Getting a Bearing on ASF Directional Corrections

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Abstract

The Federal Aviation Administration (FAA) has embarked on a study of Loran-C to evaluate its suitability as an independent radio navigation (RNAV) backup to GPS. Loran’s potential benefit to aviation hinges upon its ability to support Non-Precision Approaches (NPA), which equates to a Required Navigation Performance (RNP) of 0.3 nautical miles. Through FAA sponsoring, the U.S. Coast Guard Academy (USCGA) is responsible for conducting some of the tests and evaluations to help determine whether Loran can provide the accuracy, availability, integrity, and continuity to support NPA’s in the National Air Space (NAS). For maritime usage in Harbor Entrance and Approach (HEA) areas, the goal is to meet the required accuracy of 8-20 meters.

A major part of assessing the suitability of Loran is in understanding the nature of Loran ground wave propagation over paths of varying conductivities and terrain. Propagation time adjustments, called “additional secondary factors (ASFs),” are used to adjust receiver times of arrival (TOAs) to account for propagation over non-seawater path(s). These ASFs vary both spatially and temporally, and unless understood and/or modeled, cause a loss in accuracy and/or the ability to guarantee a hazardously misleading information (HMI) probability of less than $1x10^{-7}$. The USCGA, as a part of the FAA’s government, industry, and academic team, is striving to improve understanding of both the temporal and spatial variations in (ASF).

To mitigate precipitation static issues for aircraft, efforts have focused on H-field loop antennas for the Loran receivers. This paper reports on recent investigations in this program area; these antennas and the additional receiver front end employed to process a pair of loops cause additional variation in the TOA measurements. This paper describes these effects and approaches to mitigate them.

Introduction

The Federal Aviation Administration (FAA) observed in its recently completed Navigation and Landing Transition Study [1] that Loran-C, as an independent radio navigation (RNAV) system, is theoretically the best backup for the Global Positioning System (GPS). However, this study also observed that Loran-C's potential benefits hinge upon the level of position accuracy actually realized (as measured by the 2 drms error radius):

- for aviation applications this is the ability to support non-precision approach (NPA) at a Required Navigation Performance (RNP) of 0.3 which equates to a 2 drms error of 309 meters

- for maritime applications this is the ability to support harbor entrance and approach (HEA) requirements which equates to a 2 drms error of 8-20 meters.

A significant factor impacting the accuracy of a Loran system is the variation in the times of arrival (TOAs) observed by the receiver and presented to the position solution algorithm that are not directly navigation-position based (generally called ASFs, additional secondary factors) [2]. Hence, a key component in evaluating the utility of Loran as a GPS backup is a better understanding of ASFs and a key goal is deciding how to mitigate the effects of ASFs to achieve more accurate Loran-C positions while ensuring that the possibility of providing hazardous and misleading information (HMI) will be no greater than $1\text{x}10^{-7}$. The U.S. Coast Guard Academy, as a part of the FAA's government, industry, and academia team, is striving to improve the understanding of temporal, spatial, and directional variations in time of arrival (TOA) measurements that could be mitigated. The intent is to develop an enhanced Loran system that estimates and removes these ASFs to allow for higher precision position solutions.

Our enhanced Loran system for 2003 and beyond is based on a multi-station, multi-chain, all-in-view, DSP-based receiver observing TOA measurements with an H-field antenna [2, 3]. For the proposed enhanced Loran system, we assume that the non-noise variation in each of the observed TOAs can be decomposed into three *independent, additive* terms:

- Directional term – due to H-field antenna directional characteristics and potentially re-radiation of the Loran-C signal in the local environment.

- Spatial term – due to differences in the Loran signal propagation path (i.e. topography, land versus sea, etc.).

- Temporal term – for short term TOA variability in a local area possibly due to weather, Loran transmitter effects, etc.

Specifically, as described in [4], our approach is to model each of the three components of the ASFs, estimate parameter values for the models, and then "correct" the TOA observations using the models before applying the position solution algorithm. Figure 1 is a block diagram of a system that estimates these three corrections (per station) and corrects the corresponding TOAs before the position solution algorithm. In other papers we have considered the spatial [3, 5] and temporal [4] terms. Details of our equipment for measuring ASFs are described in those earlier papers. In this paper, we concentrate on the effects due to the local receiver; particularly directional effects in the H-field antennas and time delay issues in the receiver front end.

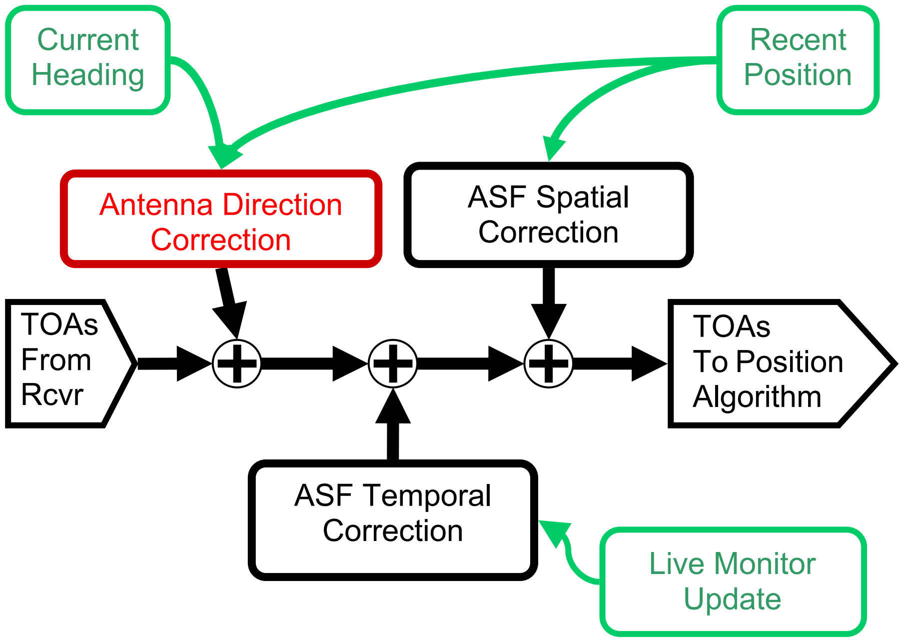

Figure 1 – Block diagram of the enhanced Loran system.

Directional Characteristics in ASF measurements

We first noticed directional effects in TOA measurements in our data sets over a year ago [2]. Instances include data taken while rotating an airplane on the ground (the FAA Technical Center's Convair 580 and Ohio University's King Air equipped with a Locus antenna/SatMate receiver and a Megapulse antenna/USCGA DDC receiver), while an airplane turned circles in the air (Convair with both receiver/antenna setups and also some data Rockwell presented in [6] showed this effect for the Locus antenna/SatMate receiver), while turning a T-boat in the Thames River, New London CT (both receiver/antenna setups), and while turning a antenna on an open field at the US Coast Guard Academy (DDC receiver with aircraft antenna, small antenna, and split loop antennas). Typical data on the variation in the TOAs appears in Figures 2 through 9. From Figure 2, which is data from rotating the Convair 580 at the FAA Tech Center in Atlantic City NJ, we see a variation in all TOA signals tracked and that the variation appears to be sinusoidal in nature with rotation. From the expansion of that plot for the Nantucket station (Figure 3), the magnitude of the effect is seen to reach ± 150 nanoseconds. The further examination of this data in Figure 4 for one full revolution of the airplane (plotted versus angle of rotation) shows the double frequency nature of the characteristic (repeating at 180 degrees) and the phase differences between different stations. The phase lags of 146 and 125 degrees marked on the figure correspond to the relative bearing differences from the airplane's position to the Loran transmitters and closely correspond to the actual phase offsets of the sinusoidal TOA variations. Note that these figures include the TOA variations due to rotation along with the spatial term (which is manifested as a constant offset from zero). Figure 5 shows similar data recorded while making two rotations of a T-boat on the Thames River in New London, CT (DDC receiver/Megapulse antenna). In this case, the data points correspond to individual position measurements (rather than averaged as above) since the boat was constantly moving, taking approximately 4 minutes to turn the two circles.

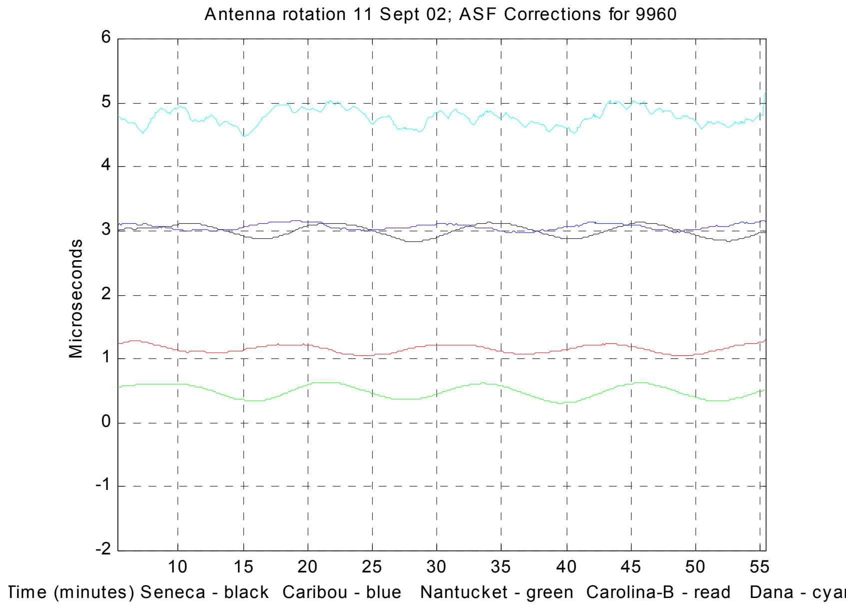

Figure 2 – Antenna delay of an antenna on the Convair 580 rotating on the ground at FAATC.

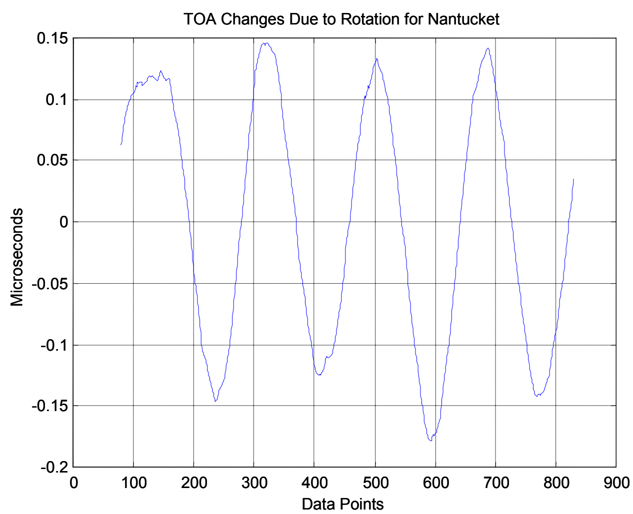

Figure 3 – Expanded view of Figure 2 showing the effect on the Nantucket 9960 signal

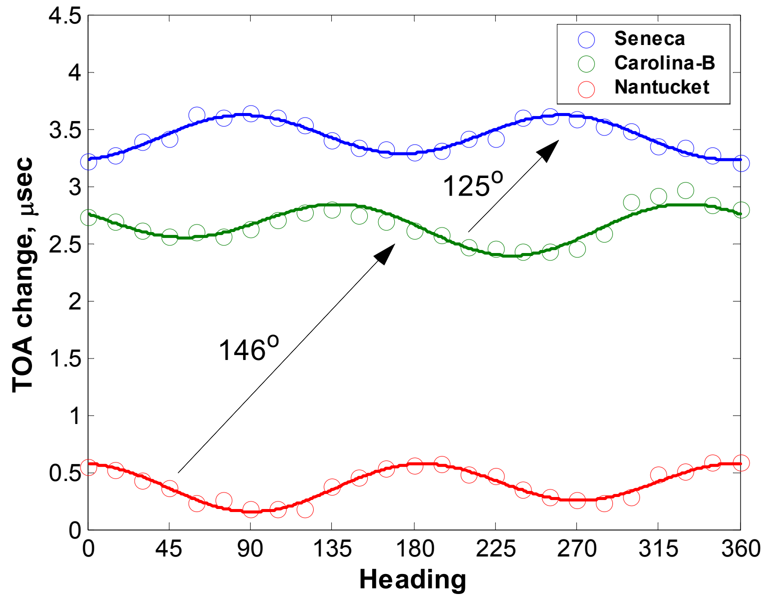

Figure 4 – Another view of Figure 2 data showing the repetition every 180 degrees and the dependence on bearing to the station

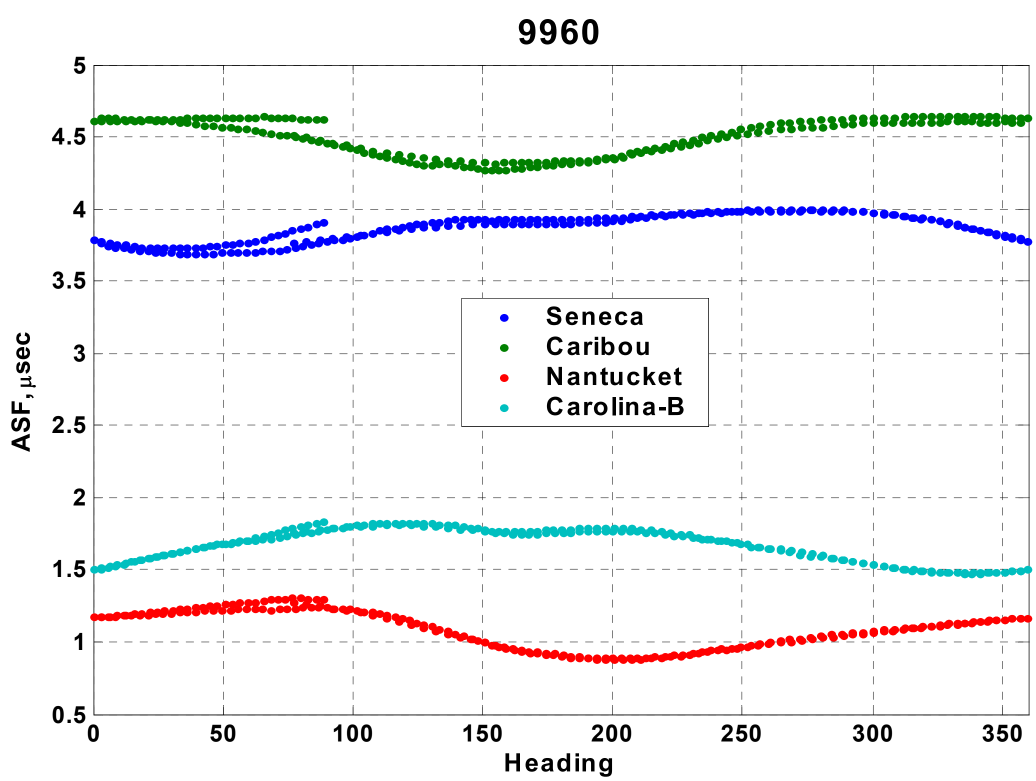

Figure 5 – TOA rotational variation data from turning a T-boat on the Thames River. There are multiple rotations here showing the repeatability of the effect.

To try to limit potential local re-radiation effects due to the vessel, data for an antenna on an open field was taken at the US Coast Guard Academy in New London, CT (view in Figure 6). Figure 7 shows the directional variation for the Locus SatMate 1020 receiver with its H-field antenna versus angle of rotation. In this case, we have subtracted out the spatial component to show the equivalence in amplitude of the effect for different stations. Again, the periodicity of this effect with respect to the relative bearing is apparent. Figure 8 shows a setup for “split loops” by physically separating two H-field loops. Similar TOA variation data for the DDC receiver/Megapulse antenna and the split loops appears in Figure 9.

Figure 6 – Testing on an open field at the USCGA in New London, CT.

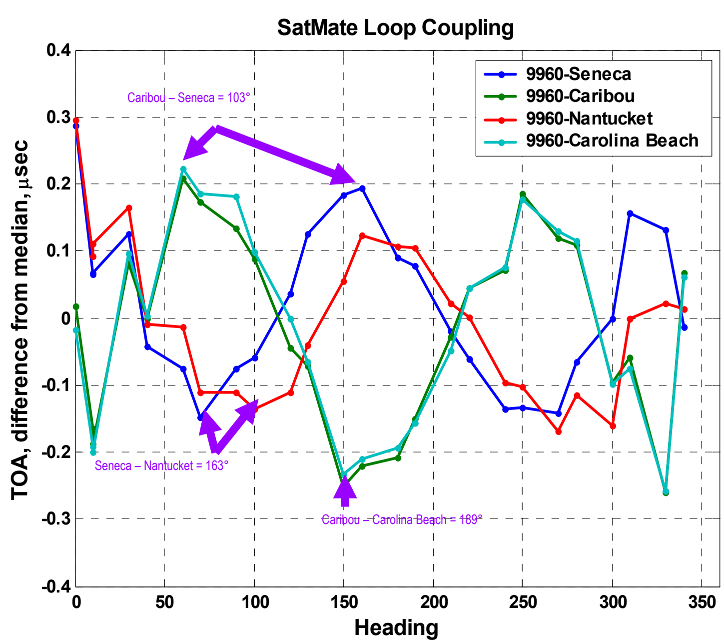

Figure 7 – Directional effect on an open field: SatMate receiver.

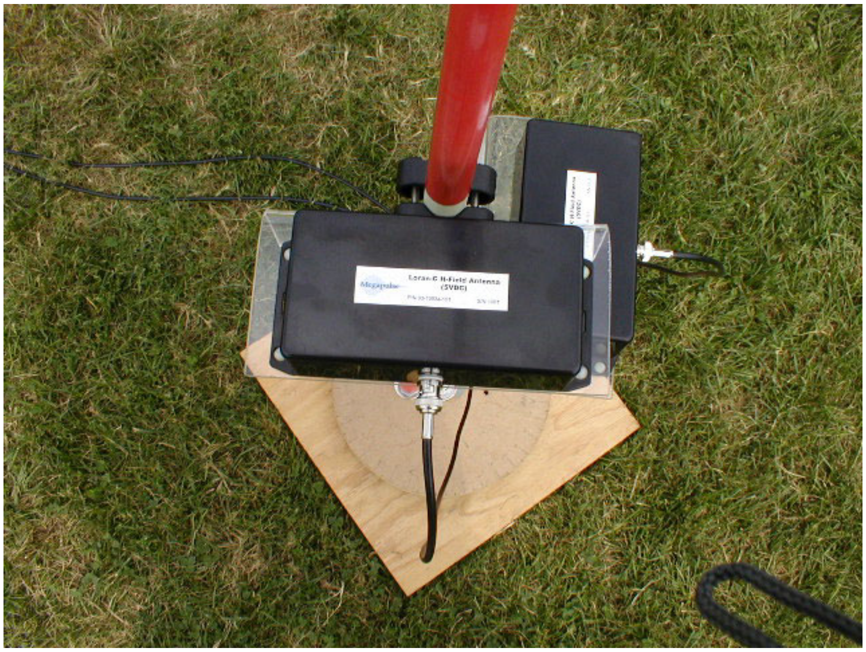

Figure 8 – Split loop antenna configuration.

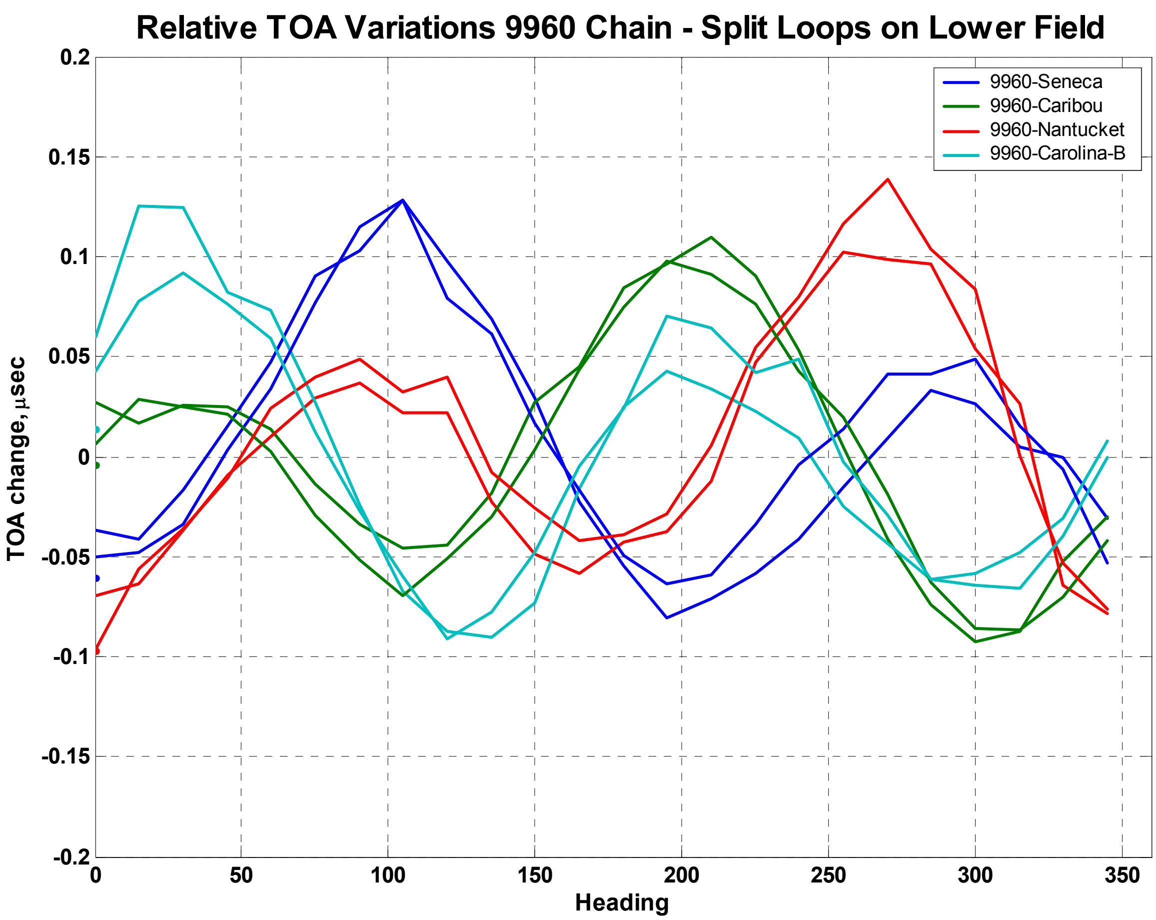

Figure 9 – Directional effect on an open field: DDC receiver.

Given that there are TOA variations as the antenna is rotated, what is the effect in the position domain? To explore this question, we simulated the navigation position solution for the New London CT area (4 station geometry shown in Figure 10) with an antenna that includes an additional 150 nsec sinusoidal (in the relative bearing to the station) phase shift to the TOAs plus noise in the TOA measurement that is typical for our location at the US Coast Guard Academy for the 9960 chain. Figure 11 shows the magnitude of the position error using four stations in the position solution. We note that blue is the performance for noise only and is quite good (less than 5 meters 95% of the time). The red curve which includes the directional variation in TOA shows large variation in the position error (up to 60 meters). This data is viewed as the actual position domain in Figure 12; again, blue is the noise only solution and red includes the directional bias. The main result of this simulation is that it is clear that we need to resolve the directional component either through further study and calibration, modification of the antennas, and/or switching to an E-field antenna to meet the desired HEA accuracy.

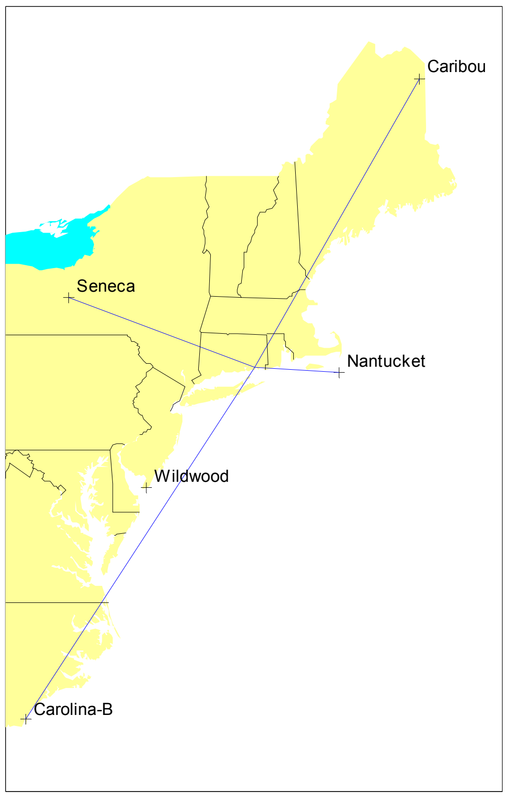

Figure 10 – Loran station orientation in New London, CT.

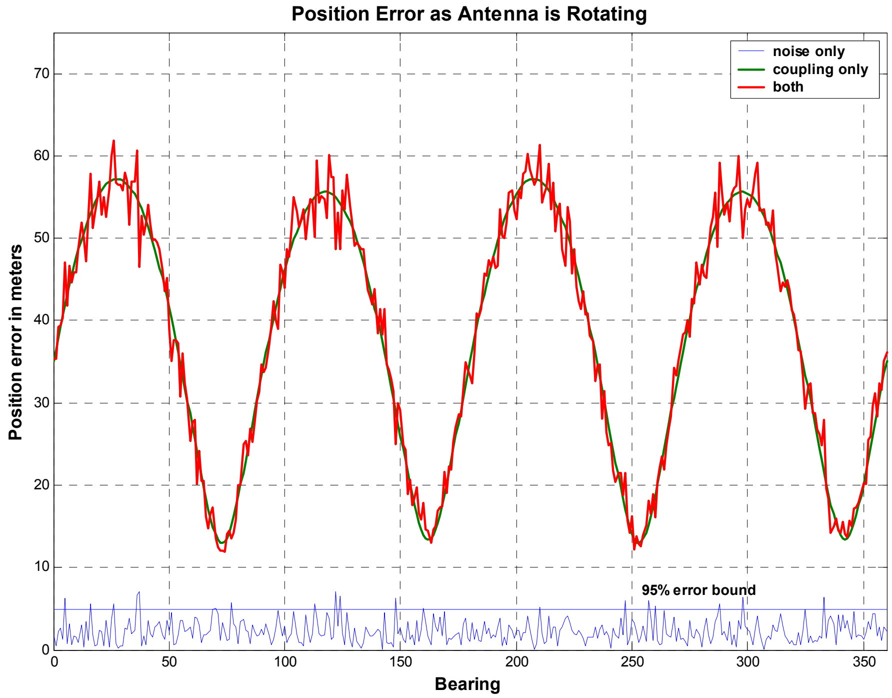

Figure 11 – Simulated magnitude of the position error – red is with the directional bias; blue is noise only

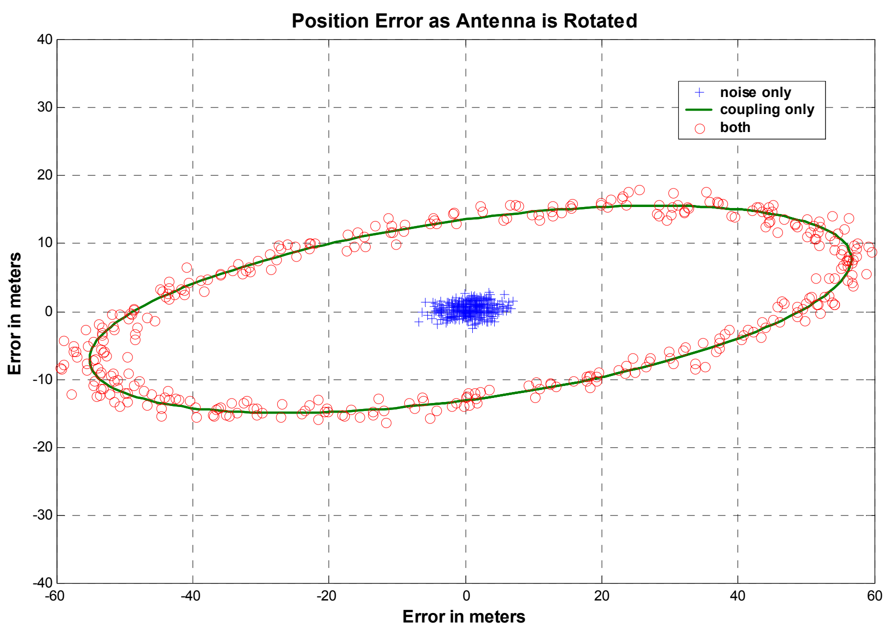

Figure 12 – Simulated position solution: red is with the directional bias; blue is noise only

Time Delays in ASF Measurements

With any modern Loran system, a certain amount of time delay is introduced by the analog front end of the receiver and by the digital filtering (this also includes the antenna itself and cabling). For any particular receiver, this delay value is a constant that applies to all TOAs measured; hence, it is irrelevant to the position solution since, as a common mode term, it is lumped into the computed clock bias. However, since H-field antennas employ two loops, and hence, two front end channels, we must be careful to guarantee that the delays for the two channels are equal.

To understand this necessity, consider the following. Ideally the two loops on the H-field antenna observe orthogonal components of the transmission. Specifically, for a Loran signal $e(t)\sin\omega t$ (envelope and modulating sinusoid) arriving at angle θ relative to the antenna axes, the ideal loop output signals are

$$x_1(t) = \cos\theta\, e(t)\sin\omega t \qquad \text{and} \qquad x_2(t) = \sin\theta\, e(t)\sin\omega t$$

The beam steering receiver combines these two signals into a resultant $x(t)$ where,

$$x(t) = \cos\theta\, x_1(t) + \sin\theta\, x_2(t) = e(t)\sin\omega t$$

independent of the bearing angle. Now, let's add delay in the front end. Assume that there is a lag of τ seconds in the second channel, so that

$$x_1(t) = \cos\theta\, e(t)\sin\omega t \qquad \text{and} \qquad x_2(t) = \sin\theta\, e(t-\tau)\sin\omega(t-\tau)$$

The beam steered resultant is now

$$x(t) = \cos^2\theta\, e(t)\sin\omega t + \sin^2\theta\, e(t-\tau)\sin\omega(t-\tau)$$

A common assumption for an expression like this is that the delay τ causes little change in the envelope of the signal

$$e(t-\tau) \approx e(t)$$

so that

$$x(t) \approx e(t)\left[\cos^2\theta\,\sin\omega t + \sin^2\theta\,\sin\omega(t-\tau)\right]$$

Using trigonometric identities, we have

$$x(t) \approx e(t)\left[A\sin\omega t - B\cos\omega t)\right]$$

with

$$A = \cos^2\theta + \sin^2\theta\cos\omega\tau \qquad \text{and} \qquad B = \sin^2\theta\sin\omega\tau$$

We notice that for small τ, $A \approx 1$ and $B \approx 0$ as they should be. To simplify further, define the angle ϕ by

$$\phi = \operatorname{acos}\left(\frac{A}{\sqrt{A^2+B^2}}\right)$$

to yield

$$x(t) \approx e(t)\sqrt{A^2 + B^2}\,\sin(\omega t - \phi)$$

The result is that a time delay scales the resultant's amplitude by the factor

$$\sqrt{A^2 + B^2} = \sqrt{1 + 2\cos^2\theta \sin^2\theta(\cos\omega\tau - 1)}$$

and introduces a phase delay of ϕ. We note that both of these vary with θ. Figures 13 and 14 show the variation as a function of θ for several values of the time delay. Specifically, we vary the product $\omega\tau$ from 0 (no effect) to 10 degrees. We note that the scaling in the magnitude is negligible while the phase offset can easily exceed 200 nsec.

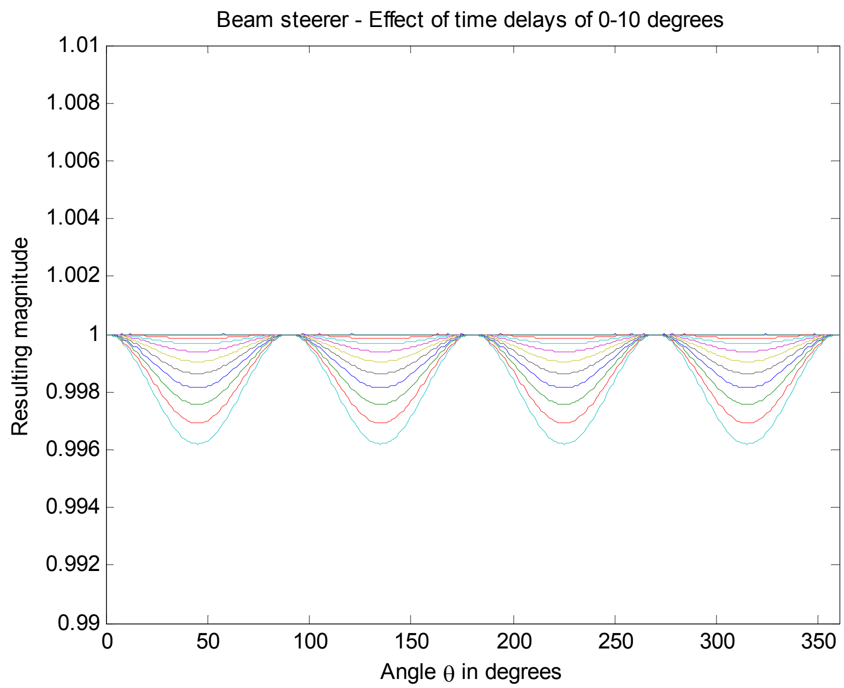

Figure 13 – Effect of a time delay on the beam steered magnitude.

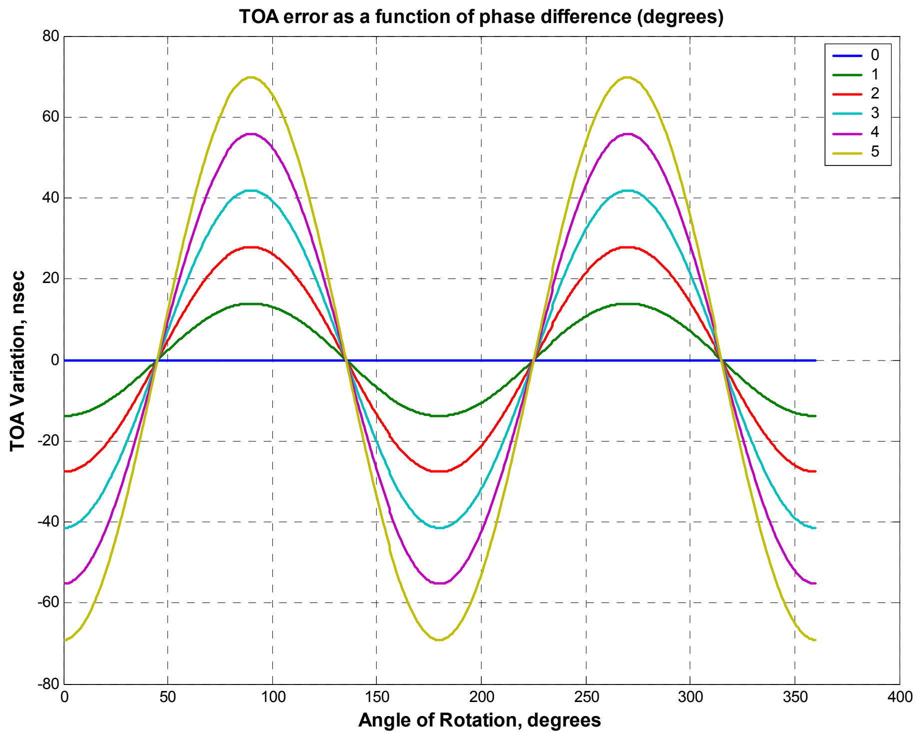

Figure 14 – Effect of a time delay on the beam steered phase (measured in time error for LORAN)

To verify that we were seeing time delays in our system, we simulated Loran RF and applied this directly to our system as described by the block diagram in Figure 15. Figure 16 shows the TOA offset obtained by simulating a rotation of the antenna; the resultant looks very much like Figure 14 with a delay, τ of about 2.5 degrees. Such a time delay is easily mitigated in software by delaying one channel's measurements relative to the other before combining. Figure 17 shows the resulting TOA variation versus antenna angle after such a software offset.

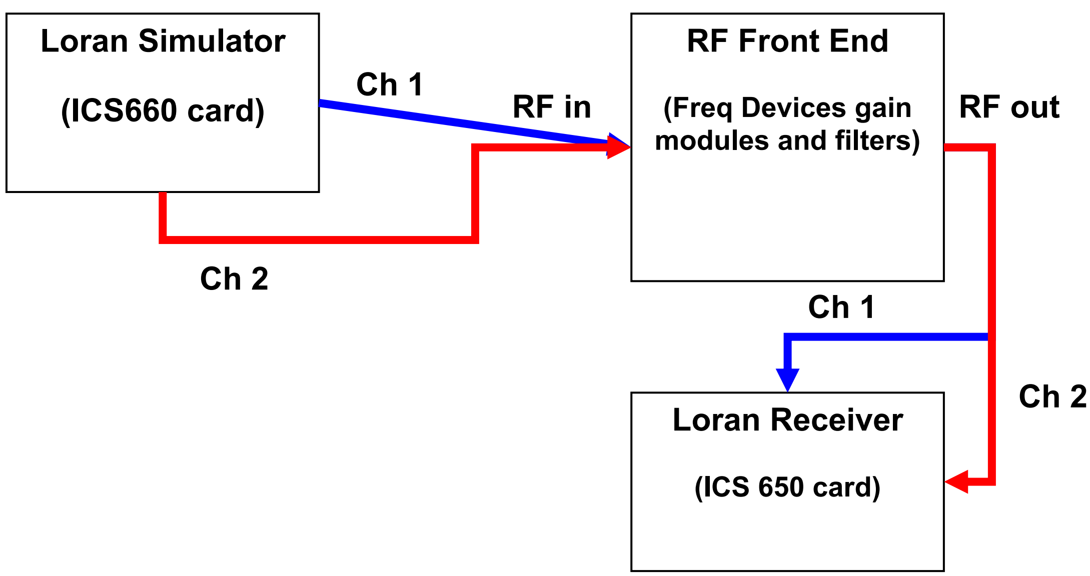

Figure 15 – Simulating the effects of receiver time delays

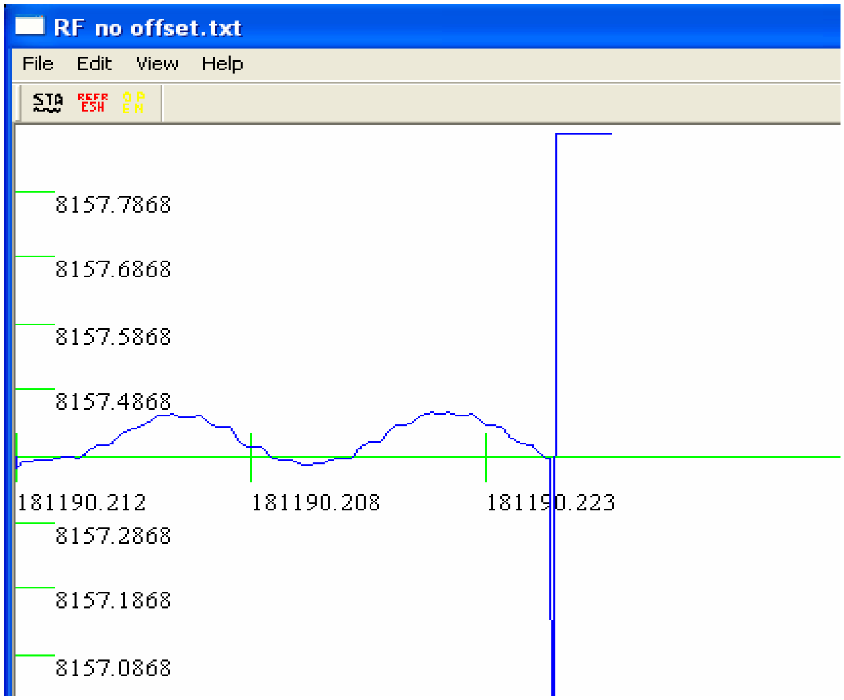

Figure 16 – Measured effect of the front end time delay

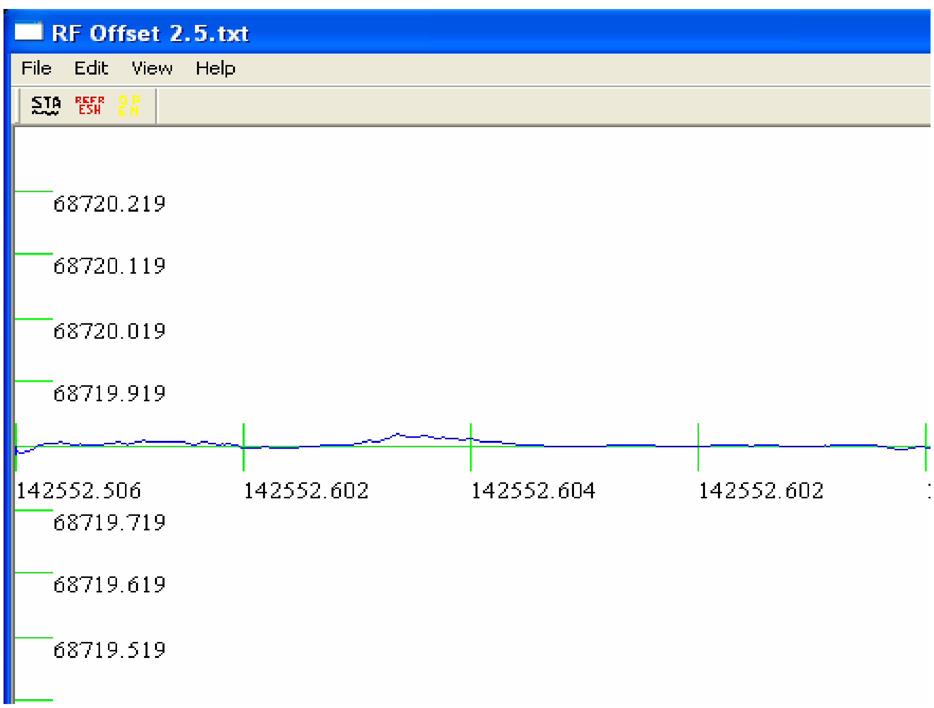

Figure 17 – Measured effect after time delay compensation

Loop Phase Shift Effect

Another source of error that we have investigated is the non-ideal phase characteristics of the physical loop antennas. Figure 18 shows the phase characteristic expected for an ideal antenna (blue, +/- 180 phase shift) as well as an approximation of what we have seen with our actual antennas (red) – a phase that shifts linearly over a period of time as opposed to instantaneously. We have attempted to correct for this by changing the beamforming algorithm. One alternative is to just use the strongest loop as this should be in the phase stable portion of the response curve. Figure 19 shows an antenna turning trial with this beamforming algorithm. The antenna was rotated in 45 degree steps, shown in Figure 20. Comparing Figures 19 and 20 it appeared that the TOA jumped at 90 degree increments, which would indicate jumping between 2 levels, corresponding to different channel delays. The data was reprocessed in Figure 21 with an interchannel delay correction of 5 degrees set. This corrected for most of the error, but not 100%.

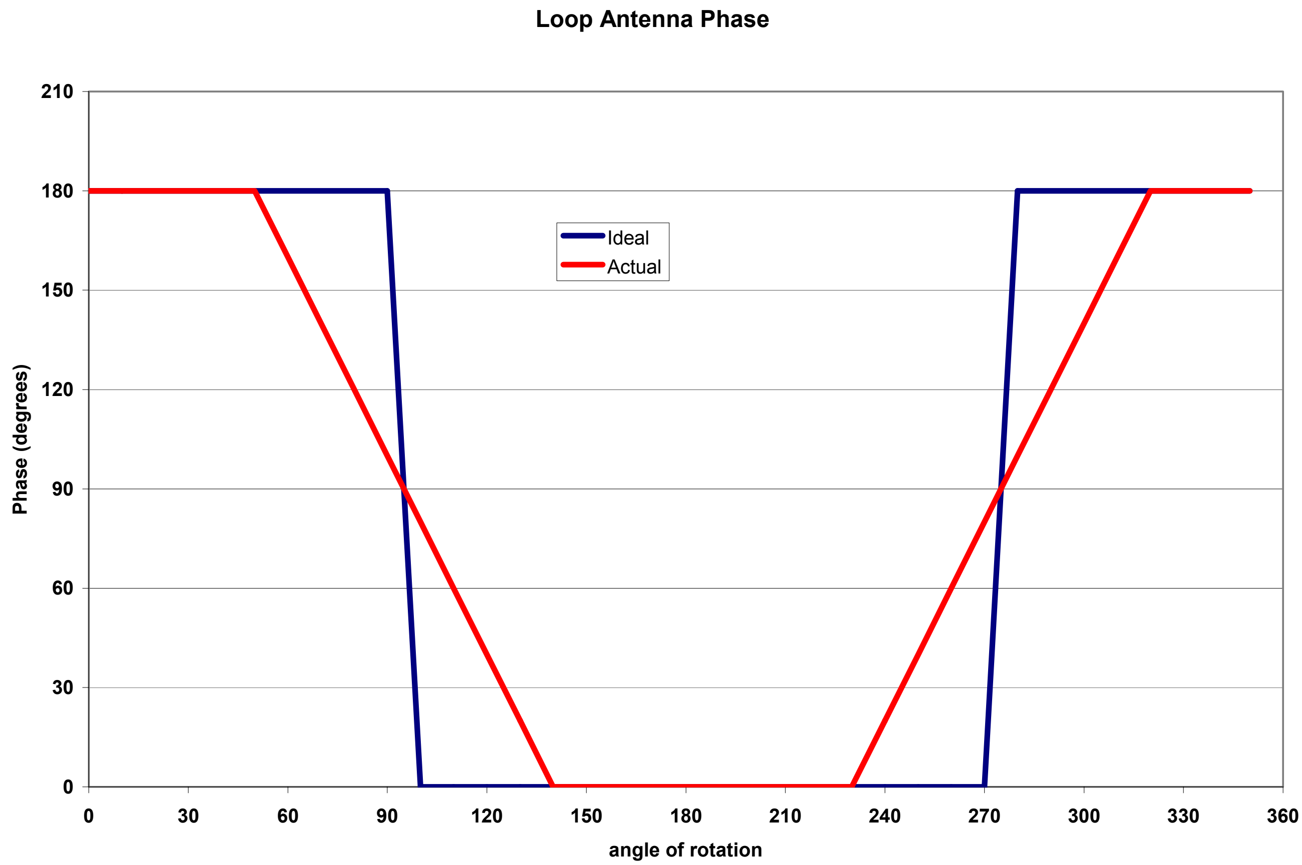

Figure 18 – Single loop coupling

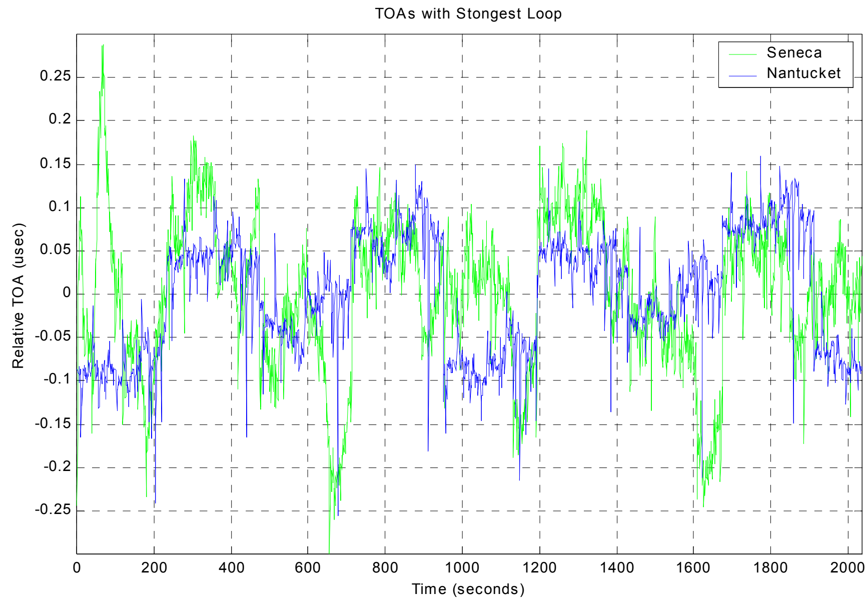

Figure 19 – Antenna rotation test, with strongest loop beamforming

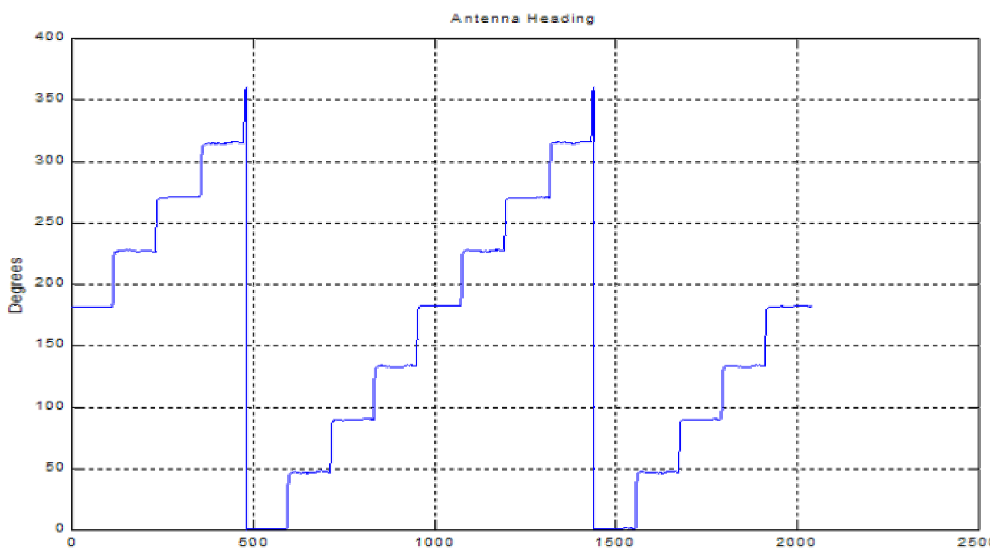

Figure 20 – Antenna rotation headings, 45 degree steps.

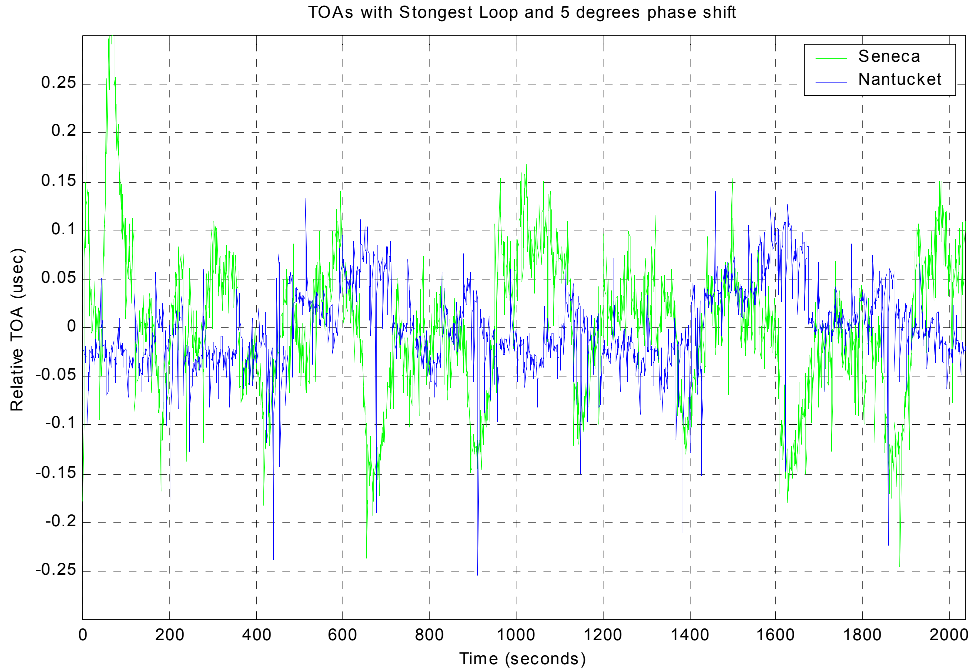

Figure 21 – Strongest beam and delay correction

Conclusion / Future Work

We have investigated many causes of TOA/ASF variation as an H-field antenna is rotated. Some of these causes can be corrected for, while others need additional study. Our work has shown that the coupling effect between the two loops can be negated by physically separating the two loops (split loops). This has been verified by testing that when a strong signal is maximum in one loop, it is close to zero in the other (orthogonal) loop. Likewise, a time delay correction in software can compensate quite well for unequal delay in the two channels of the system; whether the delay inequality is in the antenna and/or the amplifier. The Loop Phase Shift effect (the non-ideal phase performance of the loops) is still under study. We have been somewhat successful in avoiding this error by changing the beamforming algorithm to just using the strongest loop; however correcting for this effect still needs some work.

Our research has shown that indeed these types of phase variations have an impact on the position solution. As such, in order to meet the 8-20 meter accuracy requirements for HEA, it may be necessary to use an E-field antenna which does no suffer from these directionally dependent errors.

Acknowledgements

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