Performance of DSP-Loran/H-field Antenna System and Implications for Complementing GPS

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BIOGRAPHY

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ABSTRACT

The FAA has an active program to investigate Loran as a potential complement to GPS, and the USCG is modernizing its Loran infrastructure. In light of the September 2001 terrorist attacks and the DOT's Volpe Study on national vulnerabilities associated with over-dependence on GPS, the importance of objectively assessing the capabilities of a modern Loran system has greatly increased. This paper reviews the development and status of a new H-field antenna and DSP-Loran receiver system undergoing assessment by the FAA.

It has recently been demonstrated that H-field Loran antennas provide immunity to P-static interference, which can occur in aviation and marine applications. Tests on this new H-field Loran antenna demonstrate it also provides improved SNR and ECD performance in comparison to E-field antennas. In addition, DSP-processing power enables this receiver to track all Loran transmitters "in view" (i.e. up to 40 stations in North America), and provide enhanced availability and accuracy. Overall, the combination of these two new technologies offers Loran performance capabilities not previously appreciated.

The paper will document capabilities of this new DSP-Loran/H-field system, and will include test results from direct side-by-side comparisons with GPS and legacy Loran receivers. Finally, the paper will summarize how this new technology can be

utilized to complement GPS in a variety of applications, including aviation, marine, terrestrial, and timing uses. Results indicate Loran is a logical choice to become the national complement to GPS.

INTRODUCTION

Research and development of new Loran receiver and antenna technology have now produced unequivocal data [e.g. 1,2] that prove the Loran system can not only offer substantially better navigation performance than previously appreciated, but also that it can provide GPS support capabilities such as DGPS and integrity information [e.g. 3,4]. The recent tragedy of September 11, 2001 and the release of the DOT's Volpe Study [5] on September 10, 2001 have served to crystallize issues regarding national vulnerabilities, and to provide increased importance to development of integrated systems that can significantly reduce those vulnerabilities.

This paper reviews the development and current status of a new Loran H-field antenna and receiver technology, and is divided into 4 major sections: 1) all-in-view DSP receiver; 2) H-field antenna; 3) flight tests comparing new Loran receivers with GPS and legacy Loran receivers; and 4) next steps in antenna and receiver development. Throughout the paper, references are made to how this "new" Loran system can complement GPS.

All-in-View, DSP Receiver

Major advances made in Loran receiver technology throughout the 1990s have been previously reviewed [6]. Although some of those improvements were rather remarkable (e.g. SNRs improved over 20 dB), additional improvements became possible with the availability of new DSP technology. With this DSP technology, more real-time data processing resulted in performance improvements, and representative illustrations of that progression are show in Figures 1a and 1b.

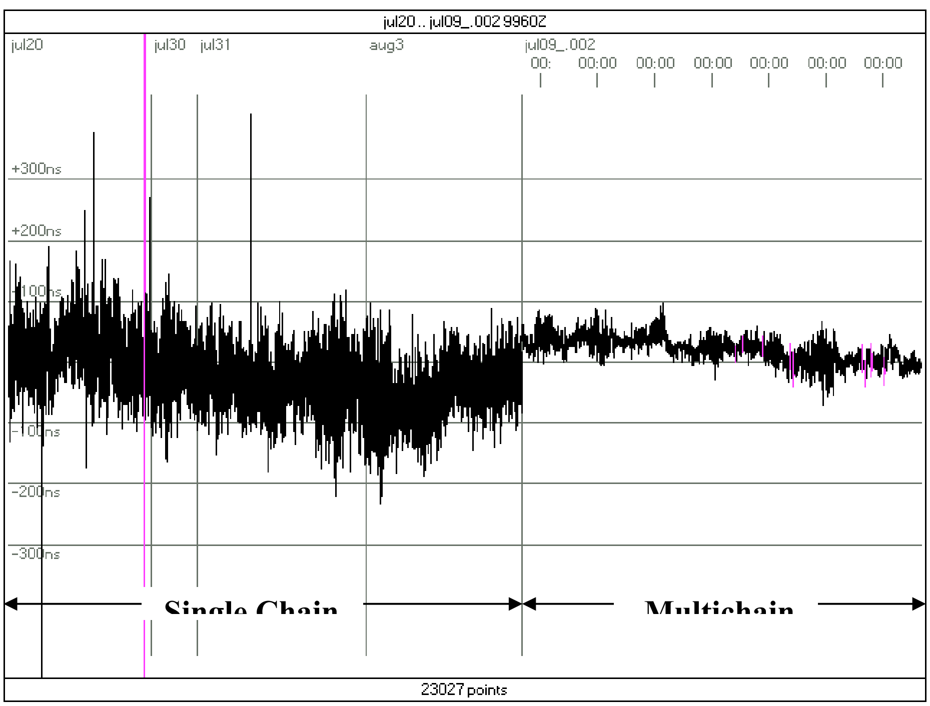

Figure 1a: Representative Comparison of Time Differences Generated by Single Chain versus Multichain Receivers. Although the single chain receiver (left) was perhaps the most advanced model available, the 1998 multichain receiver (right) showed a dramatic decrease in 9960Z time difference noise over several days of recording. 1990 and 1998 data.

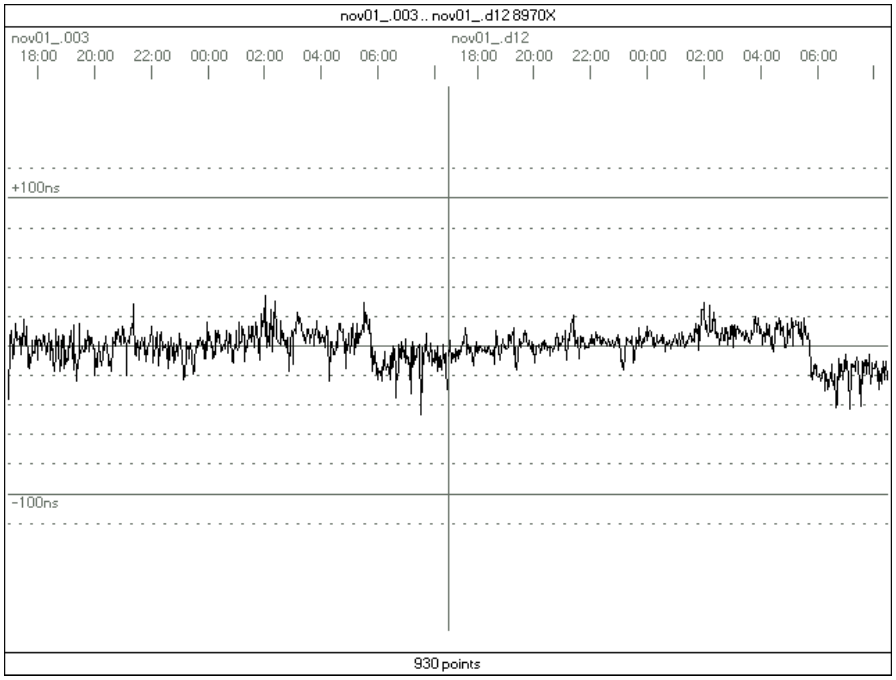

Figure 1b: Representative Comparison of Overnight Time Differences Generated by 1998 Multichain Receiver (left) versus 2001 All-in-view DSP Receiver (right). Note reduction in background noise by new receiver and clearer depiction of 40 nS transmitter timing jump near end of recording period. November 2, 2001 data.

Some of the more important performance characteristics provided by all-in-view, DSP (SatMate) Loran receivers versus older, conventional Loran receivers can be summarized as follows: 1) greater than 20 dB improvement in signal-to-noise ratios; 2) approximately 8 times improvement in envelope-to-cycle distortion (ECD) noise; and 3) a 25 - 60 times reduction in ECD averaging time. These receiver characteristics result in substantially improved availability, accuracy, and range for Loran, and some of the improvements in dynamic performance are illustrated in this paper.

H-field Antenna

In the early to mid 1990s, Locus did some initial work on an H-field antenna, and while considerable advancements in receiver technology took place throughout the 1990s, there was no comparable effort on H-field antennas during that period. Nevertheless, Ohio University performed tests on these older Locus prototypes [7]. These tests confirmed that H-field antennas were immune to precipitation static, and provided an important impetus to proceed with advancing H-field technology.

In addition to P-static immunity, H-field antennas offer several advantages over E-field antennas in virtually all Loran applications (i.e. aviation, marine, terrestrial, and timing). For example, H-fields do not require a ground, are less subject to local distortions (e.g. power lines) than E-fields, and can operate at very low antenna elevations with little degradation of signal levels. Finally, H-field antennas are small, and can be combined with GPS antennas within a single enclosure or radome.

Figure 2 presents some H-field antenna studies done in 2000, and illustrates envelope-to-cycle distortions (ECDs) and time differences (TDs) taken simultaneously from a prototype H-field antenna and an E-field antenna. The H-field antenna was located indoors (by a window) and the E-field was on the roof of Locus' office building. Note the results from the indoor H-field are noisier but quite similar to the outdoor E-field, and the H-field TDs closely follow the 20 nS timing adjustments and Cs drift that commonly occurred at Loran transmitters during that time. (Note: the USCG is currently modernizing the entire US Loran infrastructure to eliminate these problems and greatly improve system performance.)

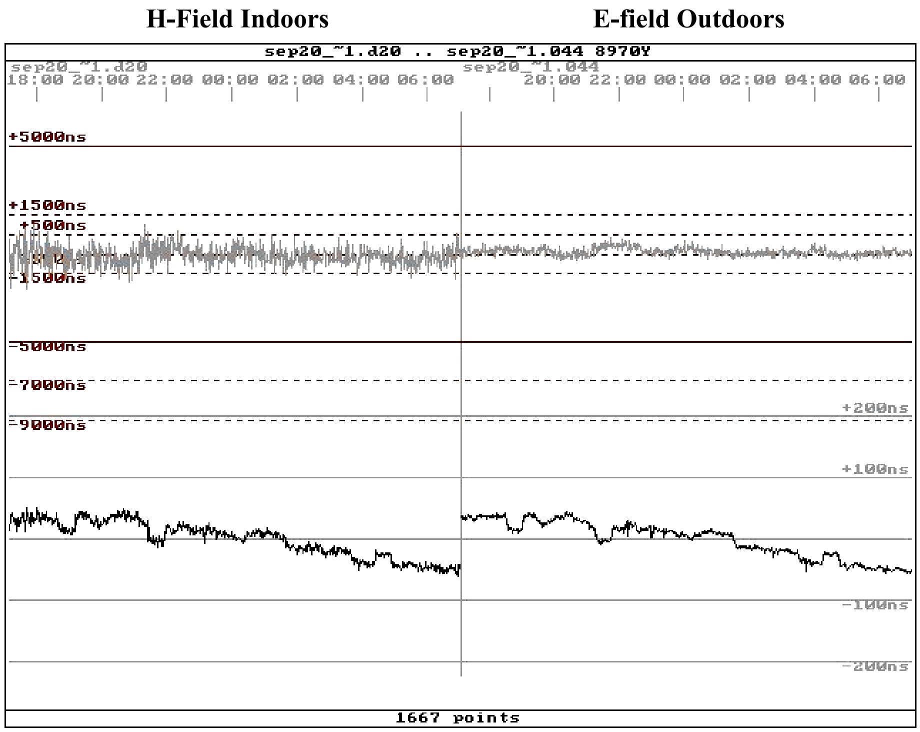

Figure 2. Overnight comparison of ECDs (top) and TDs (bottom) from H-field antenna located indoors versus E-field antenna located on Locus' roof. Data acquired simultaneously using identical SatMate receivers. Note the Cs clock drift and 20 nS timing jumps. Cs clocks and transmitter control electronics are currently being upgraded by the USCG, but still show these jumps.

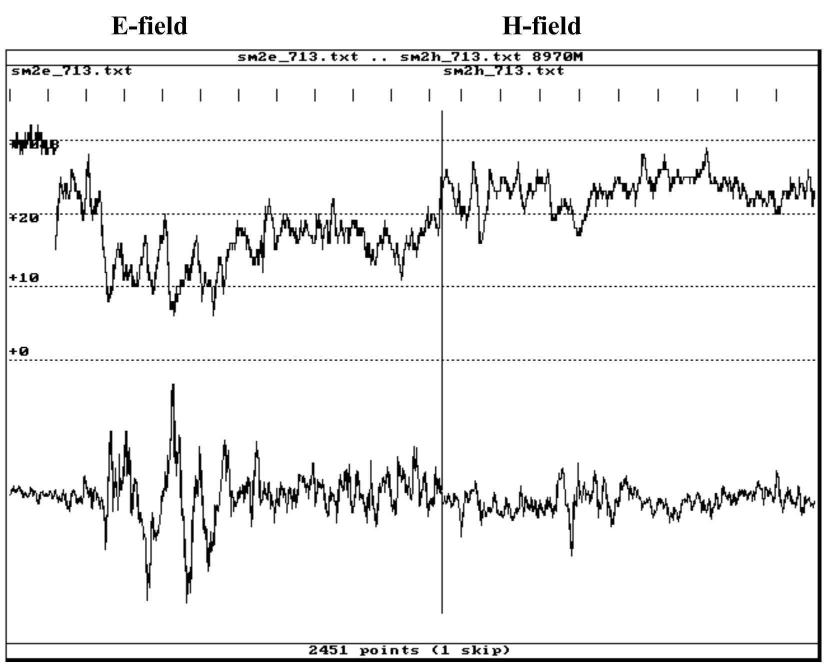

Figure 3. Simultaneous SNR (top) and ECD (bottom) data from E-field and H-field antennas taken during dynamic field trials in 2001 using identical, all-in-view DSP receivers. Note higher signal levels and SNRs with H-field, as well as lower ECDs.

The results from these and many other tests strongly suggested that an H-field antenna could be combined with a modern, DSP-based Loran receiver to provide a high level of system performance and to take advantage of important H-field antenna characteristics, such as immunity to P-static interference and opportunities for significant size reduction.

Flight Tests Comparing All-in-view, DSP Receiver with GPS and Legacy Loran Receivers

In August 2001, the FAA Technical Center flew their Convair 580 from Atlantic City, NJ to Anchorage, AK and simultaneously collected data from a 12-channel, WAAS enhanced GPS receiver, a Locus SatMate Loran receiver, and two legacy Loran receivers. Each Loran receiver was equipped with an E-field antenna. Data were collected once a second from each device, and representative data around the Sacramento, CA, Nashville, TN, and Atlantic City, NJ airports are shown.

Note that one of the legacy Loran receivers did have an additional secondary factor (ASF) table, but the SatMate and other legacy receiver did not. ASFs contribute the largest positional errors to Loran, and they are analogous to ionospheric and tropospheric corrections for GPS, except ASFs are very stable and typically only require periodic updates (i.e. in most cases they are seasonal or longer) [see 8 for a contemporary review]. In order to get some appreciation for the absolute accuracies an all-in-view, DSP Loran receiver could attain if modern, complete ASF tables were available, "quasi-ASFs" were generated post-flight and applied to SatMate data around Atlantic City. Some representative results are presented.

Figure 4 illustrates data from around Sacramento, and Figure 4a includes approach, landing, and takeoff data from the GPS and SatMate receivers. In these data, no ASF corrections were provided to the SatMate, and in this view, the offset between Loran and GPS can be seen. Figure 4b is an expanded view of the approach, landing, and takeoff area in 4a, and here the offset is clearer. SatMate and GPS tracking are extremely close, except for the consistent offset due largely to the lack of ASF corrections. Figure 4c includes SatMate and legacy receiver data of the same view, but excludes GPS data to simplify presentation. Performance differences between the all-in-view, DSP SatMate receiver and the legacy Loran receivers are striking.

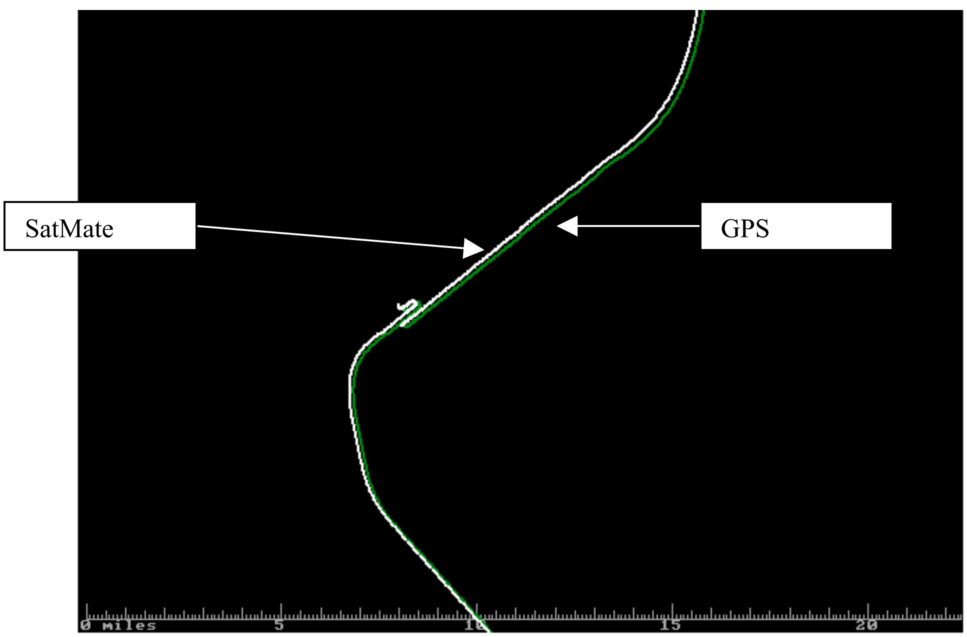

Figure 4a.

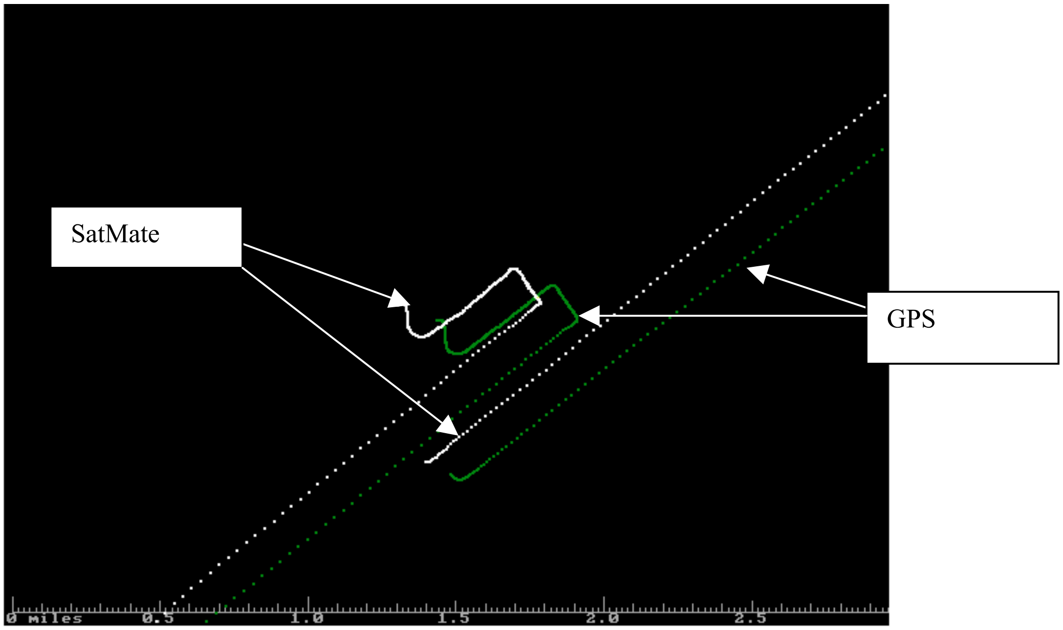

Figure 4b.

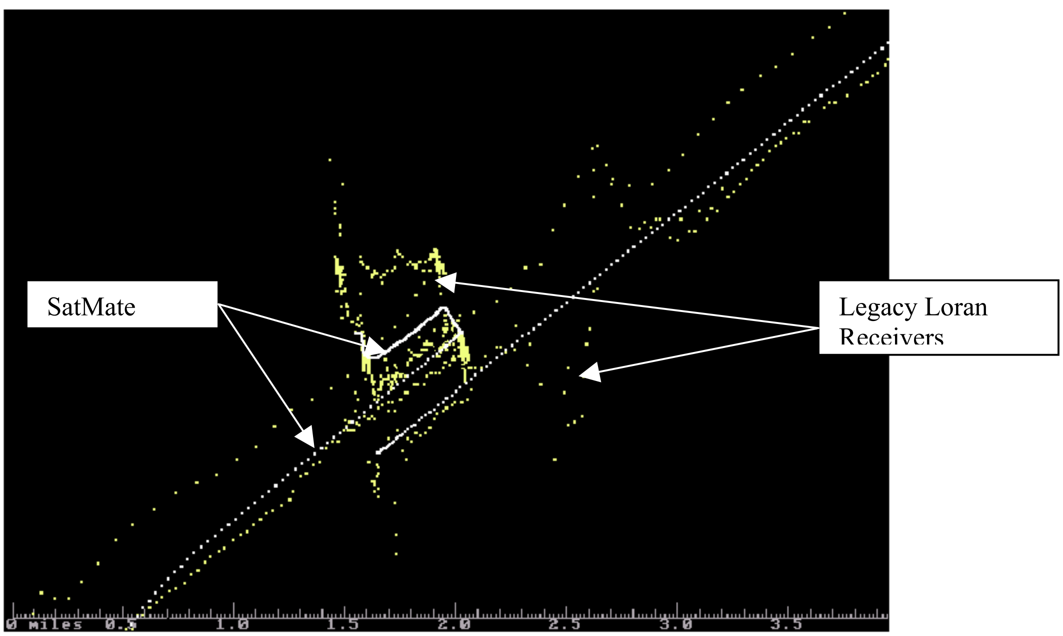

Figure 4c.

Figure 4. Figure 4a plots SatMate and GPS data around the Sacramento, CA airport in August 2001, and Figure 4b is an expanded view of the approach, landing, and takeoff area. Note the SatMate and GPS tracks are similar, except for the consistent offset due to the lack of ASF corrections on SatMate data. Figure 4c compares data from two legacy Loran receivers with SatMate data, and the improved performance seen with all-in-view, DSP technology is striking, even without ASF corrections. Scales are in statute miles.

Figure 5 presents more representative data from these flight trials, and here only close-up views are provided around the Nashville, TN airport. SatMate and GPS data from the landing and takeoff are shown in Figure 5a, and again, no ASF corrections were applied to SatMate data. Nevertheless, the tracks are extremely similar, and the offset between data sets is consistent. Figure 5b illustrates SatMate and legacy Loran receiver data, and excludes GPS for clarity. Performance differences between the SatMate and legacy receivers are clear.

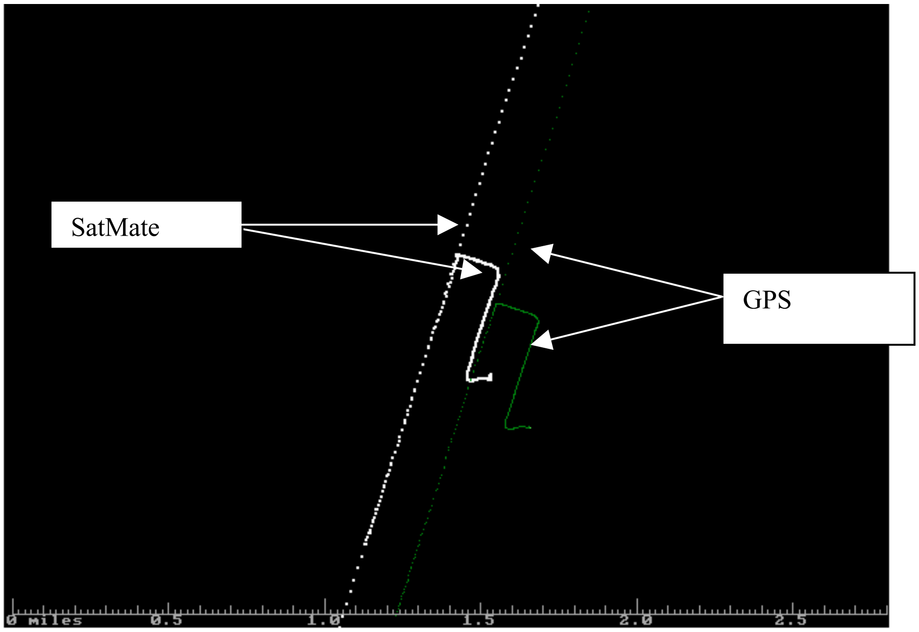

Figure 5a.

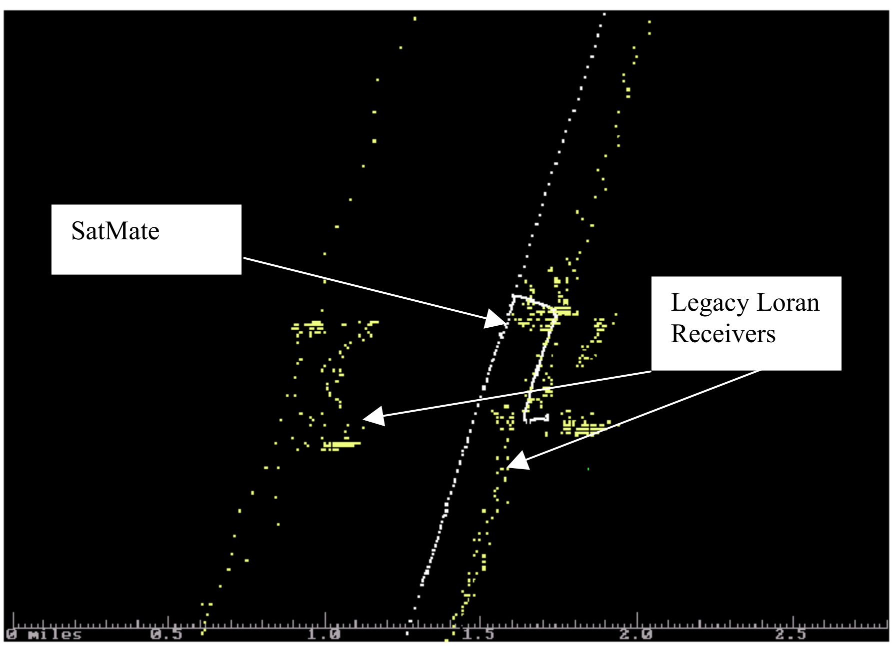

Figure 5b.

Figure 5. Figure 5a is a close-up view of GPS and SatMate data from the Nashville, TN airport, and SatMate data did not include ASF corrections. Figure 5b is a similar view of data from the SatMate and two legacy Loran receivers. Scales are in statute miles.

The flight data above clearly indicate that a modern, all-in-view DSP Loran receiver can offer substantially better performance than legacy Loran receivers, but do not provide an indication of how accurate a contemporary Loran system can be. As summarized above, ASFs are the major contributor to Loran position errors, and modern ASF corrections are not available in the U.S. In order to get a reasonable approximation of the accuracy Loran might provide if ASF corrections were available, Locus derived "quasi-ASFs" and applied them to the flight data from Atlantic City.

These quasi-ASFs were created in the following manner. SatMate data were plotted using seawater conductivity of 5 Siemens; this represents the secondary correction factor typically applied to raw Loran data. Using data acquired over approximately two minutes, the position offset between the GPS receiver and the SatMate was determined at a single, static location at the Atlantic City airport on August 20, 2001. Then measured time-of-arrivals (TOAs) from the SatMate were subtracted from the calculated TOAs from the GPS/Loran data to obtain quasi-ASFs for individual Loran stations. Since the SatMate was using 11 stations for navigation in this area, 11quasi-ASF values were generated, and these were applied to data taken on the August 28 return flight.

Figure 6 illustrates the dramatic improvement in Loran accuracy that can be obtained, even with these rough estimates of true ASF corrections. Figure 6a illustrates the route of the return flight, and the two circles (New Jersey and Maryland) indicate areas where close-ups are depicted in Figures 6b and 6c. Figure 6b shows the actual landing in Atlantic City, and data from the GPS and SatMate receivers virtually overlap. Data from Maryland and Chesapeake Bay, approximately 200 km away, are shown in Figure 6c to illustrate these corrections still aid Loran positioning considerably. Note that in the northeast section of Figure 6c, the GPS and SatMate positions are very close.

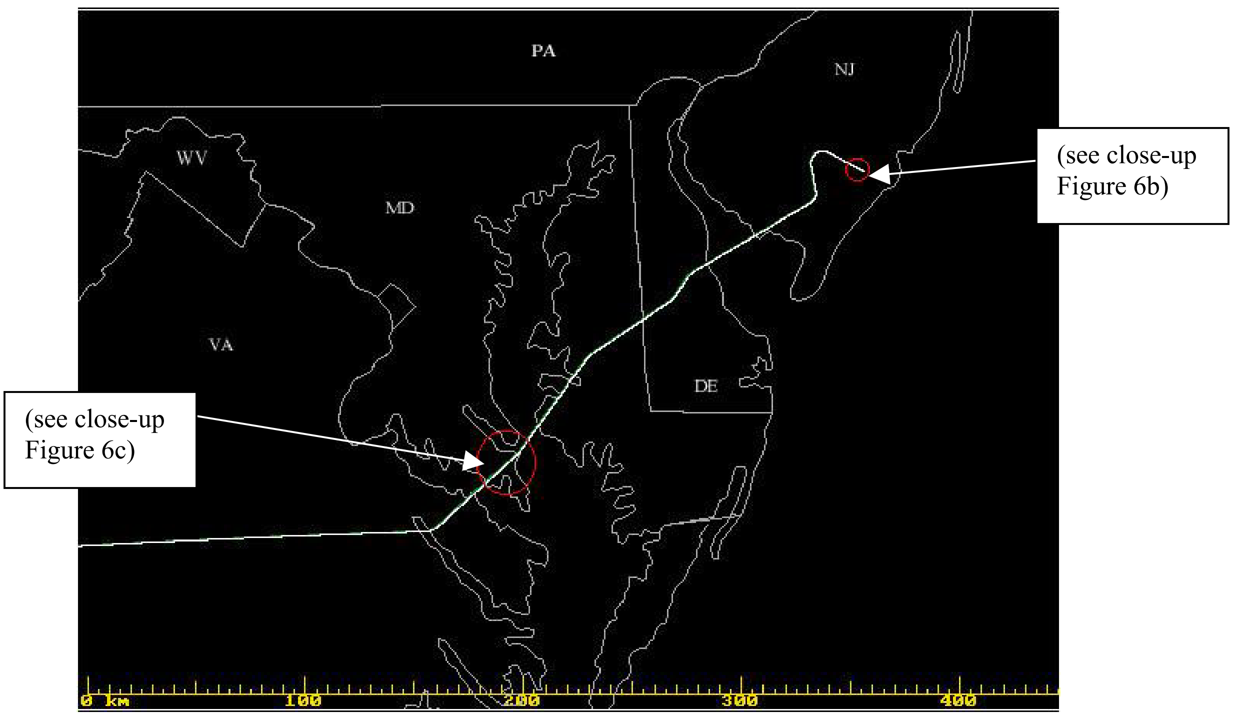

Figure 6a.

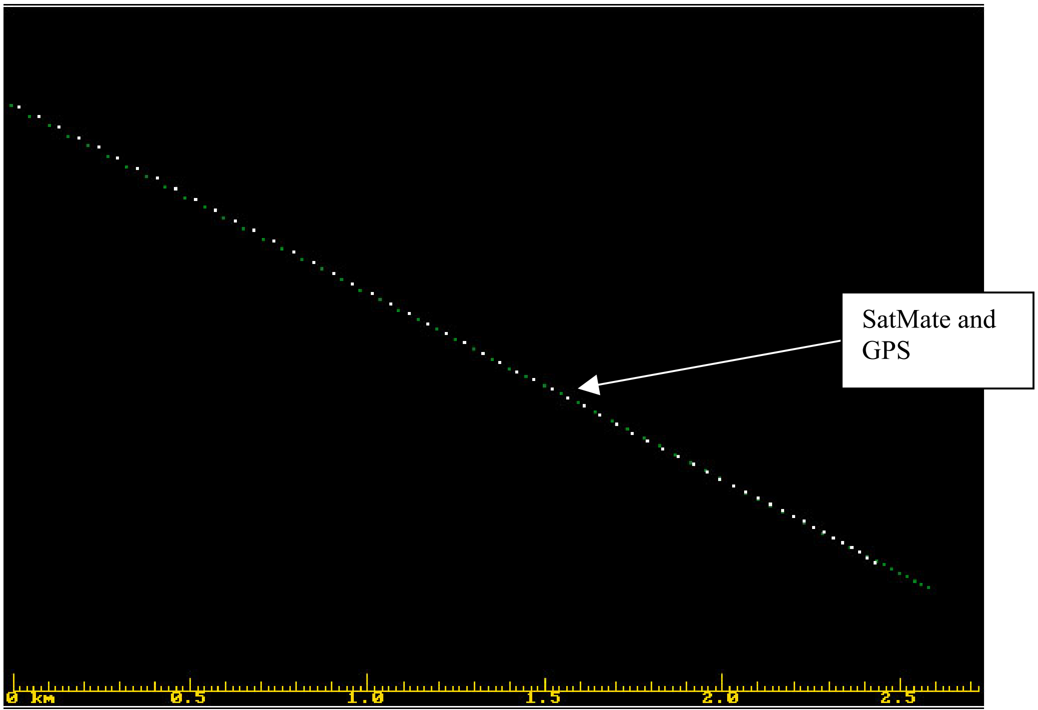

Figure 6b.

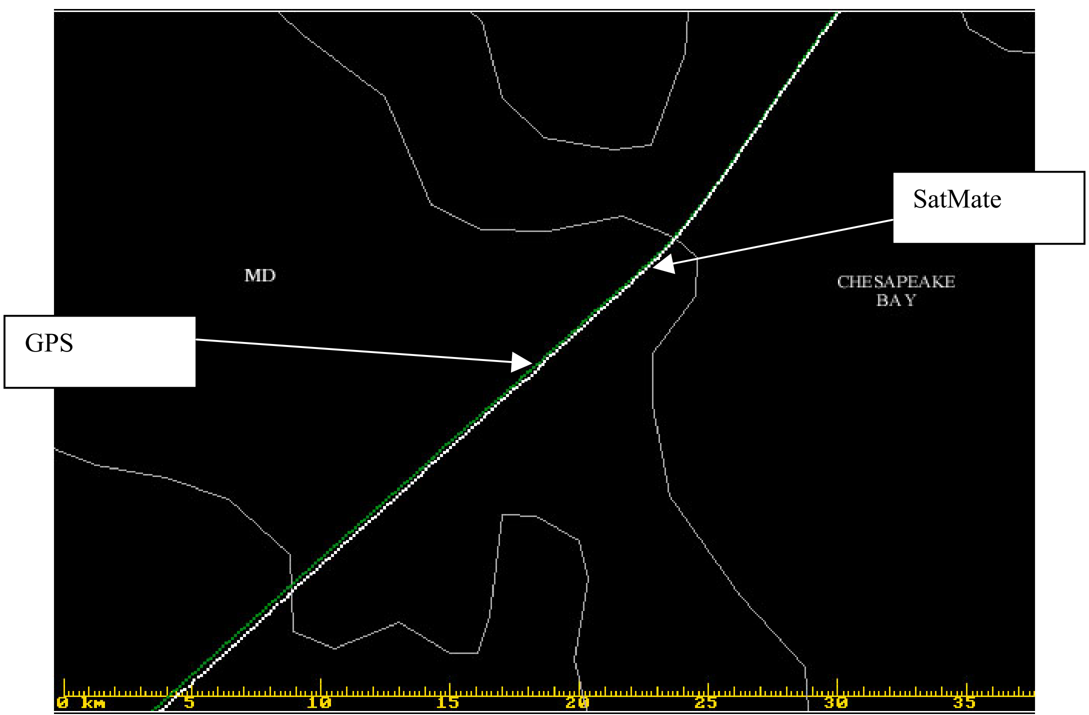

Figure 6c.

Figure 6. Flight data from GPS and SatMate receivers, with "quasi-ASF" corrections applied to SatMate data. These corrections were generated after approximately 2 minutes of data acquisition at the Atlantic City airport on August 20, 2001, and applied to flight data taken on August 28, 2001. Figure 6a shows the path of the August 28 return flight to Atlantic City, and circles indicate the location of close-up views in Figures 6b and 6c. Figure 6b illustrates the landing at Atlantic City, and Figure 6c shows the flight over Maryland and Chesapeake Bay, approximately 200 km away from the ASF correction site. Note how the GPS and SatMate tracks are virtually superimposed in Figure 6b, and closely overlap in the northeastern section of Figure 6c. Scales are in kilometers.

Preliminary Conclusions

The results of these studies enable us to draw some preliminary empirical conclusions, particularly with regard to how the "new" Loran receivers perform versus "legacy" Loran receivers, and how the new Loran can complement GPS.

These and other results document that all-in-view, DSP receivers provide substantially better accuracy, availability, continuity, coverage, and dynamic performance than legacy Loran receivers. When a form of ASF corrections is applied, these modern Loran receivers provide extremely good absolute accuracy. Moreover, new H-field antennas provide higher signal levels and SNRs, and lower ECDs than E-field antennas, so these new Loran systems also provide improved immunity to interference and more accurate tracking than possible with E-field antennas. Finally, it should be emphasized that all these results were obtained using a poorly controlled US Loran infrastructure that is currently undergoing major modernization by the USCG. When this modernization is complete, results from similar receiver tests will also improve.

There have been many publications describing the advantages of combining GPS and Loran, and review how GPS and Loran can be combined [e.g. 9 - 14]. In this paper, we have shown that it is easy to use GPS to derive a "quasi-ASF" correction for Loran, and application of that correction results in extremely good absolute accuracy for Loran, certainly well within non-precision approach (NPA) requirements. In addition, these corrections appear to work well over substantial distances (e.g. 100+ km), although additional testing should be done where terrain changes quickly and climatic conditions are extreme. The results also suggest that if GPS were unavailable for any reason, Loran could perform extremely well in most navigation applications. Finally, these results support earlier conclusions that a hybrid GPS/Loran system would provide substantially better availability, continuity, and coverage than either system alone.

Next Steps in Antenna and Receiver Development

The next steps in antenna and receiver development involve hardware and software changes that will enable these new Loran technologies to be integrated with GPS. The SatMate receiver used to generate data for this paper will undergo a substantial size reduction to an industry standard, Eurocard format (i.e. 100 mm x 160 mm). As a part of this process, the size-reduced SatMate will incorporate both RS-232 and ARINC 429 interfaces, so the receiver can be integrated with existing GPS-based systems. It is expected that the first receiver prototypes will be incorporated with a certified, multimode avionics receiver for integration with GPS and flight testing in 2002. In addition, a combined GPS and Loran H-field antenna will be developed, and that will be housed in a certified automatic direction finder (ADF) radome for flight tests of the integrated GPS/Loran system. A drawing depicting one potential configuration of a combined GPS/Loran antenna is shown in Figure 7.

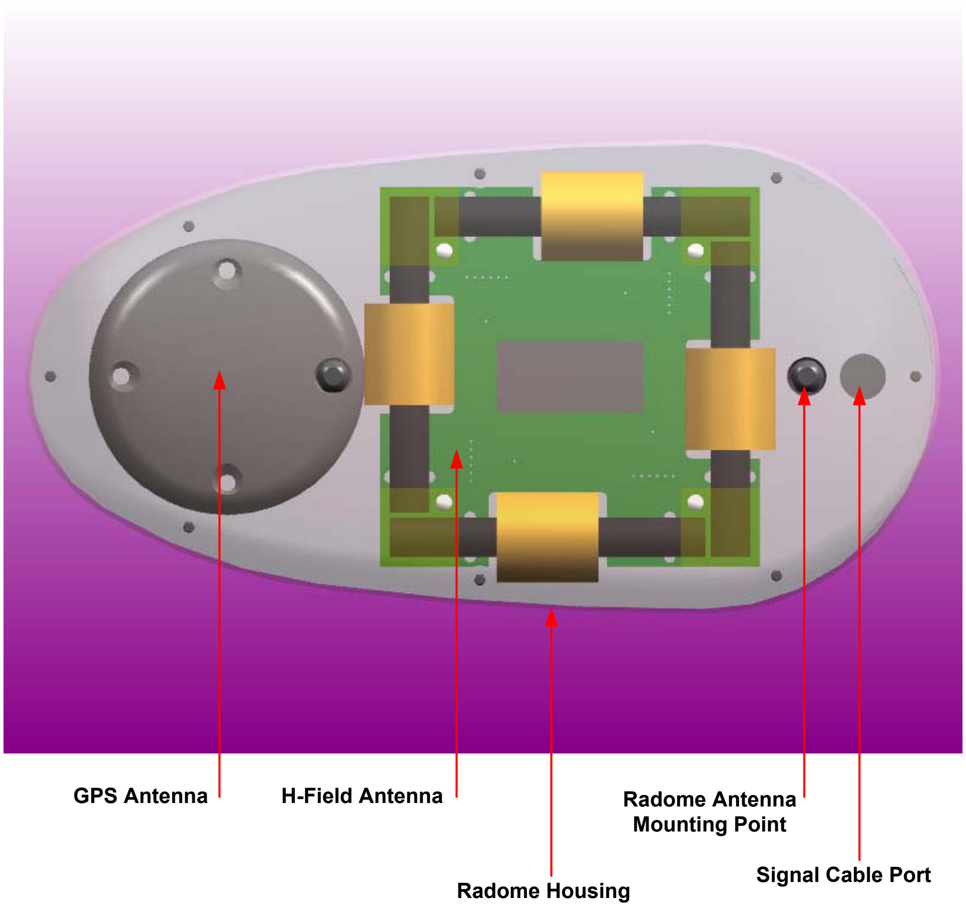

Figure 7. Mechanical drawing depicting one potential placement of GPS and Loran H-field antennas within an ADF radome. It is likely that the GPS antenna will be positioned directly above the H-field antenna in the prototype, in order to avoid imbalancing Loran reception at the H-field loops and any possible shadowing of GPS. A stacked configuration will also make the combined antenna footprint smaller, and will lead to greater size reductions in the future.

Summary

This paper has reviewed recent developments in Loran receiver and H-field antenna technology. Tests of all-in-view, DSP receivers and H-field antenna prototypes confirm Loran performance is significantly better than possible with legacy Loran receivers, and strongly suggest Loran is an appropriate partner for integration with GPS. Overall, a hybrid GPS/Loran system would appear to offer significantly better availability and continuity than either system alone. Next steps in the evolution of Loran receivers and antennas are reviewed, and these will result in a GPS/Loran prototype system for evaluation. Finally, it is noted that the US Loran infrastructure is currently being upgraded, and those upgrades will improve Loran performance documented here.

ACKNOWLEDGEMENTS

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