Temporal Variation of Loran ASFs and their Effects on HEA Navigation

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BIOGRAPHIES

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INTRODUCTION

With improvements in transmitter and receiver technologies, the U.S. Loran-C system has improved dramatically with respect to the four standard measures of performance: accuracy, integrity, continuity, and availability. The new, improved version is termed *e*Loran. To take advantage of this technology enhancement, a group of government, academic, and industrial experts have been working toward *e*Loran's acceptance in the United States as a backup system to GPS. To achieve the stated accuracy requirements, ASFs, or Additional Secondary Factors, must be mitigated. These ASFs are variations in the time of arrival (TOA) of the transmitted signal, typically caused by the non-uniform ground conductivity, topography, and weather experienced along the signal's path from transmitter to receiver.

Over the years there have been many studies of ASFs and their impact on Loran's position accuracy, the results often appearing in the symposia/conference records of the International Loran Association and the Institute of Navigation. In some prior work, these authors have modeled the ASFs as a sum of two parts:

- a *spatial* component to account for non-uniform ground conductivity and topography (in other words, the constant part of the ASF)
- a *temporal* component to account for all of the time varying aspects

Depending upon the navigation application, these two components are dealt with differently. For example, for aviation Non-Precision Approaches (NPA), the current approach to *e*Loran navigation is to measure the spatial component at the airport, generating one spatial ASF correction (per Loran transmitter) to be applied to the received data as corrections to the TOAs. In this case, the time variation in ASF is ignored and any position error due to the temporal ASF component is included within the system error budget. This approach is based upon the assumption that the spatial variation does not change too quickly with distance from the airport center (and this might yet need to be modified for airports/individual runways in some locations) and that the more relaxed accuracy needs (309m) of NPA do not require more precise knowledge of the temporal component of the ASFs. On the other hand, for maritime Harbor Entrance and Approach (HEA) with its much tighter accuracy requirements (8-20 meters), the approach to TOA corrections is to compute (via processing of survey data) the spatial ASF component at a dense grid of points covering the harbor area (latitude and longitude spacing on the order of 500 meters), interpolate the grid within the harbor area, and transmit (over the Loran Date Channel) temporal corrections to mariners. While the spatial grid provides localized corrections, the temporal correction is measured at one fixed site near the harbor (the monitor site); the assumption is that the temporal term remains relatively constant over the harbor. Additional information on the approach to these two applications can be found in [1,2,3,4].

Both of these navigation applications require an understanding of the characteristics of the ASFs. For aviation NPA, an accurate bounding of the temporal term in the error budget requires an estimate of the range of ASFs that are expected to be encountered over the course of the year; further, it is desired to be able to estimate this range (and its midpoint or other appropriate nominal value) without being required to locate monitoring equipment at each airport for an extended period of time. For maritime HEA, position accuracy is sensitive to having a good estimate of the temporal component at the vessel itself (not just the nearby monitor site), so there is considerable interest in the correlation of temporal components at varying distances from the monitor site. This information is particularly relevant to assessing the cost of the system in that it addresses how monitor sites would need to be spaced to provide sufficient coverage to HEA areas.

To attempt to answer both these, and other questions, the US Coast Guard and its partners in *e*Loran have been installing ASF measurement equipment at various sites in the United States. The ASF monitor installations began in early 2006 and continue today (a site on the Texas coast came on-line as recently as March 2008). As this ASF monitor network has grown, data at sites at varying distances from one another is becoming available to examine spatial correlation of the temporal component of the ASF. This paper, as an update to presentations made at the last two ILA symposia [5,6], briefly describes the system with analysis focusing on the spatial correlation of the temporal component as it relates to navigation accuracy.

THE SEASONAL MONITOR NETWORK

A presentation at the International Loran Association's Symposium in 2006 [5] described the beginning of the ASF monitor network. It located the six monitors in place as of that time, described in some detail the hardware and software used to measure the ASFs, showed a few examples of the recorded data, and discussed approaches to filtering the data to remove the impact of receiver noise. The somewhat obvious conclusions of that presentation included that there is a strong "correlation" of the ASFs at nearby monitor sites, that land paths experience more temporal ASF variation then do short paths, that ASFs vary more during the winter months, and that for the aviation and marine applications of interest, winter in the Northeast appears to be the most difficult location in the US.

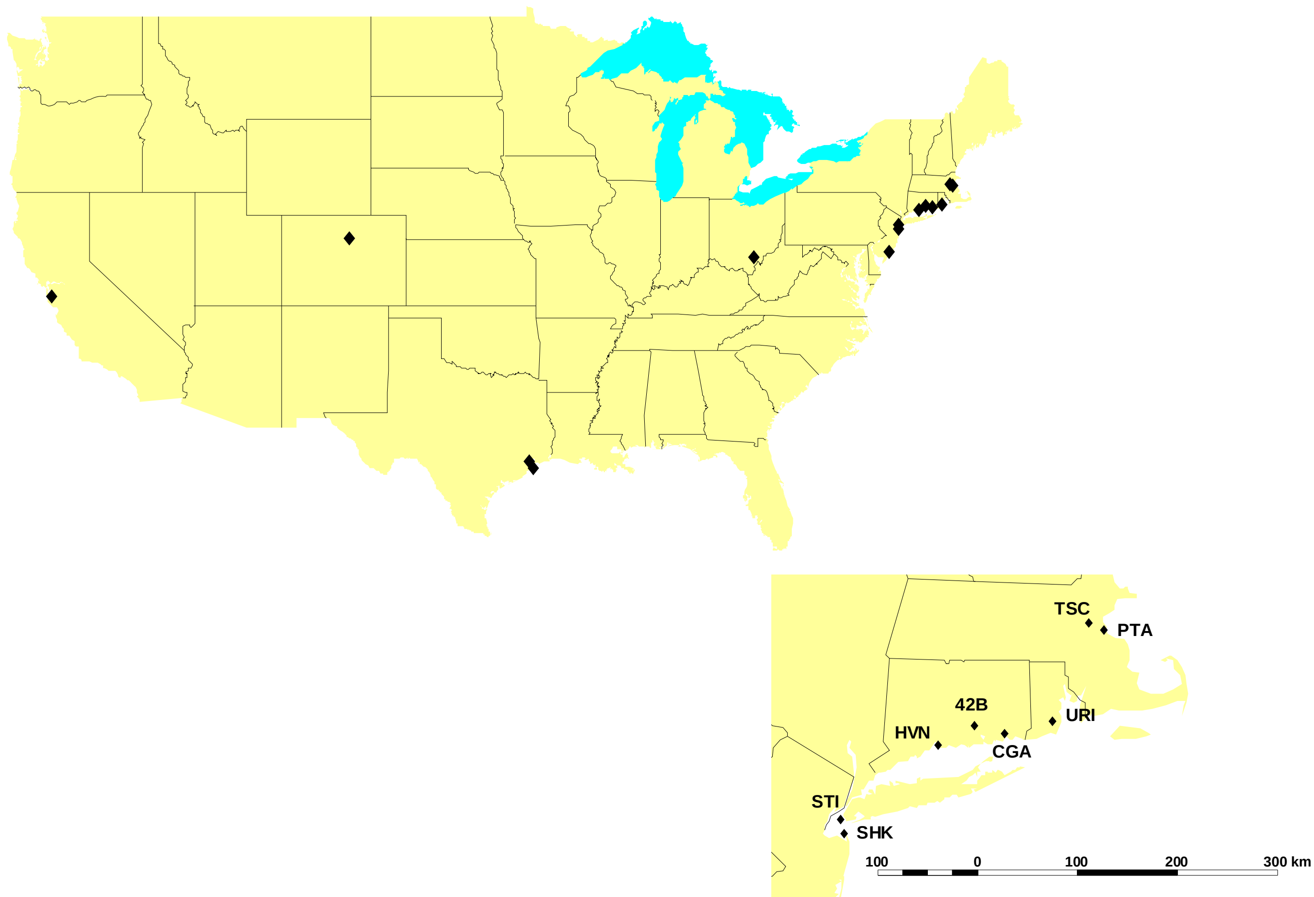

Figure 1: Locations of the Loran Seasonal Monitor sites, circa March 2008. The inset shows details for New England, of interest in this paper.

Since that time, additional monitor sites have come online. As shown in Figure 1, monitors are in place at the following locations:

- CGA – US Coast Guard Academy, New London, CT
- URI – University of Rhode Island, Kingston, RI
- TSC – Volpe Transportation System Center, Cambridge, MA
- ACY – FAA Technical Center, Atlantic City, NJ
- OUA – Ohio University, Athens, OH
- STI – US Coast Guard base, Staten Island, NY
- 42B – Goodspeed Airport, East Haddam, CT (2007 only)
- GIS – Army Core of Engineers site, Galveston Island, TX
- HOU – El Porte Airport, Houston, TX
- BCO – Timing Solutions, Inc., Boulder, CO
- HVN – New Haven Airport, New Haven, CT
- SUN – Stanford University, Palo Alto, CA
- PTA – US Coast Guard station, Hull, MA
- SHK – near US Coast Guard station, Sandy Hook, NJ

The dense concentration in southern New England is intended to aid in studying the limits of spatial re-usage of temporal corrections; the set of baseline separations (site-to-site distances) available with these monitors starts at 16 km with many pairs under 150 km. Several of the other monitor sites (OUA, BCO, ACY, and SUN) are for longer term studies of ASF variation by geographic region; the most recent pair in Texas (GIS, HOU) are for a future harbor test.

Each ASF measurement system is comprised of a pair of antennae connected to Loran and GPS receivers, which communicate directly with data collection software on a local computer. The timing of these receivers is precisely controlled by a rubidium clock, which itself is long-term stabilized by the GPS 1 PPS signal. The time of arrival data for the various Loran signals observable at the monitor site is processed locally to compute the ASF data (based upon precise knowledge of where the monitor antenna is) and these ASF values are then sent to a server at the US Coast Guard Academy through a TCP/IP connection. Typical data from the monitor site at URI for calendar year 2007 appears in Figure 2 (here, and for all work below, the data shown is one hour averages of the ASFs; the sites actually archive at a one minute rate; occasional gaps exist due to equipment down time). This figure shows only the data for four stations of the 9960 chain; the monitor actually logs data on all Loran stations observed at the location. Further, note that these are not "true" ASFs in that a constant bias due to delays in the receiver's electronics has not been calibrated out (hence, some ASFs are shown as negative in value). However, for the purposes of observing the temporal characteristics of the ASFs, this bias is irrelevant as the term is relative to the nominal site value.

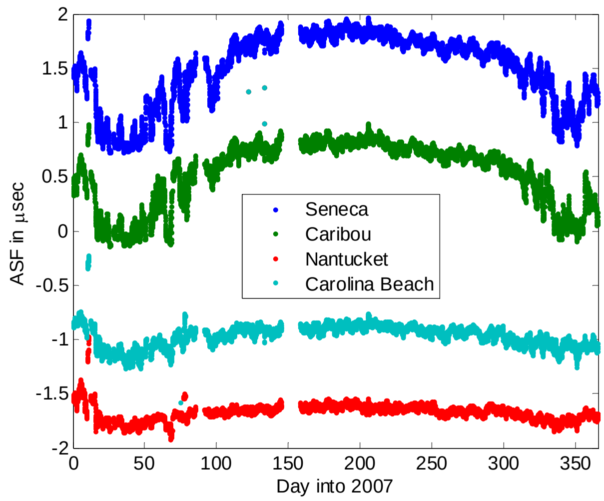

Figure 2: Typical data collected at a monitor site.

ASF DATA ANALYSIS

A second presentation at the International Loran Association's Symposium in 2007 [6] began to show in detail some of the data collected by the ASF monitor network. It demonstrated, by example, the repeatability from year to year of the ASF variations, focusing on distinct summer and winter quarters. To compare data from pairs of sites, it looked at the difference in the temporal component, both visually and via some simple statistics; no direct conclusions were drawn from this examination. While the statistics suggested a good match between the ASF measurements at some pairs of sites, there was no direct linkage to positioning performance. To get a quantitative measure of the temporal variation, the paper concluded with computations of position error under a "mismatch" situation. The exercise was defined as follows:

> *The goal is to use the temporal ASF measured at a nearby monitor site and assess the impact of the mismatch at the site of the receiver. With the data available, select the "vessel" location to be at one monitor site and use the ASF temporal corrections measured at another; while this provides vessel locations that are typically quite distant from the monitor, it does allow examination of the spatial correlation of the temporal ASF over the entire year.*

For pairs of sites, position errors were computed with each site playing the roles of both monitor and receiver. The most significant observation from this exercise was that there was little correlation between site-to-site distance and the resulting error. While some widely separated sites, surprisingly, yielded small errors, the conclusion was that HEA will require monitor-to-vessel separation of less than 30 km.

Since 30 km spacing of monitor sites appears too large, the next step in the investigation is to examine sites with smaller separation. Furthermore, a comparison of the paths that the signals traverse will be significant (since ASFs are typically generated by that portion of the path over land); some initial comparison of the paths appears below. The discussion starts with a review of some of the earlier mismatch tests.

CGA to 42B – 31 km: This pair of sites was the closest available for the 2007 experiment; the mismatch position error as computed was good in summer (15m radius for the 95% error circle), but poor in winter (40m). To begin to understand why, Figure 3 shows the temporal portion of the ASFs for the 4 stations in the 9960 chain (the horizontal axes are days into 2007). Of these four comparisons, only Nantucket seems quite different for the two sites; the other three stations track quite well. Since Nantucket plays a significant role in the position solution (being the strongest station at both monitor sites), this is key. For a clearer view, Figure 4 shows the differences of these temporal ASFs; while the four are highly correlated, the larger variation in Nantucket during the winter is now more apparent. So what's happening with the paths? Figure 5 shows the four paths of interest. In each case, the paths are shown as red lines, the Loran Station is the vertex of the two lines, the monitor locations are the red circles, and the shading indicates land (tan) or water (white). For convenience, each has been rotated and scaled to have the Loran Station on the left and the paths running left to right. The third figure, for Nantucket, appears to show substantially different paths; notably, the much longer land component for 42B (almost twice as long as the land path to CGA).

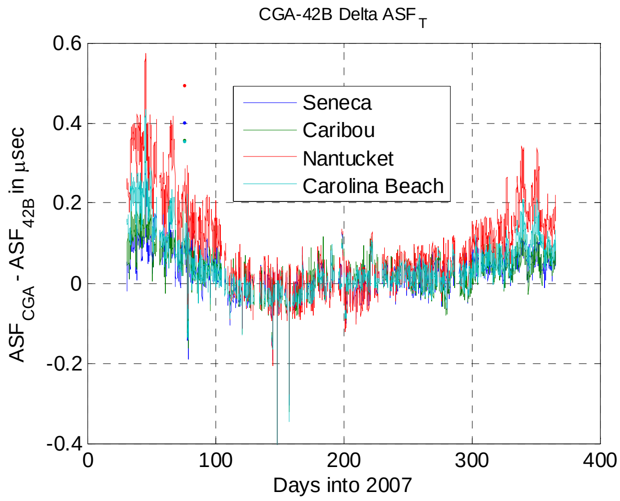

Figure 4 – Differences of temporal ASFs at 42B and CGA.

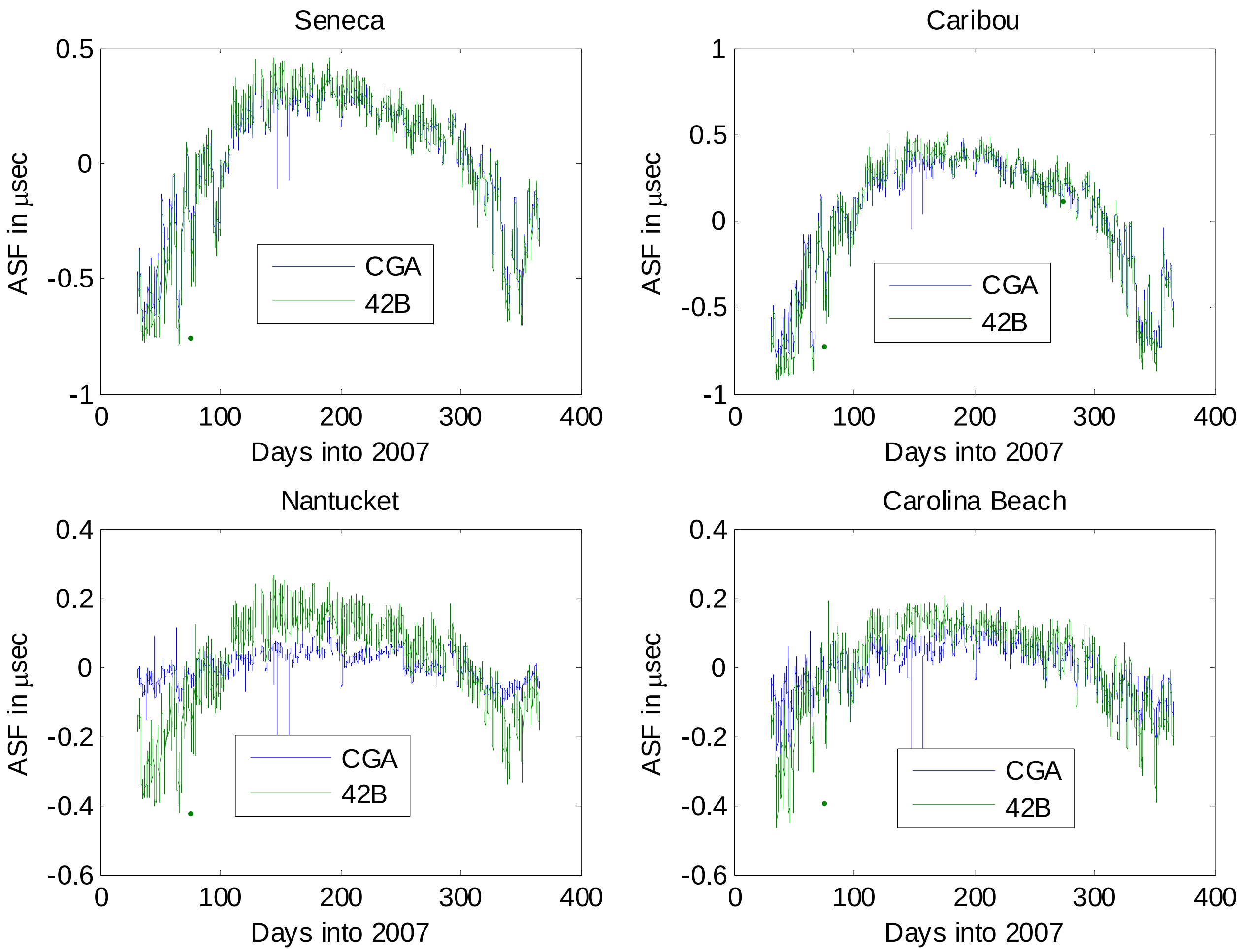

Figure 3 – Temporal ASFs at CGA and 42B.

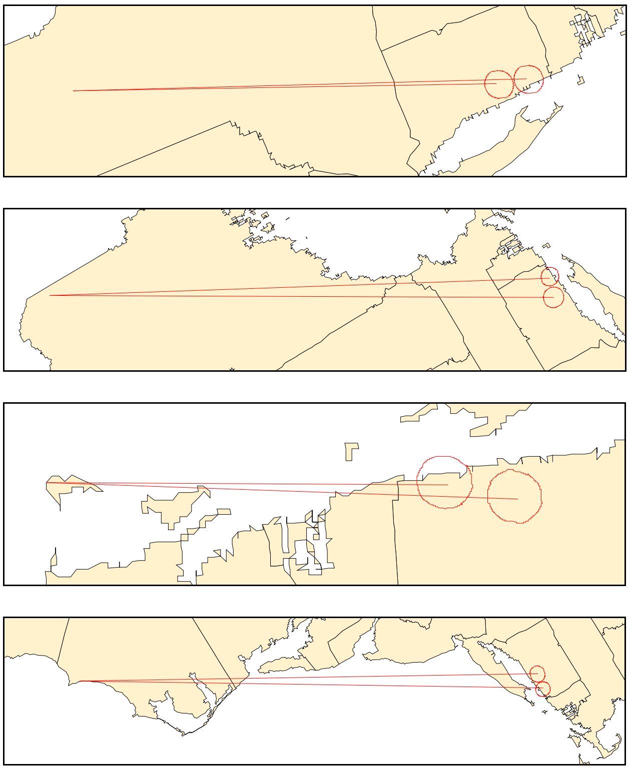

Figure 5 – Signal paths to CGA and 42B.
From top to bottom: Seneca, Caribou,
Nantucket, and Carolina Beach.

CGA/URI – 49 km: While further apart, this pair exhibited good mismatch performance in the 2007 experiment: 10m in summer and 18m in winter. Figure 6 shows the temporal ASF differences. Three of the differences are highly correlated and small in magnitude; while Caribou is very different than the others, it has low SNR and, hence, small weight in the Loran position solution which results in little impact on the position error. Figure 7 shows the four paths of interest for these two sites. In this case, from the maps, the Seneca paths are similar (although URI's is slightly longer), Nantucket's are both mostly water with similar sized portions of land at the ends, and Carolina Beach's look equivalent; only Caribou's paths seem to differ (the water component for URI) and that shows up in the ASF differences.

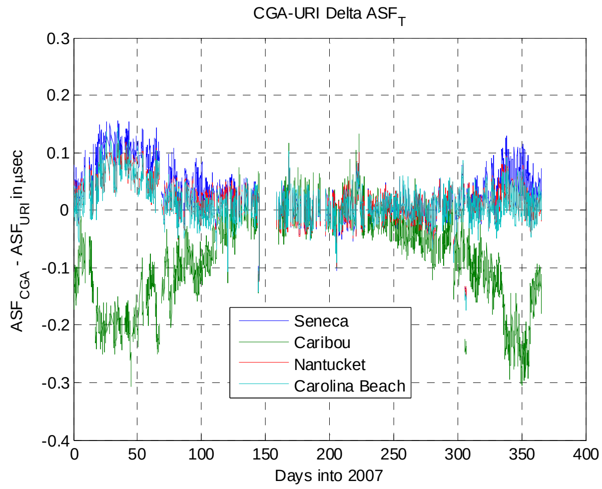

Figure 6 – Differences of temporal ASFs at CGA and URI.

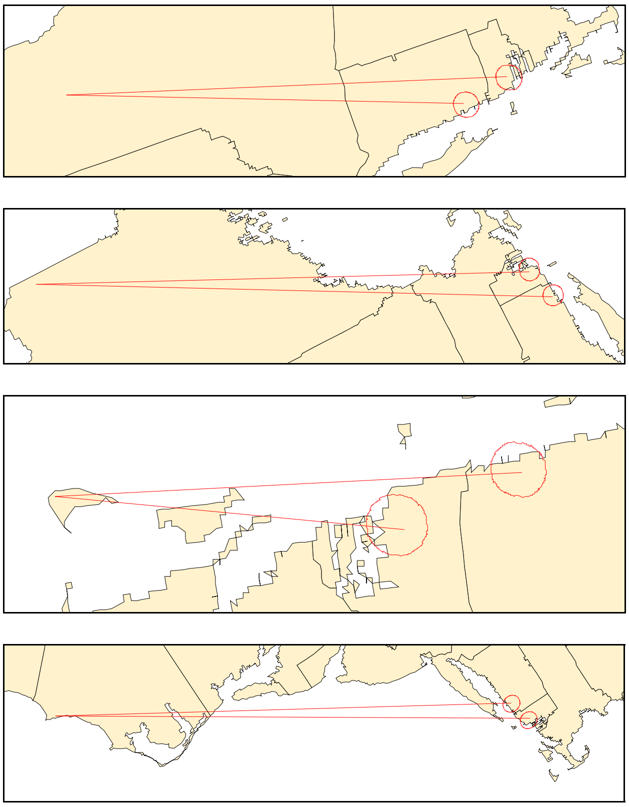

Figure 7 – Signal paths to CGA and URI.
From top to bottom: Seneca, Caribou,
Nantucket, and Carolina Beach.

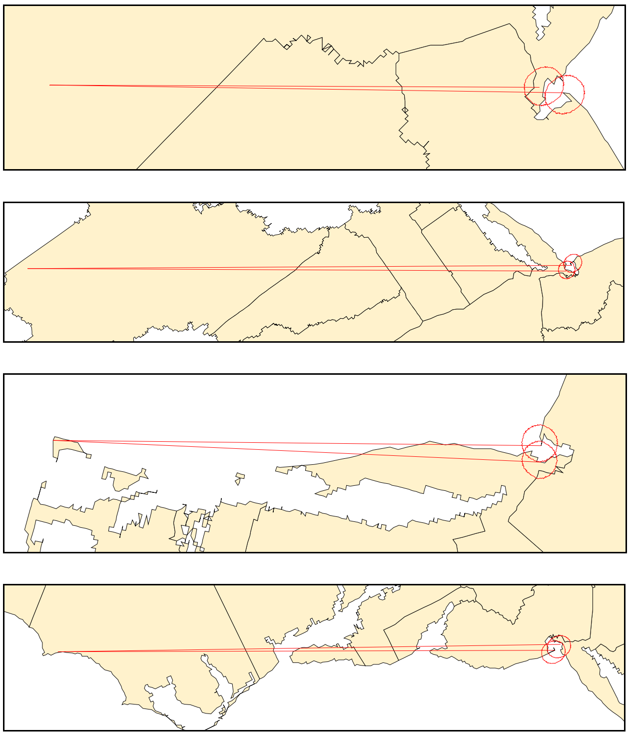

Figure 8 – Signal paths to SHK and STI. From top to bottom: Seneca, Caribou, Nantucket, and Carolina Beach.

Fortunately, some parallel ASF studies sponsored by LSU (through PIG) resulted in ASF data collection during 2007 at two additional sites close to two of the monitors above: Point Allerton (PTA) near TSC and Sandy Hook (SHK) near STI. Both locations are now regular members of the seasonal monitor network. While the mismatch experiment can be run with 2007 data from these two sites (although the data collected at these two is on a 6 minute interval) and is done so below, some initial comparison of paths appears first.

<u>SHK/STI – 15 km</u>: Figure 8 shows the paths to the SHK and STI sites. From these simple maps, Seneca and Caribou look fine, Nantucket could be an issue due to the southern Long Island land mass (however, this area probably does not experience the cold necessary for strong ASF variation), and Carolina Beach appears fine. Examining the data, the delta ASFs in Figure 9 confirm these comments by demonstrating small magnitudes and high correlation. Repeating the mismatch experiment, Figure 10 shows scatter plots of position error for STI corrections at SHK, summer and winter of 2007. Figure 11 shows the scatter over the entire year year. As expected, summer yielded the best performance (95% error radius under 8m), winter was worst, and the entire year yielded acceptable performance (15.2m). The reverse scenario, SHK corrections at STI, yielded similar results.

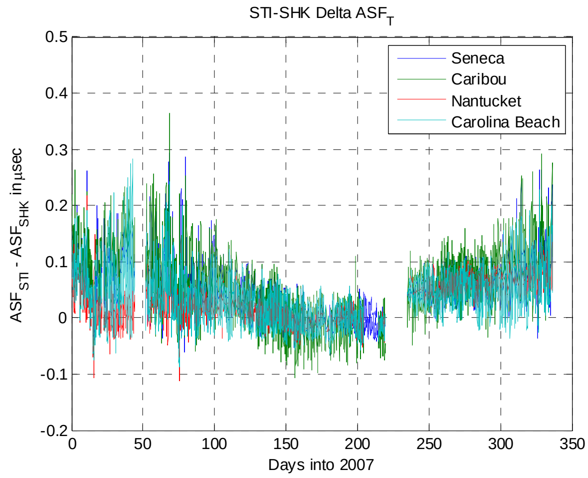

Figure 9 – Differences of 2007 temporal ASFs at STI and SHK.

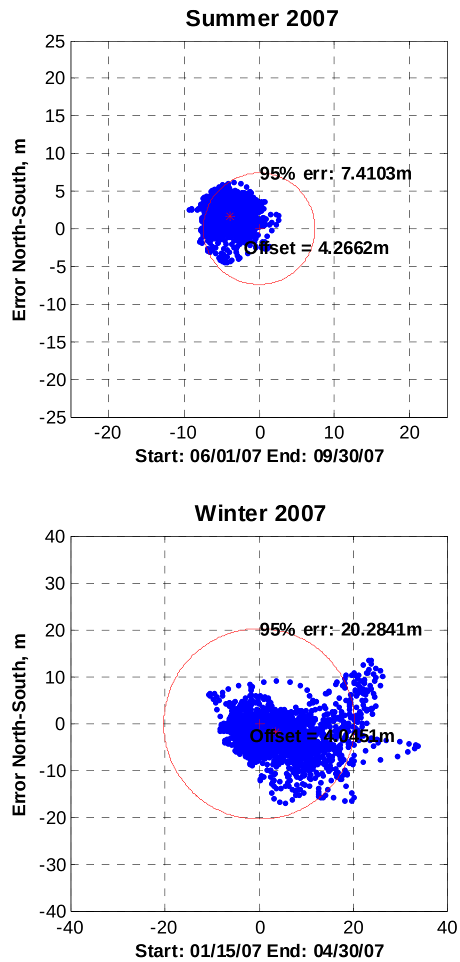

Figure 10 – Scatter plot of position error in 2007, STI corrections at SHK, summer (top) and winter (bottom).

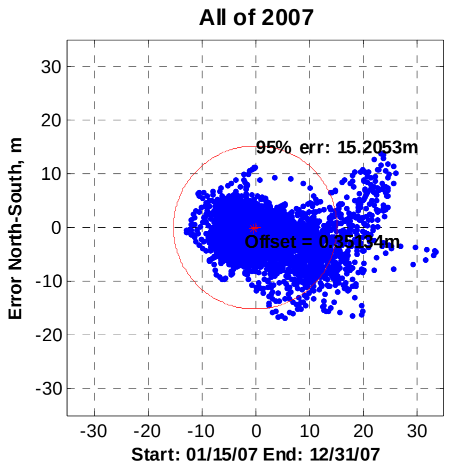

Figure 11 – Scatter plot of position error, STI corrections at SHK, 2007.

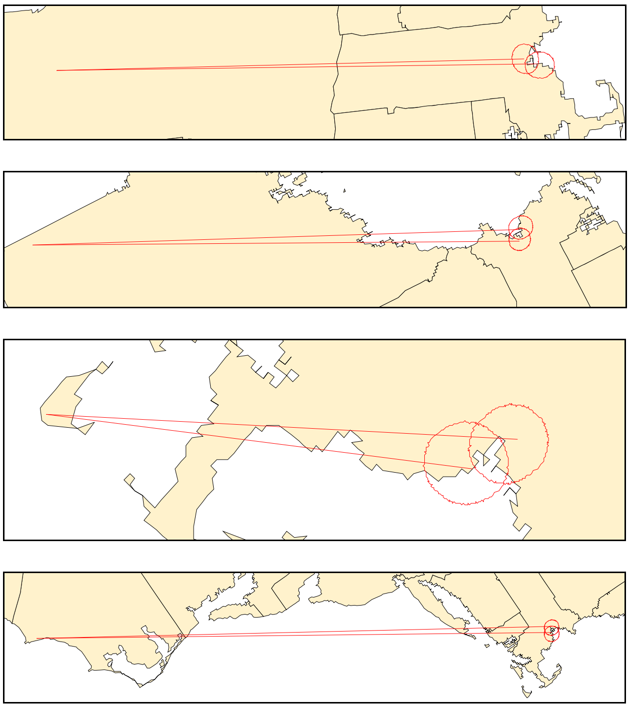

Figure 12 – Signal paths to PTA and TSC. From top to bottom: Seneca, Caribou, Nantucket, and Carolina Beach.

<u>PTA/TSC – 16 km</u>: Figure 12 shows the paths to the PTA and TSC sites. Seneca looks fine, as does Carolina Beach (although due to its low SNR, Carolina Beach plays a minor role in the Loran position solution); Caribou's paths show some differences (the additional water off of Boston) as do Nantucket's (considerably more land for TSC). Examining the monitor data, however, the ASF differences in Figure 13 look pretty good; while the individual magnitudes of the differences may be greater than the previous example, and have greater variation, the four differences are generally highly correlated (and this correlated component washes out of the position solution). The mismatch experiment (TSC corrections at PTA) shows moderate results; 8m in summer, 23m in winter, and 20m over the entire year (Figure 14). The reverse experiment is similar.

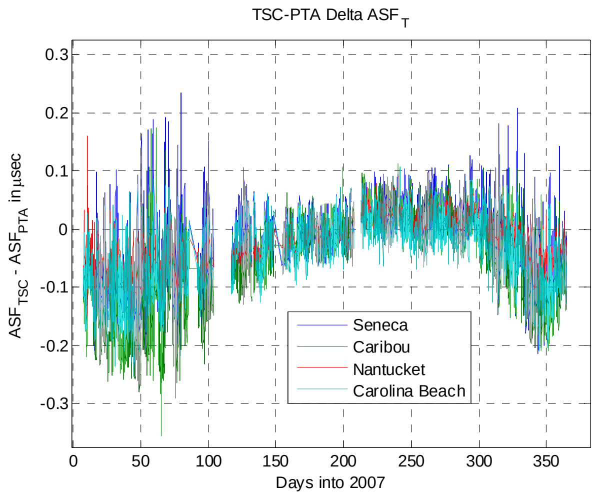

Figure 13 – Differences of 2007 temporal ASFs at PTA and TSC.

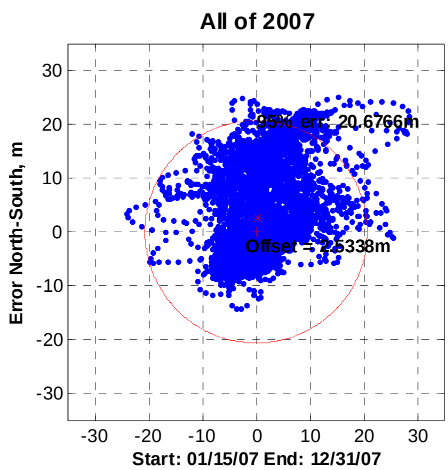

Figure 14 – Scatter plot of position error, TSC corrections at PTA, 2007.

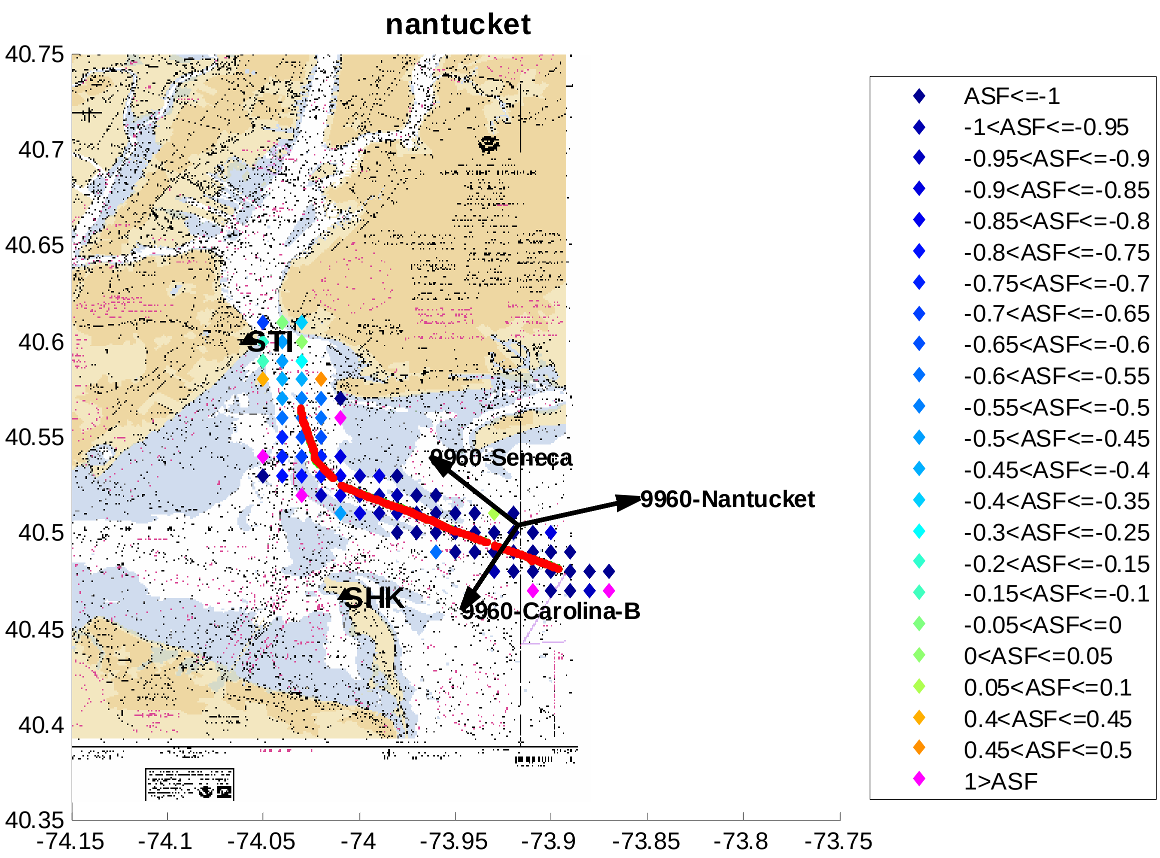

Figure 15 – Chart of New York harbor showing monitor sites (SHK and STI), boat track under test (red line), ASF spatial grid for Nantucket (colored diamonds), and directions to the three primary. The legend for the ASF grid is shown.

INTERPOLATING BETWEEN MONITOR SITES

When a vessel is located between two monitors, a natural question to ask is "How do you integrate the two temporal corrections into the position solution?" The pair of monitors at SHK and STI allow for such a test on vessel data collected in New York harbor.

In previous work on ASF spatial grid creation [4], data was collected for the outer New York harbor area. As shown in Figure 15, imagine that the vessel sails northwest up the main channel (along the red line) using the spatial grid (relative to STI) as shown (only the values for Nantucket appear in this figure; equivalent grids for Seneca and Carolina Beach were used in the following). Since ASF monitors exist at both SHK and STI, there are multiple choices for temporal ASF corrections: use STI's, use SHK's, or use some combination.

It was hoped that this experimental situation would provide insight into what interpolation technique is most appropriate. However, irrespective of which correction set was applied (SHK or STI), nearly equivalent error performance was achieved – 17m for a 95% radius. Figure 16 shows the scatter plot for the error; Figure 17 shows the error versus time into the track (position sample, #1 at the lower right in Figure 15).

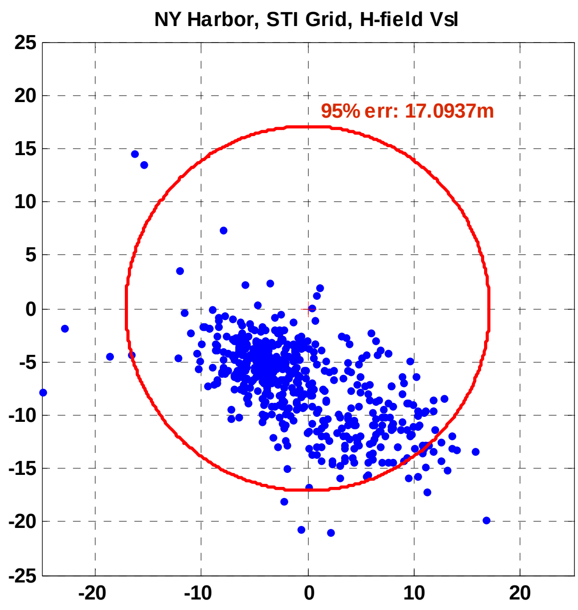

Figure 16 – Scatter plot of position errors for the New York harbor trial.

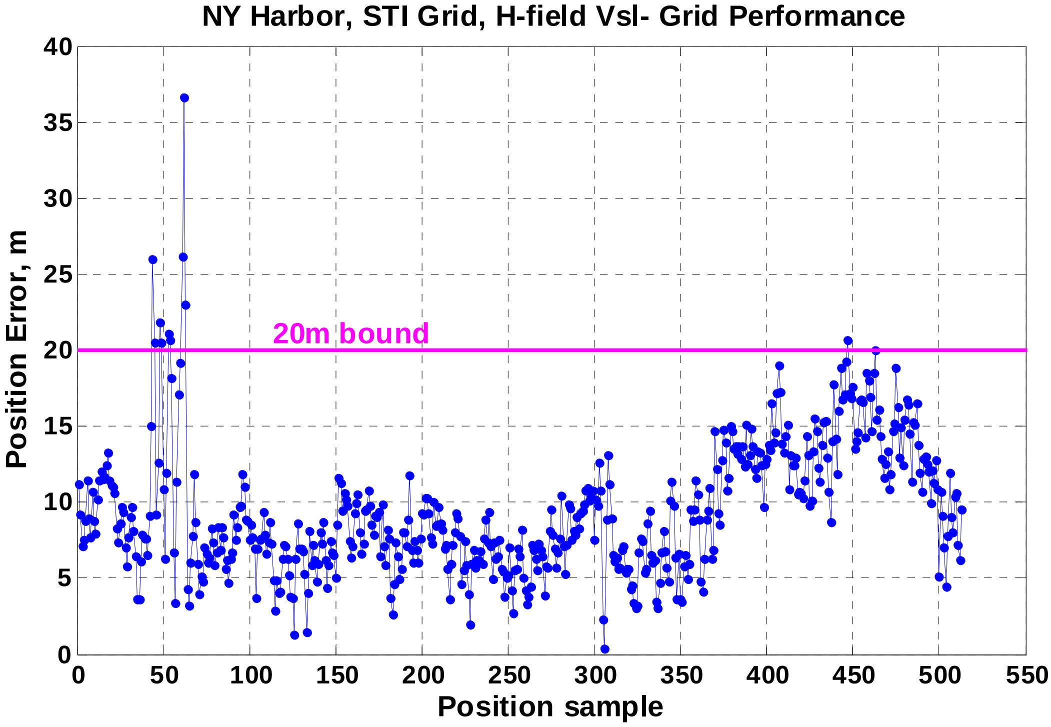

Figure 17 – Position error versus sample along the track in the New York harbor trial.

CONCLUSIONS/FUTURE

An analysis of the data collected to date using the ASF monitor network show marked similarities in the measurements, sometimes for monitors with wide separations. However, as the positioning accuracy is quite sensitive to mismatch, the results to date indicate that monitors will need to be quite close to vessels in order to reach the HEA accuracy goals. Further, the geometry to the Loran Stations (specifically, the characteristics of the Loran signal's paths) is key in understanding when an ASF temporal correction has high spatial correlation and when it does not.

The examination to date was conceptual; for example, no detailed measurement of the path length over land was attempted. Long paths, especially over land, appear to yield highly correlated temporal terms. Signals from nearby Loran Stations, since the path geometry can be quite different, or those with combined land/water paths appear to determine the spatial reliability of the position solution.

A first experiment on interpolating between two temporal monitor sites was attempted. Unfortunately, the high correlation of the temporal corrections from the two monitor sites during the time of the test yielded inconclusive results.

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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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