Warping Time and Space: Spatial Correlation of Temporal Variations

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Abstract

The Loran system's biggest obstacle to modern expectations for accuracy lie in Additional Secondary Factors (ASFs). These ASFs correspond to a slight retardation in the time of arrival (TOA) of the transmitted signal, and can vary greatly due to the non-uniform nature of ground conductivity and topography. Alion has been responsible for work on developing procedures for ASF surveys for both airports and harbors [1-4]. One of the remaining issues for the airport survey methodology has been how to choose ASF values in the middle of the seasonal range, which can show great variance in ASFs due to ground conductivity's sensitivity to temperature. One of the issues for the harbor methodology has been to determine what spatial separation of ASF readings is appropriate, so that a whole region's ASFs can be reasonably determined despite these variances. In order to answer these questions, Alion has installed and maintained a number of Seasonal Loran Monitors in the north east US, hoping to characterize the correlations between ASF variation, in both time and space. This paper outlines the Seasonal Monitor system, from the data collection equipment at the monitoring site to the chain of communication in the system itself. It examines a representative sample of the data, drawing conclusions from those observations. Lastly this paper suggests some solutions for filtering the incoming data to make it possible to accurately predict regional ASFs for the harbor temporal correction concept.

Introduction

With advances in technology, over time the Loran system has become more reliable and accurate. However, the limit to its accuracy lies in the timing of the Loran signal pulse, and the effect on this pulse caused by ASFs, or Additional Secondary Factors. These ASFs correspond to a slight retardation in the time of arrival (TOA) of the transmitted signal, and can vary greatly due to the non-uniform nature of ground conductivity and topography. There have been numerous studies and reports on this in the past including the Harbor Monitor and Stability studies done by the USCG R&D Center in the 1980's [5-9]. More recently the Alion Science & Technology (Alion) team in conjunction with the U.S. Coast Guard Academy (CGA) has been revisiting this issue and has written a number of reports documenting the findings [10-14]. There have been efforts to pre-compute ASFs based on ground conductivity survey maps (LUPS) and conductivity combined with topography (BALOR), but since ground conductivity is not constant either, it can have as much seasonal as geographical variance. Alion has been responsible for work on developing procedures for ASF surveys for both airports and harbors [1-4]. One of the remaining issues for the airport survey methodology has been how to choose ASF values in the middle of the seasonal range. One of the issues for the harbor methodology has been to answer the question "What is the spatial range of validity of the temporal corrections?", or in other words, "How close together do harbor monitor sites need to be?" In order to answer these questions, we have installed and maintained a number of Seasonal Loran Monitors in the north east United States, hoping to characterize the correlations between ASF variation, in time and space. The Seasonal Monitor network and the analysis of the data it generates is a work in progress. The first Monitor was installed less than a year ago, and the sixth went online in September of 2006.

This paper will first describe the Seasonal Monitor system, from the data collection equipment at the monitoring site to the chain of communication in the system itself. Then we will examine a representative sample of the data, drawing conclusions from those observations. Lastly, this paper will suggest some solutions for filtering the incoming data to make it possible to accurately predict regional ASFs for the harbor temporal correction concept.

Seasonal Monitor Network

At the beginning of this year, we assembled and installed 6 Seasonal Monitors in the north east U.S. and Ohio. The locations of the monitoring sites, shown in Figure 1, are primarily Coast Guard installations and partner institutions; sites provide power, a secure location for equipment, a spot for antenna mountings, and an Internet connection. The Seasonal Monitor sites installed at the time of this writing include Ohio University at Athens (OUA), the FAA Technical Center in Atlantic City NJ (ACY), the Volpe Transportation Center in Cambridge MA (TSC), the Staten Island NY Coast Guard Base (STI), the University of Rhode Island in Kingston RI (URI), and the US Coast Guard Academy in New London CT (CGA). The proximity of these sites, noting their varying separation, gives us the opportunity to study effects of ground conductivity in one concentrated region with variable distances between points, as well as a similar climate.

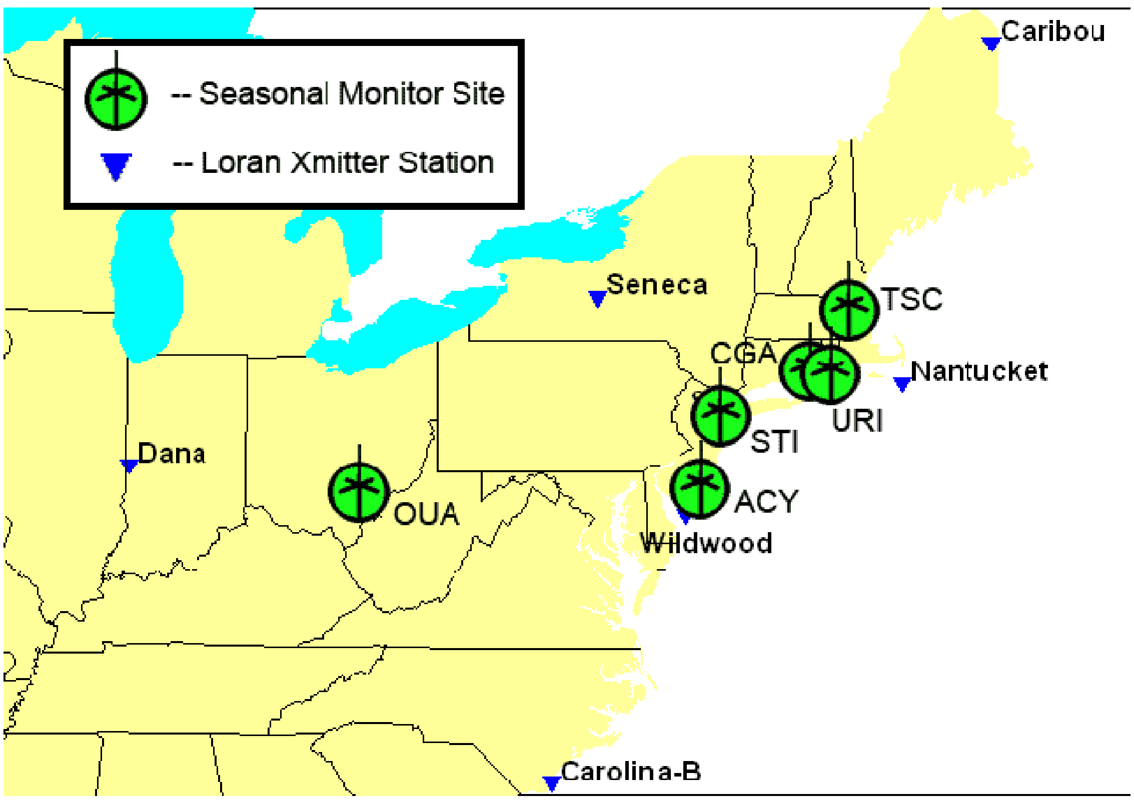

Figure 1: Locations of the Loran Seasonal Monitor sites.

At each Seasonal Monitor site, we have installed a self-contained unit consisting of Loran and GPS logging equipment. The unit itself is usually enclosed by a building or shed with the exception of the antennae. Weatherproofing is crucial considering the length of time these units are expected to be left in the field. In the example shown in Figure 2, the system resides within a metal shack, while the antennae are mounted to its roof.

Figure 2: Photographs of a typical Seasonal Monitor installation.

The unit itself is comprised of a pair of antennae connected to Loran and GPS receivers, which communicate directly to data collection software on a laptop 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 the Coast Guard Academy server through a TCP/IP connection. These units are very self-sufficient. All units also include a UPS with extended battery back-up, so even if power is lost for a length of time, the Seasonal Monitor logging can continue uninterrupted. See Figure 3 for a diagram of the setup.

The ASF data computed by the Seasonal Monitors is sent to the Coast Guard Academy server at 1 minute intervals for storage and dissemination. This frequent communication allows us to keep an eye on the performance of the Monitors ourselves, as well as review data trends over the course of its operation. If a Monitor stops communicating for any reason (and this has happened due to extended power outages), we are able to act quickly to rectify the situation. With such autonomy, the owners of the installation where the Monitor resides do not need to be overly concerned with the Monitor's operation.

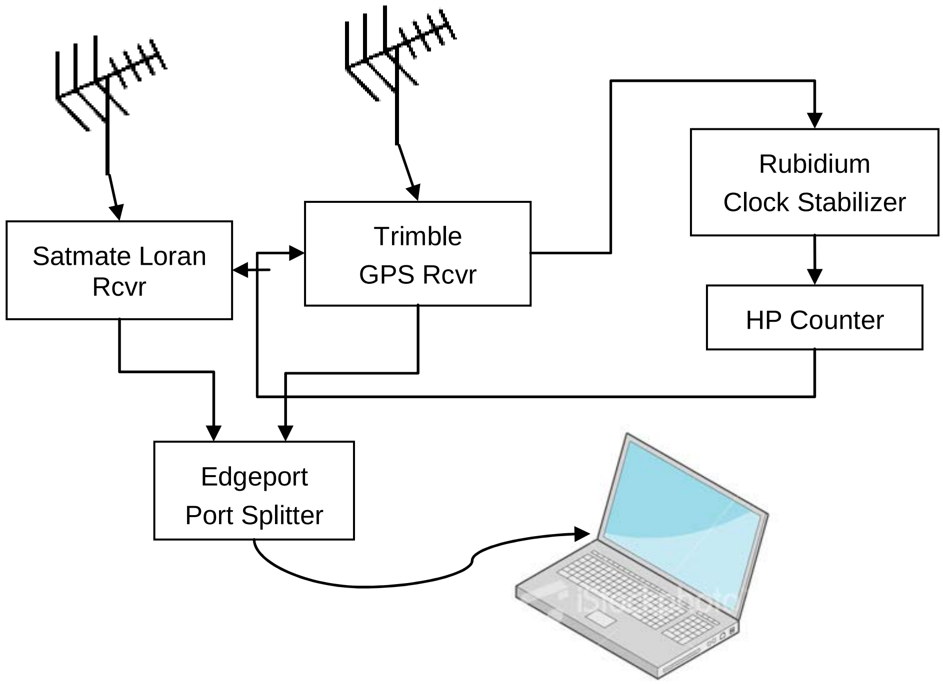

Figure 3: Block diagram of a Seasonal Monitor configuration.

At the Academy, the Seasonal Monitor server is running two different programs that handle the incoming ASF data. The first is the collection software, which aggregates all the incoming data and stores it for future reference. The second is the differential Loran corrections transmitter which has two functions. First, it converts the raw ASF values into offsets from the base or reference ASF values, and then writes the values into a file in the format needed by the Loran Data Channel modulator. The base values that act as the center point of these offsets are calculated to be the middle value (as opposed to the median or mean of the data set) of the bulk of the ASF data. These values (one for each Loran signal being tracked) are pre-determined for each Seasonal Monitor site, and are published in the differential Loran almanac. Second, the transmitter software sends this file of differential corrections to a server at the Coast Guard Loran Support Unit (LSU) using ftp.

The ftp server at LSU acts as a repository for the differential Loran corrections from all of the sites generating the corrections. With every new update, this message changes and is always available for access on the LSU server. For those LORAN towers transmitting the corrections (using 9th pulse transmission), another program downloads the desired correction files and transmits the messages, completing the communications chain in the dLORAN system. Figure 4 shows the movement of data, in this case showing Seneca as the 9th pulse modulator.

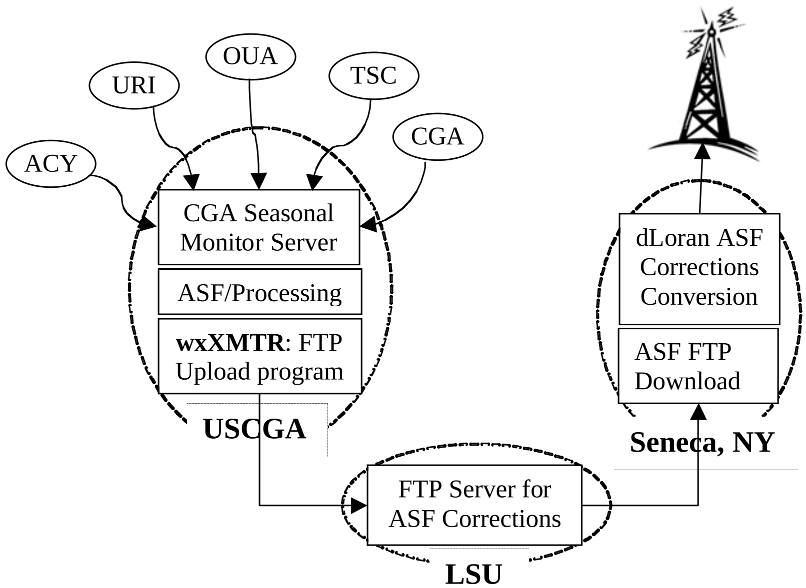

Figure 4: Differential Loran correction data distribution.

Seasonal Differences

The monitor site locations were chosen mostly in the north east U.S., where seasonal variation is expected to be largest, and at varying separations to be able to observe spatial correlation across baselines of different distances. Currently, those separations vary from 10's of km (URI-CGA) to over 1000km (OUA-TSC). Figure 5 shows a map with some of these baselines between stations drawn.

Figure 5: Seasonal Monitor site locations and baselines.

One of the baselines shown on the previous figure is that between Atlantic City (ACY) and the University of Rhode Island (URI); at 343 km apart, this is our median separation between Monitors. Figure 6 shows a plot of the ASFs (hourly averages of the one-minute data) at each of these sites for the Loran station Seneca on the 9960 chain. The top subplot in this figure shows the two ASFs versus time. (In both cases we have subtracted out their median values. While this creates the impression of negative ASFs – which, of course, is incorrect – removing this constant brings the two results together on the common axes and allows us to better assess their correlation.) The time coordinate of this data starts from when both sites came online in January 2006 and ends this past September. While these two sites are quite far apart from each other, they are both approximately the same distance to Seneca, NY, where the Loran transmitter is located, with only a 50 km difference in total path length. Further, both experience land paths for the Loran signal. The lower subplot in this figure shows the difference between the two ASFs. It is evident that the path differences are much greater during the winter months (up to 300 nsec) than during the summer (<50 nsec).

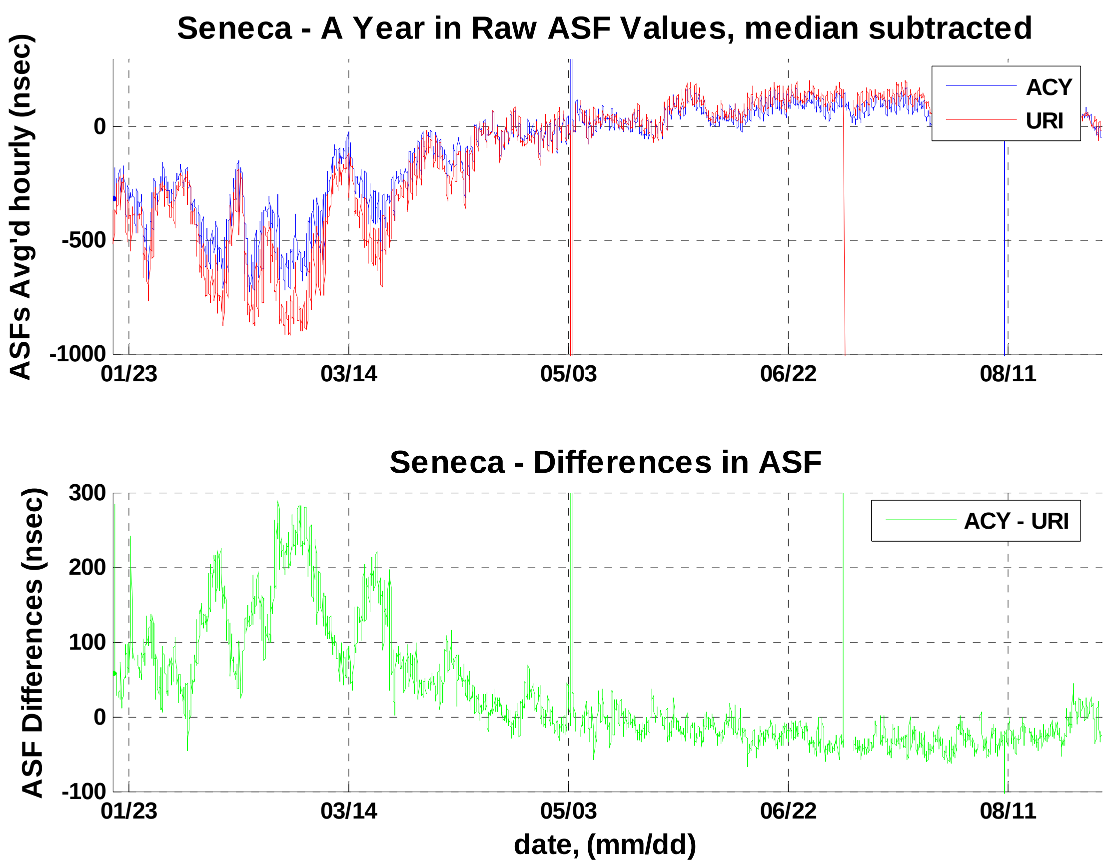

Figure 6: ASFs and their difference – Seneca at ACY and URI.

For these same two Monitor sites, Figure 7 compares the ASFs for Loran station Nantucket. The major difference is that now both signal paths are primarily over water. In the upper subplot, the two ASFs are seen to more closely track at the two Monitors, even in the winter months. The difference (lower subplot) is now quite uniformly small; typically below 50 nsec, both winter and summer.

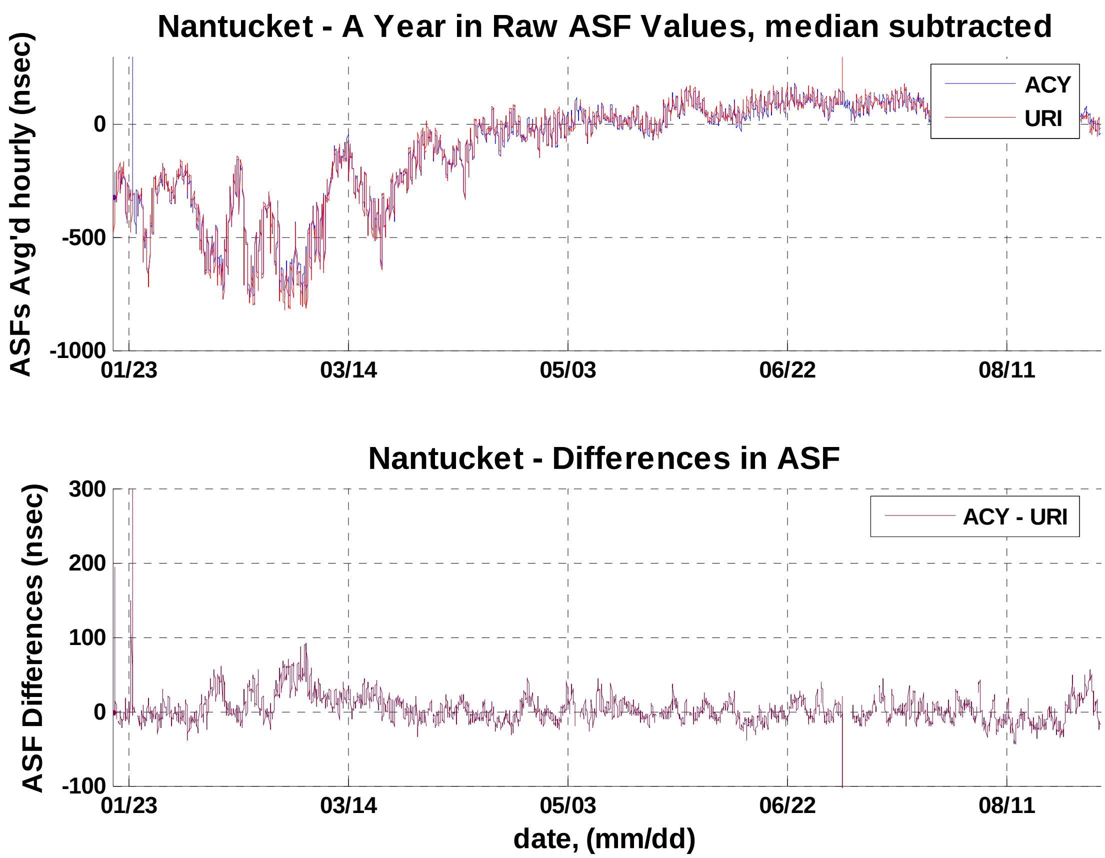

Figure 7: ASFs and their difference – Nantucket at ACY and URI.

To better compare the winter/summer differences shown above, we replot in Figure 8 both sets of differences. A thumbnail within the graph recalls the baseline distance between the Monitors; this thumbnail also clearly shows the land versus water paths for the two Loran Monitor sites. It is evident that the ASFs for land paths are more noticeably impacted by seasonal variations (as is expected).

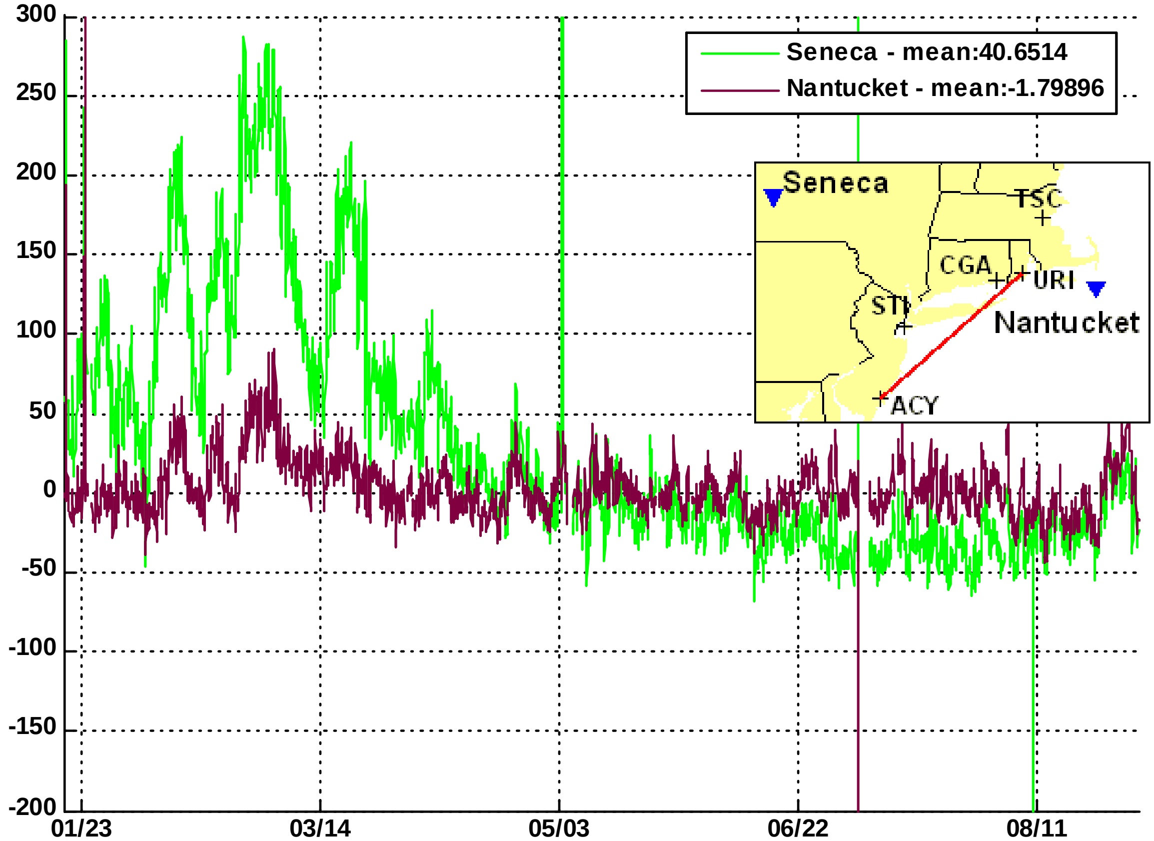

Figure 8: Seneca and Nantucket ASF differences for ACY-URI.

The figures above demonstrate ASF variation on a macro time scale; we now look at a portion of this same data for a single day. Specifically, we selected a day in September 2006 for which we expect the seasonal ASF differences between monitor sites would be small. Figure 9 shows this data (now one minute ASFs) versus time of day for Loran station Seneca. As expected, both ASFs (in the upper subplot) are relatively constant, wandering perhaps ±50 nsec over the course of the day. Further, the difference plot (the lower subplot) also shows about 50 nsec of variation. Jumping to a comparison of the differences for Seneca and Nantucket, Figure 10 shows comparable performance with a diurnal pattern.

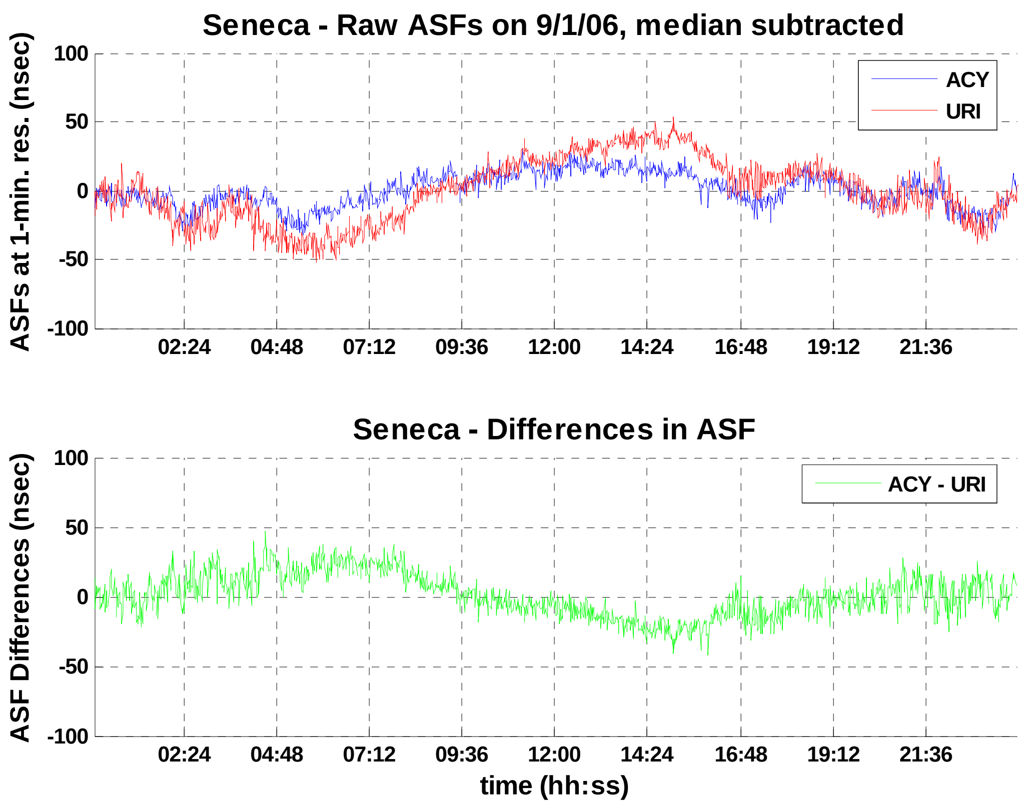

Figure 9: ASFs on a typical September day.

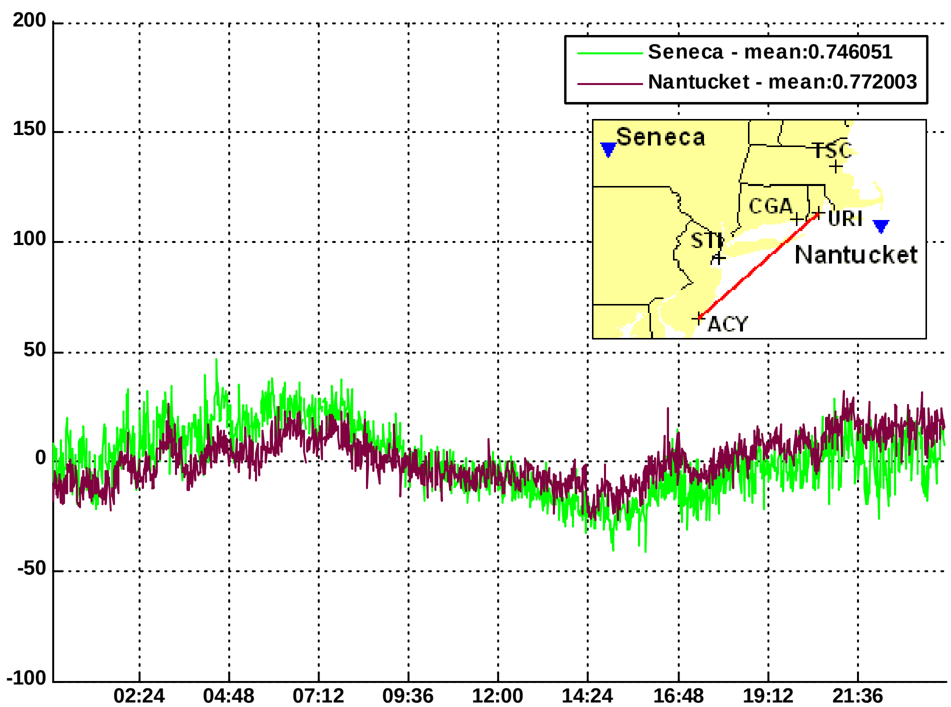

Figure 10: Seneca and Nantucket ASF differences (ACY-URI) for one day in September.

The figures above considered ASF correlation at a significant distance (343 km); next we examine a much shorter baseline. As part of a harbor data collection effort, we set up a temporary monitor site at Sandy Hook, NJ (SHK), approximately 15 km from the monitor at Staten Island, NY. Figure 11 shows the ASF differences for both Nantucket and Seneca at these two sites over one full day, August 28, 2006. Both difference signals appear negligible when compared to the receiver noise.

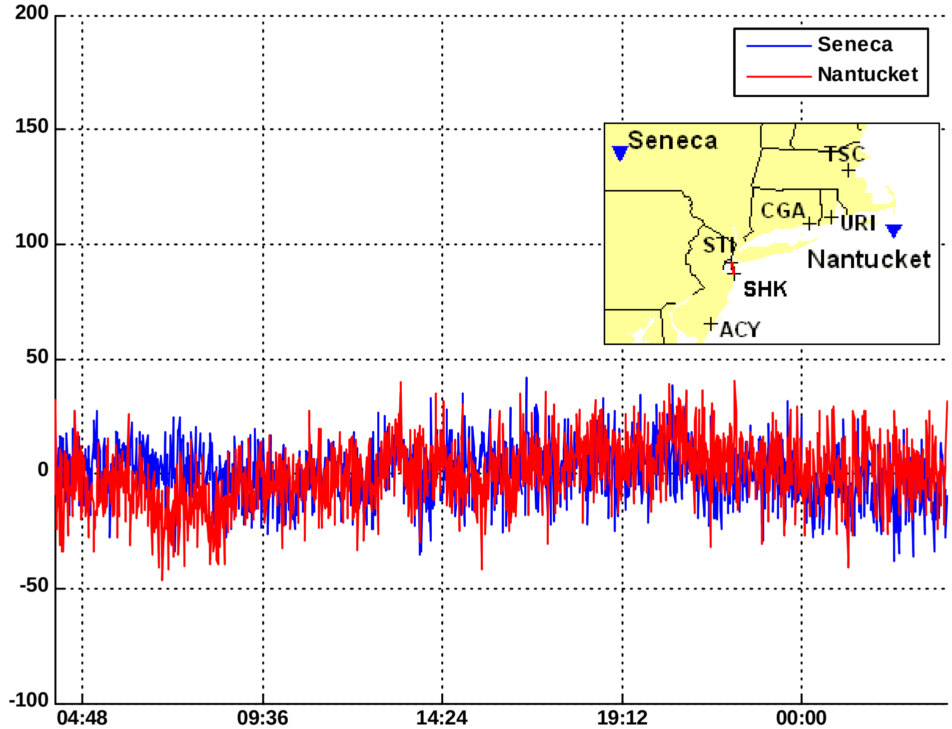

Figure 11: Seneca and Nantucket ASF differences (STI-SHK).

The amount of noise present in the signals of the last figure leads us to ask, "Just how accurate are these ASF measurements? How can we know that our readings at one-minute intervals deserve that kind of resolution? In transmitting the temporal variations for harbor navigation, do we want to track a noisy signal?" In response we have started experimenting with various filtering methods to remove some of the noise on the Seasonal Monitor side of the operation to provide a more reliable estimate of the temporal variation.

Filtering Techniques

The primary filtering technique that we have investigated to date is a moving average (MA) low-pass filter. This is a simple, non-causal filter, relying on averaging data in equal parts from the past and the future of the data point in question. Varying cutoff frequencies are achieved by inversely-proportional filter window lengths, so the longer the window, the more high-frequency content (including noise) is removed from the signal. Figure 12 shows this filter in action with the original data in green, and three examples of the moving average filter of different window sizes overlaid. As you can see, a significant amount of noise is removed even by the smallest window size shown. As effective as this filter might be, however, it is non-causal so that our system would have a latency of one-half of the window size, in minutes, to receive our ASF update. As this is potentially unacceptable, we are beginning to look at predictive filtering.

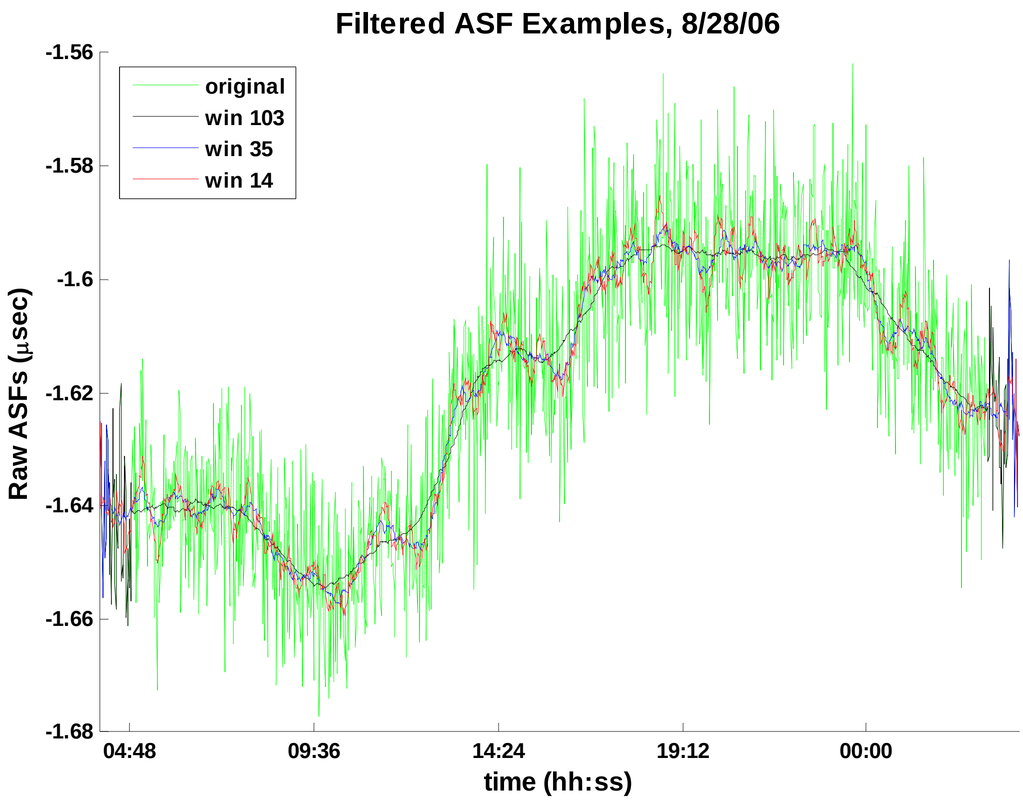

Figure 12: ASF filtering examples.

Conclusions/Future

By the mere fact that we're seeing a steady stream of Loran ASF data from each Seasonal Monitor, and that those ASFs seem to correlate (or not) in a logical fashion, the Seasonal Monitor network development has been a success. As expected, the correlations we do observe seem to be impacted more by the type of path between station and Monitor site (land versus water) rather than the length of the separation, and that this appears to be compounded most by seasonal climate change. In the summer; the data is highly correlated even over very long path lengths. For seawater paths, the data is highly correlated regardless of path length or season. Since we are concerned with bounding the position error for a harbor for all seasons, we must be concerned with the worst-case error. Therefore, in order to make a decision on what baseline separations are appropriate for total seasonal monitor coverage, it will be necessary to fit them to a worst-case scenario guideline. This means there will likely be no one-size-fits-all solution to the placement strategy of harbor monitors.

In the future, there will be a continuation in seasonal monitor data collection. In order to make valid claims about the effects and scale of the seasonal variation, it is important to show that these effects are repeatable. There will likely be more Seasonal Monitors installed throughout the Northeast; this being the region of the U.S. that experiences the most extreme swings from season to season in ASF and in ASF difference along the baselines.

Also, there will be more work done on filtering strategies, specifically predictive filtering (e.g. Kalman). Eventually this filtering should enable us to make intelligent ASF predictions for a given region. It will also be important, given the constraints of the Loran Data Channel (the channel used to transmit ASF corrections), to find a workable balance between the volume of the ASF data being transmitted, and the quality of the data being sent. Coupled together with the most effective choice for baseline separation of seasonal monitoring sites, these advances should give us comprehensive ASF correction coverage for a given region.

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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.

Biographies

Mr. Michael Kuhn is an engineer at Alion Science and Technology, having worked part-time for them for over two years. He graduated from the University of Rhode Island with a BS in Electrical Engineering, and is continuing his education in the graduate program there. His concentration is digital signal and image processing, and communication systems.

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.

Dr. Peter F. Swaszek is a Professor of Electrical Engineering at the University of Rhode Island. He received his Ph.D. in Electrical Engineering from Princeton University. His research interests are in signal processing with a focus on digital communications and navigation systems. Prof. Swaszek is a member of the Institute of Electrical and Electronics Engineers, the Institute of Navigation, the International Loran Association, and the American Society of Engineering Education.

Capt Richard Hartnett is “Head” of 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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