The Big Picture on ASFs: The Validity of Predicted ASFs over Long Distances

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Abstract

Recently, the Loran-C system was identified as a possible backup for GPS in en route aircraft navigation to replace the current radar-based systems. In its current state, the Loran-C position determination solution assumes a uniform propagation speed of the Loran signal, regardless of weather, terrain, or ground conductivity. In reality, these factors severely affect the propagation speed and, hence, the Loran position solution - at times offsetting it by more then a mile. Efforts are currently underway to survey major harbors and airports to create ASF correction grids. In addition, a network of Loran ASF monitors is being deployed. However, these correction grids and monitors will be useful only in few select locations; there are no plans for wide area surveys. In this paper we evaluate an alternative method for improving Loran accuracy by using computer generated ASFs. The paper discusses four different ASF modeling methods provided by two different software packages, namely Balor and Lups. The evaluation is based on measured ASFs that were collected on board of an FAA airplane, flying long straight paths between chosen Loran towers. The paper shows graphical and quantitative analysis of the ASF modeling tool's performance, highlighting specific cases of their fallibility, differences between methods, and a comparison with measured data. To demonstrate what level of improvement in accuracy can be achieved using computer generated ASF grids for CONUS, those ASFs were employed in the Loran position solution of sample Loran data and compared with non-corrected positions. This paper shows that ASF modeling tools do improve Loran accuracy. Further, for the examples tested, the predicted ASFs were able to meet RNP (1.0) requirements; however additional evaluation should be done to prove it for larger navigation areas.

Introduction

The position solution available from the Loran system, while highly repeatable, suffers from poor absolute accuracy (particularly when compared to GPS). The primary reason for this is something called Additional Secondary Factors (ASFs) which are additional time delays in the propagation of the Loran signal between the Loran station and the user receiver. Common causes of ASFs include varying ground conductivity, topography, and weather.

Much effort has been expended over the years to mitigate the effects of ASF – primarily by trying to estimate the ASF (per Loran signal) and remove it before implementing the Loran position solution, including work by these authors [1-7]. As part of this work researchers have followed one of two approaches: (1) measuring the ASFs at fixed ground points (via some survey methodology) and then interpolating these fixed points for locations in between and (2) constructing a mathematical model (perhaps based on ground conductivity and topography) and computing/predicting the ASF at desired locations. While the first method can produce high quality measurements at the survey points, it obviously suffers from high cost if the number of points to be collected is large, the difficulty of deciding how close the survey points need to be (and where), the question of how far away one can be from a survey point and still believe that the ASF value is reliable, and the potential inability to easy access the chosen survey points. The second method, being computational, allows one to potentially generate large grids of ASF predictions; the primary concern is how accurate those predictions really are.

One of the tasks for the ASF Working Group of the Loran Accuracy Panel (LORAPP) is to examine the use of Loran for various types of navigation with their different accuracy requirements; these include non-precision approach (NPA) at airports with a Required Navigation Performance of 0.3 NM (RNP 0.3), ship navigation in harbor entrance and approach (HEA) with a 8-20 meter requirement, and more recently en route aircraft navigation with RNP 1.0. In prior work on this tasking we have considered the use of the BALOR[1] model for predicting the ASFs for both the non-precision approach and harbor entrance and approach scenarios [3, 4, 8]. The primary result of these investigations was that the accuracy requirements for these two navigation situations were sufficiently stringent to preclude the use of BALOR as the primary ASF tool. BALOR is still proposed to do some initial modeling for large scale effects, but surveys are envisioned for the actual ASF computation. For the non-precision approach scenario, a single ASF point at the airport center has been proposed and tested [7]; for the harbor entrance and approach problem, a relatively dense grid of ASF values is to be developed [9]. More recently, we have begun exploring the ASF correction problem for en route navigation.

The primary issue with extending the harbor grid method to en route navigation is the cost of measuring the ASF grid values themselves. While site surveys provide accurate values, it is not practical to conduct ground surveys for the extremely wide areas needed for en route navigation. While we do envision that the non-precision approach task will produce ASF values at airports covering CONUS, this “grid” is probably not dense enough to provide sufficient ASF accuracy for RNP 1.0. Further, the accuracy requirements of RNP 1.0 do not require the same precision of survey as does harbor or airport navigation. Hence, in this case, it might be possible to use computer modeling to provide sufficient ASF accuracy to meet the requirements that uncorrected Loran can not meet by itself. Such is the topic of this paper.

In this paper we present our findings on where using predicted ASFs (pASFs) make sense, and also scenarios where they fail. In the first section “Previous BALOR Validation” we briefly highlight our previous pASF analysis for small areas such as harbors and airport approaches. The rest of the paper will deal with predicted ASFs for en route aircraft navigation and generating large coverage area ASF grids for the whole continental United States.

Previous BALOR Validation

In our previous work with ASF modeling we evaluated BALOR’s usefulness for harbor entrance and approach pre-survey evaluation [4]. We also compared BALOR grids with our survey data from non-precision airport approach (NPA) ASF mapping, where we surveyed runway approach paths, 10 miles out, at 2 miles spacing [5, 7, 8]. We found the current version of ASF prediction software to be unsuitable for these cases. Over small areas, the BALOR conductivity database does not have a fine enough granularity to predict local variations, as the following two airport examples will illustrate.

Figure 1 shows the ASFs for Loran Station Nantucket obtained during the summer of 2005 in Portland, Maine. The blue line is the measured data (with error bars) and the red and green lines

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[1] BALOR is a Loran ASF and signal strength prediction tool originally developed by the University of Wales at Bangor. Further development on the software has been done by Ohio University with FAA funding.

are predicted values generated by two different BALOR methods (Wait and Monteath). This is a fairly complex case for the modeling software as the signal's propagation path from the tower is a combination of both seawater and land. For the measured data, we used the value at the runway end to remove any bias in the measurements; in other words, at the runway end (the left hand point in this graphic) we biased the measured ASF so that all three values were equal. Notice that as we go farther out from the airport (moving to the right in this graphic) the measured ASFs increased significantly while the predicted ASFs stayed relatively constant. Figure 2 shows similar results for a runway approach in Lorain County, OH. In this case it is an all land path to the transmitter. Again the measured survey data bears little correlation to the predicted ASFs although the absolute difference is small (under 200 nsec).

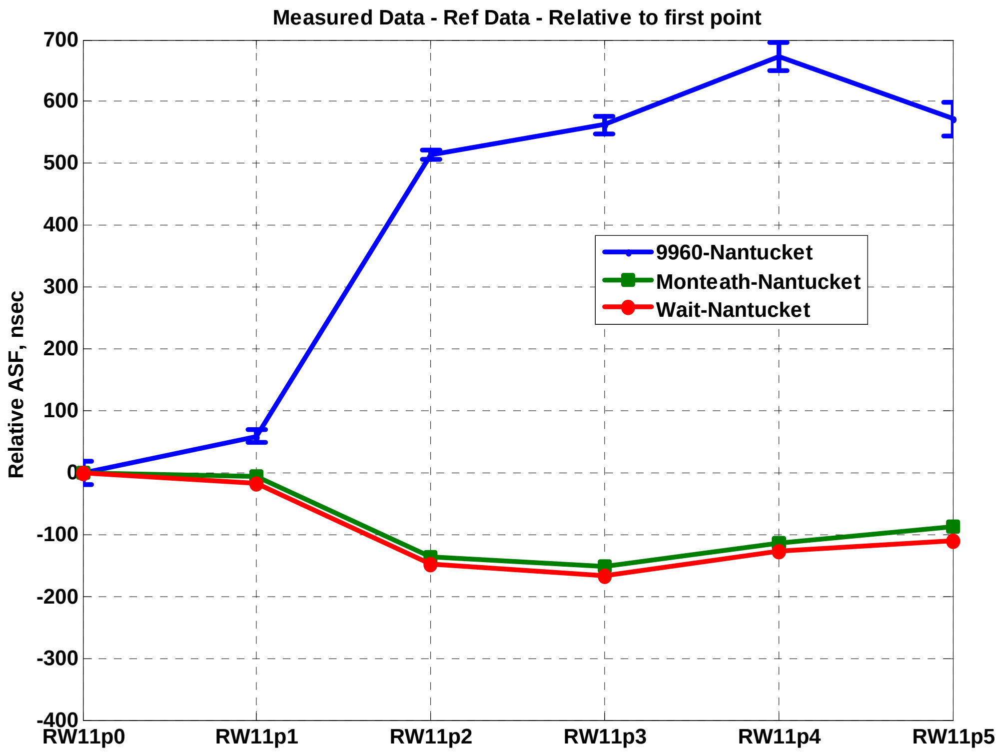

Figure 1: Nantucket ASFs along the approach path for Runway 11 at Portland International Airport (PWM).

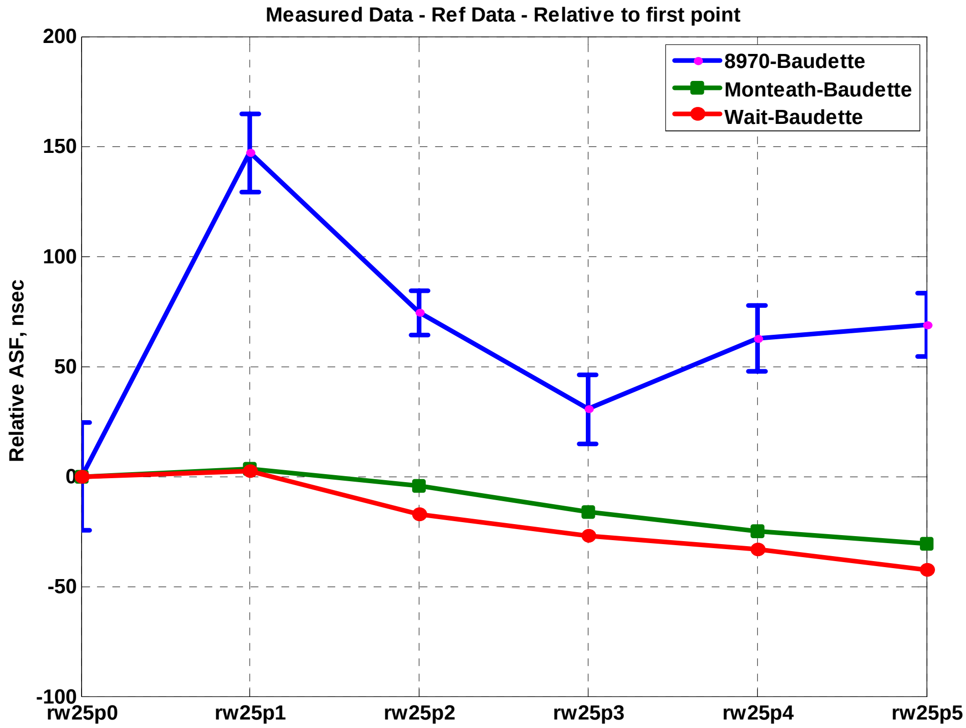

Figure 2: ASF data for Baudette along the approach to runway 25 at Lorain County airport (LPR).

Long Baseline Flights

Although the current implementation of BALOR does not seem to adequately model the fine variations along runway approaches or within harbors, it may be suitable for examining ASF variations on a larger scale. This would allow it to be used for CONUS-wide predictions to improve en route navigation and, potentially, for ADS-B. In this section we evaluate the usefulness of BALOR for en route navigation by comparing predicted ASFs with ASFs recorded onboard an aircraft, flying relatively straight paths, for long distances. Of particular interest are flights along a baseline between Loran stations for which the propagation path of the signal is common.

Our analysis below is based on data collected with the FAA Convair 580 aircraft in June of 2006. Figure 3 illustrates the ground path flown by the airplane, as well as relative bearings to the relevant Loran towers. The GPS positions along each path are indicated in blue. The cyan arrows indicate the bearing to the tower being flown towards; the magenta arrows the bearing to the tower being flown away from. The green and red arrows indicate the bearing to the towers off to the side of the path (and show the most variation in bearing). In our examination below, this flight is broken down into five discrete segments: Nantucket to Dana, Dana to Raymondville, Raymondville to Jupiter, Jupiter to Carolina Beach and Carolina Beach to Nantucket.

Figure 3: Flight paths for the long baseline flights in June 2006.

For each segment the measured ASF was compared to predicted ASFs using the following methods: BALOR v3.1 Wait, BALOR Monteath, BALOR v3.2 Wait, and LUPS[2]. For the measured data, the receiver averaging was removed; further, we compensated for the altitude of the receiver (as described in [6]). We factored out altitude from the measured ASFs because the ASF prediction methods currently do not take into account the altitude of the receiver. Overall though, for the altitudes flown, the altitude correction is fairly minor, under 100 ns. Relative bearings to the towers were also checked to ensure that variations in bearing did not contribute to ASF mismatches from H-field antenna directional effects since the pASFs do not include any antenna effects.

Figure 4 is typical of our analysis, showing the Jupiter to Carolina Beach flight. The x-axis on each subplot is the distance from the Jupiter tower. The top graph shows the measured ASFs for Jupiter, with and without altitude correction, along with the four predicted values. Note that the altitude was kept nearly constant for the duration of the flight, as illustrated by the middle graph, so it will not contribute to any mismatch between the measured and predicted ASFs other than a small bias term. As this was the case for all of the flights, altitude will not be shown on the subsequent plots. Further, for this segment, the relative bearing to the Jupiter tower was also fairly constant, so any directional effect of the H-field antenna used for measured data was minimal. Again, for the towers at the endpoints of the segments this was generally the case.

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[2] LUPS is another ASF prediction tool; this software was originally developed by Illgen Technology for the FAA. Further development on the user interface was done by Alion Science & Technology.

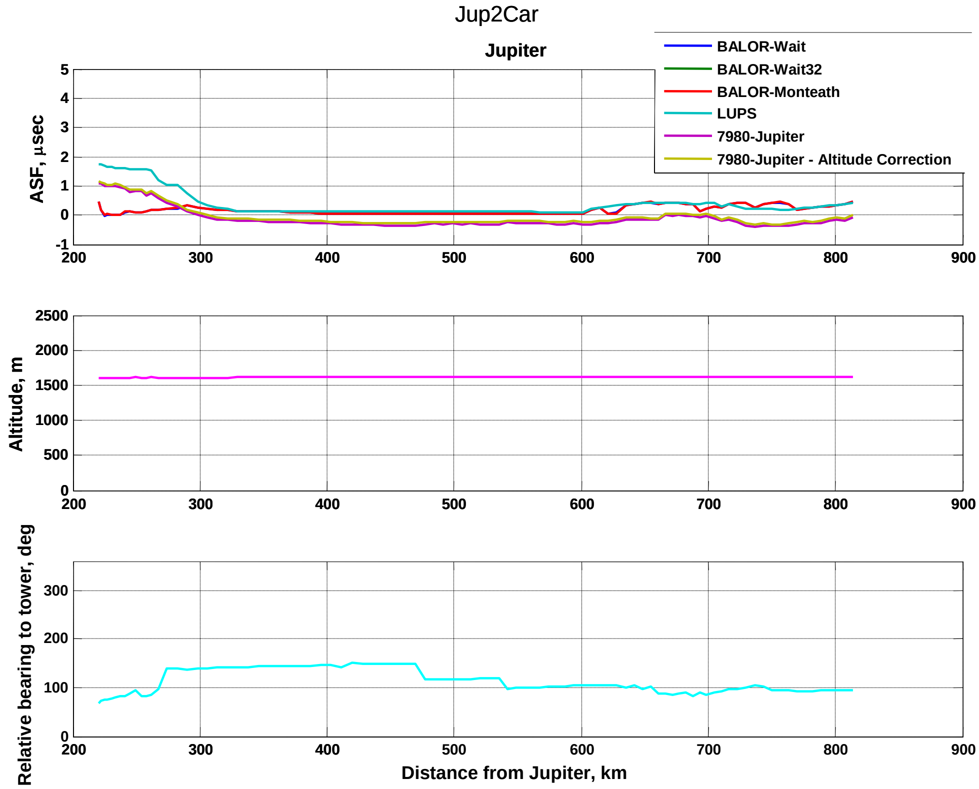

Figure 4: ASFs, Altitude, and Relative Bearing for Loran Station Jupiter on the Jupiter to Carolina Beach leg.

Difference between Methods

Figure 5 is a close-up of a portion of the ASF plot in Figure 4 to illustrate the differences between the methods used to predict ASFs. Specifically, we note that improvements in BALOR Wait version 3.2 made it very close to the LUPS prediction (the green and cyan lines); both of which tracked very closely (except for a bias) with the measured data (purple and mustard lines). The BALOR Wait version 3.1 performed similarly to the BALOR Monteath version 3.1 method (blue and red lines), both of which were poorer in performance than the newer version of BALOR. This shows that the changes made to the BALOR code have improved performance; thus only BALOR v3.2 results will be shown in the subsequent plots.

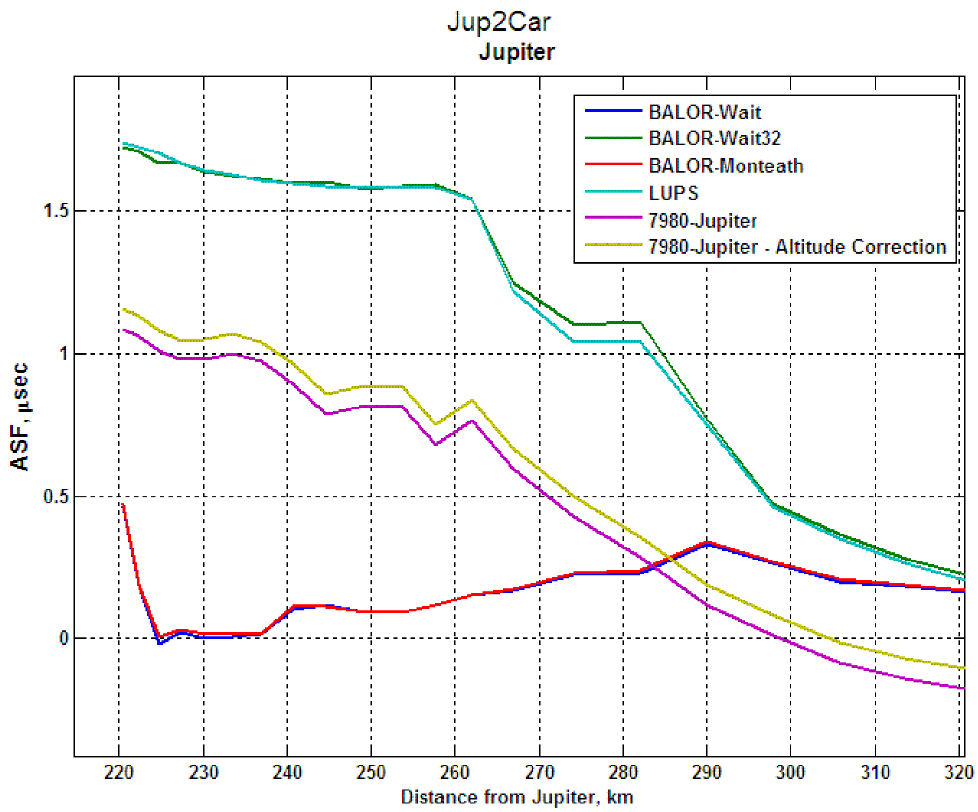

Figure 5: Close-up of Figure 4.

Figure 6 shows the Nantucket to Dana segment, this time for the Dana Loran signal. Here the BALOR method follows LUPS very closely. Both pASFs track the measured data (purple) closely although the measured data has a bit more slope then the pASFs. Figure 7 shows how the pASFs compare to measured data for the Nantucket tower on the same segment. As already noted, heading and altitude were constant so that antenna and altitude effects were minimal. Again the pASFs track well with the measured ASFs. Interestingly, here the BALOR Wait 3.2 method has a constant offset that is probably introduced by an error in BALOR's coastline conductivity database. LUPS is very close to the observed ASFs although smoother.

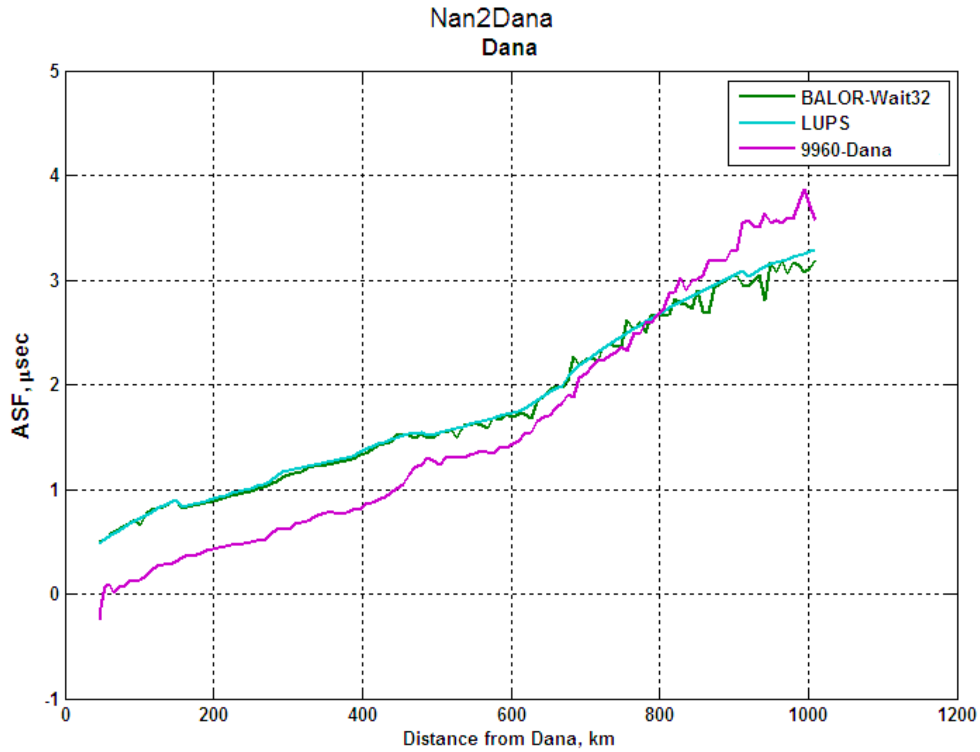

Figure 6: ASFs for Loran Station Dana on the Nantucket to Dana segment.

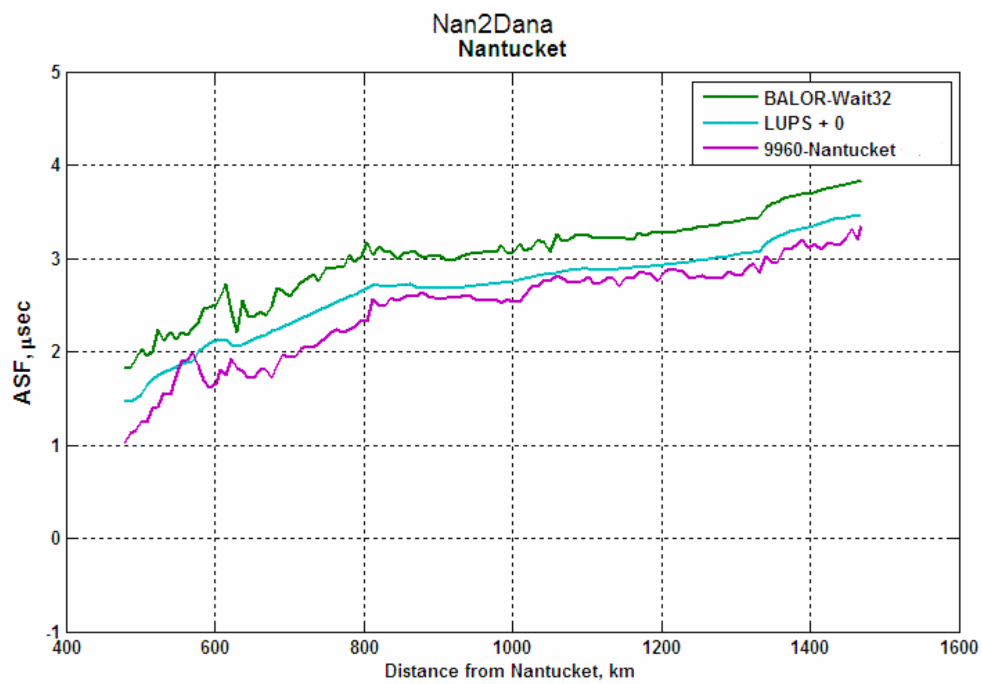

Figure 7: ASFs for Loran Station Nantucket on the Nantucket to Dana segment.

Directional Effect of H-field Antenna on Measured Data

One of the issues that we encountered was a directional error in measured data from an H-field antenna. This has been investigated and reported on in the past [10-12] and continues to be a noticeable effect. For example, on Raymondville to Jupiter segment (see Figure 8), the relative bearing from the airplane to the Malone transmitter (green arrows) went through a 90 degrees shift. The impact of this on the measured ASFs can be clearly seen in Figure 9. As the plane passes the Malone station, the signal path is mostly seawater, so we would expect ASFs for incoming and outgoing legs to be quite similar, close to the predicted values (green and cyan lines). However, the purple line shows that the measured data is affected by antenna heading, by as much as 400 nanoseconds. For this reason, analysis was only done on those stations at the endpoints of the paths as the relative bearings to those stations was generally constant.

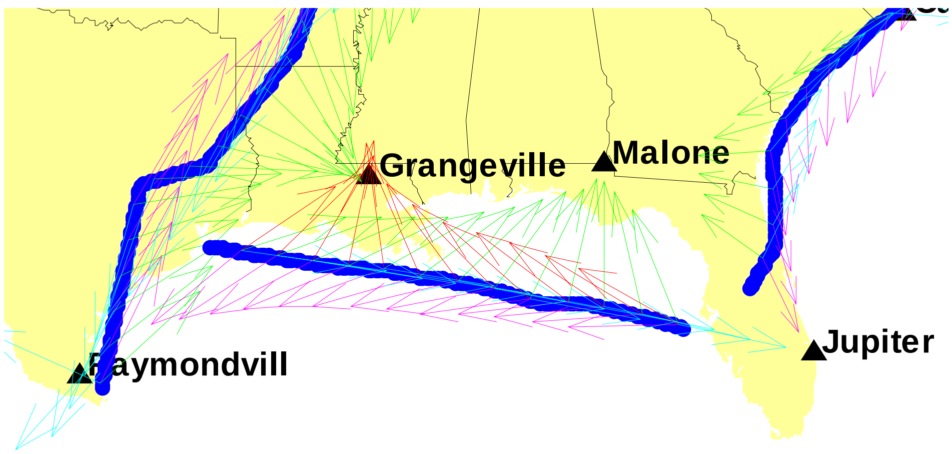

Figure 8: Close-up view of the Raymondville to Jupiter segment.

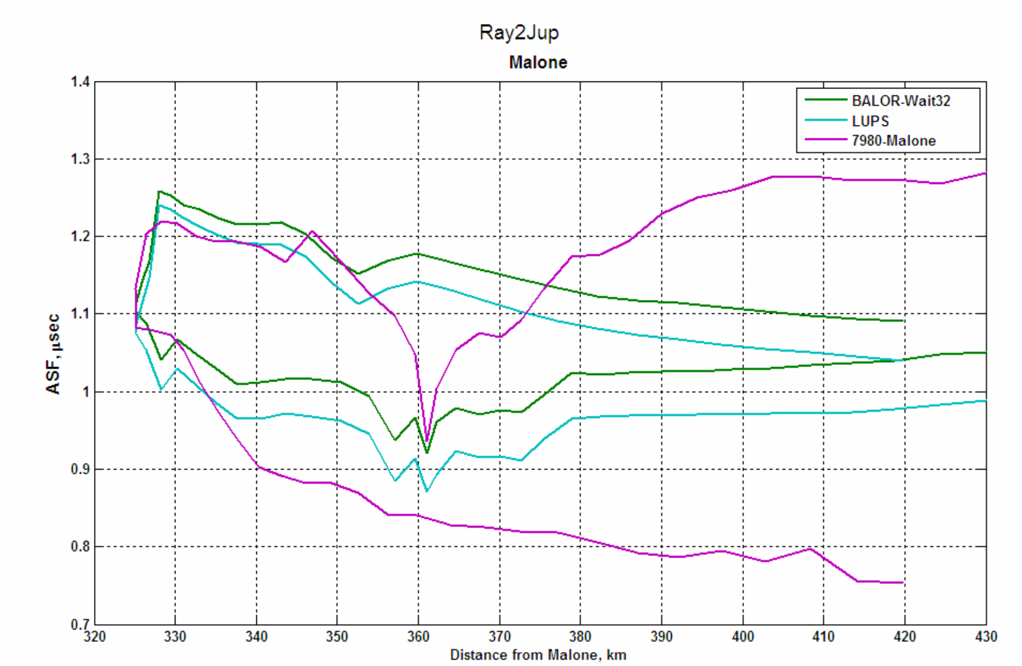

Figure 9: ASFs for Loran Station Malone on the Raymondville to Jupiter segment.

Measures of "Goodness"

One question we attempted to answer was which pASF method was better. We attempted to answer this by looking at the root mean square error (RMSE) between the pASF and the measured ASF values along the paths. We also looked at the bias terms – ideally these should be constant for all stations in the same chain on the same path. Table 1 is a breakdown of the quantitative analysis of measured vs. predicted data for the flight from Nantucket to Dana. In this case LUPS outperformed the BALOR Wait method as the RMSE was about 10% lower. Also, the computed bias was consistent for Dana and Nantucket stations for LUPS, while for BALOR it was 4µs for Nantucket and 3.7µs for Dana. Bearings to both stations on this flight were fairly constant, so antenna error is minimal. Altitude was also constant.

Table 1 – Sample analysis for the Nantucket to Dana segment

	Wait 3.2	LUPS
Nantucket RMSE	137 ns	115 ns
Dana RMSE	365 ns	335 ns
Nantucket Bias	4059 ns	3705 ns
Dana Bias	3699 ns	3729 ns

One of the problems with predicted ASFs is inconsistent accuracy. Table 2 has the calculated average accuracy for LUPS along each of the segments. In some cases this error was pretty low, around 110 nanoseconds for the Carolina Beach to Nantucket, and the Jupiter to Carolina Beach flights; while in case of the Dana to Raymondville flight it was twice as big, on the order of 240 nanoseconds.

Table 2 – LUPS path accuracies

Path Segment	RMSE Error
Nantucket to Dana	221 ns
Dana to Raymondville	244 ns
Raymondville to Jupiter	129 ns
Jupiter to Carolina Beach	110 ns
Carolina Beach to Nantucket	106 ns

Our final comparison of pASF methods, in Table 3, shows the RMS error between the measured and predicted ASF, averaged for all five segments that were flown. The results in this table show a significant improvement in the Wait method from version 3.1 to 3.2. For this comparison we only used stations with constant relative bearing so as to minimize inaccuracies in measured data from the directional effect of H-field antennas.

Table 3 – RMSE averaged across all 5 paths for each method

Method	Avg. RMSE Error
LUPS	164 ns
BALOR Wait v3.2	181 ns
BALOR Monteath v3.1	231 ns
BALOR Wait v3.1	251 ns

CONUS Grid

To provide an idea of the real-world accuracy performance of the pASF algorithms we generated predicted ASFs grids for the continental United States (CONUS) using both the LUPS and BALOR Wait 3.2 methods. These ASFs were than applied to TOAs measured by a SatMate 1030 receiver on several long flights during which we simultaneously recorded Loran TOAs and GPS position, the goal being to measure performance in the position domain.

Figure 10 shows the pASF grid for Nantucket generated using the BALOR v3.2 Wait method. The ASFs are plotted using contours in the range from 0 (dark blue) to 12 (dark red). Nantucket tower is in the upper right corner.

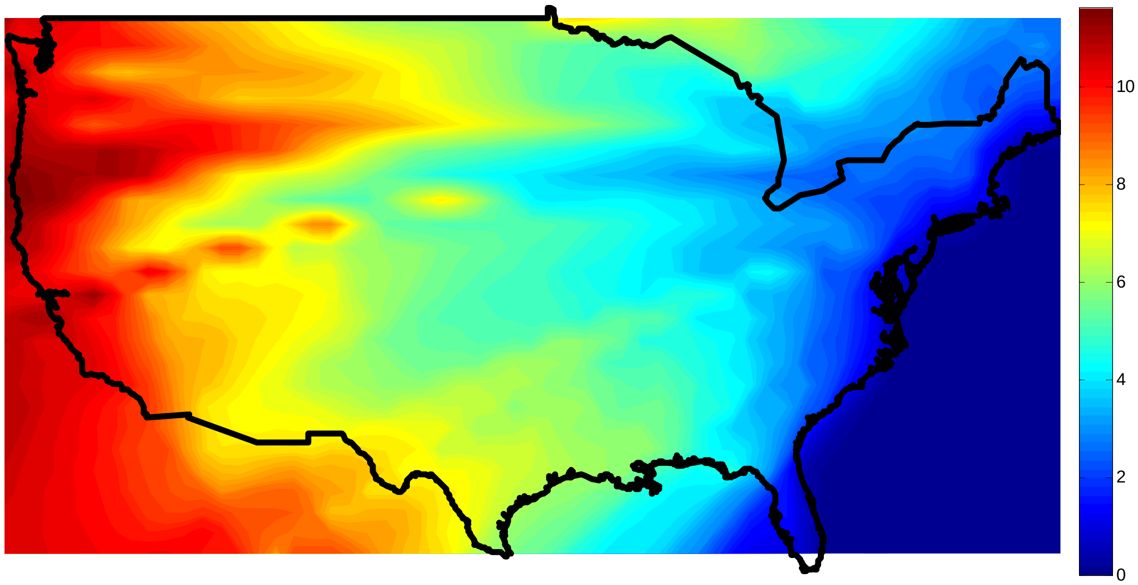

Figure 10: BALOR Wait 3.2 Predicted ASF grid for Nantucket.

Before we continue, we provide a snapshot of how BALOR works. Specifically, BALOR calculates grids by integration along radials as shown in Figure 11. These radials are then interpolated to produce an evenly spaced grid. In the future, BALOR's accuracy is expected to improve as there is work being done on its conductivity database. It has been noted that the current conductivity database (as surveyed in the 1950s) doesn't align well with the coastline. This leads to errors in the ASFs along some radials (which are visible in Figure 11).

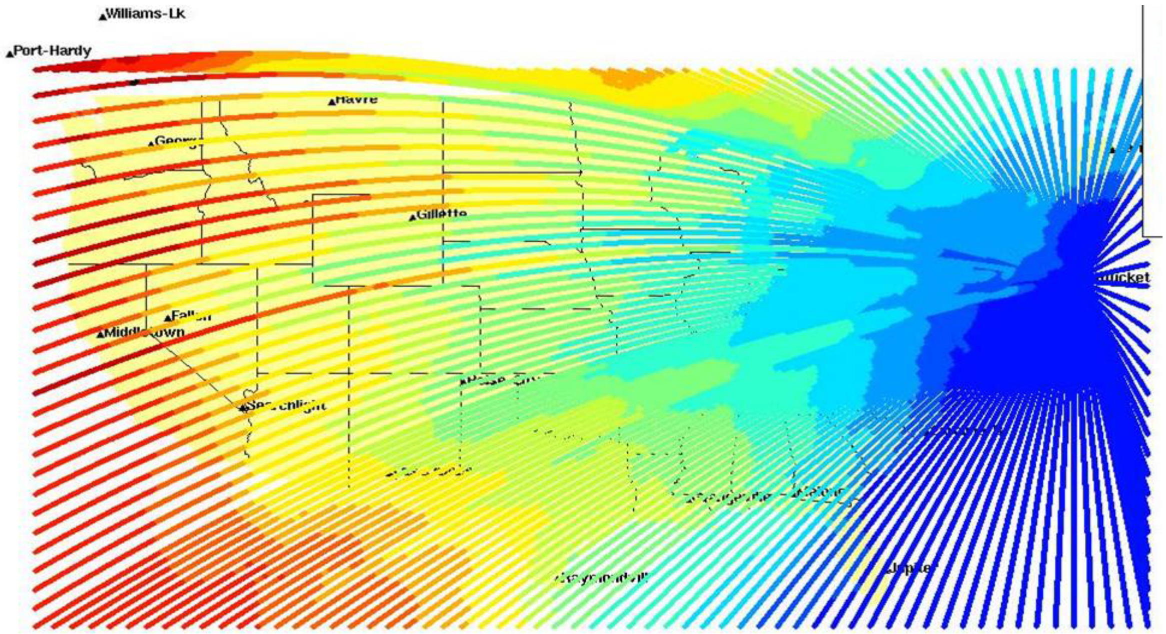

Figure 11: BALOR Wait 3.2 ASF radials for Nantucket.

Figure 12 shows the pASF grid for the CONUS calculated using LUPS for the same Loran station, Nantucket. The LUPS contour plot is similar to BALOR, but smoother.

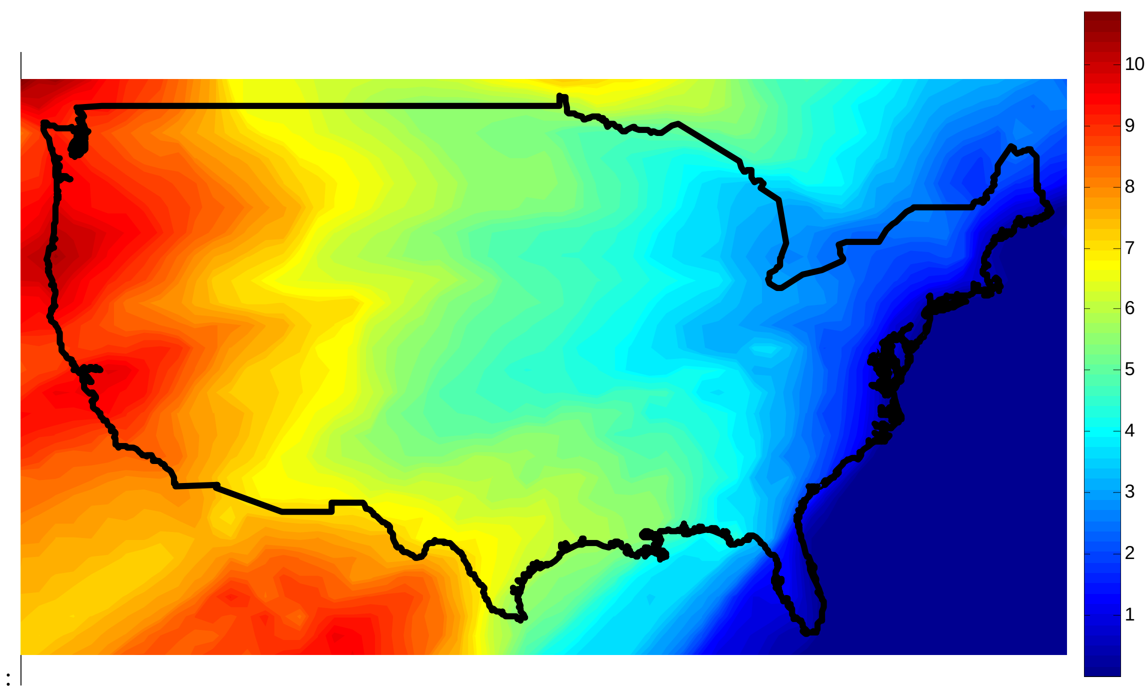

Figure 12: pASFs grid generated using LUPS method.

These predicted grids (one for each Loran station in the U.S.) were used to calculate the position domain accuracy of Loran using pASFs for a flight from Atlantic City, New Jersey to Little Rock, Arkansas. Figure 13 shows the error in the uncorrected Loran position solution and the Loran position recalculated using predicted ASF values generated by BALOR Wait 3.2 and LUPS methods, all versus time into the flight. Uncorrected Loran's 95% position error was about 1300 meters, while using predicted values improved the accuracy to less than 400 meters. A second example is shown in Figure 14. This flight was performed in July of 2006 with the plane en route from Kansas City, KS to Atlantic City, NJ. Here the BALOR and LUPS methods produce nearly identical solutions with significant improvement in the position accuracy (from about 1500m to less than 400m 95% accuracy).

Note that there is not much correlation of error with altitude (green line) in these two graphics. Also note that the corrected Loran error is not 0m when on the ground at any of the airports. This shows that the pASFs are not exact and performance could be improved by including the measured airport ASFs in the grids.

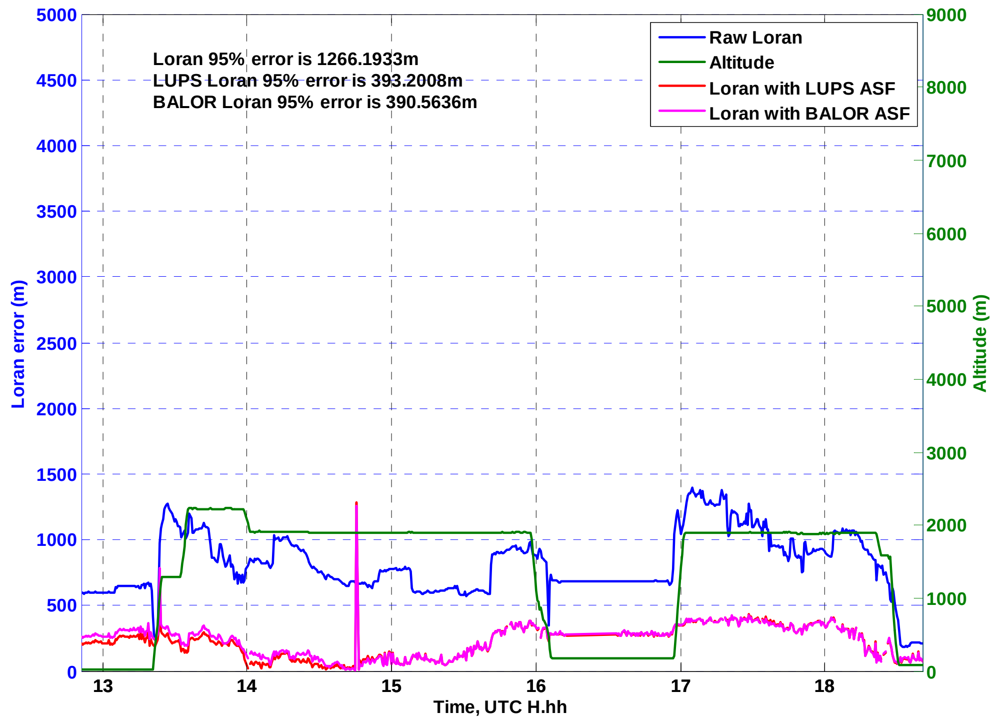

Figure 13: Loran position error along the flight from Atlantic City to Little Rock.

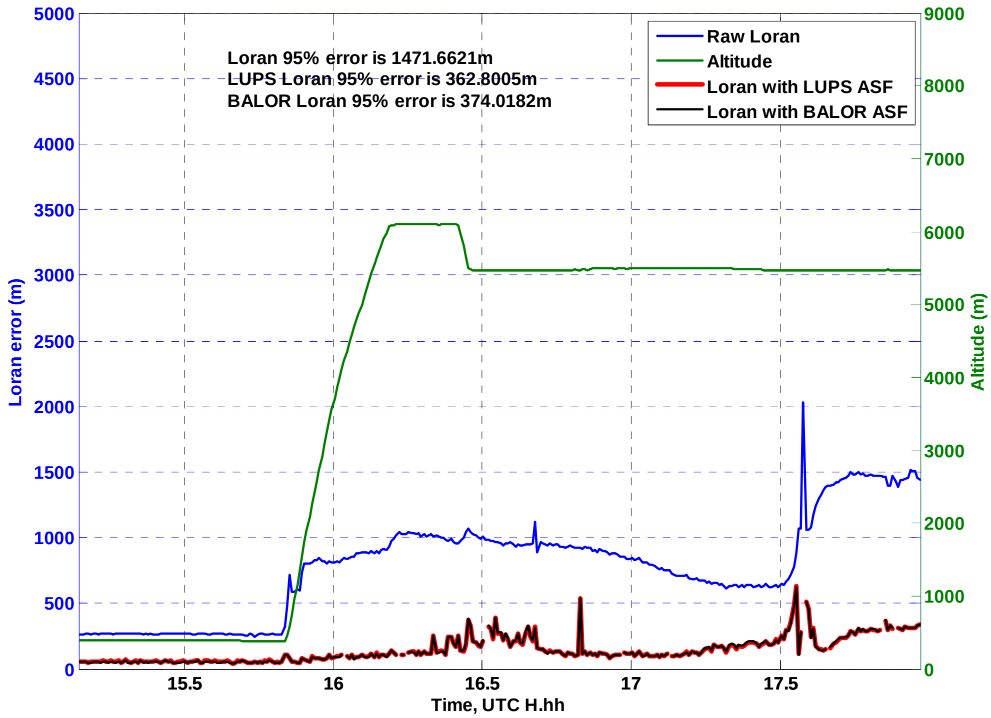

Figure 14: Loran position error along the flight from Kansas City to Atlantic City.

Conclusions

Using pASF improves accuracy compared to not using pASFs for en route navigation. While this level of accuracy is not sufficient for NPA or HEA, it may be good enough for en route (and ADS-B). In addition, accuracy might be improved by pinning down the predicted grid with measured airport ASFs.

Our findings show that receivers can benefit from using a built-in predicted ASF grid, if there are no nearby surveyed locations available. The BALOR Wait method was improved in the latest iteration, and work continues to produce more refinements. The LUPS method is older, and relies on less sophisticated techniques, but produces comparable readings. However, LUPS is no longer being developed, so we expect BALOR to outperform LUPS as BALOR's underlying databases improve. The older BALOR Wait method and Monteath method were outperformed in both speed and accuracy.

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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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Mr. Ruslan Shalaev is a Software Engineer at Alion Science and Technology. He develops custom software for Alion Science clients, and performs internal development for needs of data collection. Mr. Shalaev current and recent projects include developing ReceiversIntegration software that facilitates Loran ASFs field data collection, Loran Long Term Seasonal Monitors Clients/Servers network that is now integrated with Loran 9'th pulse corrections, Loran Data Capture System, DGPS Field Strength Prediction. In addition, he works on processing and analysis of data collected in the field by Alion team, and comparison of measured data with predicted values using ASF modeling software such as BALOR. Mr. Shalaev has BS degree in Computer Science from Binghamton University.

Dr. Gregory Johnson is a Senior Program Manger at Alion Science & Technology. He heads up the New London, CT office which provides research and engineering support to the Coast Guard Academy and R&D Center. Recently he has been working on projects in Loran, DGPS and WAAS. Dr. Johnson has a BS in Electrical Engineering from the USCG Academy (1987), a MS in Electrical Engineering from Northeastern University (1993), and a PhD in Electrical Engineering from the University of Rhode Island (2005). He has over 17 years of experience in electrical engineering and R&D, focusing on communications, signal processing, and electronic navigation and has published over 35 technical papers. Dr. Johnson is a member of the Institute of Navigation, the International Loran Association, the IEEE (Institute of Electrical and Electronics Engineers), and AFCEA (the Armed Forces Communications Electronics Association). He is also a Commander in the Coast Guard Reserves.

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