An Investigation into the Temporal Correlation at the ASF Monitor Sites

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ABSTRACT

To fulfill the envisioned role of a backup navigation system to the GPS, Loran needs to satisfy the user requirements of accuracy, integrity, continuity, and availability. The biggest obstacle to accuracy lies in what are called Additional Secondary Factors (ASFs) which are changes in the time of arrival of the Loran signal due to its non-uniform propagation speed from the transmitter to receiver antennas. This variation is due to a combination of the non-uniform conductivity of the terrain, the varying topography, and the weather experienced along the path. To better model these ASFs, with the goal of bounding or mitigating their effect on navigation position accuracy, Alion Science & Technology under contract to the US Coast Guard Academy has established a network of Loran monitors that track and archive the ASFs at particular locations. One goal of this network is to monitor the seasonal variation of the ASFs; this result is important for aviation applications. For those locations near a port area, the monitor is also used to provide temporal corrections for Harbor Entrance and Approach applications. The Academy's ASF monitor installations began in early 2006; hence, for some locations, data has been collected for two summer and two winter seasons. As the monitor network has grown, data at sites at varying distances from one another are available to examine spatial correlation of the effects. This paper, an update to a presentation made at last year's ILA, provides a deeper look into the data collected, along with some analysis focusing on the correlation of the temporal portion of the ASF as related to separation distance.

INTRODUCTION

With technological improvements to both transmitters and receivers, the Loran system has improved dramatically with respect to the four performance horsemen of accuracy, integrity, continuity, and availability. To take advantage of the technology, a group of government, academic, and industrial experts have been working toward Loran's acceptance as a backup system to the 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, often appearing in the ILA's technical symposium records. In some prior work, we have modeled the ASFs as a sum of two parts:

- a *spatial* component to account for the 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 application, these two components are dealt with differently. For example, for aviation, the plan for navigation is to measure the spatial component at the airport under examination, generating one spatial ASF correction (per Loran transmitter) to be applied to the received data. In this case, the time variation in ASF is ignored and any position error due to the temporal ASF component is included in the 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 in more difficult locations) and that the more relaxed accuracy needs (309m) of the aviation application do not require more precise knowledge of the temporal component of the ASFs. On the other hand, for Harbor Entrance and Approach (HEA) with its much tighter accuracy requirements (8-20 meters), the approach to TOA corrections is to measure 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 applications require an understanding of the characteristics of the ASFs. For aviation, 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) without being required to locate monitoring equipment at each airport for an extended period of time. For 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 Academy and its partners have been installing ASF measurement equipment at various sites in the Northeast United States. The ASF monitor installations began in early 2006; data has been collected over two summer and two winter seasons. As the 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 a presentation made at last year's ILA [5], briefly describes the system and provides a glimpse into the data collected, with some analysis focusing on the correlation as related to separation distance.

THE SEASONAL MONITOR NETWORK

A presentation at last year's ILA-35 initially described the network of ASF monitors [5]. That paper located the six monitors in place as of Sept. 2006, 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 while still providing the level of accuracy needed for accurate positioning within the available update rate of the LDC transmission system. The conclusions of that work included noting the obvious "correlation" of the ASFs at nearby sites, that land paths experience more ASF variation, and that ASFs vary more during the winter months. Further, for the aviation and HEA applications of interest, winter in the Northeast appears to be *the long pole in the tent*.

Since that prior presentation, two 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 – Avionics Engineering Center, Athens, OH
- STI, US Coast Guard base, Staten Island, NY
- GSPD, Goodspeed Airport (42B), East Haddam, CT
- HVN, New Haven Airport, New Haven, CT

The last two are the new additions (the gap in the map in Figure 1 allows for the wider spacing to the monitor in Athens, Ohio). Note that the Loran Support Unit, through installations by Peterson Integrated Geopositioning, is also collecting ASF data at several other sites in the Northeast. As part of some future work, we intend to compare and contrast collected data with that from those sites. This enlarged collection of sites, with its denser concentration in southeastern New England, provides a large set of baseline separations (site-to-site distances). Figure 2 graphically shows some of these different baselines, from the shortest up to approximately 150 km.

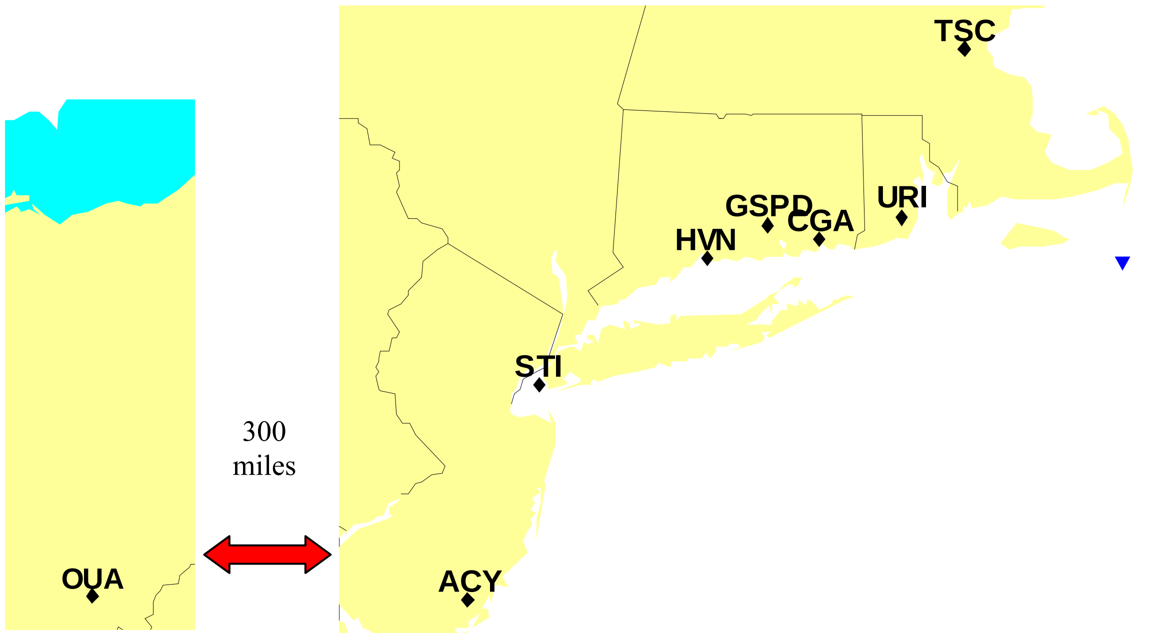

Figure 1: Locations of the Loran Seasonal Monitor sites, circa Oct. 2007.

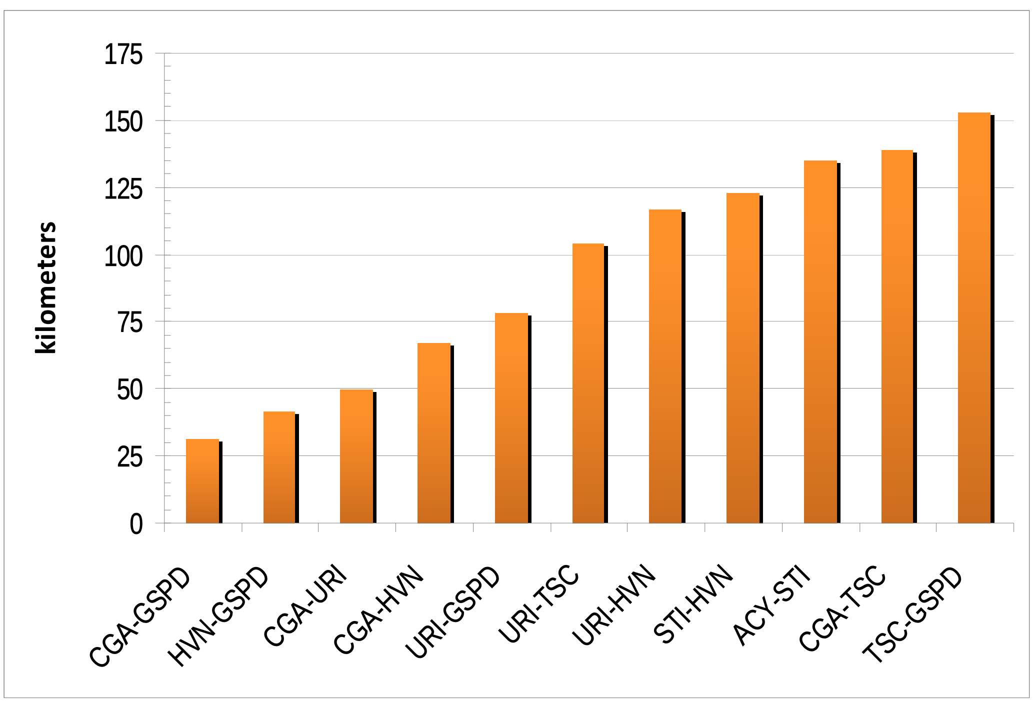

Figure 2: The short baselines, circa Oct. 2007.

Each ASF measurement system unit itself is comprised of a pair of antennae connected to Loran and GPS receivers, which communicate directly to 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 2006 appears in Figure 3 (here, and for all work below, we are using one hour averages of the ASFs; the sites actually archive at a one minute rate). 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. However, for the purposes of observing the temporal characteristics of the ASFs, this bias is irrelevant. During 2006, the 9960 chain was operated under SAM control, but the ASF data has been adjusted using the exact time-of-transmission date from the stations.

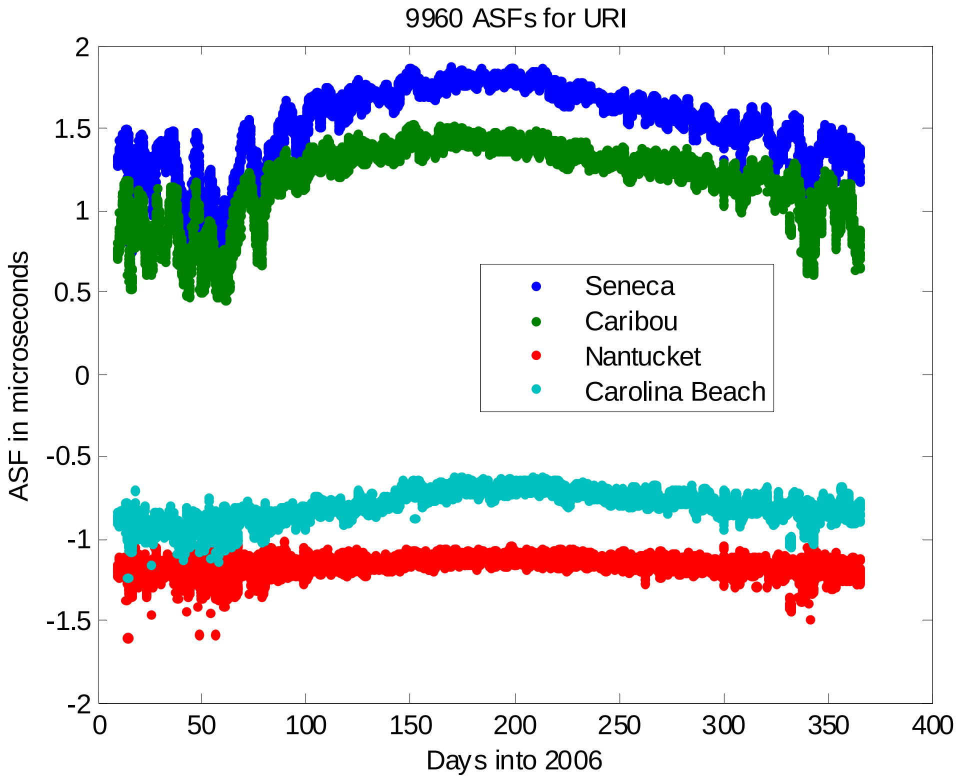

Figure 3: Typical data collected at a monitor site.

TYPICAL ASF DATA

As noted above, the ASF is modeled as a sum of independent terms, actually three:

- A *spatial* term dependent upon path topography and ground conductivity
- A *directional* term to account for effects of H-field antennas on a moving platform
- A *temporal* term to account for any time varying effects

For a stationary monitor, the directional term is assumed to equal zero. Further, as the interest here is the temporal component, the spatial term is modeled as the average ASF measured over the year and is removed from the data. As an example, the remaining temporal components of the ASFs shown in Figure 3 appear in Figure 4. In this figure, note the wider swings of ASF for stations Seneca and Caribou, both land paths to URI. From Figure 4 it is also apparent that the temporal component is quite different summer to winter. For the data analysis below, the data will be separated into obvious subsets of these seasons

- Summer (June1 – August 31)
- Winter (January 1 – March 31)

These portions of the year are marked in the figure.

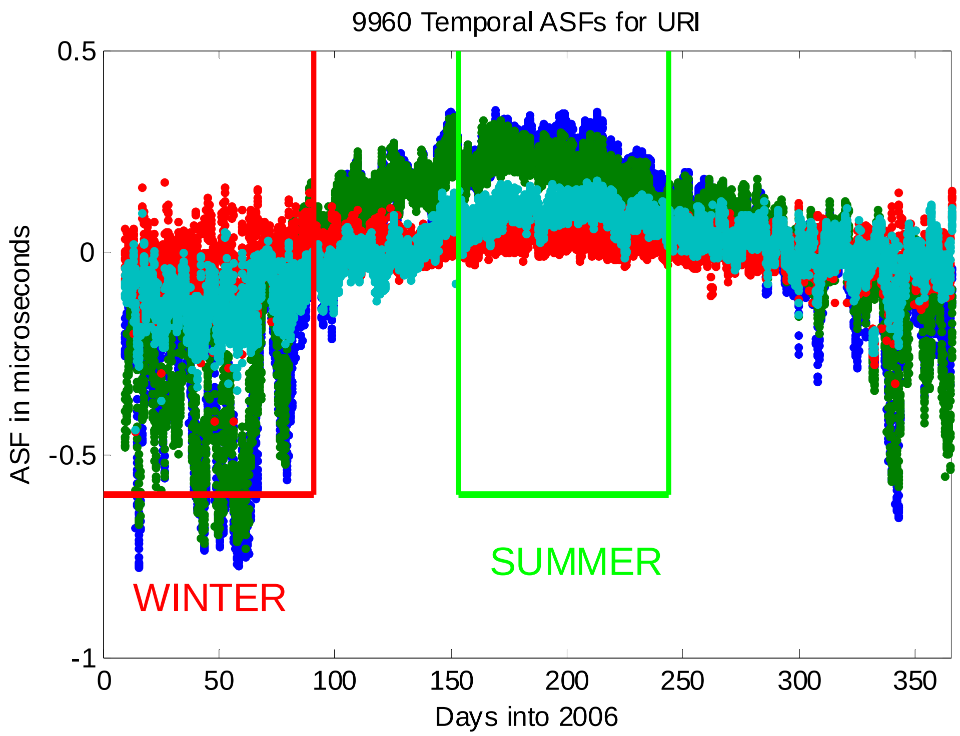

Figure 4: Typical temporal ASF data.

For a first look at temporal data, Figure 5 shows ASFs (again only for 4 stations of the 9960 chain) recorded at the Coast Guard Academy; the two subplots are arranged to allow for comparison of measurements during both 2006 and 2007. This comparison exhibits regions of great similarity and great difference; to examine this further, Figures 6 and 7 zoom into the summer and winter portions of the data, respectively.

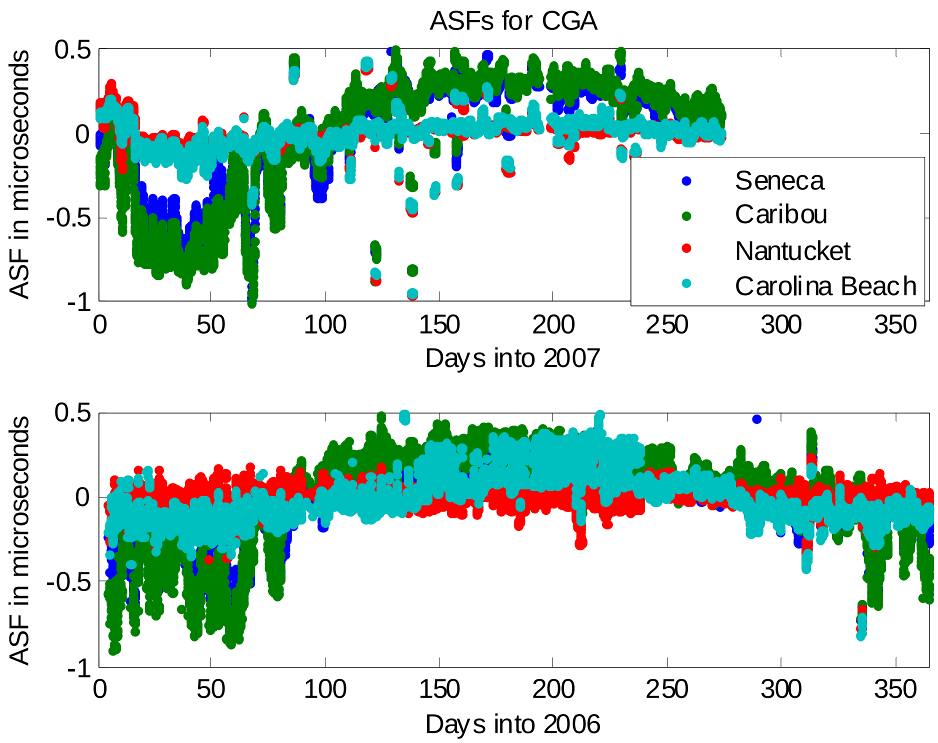

Figure 5: Two years of ASF data at CGA.

Figure 6 demonstrates the expected similarity of ASFs on the summer months[1]; on the other hand, Figure 7 shows how the weather can produce significantly different results (this is particularly noticeable between days 20 and 50 for stations Caribou and Seneca). It is also interesting to note that predominantly water paths, Nantucket and Carolina Beach to CGA in this example, seem relatively immune to seasonal variation.

[1] Note that there was an interference problem at the CGA site (due to an A/C unit) that started in May until the antenna was relocated at the end of August (~days 140-240). This caused there to be 100-200ns jumps in the data during this period.

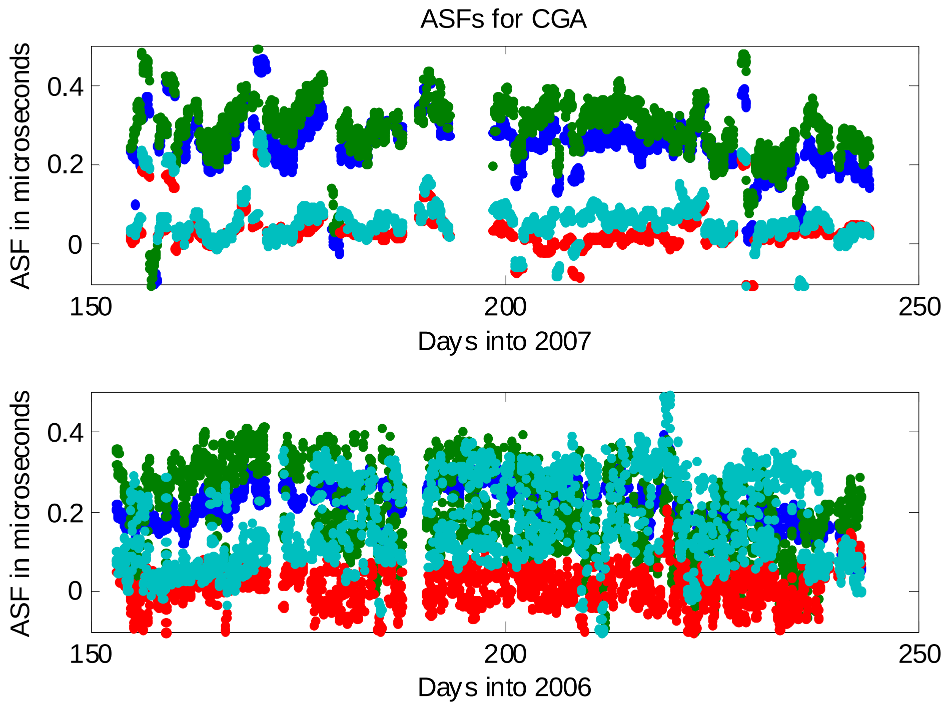

Figure 6: Two years of summer ASF data at CGA.

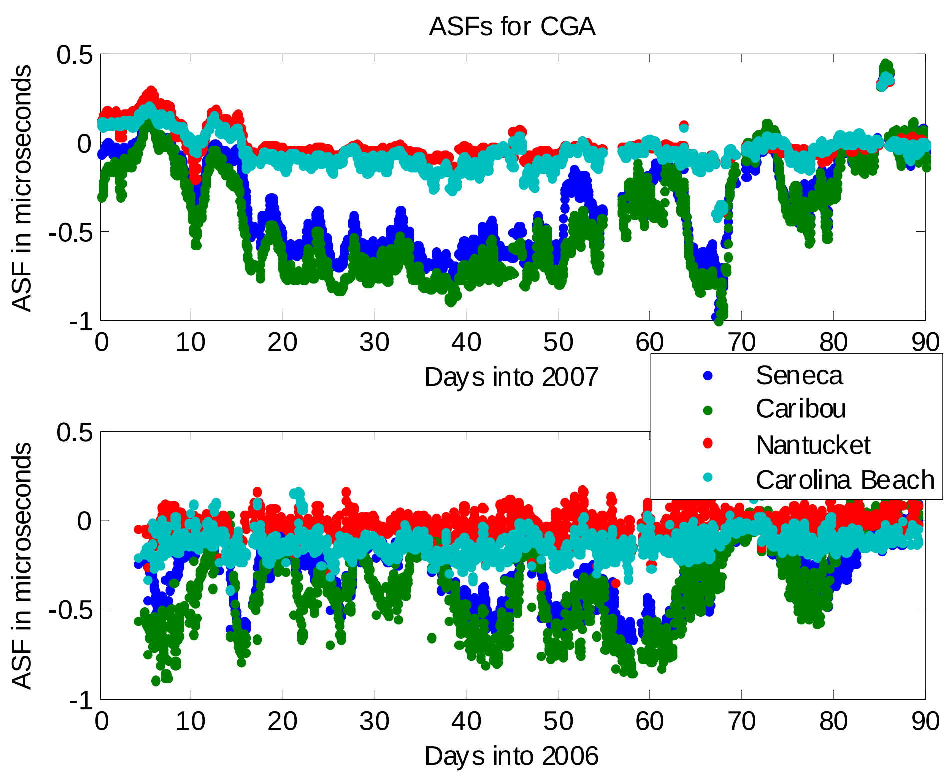

Figure 7: Two years of winter ASF data at CGA.

Next in this examination of ASF data, Figures 8 and 9 compare ASF measurements at two different monitors, so as to examine spatial correlation of the ASFs; the subplots allow for an uncluttered view of the data from each Loran tower. Again, these figures concentrate on four stations in the 9960 chain; as of January 2007 this chain is on TOT control (eliminating the need to adjust the data for time-of-transmission). Figure 8 looks at two relatively close monitor sites, CGA in New London CT and HVN in New Haven CT, a distance of 67 km. For the scale displayed (a vertical range of ±0.5 μsec) these results appear very close. Figure 9 looks at two more distant monitor sites, CGA in New London CT and OUA (or OU) at Ohio University in Athens Ohio, a separation of almost 900 km. In this case, as is expected for such distant monitors, there is a dramatic variation in the measured ASF for all towers.

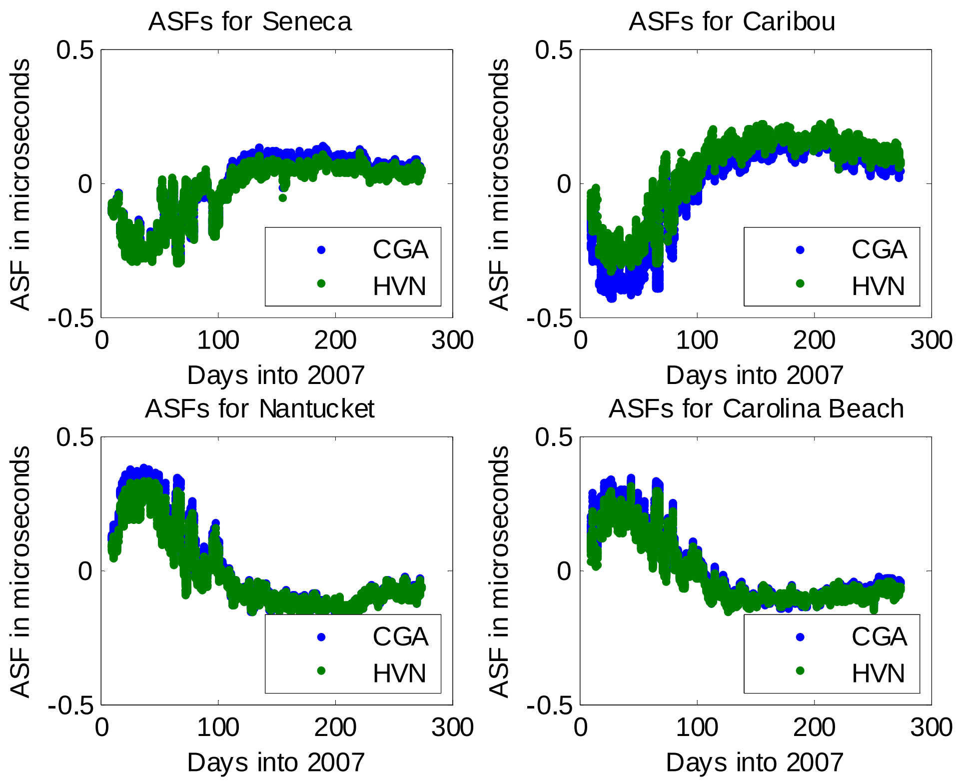

Figure 8: ASF data at two nearby monitor sites.

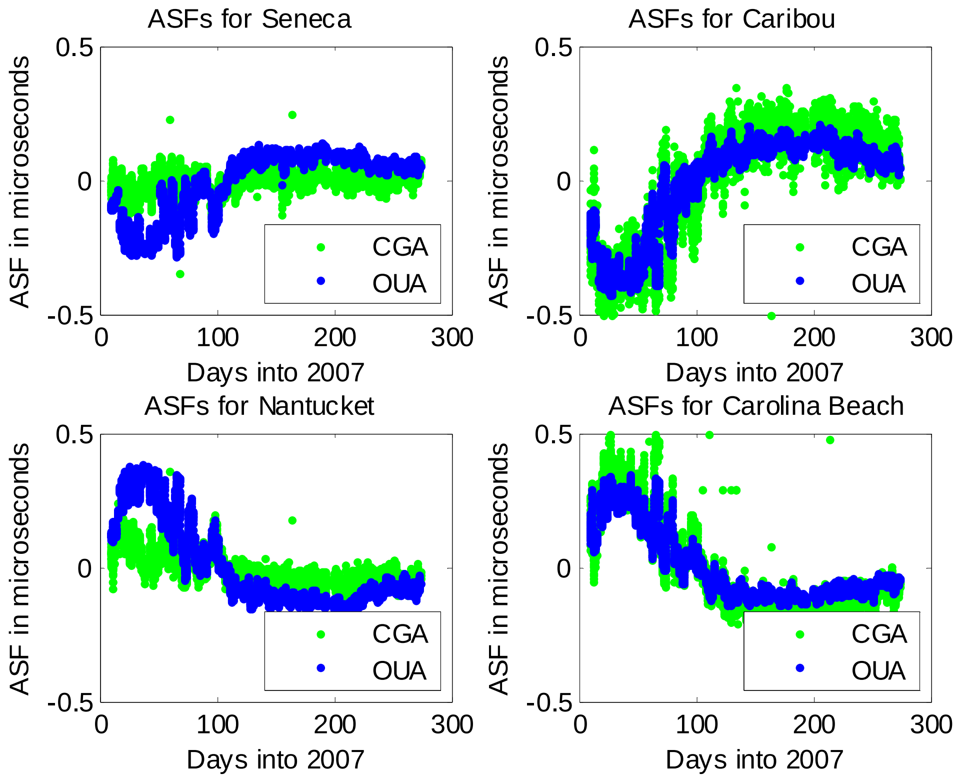

Figure 9: ASF data at two distant monitor sites.

Clearly, there can be great similarly or great difference in the ASFs as measured at different locations; this variation is made more apparent by examining the difference in the ASFs. Further, to aid in visually analyzing such data, it is convenient to shift the differences to have zero mean (at each point in time) since a Loran receiver is sensitive to any bias common to the TOAs. This shifting allows for easier identification of periods of small versus large ASF mismatch. As examples of this differencing/shifting, Figures 10 and 11 show the ASF data comparing CGA to HVN and OU, respectively. A comparison of the vertical scales in these two figures makes it clear that the ASFs of CGA and HVN track closely while CGA and OU do not.

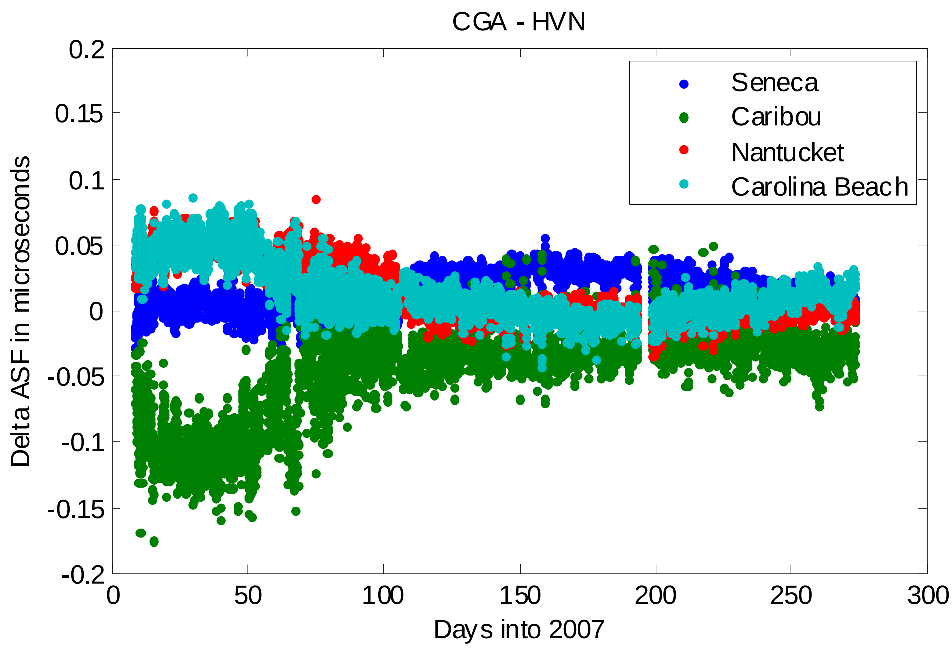

Figure 10: Shifted difference ASF data at two nearby monitor sites.

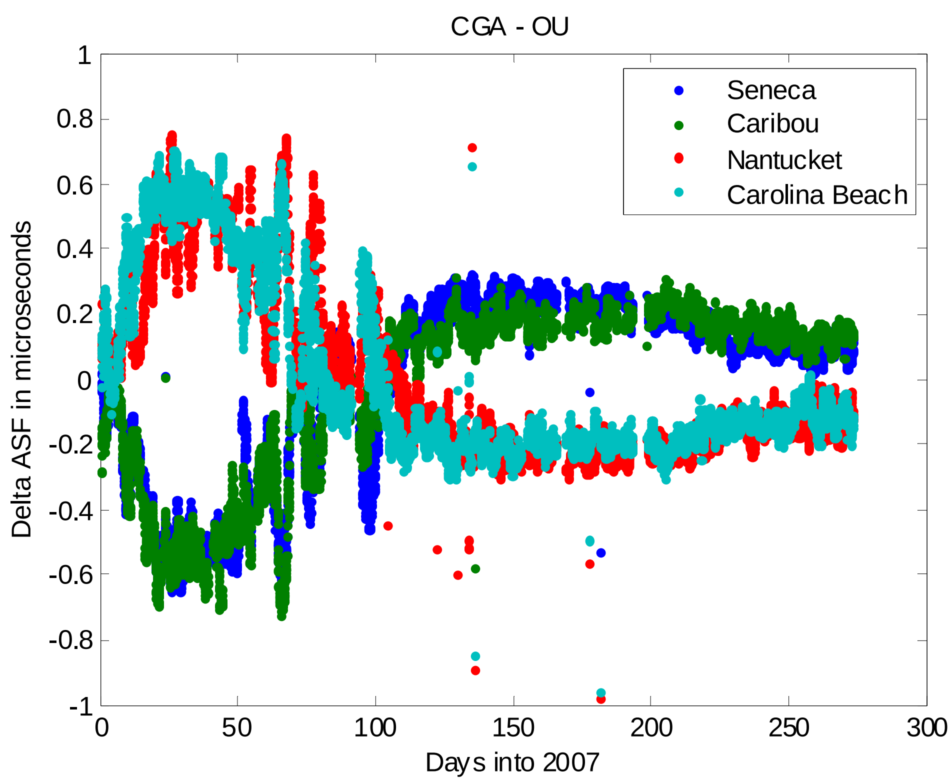

Figure 11: Shifted difference ASF data at two distant monitor sites.

STATISTICS

While the figures above, and many others like them, visually show the relationship of ASFs at the various monitor locations, the monitor network has resulted in a large collection of data; there is great value in reducing the data into some more manageable form, some sort of statistic. The question is what to compute. In the discussion above, the term "correlated" was repeatedly employed to indicate that ASF measurements at different sites "look" like measurements at another. This notion naturally leads to the traditional statistic of the correlation coefficient which, for two variables x and y, is defined as

$$\rho = \frac{E\{(x-\mu_x)(y-\mu_y)\}}{\sigma_x \sigma_y}$$

In this expression, μ_x and μ_y are the means of x and y, respectively; similarly, σ_x and σ_y are the standard deviations. By definition, the correlation coefficient is bounded between –1 and 1; a value close to 1, deemed "highly correlated," implies that x and y are statistically very similar. Unfortunately, as defined, this measure is scale and bias invariant and is really looking for a linear relationship between the variables. In other words, x and y could be growing at different rates, yet still maintain a high correlation coefficient. In the navigation context, such a relationship would seriously impact position error; hence, correlation is not the appropriate measure for comparing ASFs.

What seems more relevant, especially after examining Figures 10 and 11, is some measure of the spread of the ASF differences. As the computation above includes shifting (bias removal), the differenced ASFs already have zero mean; hence, one could compare ASF measurements at different monitor sites by computing the standard deviation at each point in time (standard deviation is a typical measure of the spread of data). Further, since the monitors collect data for many points in time, data reduction is achieved by averaging the resulting standard deviations

$$E\{\sigma(ASF_1 - ASF_2)\}$$

in which ASF_k is the vector of temporal ASF values at the k^{th} monitor site; the unit for the measure is nanoseconds. Table 1 contains this statistical measure for a selection of pairs of the monitor sites using the 2007 monitor site data. The table lists the monitor site pair, their distance, and the statistic averaged over three ranges: the entire year as well as just the summer and winter months. As expected, winter numbers are larger than summer for all pairs. What was hoped for was a clear dependence of the statistic on distance; particularly, an increasing relationship. However, this is not apparent. For example, the URI/TSC pair, over 100 km apart, had quite a good match at the ASF level.

Table 1: The averaged range of ASF differences for selected pairs of ASF monitor sites.

Monitor site pair	Distance km	Yearly average	Summer average	Winter average
CGA/GSPD	31	46	45	62
HVN/GSPD	41	83	55	121
CGA/URI	49	44	42	61
CGA/HVN	67	65	50	98
URI/GSPD	77	59	63	73
URI/TSC	104	36	32	52
ACY/OU	658	218	178	333

POSITION ERROR PERFORMANCE

It was noted above that the proposed statistical measure (the averaged spread of the ASF differences) suggested a good match between the ASF measurements at URI and TSC. The real question, though, is "Are they close in the performance measure that is cared about, position error?" Recall that one goal of the monitor site data collection effort is to estimate how close monitors would need to be for HEA. Is one monitor sufficient for a large harbor, such as New York, or is a second monitor needed? Can a temporal monitor at one harbor service HEA applications at a nearby harbor? The answer, obviously, determines the cost of implementing Loran for HEA.

Prior work on surveying the spatial component of the ASF provides some answers to these questions. Specifically, when doing actual harbor surveys (see [4,6,7,8]), computation of positioning performance was done in parallel, both in post processing mode and real time (post processing was implemented primarily to assess the required grid size for spatial ASF corrections, real time positioning was used to demonstrate the system to Coast Guard sponsors). In such experiments the position error is due to the combination of the receiver's noise, errors in the spatial ASF grid, and differences in the temporal ASF at the actual location and that broadcast from the local monitor site. In New York, Boston, New London, and Norfolk harbors, this testing yielded good positioning performance. However, in each case, the temporal monitor was quite close to the vessel. Further, the tests occurred sporadically; there is no assessment over an entire year.

To address the broader concern, consider the following, more detailed question: "How much do the ASF temporal differences contribute to the position error performance over the course of a season/year?" To answer this question, imagine the following position problem. TOA measurements are made at some location. Assume that the measurements are free of receiver noise and that the spatial term of the ASF is perfectly estimated; the only remaining variation on the TOA is the temporal ASF. The approach is to use the temporal ASF measured at a nearby monitor site and assess the impact of the mismatch. With the data available, select the vessel location to be at one monitor site and use the corrections measured at another; while this provides vessel locations that are typically quite distant from the monitor, it does allow examination of the impact of the temporal ASF over the entire year.

As a first example, consider the pair TSC and URI, noted above for good statistical match. For this example, the two sets of ASF differences are shown in Figure 12. To review the scenario, the vessel is located at one of these monitor locations and employs the temporal corrections at the other; other impairments to the TOAs are either known or zero. Next, compute the Loran position and the position error for each point in time. A scatter plot of the resulting errors is shown in Figure 13, separating performance into summer and winter months. As expected, Loran performance (with ASF mismatch) for the summer is better than that during the winter. Also, while tending to mirror each other, the errors at TSC versus URI are not exactly opposite in that the two sites have somewhat different geometry to the Loran towers (being further north, TSC has better geometry with Caribou). The most significant observation is the average size of the error; the temporal mismatch alone of these two "correlated" sites yields a large position error. The blue circles in Figure 13 are the 95% error radii, meaning that 95% of the observed errors fell within that circle. Figure 14 shows the error performance for the closest pair of monitors, CGA and HVN. While the error is reduced, the impact of just the temporal ASF is still too large for HEA applications (since we will also experience spatial ASF mismatch and receiver noise). Figure 15 shows the result for all pairs of monitor sites; the conclusion is that HEA will require monitor-to-vessel separation of less than 30 km.

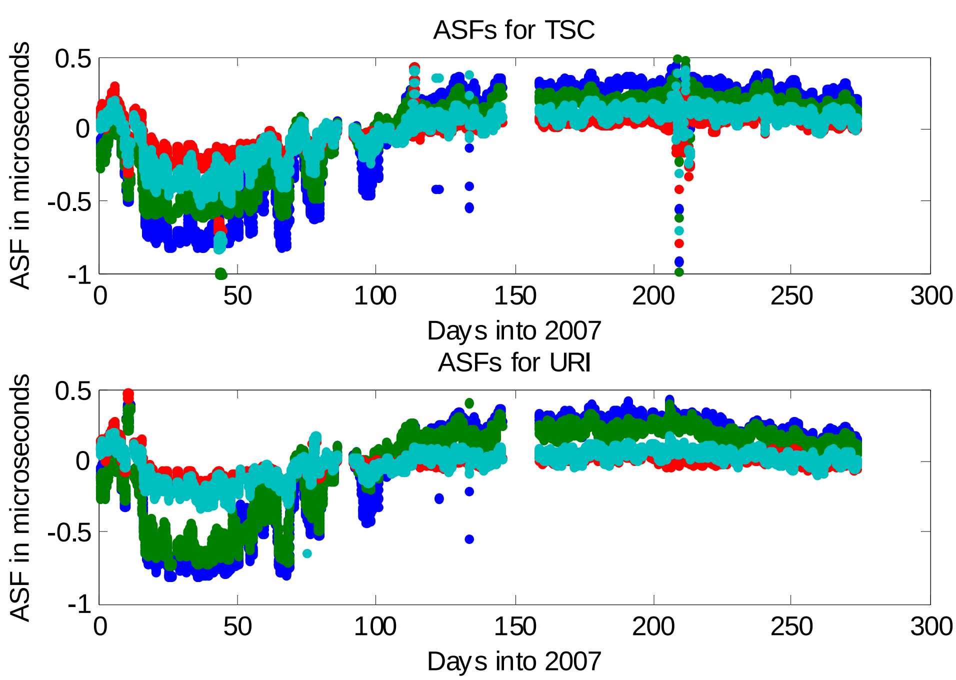

Figure 12: Shifted difference ASF data for TSC and URI.

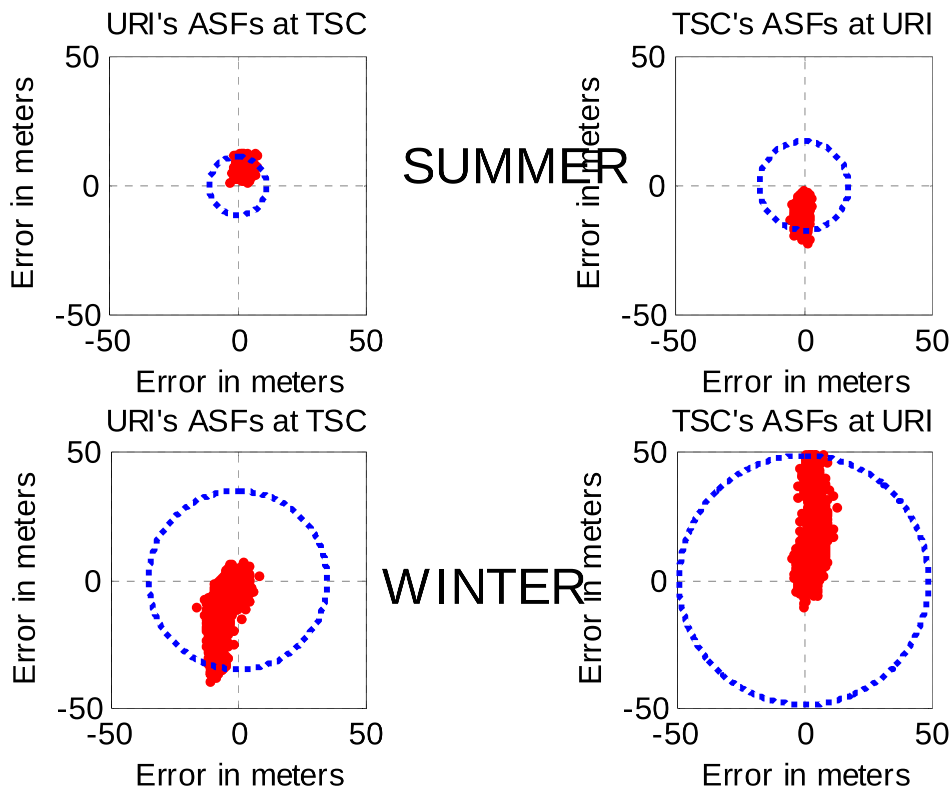

Figure 13: Position error, swapping temporal ASFs at TSC and URI.

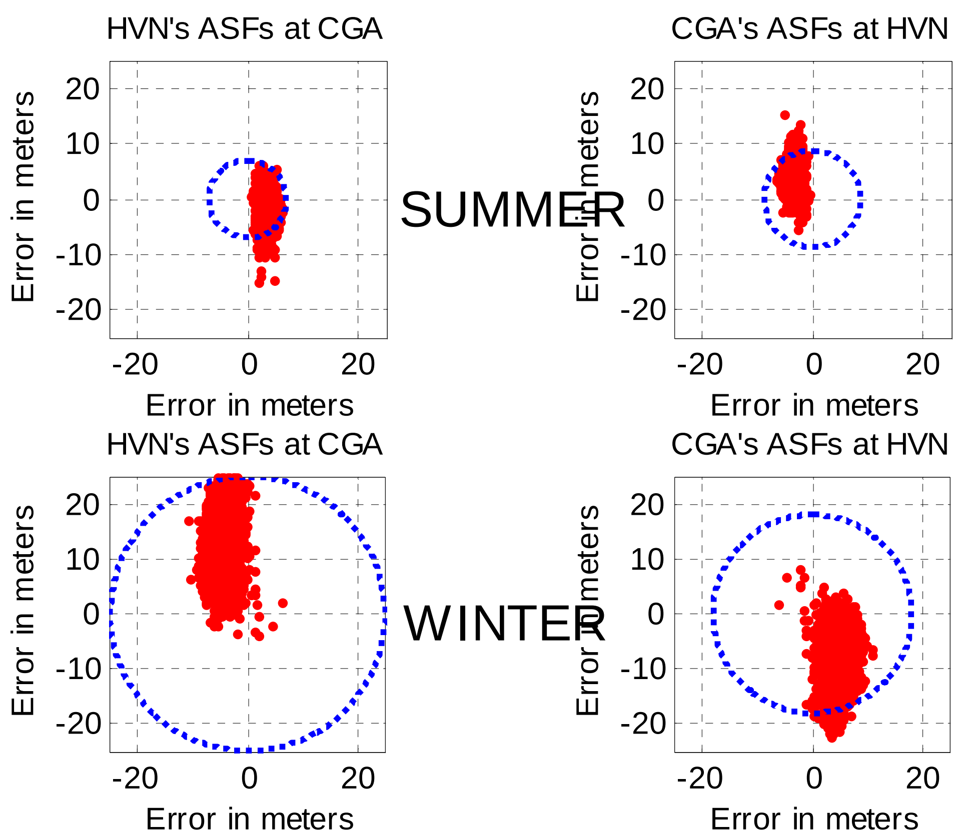

Figure 14: Position error, swapping temporal ASFs at CGA and HVN.

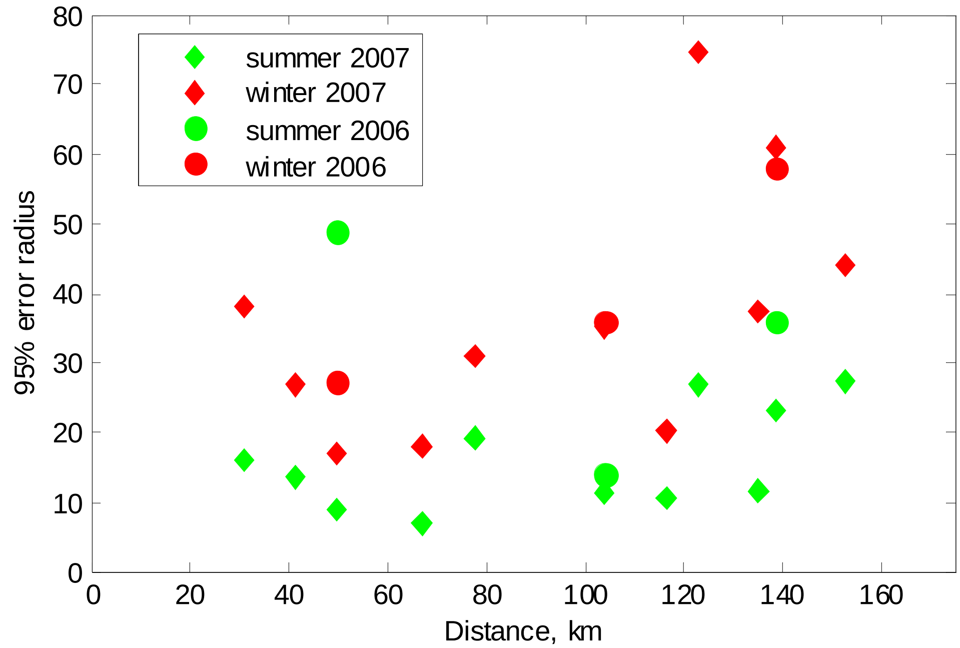

Figure 15: Position error as a function of distance, winters and summers of 2006 and 2007, for selected baselines.

CONCLUSIONS/FUTURE

An analysis of the data collected to date at the ASF monitor sites show marked similarity 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. For the aviation application, the mismatch due to the temporal component seems quite within the error budget envisioned.

The next step in this investigation will be to gather data from the LSU/PIG sites at Point Allerton (MA) and Sandy Hook (NJ) for testing. Both of these sites will provide shorter baselines (to TSC and STI, respectively) for mismatch testing.

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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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Capt Richard Hartnett is a professor in the Engineering Department at the U.S. Coast Guard Academy (USCGA). He graduated from USCGA with his BSEE in 1977, and earned his MSEE from Purdue in 1980, and his PhD in Electrical Engineering from University of Rhode Island in 1992. He holds the grade of Captain in the U. S. Coast Guard, and has served on the faculty of the Coast Guard Academy since 1985. He is the 2004 winner of the International Loran Association Medal of Merit.

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