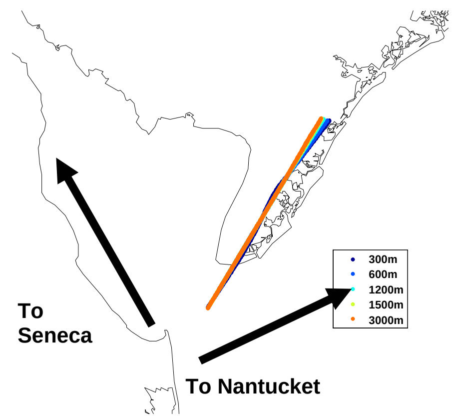

Figure 3: Ground track from aircraft test October 2004.

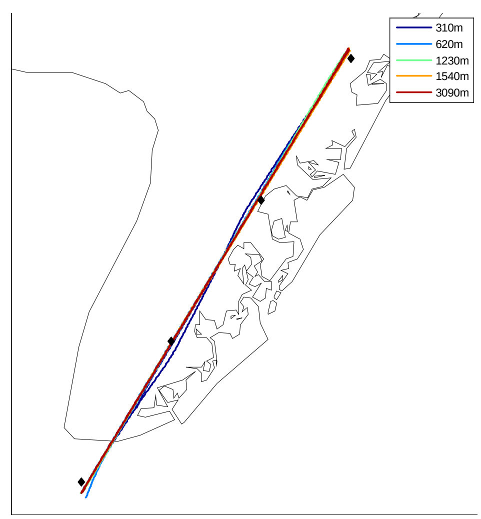

Figure 4: Ground tracks for flights in November 2005.

The measured ASF values during the flights are shown in the following sets of figures. Data for Nantucket is shown in Figure 5; data for Seneca is shown in Figure 6. In each case the ASF data has some receiver calibration bias that has not been removed so the absolute values cannot be compared; however, the relative values can be compared and it can be seen that the results were very similar from one test to the other. In the case of Nantucket there was approximately 100ns of variation across the different altitudes and along the flight track. In the case of Seneca, there was much greater variation seen, and this correlated from one year to the next.

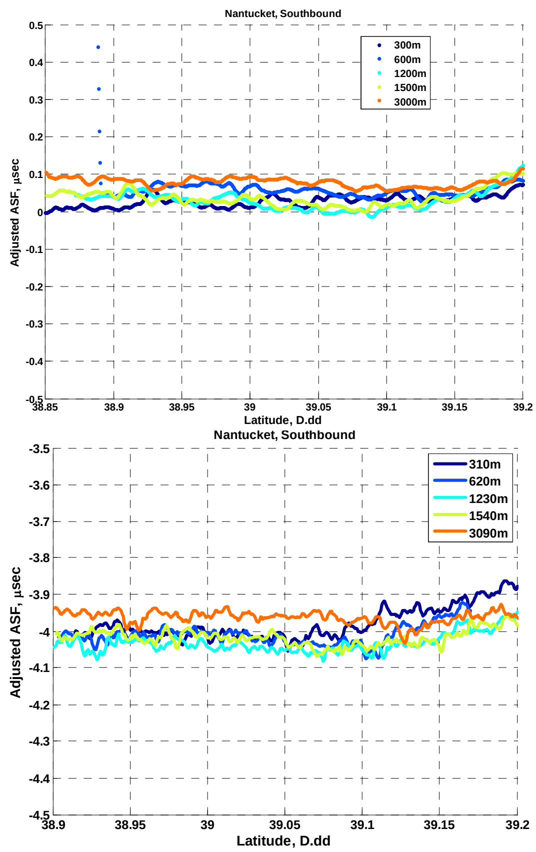

Figure 5: Nantucket ASF data; Oct 2004 on top, Nov 2005 on bottom.

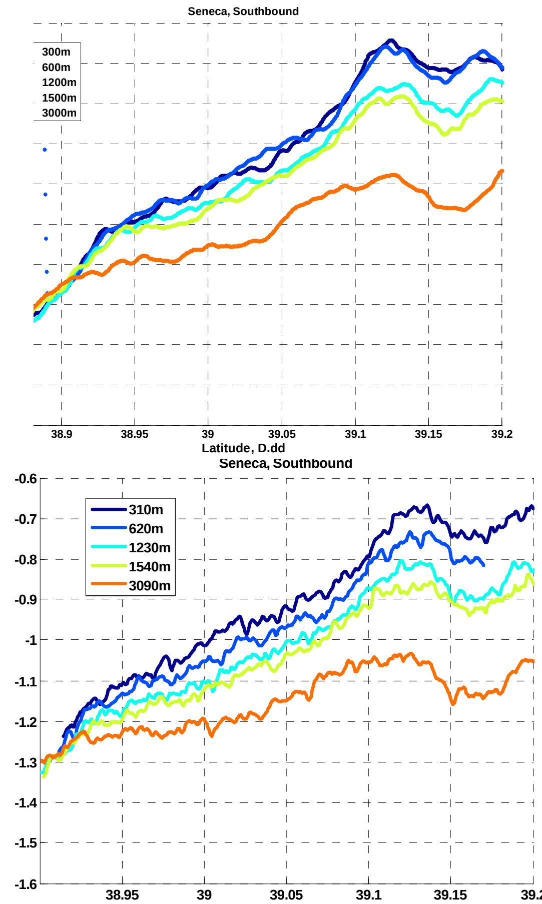

Figure 6: Seneca ASF data; Oct 2004 on top, Nov 2005 on bottom.

GROUND DATA

Additional repeatability testing was conducted using the ground measurement equipment in the test van. Data was collected for 30-60 minutes at static locations and then averaged to provide ASF estimates for that location. The van drove away and then returned to repeat the test at the exact same location some period of time later. Three test locations were used; a location near the waterfront at the USCG Academy (Figure 7), a location near the woods in Waterford, CT (Figure 8), and a location near Ocean Beach in New London, CT (Figure 9). For each test location, data was collected on two independent systems; one using an E-field antenna and one using an H-field antenna. E-field data can be compared and H-field data can be compared between the two instances, either hours or days apart. The E-field and H-field data cannot be directly compared as the two systems do not have the calibration bias removed. Data is shown for the four strongest stations. In all cases the measurements were very repeatable, with the worst case difference being 150ns, two days apart. This difference is well within the normal variation in ASFs over time.

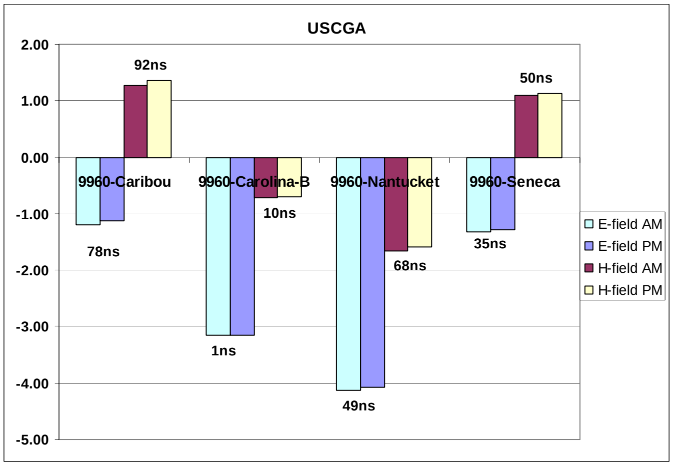

Figure 7: ASF data collected at the USCG Academy, AM and PM.

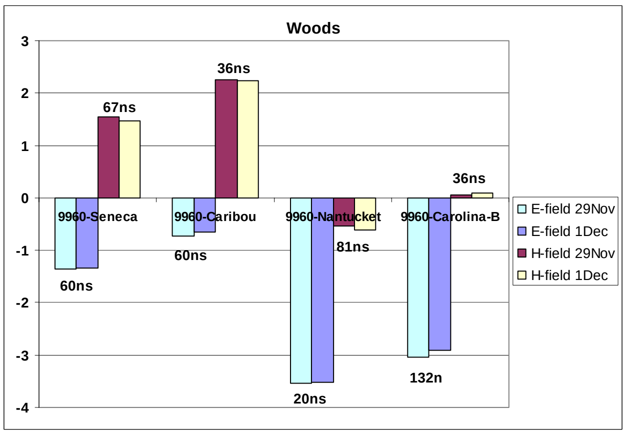

Figure 8: ASF data collected near some woods in Waterford, CT; data collected two days apart.

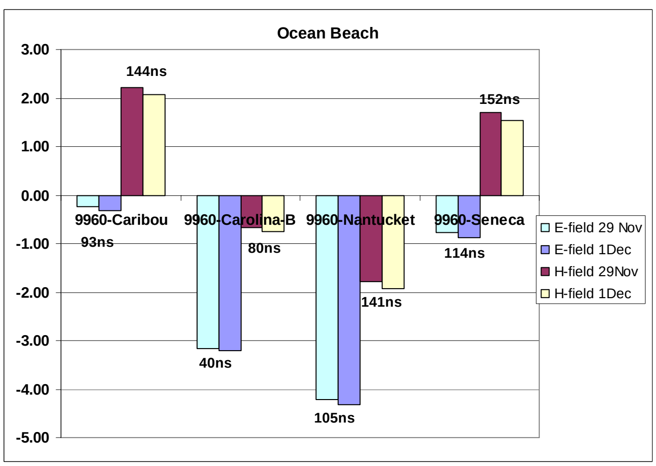

Figure 9: ASF data collected near Ocean Beach in New London, CT; data collected two days apart.

BALOR VS. MEASURED

With confidence in the measured values established, we can look at the comparison between measured values and BALOR predictions to establish the validity of the BALOR model. Two of the four airports will be presented.

PORTLAND MAINE (PWM)

For Portland, Maine, the Loran stations available for use are shown in Figure 10. The towers within 1000 km are those inside the blue circle (Nantucket, Seneca, and Caribou). Those between 1000 and 1500 km are in the pink ring (Carolina Beach, Dana, Cape Race, Comfort Cove, and Fox Harbor).

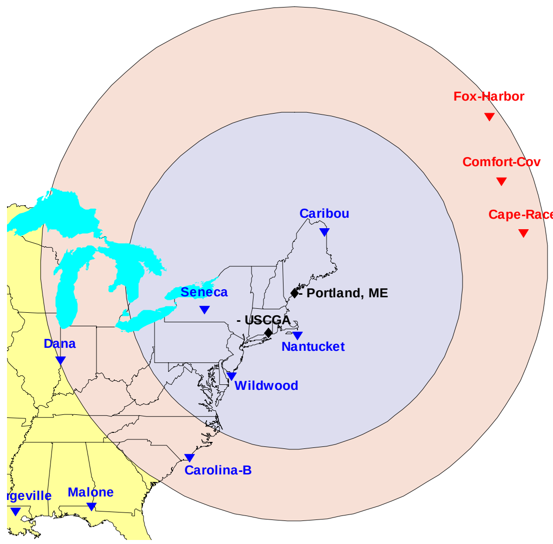

Figure 10: Loran towers around Portland; circles are at 1000 and 1500 km.

The BALOR software was used to estimate the ASFs for these stations in the area around the airport. A bounding box that contained all four airport approaches (out to 10NM was used). As an example, Figure 11 shows the ASFs for Loran station Nantucket (the approaches and coastlines are overlaid on this contour plot for convenience of viewing). This plot looks very nice; however, when compared to the measured values, it seems to fall short of our expectations. In Figure 12 the measured data for each of the survey points along the runway 11 approach (labeled RW11p0 through RW11p5) is compared to the BALOR predictions for the exact same locations. The BALOR model has two prediction methods; one based on Monteath and one based on the Wait. Each of these was run, and produced similar, but different, ASF estimates. The measured data shown in this figure is the median value for the ASF at each location. (Recall that the ground reference value has been subtracted to remove any temporal variation.) The combined noise in the actual measurement is shown by error bars (showing $\pm 1\sigma$). In an attempt to make the comparison as fair as possible, and to remove any biases in the BALOR or measured data, only relative differences are shown (the value of the first point at the airport end of the approach has been subtracted from each location's value so that all ASF values are relative to that first point). As can be seen, the measured data exhibits very different results (+500-650ns from pt0) from the BALOR predictions (-150ns from pt0).

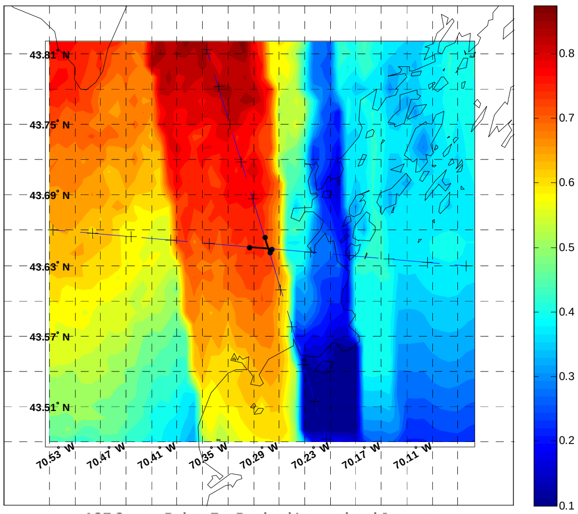

Figure 11: BALOR for Nantucket about PWM.

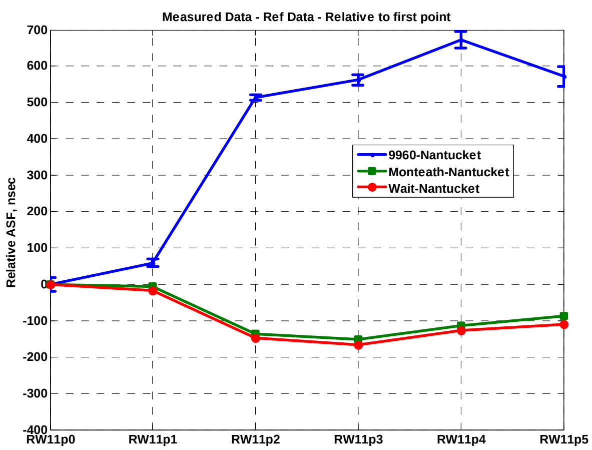

Figure 12: PWM runway 11, Nantucket, measured vs. BALOR ASFs (relative to first point).

To ensure that these results made sense (specifically, the increase in measured ASF as we moved inland), the radials from each of the Loran towers to each of the measurement points were plotted and examined (see Figure 13). Looking at Nantucket in the close-up (Figure 14), it can be seen that the paths for points 2 through 5 all cross over additional land compared to paths for points 0 and 1. This would lead to additional ASF being accumulated which matches the measured results seen in Figure 12, where there is a jump in ASF value between points 1 and 2.

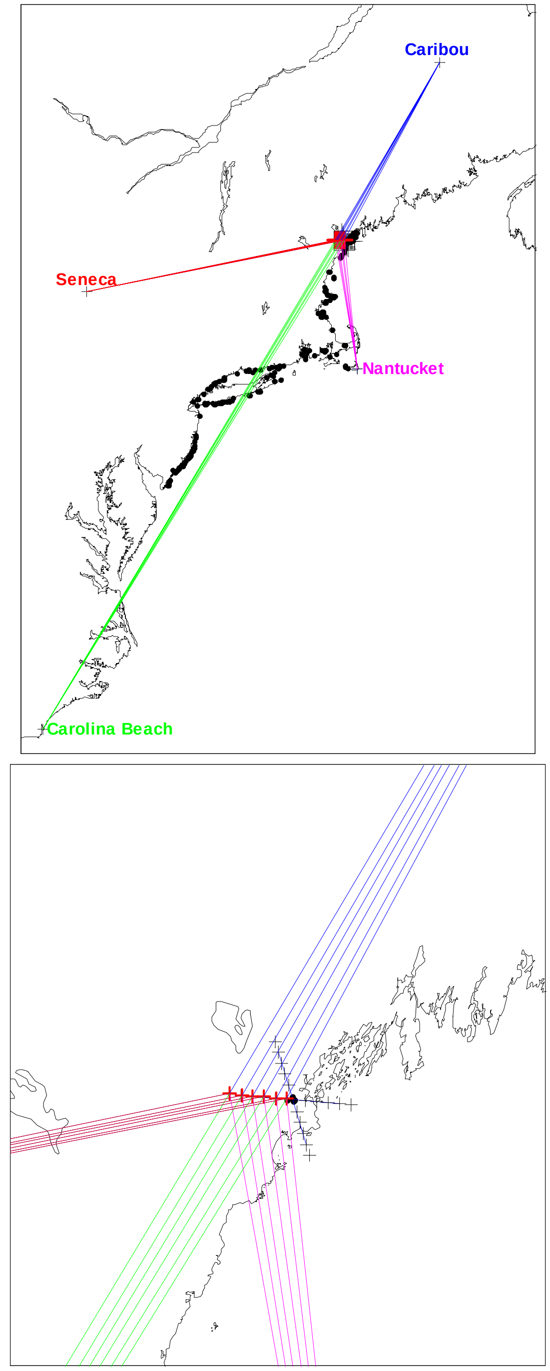

Figure 13: Radials from each of the Loran stations to each of the measurement points. Red-Seneca, Blue-Caribou, Magenta-Nantucket, and Green-Carolina Beach.

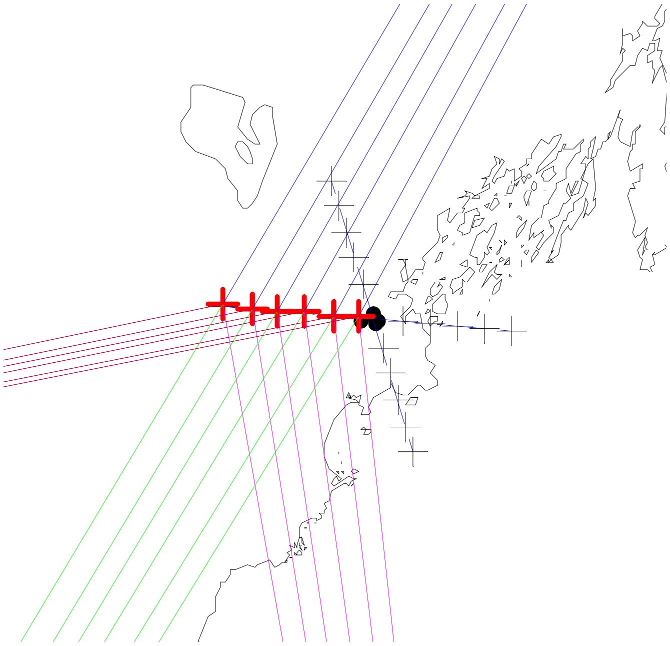

Figure 14: Further close-up of Figure 13.

LORAIN OHIO (LPR)

The second example is Lorain County Airport (LPR) in Ohio. The Loran stations available are shown in Figure 15; those towers within 1000 km are those inside the blue circle (Dana, Seneca, and Carolina Beach) and those between 1000 and 1500 km are in the pink ring (Nantucket, Malone, Baudette, Grangeville, and Caribou).

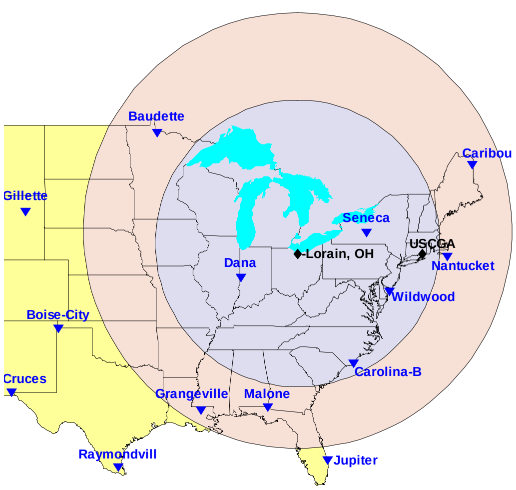

Figure 15: Loran towers around LPR; circles are at 1000 and 1500 km.

The BALOR software was used to estimate the ASFs for these stations in the area around the airport. Again, a bounding box that contained all airport approaches (out to 10NM) was used. In general, BALOR estimates of the ASFs for these stations show little variation over the airport region; as an example, Figure 16 shows the ASF for Loran station Baudette (a spread of only 100 nsec over the entire area). As before, the airport and approaches are overlaid on this contour plot for convenience of viewing. Even in this region with much fewer coastal boundaries, the correlation between the BALOR model and measured data is poor. In the comparison (Figure 17), the measured data for each of the survey points (labeled rw25p0 through rw25p5) is compared to the BALOR predictions for the exact same location. Again both Monteath and Wait BALOR prediction methods are shown, with slight differences between them. The measured data is the median value for the ASF at that location. As before, the ground reference value has been subtracted to remove any temporal variation and the ASF difference from the first point is plotted. The combined noise in the measurement is shown by the error bars (±1σ). As can be seen, the measured data exhibits very different results (+150ns max difference from pt0) from the BALOR predictions (-50ns max difference from pt0).

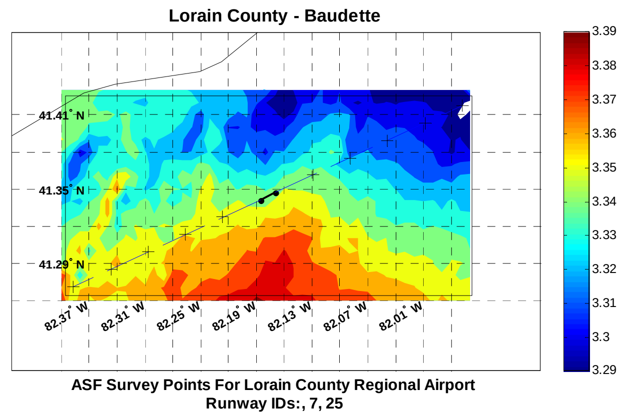

Figure 16: BALOR for Baudette about LPR.

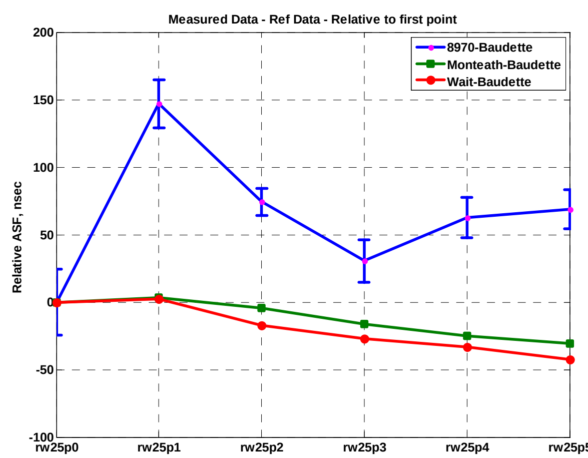

Figure 17: LPR runway 25, Baudette, Measured vs. BALOR ASFs (relative to first point).

Again, to see if there are any geographic clues as to the results, the radials from the Loran towers to each of the measurement points are plotted (Figure 18). A close-up is shown in Figure 19. Unfortunately, neither of these pictures gives any real clues as to why point 1 is so much higher than point 0.

Figure 18: Radials from each of the Loran stations to each of the measurement points: red-Seneca, blue-Dana, magenta-Baudette, and green-Carolina Beach.

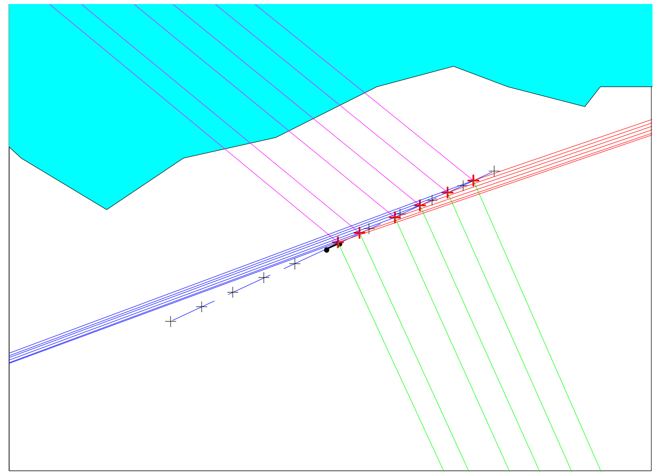

Figure 19: Close-up of Figure 18.

As described in [11, 12] BALOR employs both a terrain and ground conductivity database as inputs for its calculations. The DTED terrain database is quick detailed, with small resolution cells. Unfortunately, the same cannot be said for the existing ground conductivity database. Its basis is the FCC conductivity map developed in 1954 (reproduced in Figure 20). This database has a very poor resolution, which undoubtedly leads to errors in the ASF calculations, especially over short distances

Figure 20: Ground Conductivity of the U.S., from the FCC Conductivity Database of 1954.

FLIGHT VERIFICATIONS

IN-FLIGHT ASF MEASUREMENTS

During the Convair flights the TOAs were measured and the ASFs calculated. The difficulty with in-flight ASF calculations is that the Loran receivers average the TOA readings over a period of time. Since the aircraft is moving fairly rapidly, this leads to large errors in the ASF calculations. By making measurements of the Loran receiver's performance using our Loran simulator we have been able to model the receiver characteristics in order to minimize the effect of this receiver averaging and determine the correct ASFs (in a post-process mode). The ASFs calculated from the flight data are not as accurate as the ground measurements because of this procedure, the higher noise environment of the aircraft, and the inability to average the data as is done for the static locations. However, the advantage of the in-flight ASF measurements is that data samples are collected every second along the flights allowing for data points nearly continuously along the 10NM approach paths. Data across a wider area can also be collected much more rapidly.

The GPS ground tracks for the flights at Portland International (PWM) are shown in Figure 21. Approaches were flown for each of the four runways, five times each. The four runway approaches (from 10NM out to the runway threshold) are color-coded. To save flight time, some approaches are flown inbound to the runway end and some outbound. The black crosses indicate the locations of the ground static measurements.

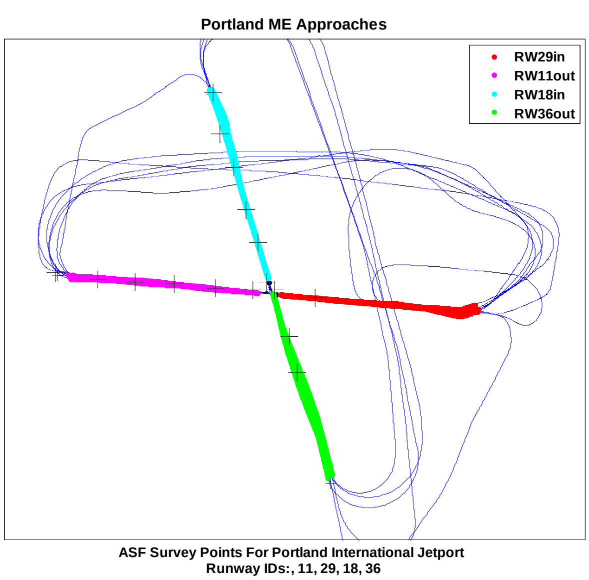

Figure 21: Portland, ME (PWM) flight tracks: each runway approach is color-coded; crosses indicate the locations of ground measurements.

The ASF data from the strongest stations are plotted for runway 36 (Figure 22 – Loran stations Seneca, Caribou, Nantucket, and Carolina Beach) and runway 11 (Figure 23 – Seneca, Nantucket, and Carolina Beach only). In each case, the ASF value relative to the ASF value of the runway threshold is plotted as a function of distance from the runway threshold. As can be seen, the data is very repeatable across the 5 approaches, with 50-100ns of noise variation. The maximum spread in ASF values is about 700ns at 9.5NM for runway 36 and about 600ns for runway 11.

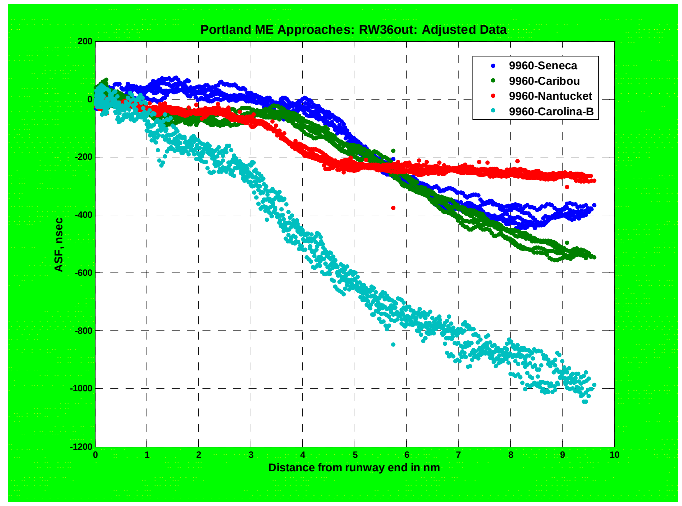

Figure 22: PWM Runway 36 (green track in Figure 21) – five approaches, all plotted as ASF relative to the runway end versus distance from the runway end.

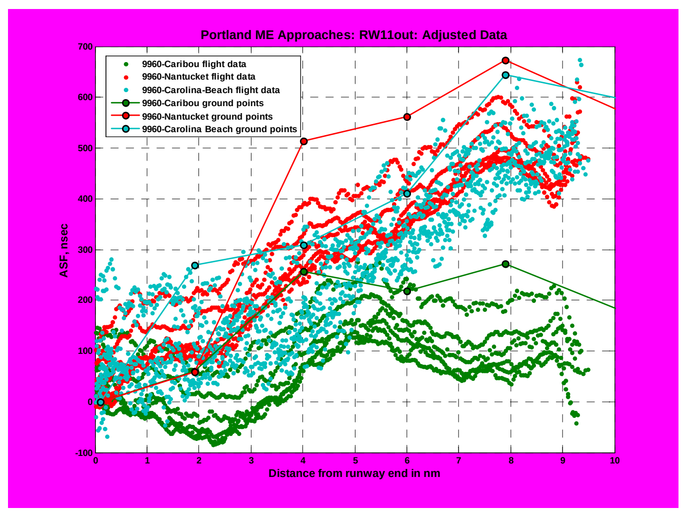

Figure 23: PWM Runway 11 (pink track in Figure 21)– five approaches, all plotted as ASF relative to the runway end versus distance from the runway end.

As a comparison, the more accurate ground measured ASF values are plotted on runway 11 (Figure 23) where we have data for the entire approach path (since it is over land). As can be seen, there is reasonable agreement between the ground and in-flight measured data. Some differences are to be expected due to the altitude differences (discussed at length in [9]) and small cross-track variations in position.

Similar data is presented below for Lorain County (LPR) airport. The GPS ground tracks and the two color-coded approaches are shown in Figure 24. The black crosses again mark the locations of the ground measured data. The ASF data, in the same format as described previously (relative ASF versus distance out) is shown for both runways; runway 7 in Figure 25 and runway 25 in Figure 26. For runway 7 data is shown for the three strongest stations; Dana, Seneca, and Carolina Beach. The flight data still shows the 50-100ns noise variation. For this airport the ASF variation is much smaller than at PWM, showing a maximum spread of perhaps 250ns. Since the ASF variation is not much larger than the noise, a polynomial fit to the flight data is shown for Carolina Beach (solid line). The ground measured data for Carolina Beach is also shown and shows reasonable agreement. For runway 25, the ASF variation is also small. To improve visibility of the graph only the flight data from Seneca is shown. A polynomial curve fit has been added (solid line) and the ground data. Again good agreement between ground and flight data is seen.

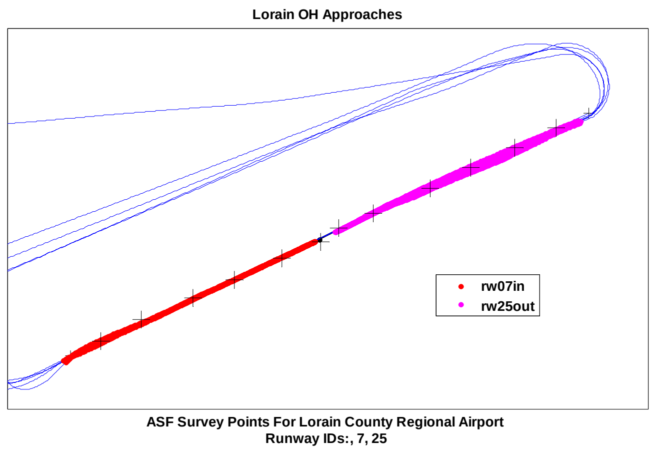

Figure 24: Lorain County, OH (LPR) flight tracks: each runway approach is color-coded; crosses indicate the locations of ground measurements.

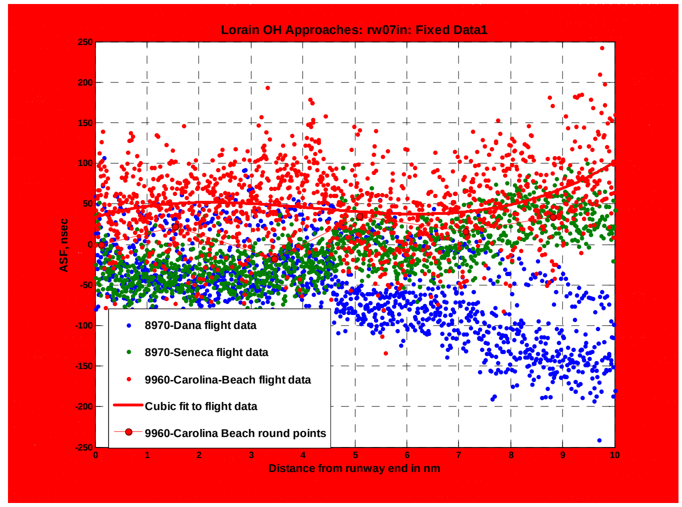

Figure 25: LPR Runway 7 – five approaches, all plotted as ASF relative to the runway end versus distance from the runway end.

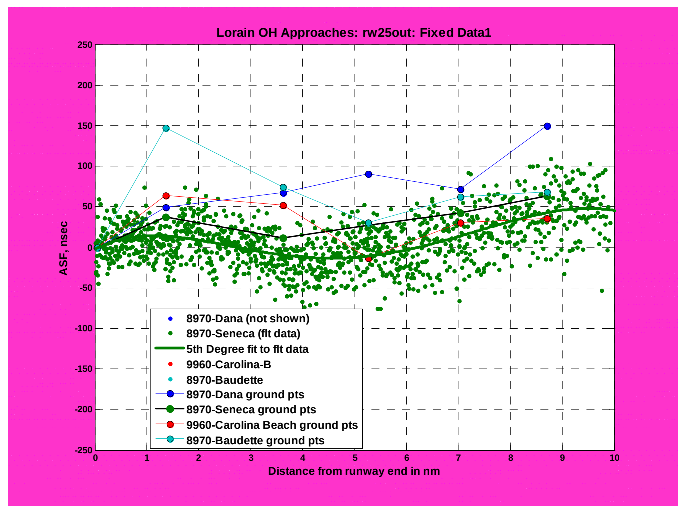

Figure 26: LPR Runway 25 – five approaches, all plotted as ASF relative to the runway end versus distance from the runway end.

POSITION ACCURACY

The key performance metric is the position error along the flight path. The bound allocated to the position domain is 120m (cross-track). For each of five approaches to each runway at each airport, the position error (using GPS as the ground truth) is calculated for each Loran position. The uncorrected Loran position error is shown in each graph in red.

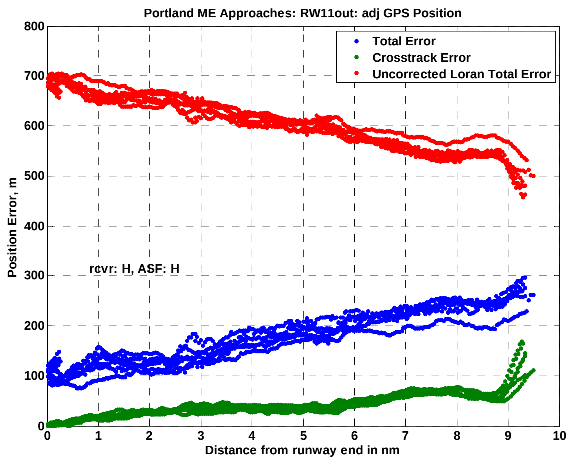

Figure 27: PWM, runway 11 – position error along the approach, plotted as error versus distance from the runway end.

A single set of static ASFs for each runway is applied to the measured TOAs and correct Loran positions calculated. The error in this corrected Loran position is shown in blue. The error is then split into the along-track and cross-track components, and the cross-track error shown in green. In all cases the error is plotted as a function of distance from the runway end. Two examples are presented here: PWM runway 11 (Figure 27) and LPR runway 25 (Figure 28). In both cases, the total error exceeds 120m at some points, but the cross-track error is always less than the 120m bound. There is less error with distance at LPR since the ASFs do not vary spatially as much as at PWM. The sharp rise in error beyond 9NM at PWM runway 11 is due to the aircraft starting a turn at that point.

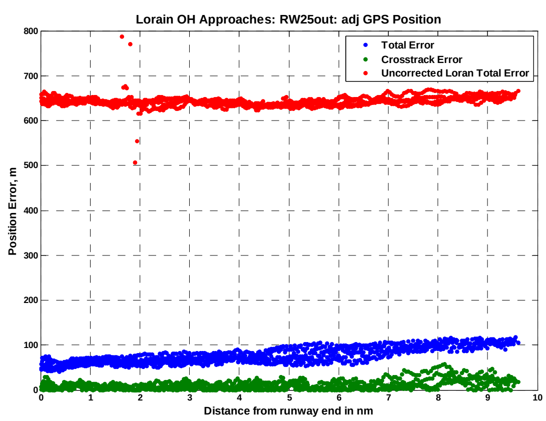

Figure 28: LPR, runway 25 – position error along the approach, plotted as error versus distance from the runway end.

CONCLUSIONS / FUTURE WORK

The BALOR model for estimating ASFs has shown to have poor correlation with measured data. This makes it not as useful for the proposed "ASF Airport Methodology" as we had hoped. Some of this error appears to be due to code/algorithm errors in not always recognizing the crossing of coastal boundaries. This may be resolved in the near future as colleagues at Ohio University are working on fixes/enhancements to the BALOR code. A second potential error source is the poor resolution of the conductivity database; unfortunately there is no short-term fix for this.

Some additional work will be done in the future to examine BALOR performance across longer distances. Flights will be conducted in March 2006 along 1000+km baselines towards and away from Loran towers. The measured ASFs along these baselines will be compared to the BALOR predictions along these paths to see if the BALOR model provides reasonable results on a macro scale.

One conclusion from this work is that the proposed airport ASF methodology should be re-examined and changed to an alternative method with less reliance on the BALOR software. One such approach may require more field testing at each airport than originally planned; possibly using flight data in order to guarantee that the worst-case ASF variations are captured and do not exceed the position domain error bounds.

For the airports and runways tested to date, applying a single set of static ASF corrections before computing the Loran position keeps the cross-track error below 120m along the approaches.

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DISCLAIMER AND NOTE

The views expressed herein are those of the authors and are not to be construed as official or reflecting the views of the U.S. Coast Guard, Federal Aviation Administration, or any agency of the U.S. Government.

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