Development, implementation, and verification of the TOA Measurement System

Wouter J. Pelgrum (wouter@pelgrum.org)
Arthur W.S. Helwig & René Kellenbach, Reelektronika
David W. Diggle, Ohio University
Mitchell J. Narins, US Federal Aviation Administration

Biography

Wouter Pelgrum received his M.Sc. degree in Electrical Engineering cum laude from Delft University of Technology in 2001, for his research on an H-field antenna for low-frequency radionavigation systems. From 2001 until 2006 he worked for Reelektronika, a company specialized in the research and design of integrated navigation, for which he contributed to the development of an integrated GPS-eLoran receiver. Wouter Pelgrum successfully defended his Ph.D. dissertation "New Potential of Low-Frequency Radionavigation in the 21st Century" on November 28th 2006. Currently Wouter works as a consultant for among others Ohio University.

Arthur Helwig holds an M.Sc. and Ph.D. degree in Electrical Engineering, both from Delft University of Technology in the Netherlands. Currently, he is working full-time for Reelektronika. Arthur Helwig is one of the main developers of the Eurofix concept and its implementation, and is currently involved in the development of integrated navigation solutions using GNSS, Loran-C and other sensors for a variety of applications. Besides awards for a number of scientific papers on radionavigation systems, he also received national and international awards for his software development skills. In 2003, Arthur Helwig was rewarded the prestigious Medal of Merit award from the International Loran Association for recognition of his work on Eurofix and Loran-C.

René Kellenbach, who received his M.Sc.EE from Delft University of Technology in 1988, is Reelektronika's senior specialist in the field of radar and Loran-C signal processing. He designed and developed data compression techniques for real-time transmission of high-resolution radar images through standard public telephone lines. He is also designer of radionavigation receivers and active LF-antennas. René Kellenbach is the key developer of the DSP and analog/digital parts of the miniature LORADD integrated GPS/SBAS/Loran-C/Eurofix receiver.

Dave Diggle is the Associate Director of the Avionics Engineering Center at Ohio University in Athens, Ohio. In addition to his duties as Associate Director, he leads the Loran Support Team at the Avionics Engineering Center. Dave is a member of the Institute of Navigation and the International Loran Association, and has received the RTCA's *William C. Jackson Award* for outstanding contributions in the field of avionics. He received his Ph.D. in Electrical Engineering from Ohio University and holds a private pilot certificate.

Mitch Narins is the Senior Systems Engineer with the FAA's Navigation and Landing Product Team who leads the FAA/USCG/Academic/Industry Team evaluating whether the Loran C system can provide benefits for the aviation, maritime, and timing and frequency communities. Mr. Narins has held a number of program-manager and lead-engineer positions at the Naval Electronic Systems Command and at the Federal Communications Commission. He holds a Bachelor of Engineering (BE) degree from the City College of New York and a Masters of Engineering Administration/Management degree from the George Washington University.

Introduction

The Additional Secondary Factor, or ASF, is one of the most significant challenges for low-frequency radionavigation. Omitting correct compensation for ASFs leads to significant positioning errors, too significant for the stringent demands of many contemporary applications. The phase velocity of a 100 kHz ground wave, and thereby also the ASF, is a complex function of the ground conductivity, terrain variation, and the refractive index profile of the atmosphere. In the past, significant effort has been invested, by for example Millington, Monteath and Wait, in modeling these phase variations. The Bangor Universities BALOR software package uses these models to efficiently predict the ASF variations over large areas. Until now, no sufficiently accurate measurement systems have been available to validate and possibly iterate the models and underlying

assumptions and simplifications. The TOA Measurement System (TMS) provides the necessary platform and is therefore a crucial step forward in the mitigation of ASF related positioning errors.
This paper outlines the design and implementation of the TMS and shows the results of preliminary airborne testing.

TOA Measurement System

The Additional Secondary Factor, or ASF, knows various definitions in literature. The traditional and most stringent definition of ASF only accounts for the additional propagation delays over land caused by the land's conductivity. More commonly, also the influence of topography on the propagation delay is included. The latter definition will be assumed for the remainder of this paper. It is the author's opinion that the ASF is a far-field phenomenon and thereby excludes local effects from the definition. This makes the ASFs equally valid for a receiver equipped with an H-field antenna as for a receiver equipped with an E-field antenna. Furthermore, the author suggests to define ASF as received at ground level, in other words to preclude receiver altitude from the definition of ASFs.

Given this definition of ASF, the measurement of ASFs requires:
- Accurate knowledge of the Time of Transmission of the Loran-C pulses at the transmitter,
- determination of the Time of Arrival (TOA) of the Loran-C signals with respect to the same time standard used by the transmitter,
- the precise position of the receiving antenna, and
- compensation for receiver altitude.

It is not trivial, and often even impossible, to guarantee the requirements mentioned above. Therefore, the TOA measurement system described in this paper does *not* measure the ASF but
- measures the TOA of the Loran-C signals with respect to UTC_{USNO},
- measures the position of the receiving antenna using GPS-WAAS, and
- calculates the Primary and Secondary Factor (PF and SF) based on the measured position.

Then an *indication* of the ASF can be derived by subtracting the PF and SF from the TOA. More precise *differential* "ASFs" are obtained by using a second TMS at a stationary location. Note that for an airborne receiver direct measurement of ASFs is not possible, because a non-trivial correction for the influence of altitude is necessary.

The design goals of the TMS include:
- High quality absolute TOA measurements by using advanced Loran signal processing, a simulator signal for antenna, front-end and receiver delay calibration, and an accurate and deterministic relation between GPS time, and the Loran-C receiver time, and the Loran signal simulator.
- High reliability, robustness.
- Turn-key or "plug-and-play" behavior allowing most efficient measurement campaigns.

Hardware Development

The basis of the TMS is formed by the Reelektronika LORADD eLoran receiver. Furthermore, a NovAtel OEM4 GPS-WAAS receiver provides accurate GPS position and time. The GPS time (1PPS) is tracked by a Temex GPS disciplined Rubidium clock which provides, next to a smoothed 1PPS, also a highly stable frequency source. A Xilinx FPGA (Field Programmable Gate Array) accurately time tags the smoothed 1PPS with respect to the LORADD ADC (Analog to Digital Converter) sample clock.

The measurement results depicted in this paper are derived using a Reelektronika TMS prototype, as shown in Figure 1. Currently, Reelektronika finalizes the development and production of the final Loradd TMS receiver, which further enhances timing stability and system robustness and at the same time allows for a smaller overall form factor. This new receiver will also contain a hardware Loran signal generator enabling highly precise and deterministic timing through signal injection into the antenna.

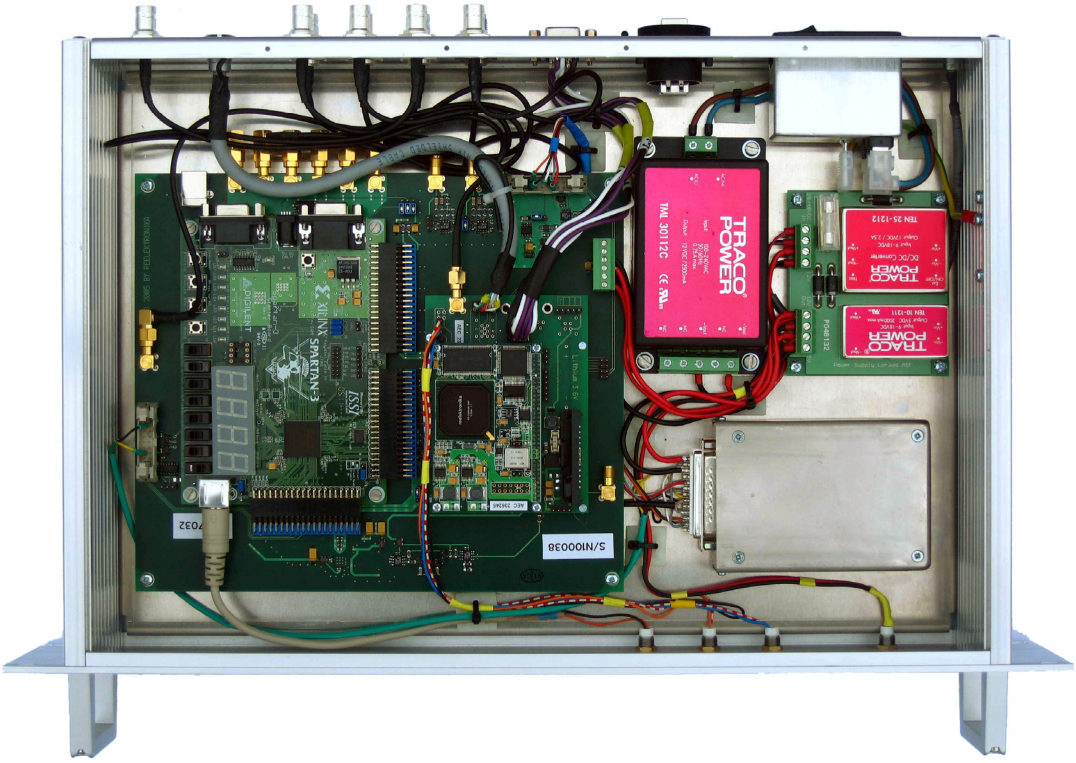

Figure 1: Reelektronika TMS prototype

Precise timing

Precise timing of the Loran-C signals with respect to UTC is a crucial part of the TMS. First the GPS-1PPS is smoothed by a GPS-disciplined Rubidium oscillator. The resulting 1 PPS is then time tagged with respect to sample clock of the Loradd receiver by the FPGA digital circuitry. What still remains is an unknown time delay between the Loran-C signal at the antenna and the filtered and digitized signals in the receiver. This unknown delay can be approximated by a one-time calibration using for example an all-sea water path. This approach has been followed by the implementation of the Reelektronika TMS prototype which is used to obtain the measurement results described in this paper.

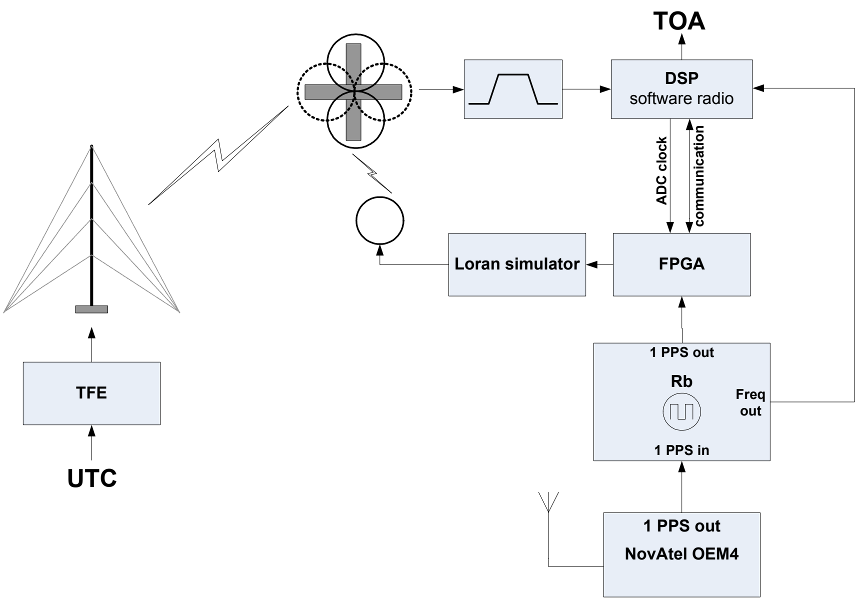

Figure 2: TMS timing setup

One-time calibration of the (analog) antenna and (analog and digital) filter delays assumes correct timing of the transmitted signal and also temporal stability of the (analog) antenna and filter delays. Such an assumption is hard to proof valid for the level of timing accuracy targeted with the TMS. Therefore, the TMS has been expanded with a Loran signal simulator. The simulated Loran-C H-field signal has a known timing relation with the Loradd receiver sample clock and thereby also with UTC_{GPS}. Injection of the simulated Loran-C signal directly into the antenna ensures a deterministic timing relation between the received Loran-C EM-field at the antenna and UTC_{GPS}, as outlined in Figure 3.

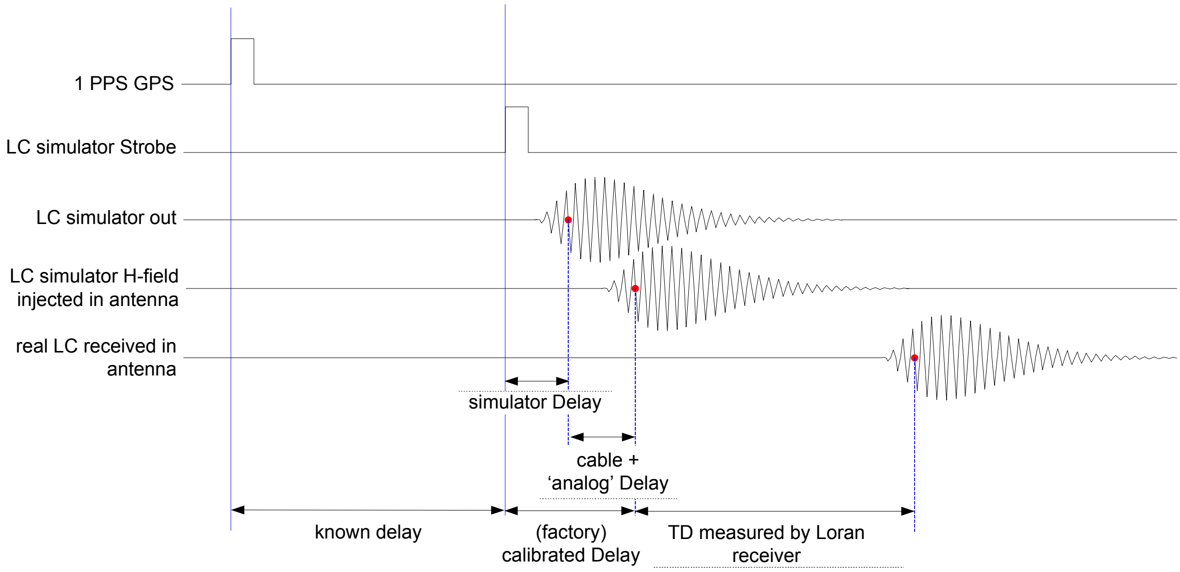

Figure 3: Precise time tagging using synchronised Loran-C signal simulator

Software Development

The basis for the TMS signal processing is Reelektronika's LORADD firmware. The following modifications have been implemented:

High velocity

The Reelektronika LORADD firmware was originally designed for relative low speeds (automotive and maritime). After modifications the firmware is now capable of tracking at speeds exceeding 400 knots to be used for airborne measurement campaigns.

Time and frequency domain interference mitigation

Frequency domain interference mitigation is achieved by digital bandpass filtering cascaded by a maximum of 30 notches on both H-field antenna channels. Interference rejection in the time domain is implemented using novel fully adaptive algorithms ensuring stable tracking under harsh conditions.

Station acquisition by UTC

For research purposes it can be useful to acquire and lock on to stations even if their signal quality is not sufficient for positioning. This is facilitated by the TMS UTC station acquisition capability. The availability of precise UTC allows for deterministic determination of the expected arrival time of the signals of the desired stations. This eases the acquisition process significantly: it is no longer required to correlate PCI-integrated signals with the phase codes, stations can now be directly pointed out, even under unfavorable signal conditions.

Receiver calibration

Common-mode phase errors cancel in a positioning solution as a receiver clock error and are therefore generally not of great concern for the designer of a Loran-C receiver. The objective of the TMS, however, is to accurately measure the absolute TOA for which both differential and common mode phase errors should be avoided. Therefore, the Automatic Gain Control of Reelektronika's LORADD receiver has been optimized to remove any gain-dependent phase errors. Furthermore, the continuous feedback compensation by simulator signal injection mitigates any remaining common and differential mode phase errors.

Firmware validation

The modifications of the LORADD firmware have been extensively tested using raw data recordings from previous measurement campaigns. Data is available from stationary, land-mobile, maritime, and airborne campaigns. This post-processing data analysis allows for careful validation of most of the new algorithms in the firmware. Currently, extensive live testing is being undertaken of which part is presented in this paper.

System Integration and validation

The TMS is designed to operate across all modalities under various circumstances. From a cost perspective, it is beneficial if antennas can be used, which are already installed, especially for airborne campaigns. Therefore, the TMS is targeted to work with the following commonly used antennas:

- Reelektronika H-field antenna
- Locus H-field antenna
- Locus E-field antenna
- Apollo E-field antenna

For this task, adapter circuitry has been built combined with firmware modifications to cope with the different antenna characteristics. Satisfactory performance of all of these antennas in combination with the TMS has been validated.

A crucial part of the TMS is the data collection setup. This setup ensures reliable recording of all the necessary information and also allows for real-time performance validation. The tracking quality of both GPS and Loran is available to the operator as well as a qualitative display of the measured ASF fluctuations. This allows the operator to fine-tune the installation for optimal performance and to optimize the measurement campaign according to the preliminary data analysis obtained in real-time.

The final stage of the TMS development is a rigorous testing and validation scheme consisting of stationary, land-mobile and airborne operation.

The remainder of this paper describes the results of an airborne equipment and firmware performance validation using the TMS prototype.

Preliminary Equipment Validation – OU October Flight Test

In October 2006 the prototype TMS has been subjected to airborne tests with the following objectives:

- Performance validation of the TMS hardware platform by using the prototype TMS. With the exception of a Loran signal simulator, this prototype basically has the same functionality as the final TMS.
- Tests of firmware modifications
- An assessment of the overall TMS performance

Reference station

Most Loran-C transmitter stations in proximity of the measurement location (Athens, Ohio) are still controlled by System Area Monitors (SAMs). This method of transmitter timing control causes undesired fluctuations and a significant bias in the time of transmission of the Loran-C signals. To a minor extend, also the fluctuations in groundwave propagation caused by diurnal and weather related effects hinder the signal stability and thereby potentially frustrate the TMS performance analysis. To overcome these nuisances, a local reference station has been installed.

The reference station consists of a Locus E-field antenna, mounted on the roof of the Ohio University Avionics hangar. This antenna is connected to a Reelektronika prototype TMS. Precise time and position is provided by a NovAtel OEM4-G2 L1/L2 GPS receiver.

Figure 4 shows the reference station measurements for the approximately 4 hours duration of the measurement campaign. The ASF of one of the two rates (8970M) of the closest station Dana, has been set to zero for reference. From the land path towards this station it is clear that the actual ASF will not be zero but for the purpose of this campaign that is of no influence. Note that Loran-C signal simulator of the final TMS will allow for a more deterministic calibration of the currently unknown receiver timing delays. From Figure 4 it becomes clear that the SAM control currently employed causes significant offsets. Two rates of the same transmitter have by definition the same ASF whereas the plot shows discrepancies of more than 200 ns. In normal operation, these discrepancies severely hinder the usage of all-in-view receivers. For this measurement campaign, the reference station can accurately compensate for most transmitter timing deficiencies as well as for the (fluctuations in) groundwave propagation characteristics.

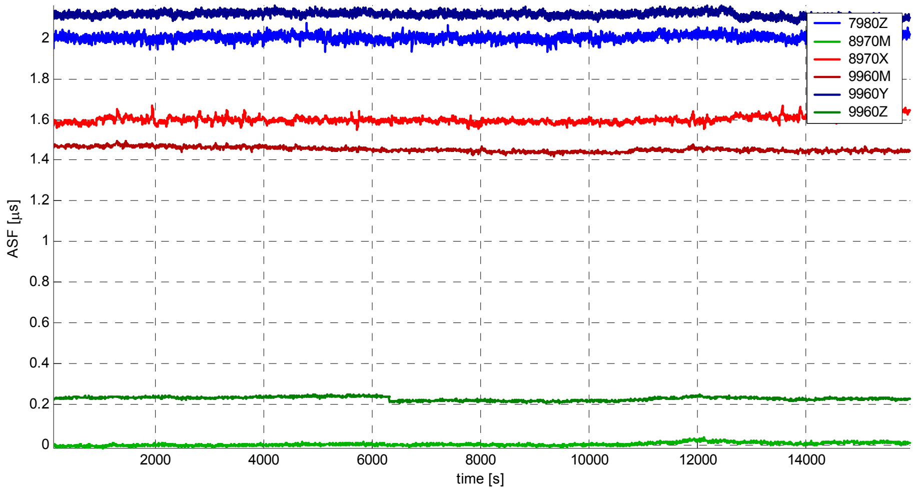

Figure 4: "ASF" measurements of Dana (green), Seneca (red) and Carolina Beach (Blue) as reported by the TMS reference station. Every data point is a 5-seconds integrated independent measurement.

Figure 5 shows the same measurements as Figure 4 only now integrated for 30 seconds and with an arbitrary offset applied for displaying purposes. The clearly visible non-Gaussian fluctuations are most likely caused by transmitter timing circuitry such as PATCO (Phase Amplitude Timing and Controls), LPA (Local Phase Adjustment) and potentially by imperfections of the (cross-rate) interference mitigation by the Loran-C receiver. The rapid fluctuations caused by the internal transmitter timing control limits the maximum integration time of the reference station. For this campaign, a non-causal 60 sec median filter has been chosen to smooth the reference station measurements. This filter preserves the step response of for example LPAs. In real-time dLoran scenarios such as Harbor Entrance and Approach (HEA), the usage of non-causal filtering is obviously not possible.

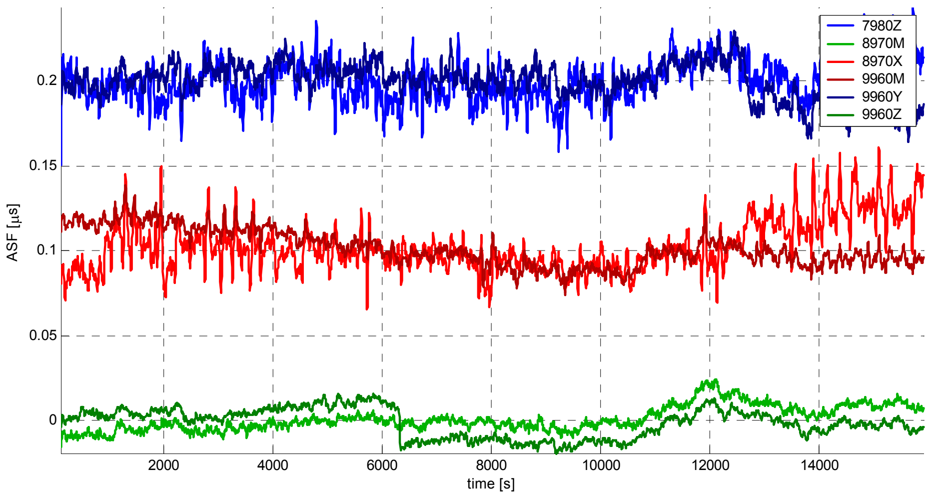

Figure 5: Same data as shown in Figure 4 only now integrated for 30 seconds and with arbitrary offsets applied for presentation purposes.

Mobile setup

Ohio Universities Piper Saratoga has been used as a mobile measurement platform to test the TMS prototype. A custom converter box matches the impedance of either the Locus H-field antenna (mounted on the bottom of the fuselage of the plane, next to the strobe light) or the Apollo E-field antenna (mounted on top of the plane) to the prototype TMS. A laptop PC has been used for data recording and real-time analysis.

Figure 6: Ohio University Avionics Engineering Center - Piper Saratoga

Flight track

The primary interest of the tests is the validation of the equipment performance, not the propagation phenomena themselves. Although the latter might be scientifically interesting, they blur the equipment performance validation process. Therefore, a flight track has been chosen with minimal expected ASF variations. Unfortunately, the area around Athens Ohio is slightly hilly which causes fluctuating ASFs. About 15 minutes north-west of the Ohio University airport, the terrain is smoother making it more suitable for the tests. Figure 7 shows the measurement route and the station geometry with respect to the Loran stations Dana (8970M, 9960Z), Seneca (8970X, 9960M) and Carolina Beach (7980Z, 9960Y).

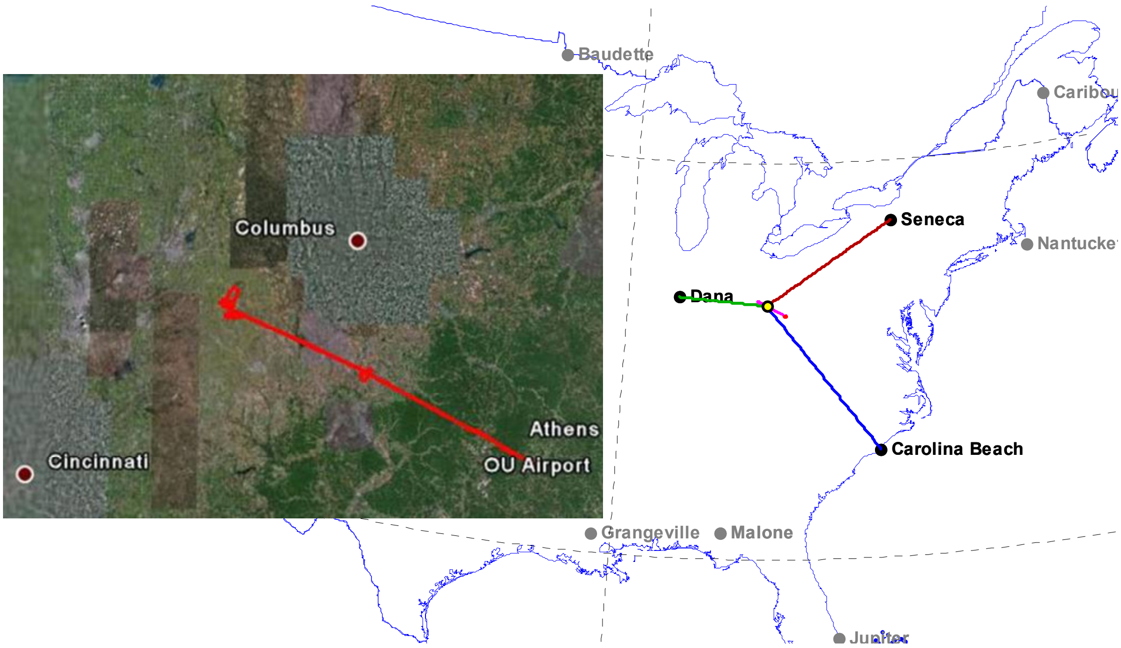

Figure 7: Flight track for the TMS performance validation

The measurements were conducted at a constant altitude of 2000 ft. This altitude was chosen based on the rather poor weather conditions at the time of the measurements. First the H-field antenna has been flown, starting with the take-off from the OU airport, across the hills towards Circleville, followed by about 15 minutes at 116 kts to the north-west, some circles, and back to Circleville. At the Circleville airport the H-field antenna was replaced by the E-field, four 15 minutes legs to the north-west, which after the plane returned to the OU airport:

- Date: October 20th 2006
- H-field: 14:54 - 16:07 UTC, 73 minutes, 250 km
- E-field: 16:15 - 17:49 UTC, 88 minutes, 340 km

- Altitude 2000 ft
- Average speed: 116 kts

Next, the performance of the TMS is validated by assessing the following:
- Dual-rate repeatability
- Phase stability during circles
- Track-to-track repeatability
- E-field versus H-field repeatability
- Position error relative to GPS-WAAS

All results shown are 5 sec independent integrate-and-dump measurements and have been corrected with the reference station data. The majority of the transmitter-timing and propagation fluctuations is thereby removed.

Dual-rate repeatability

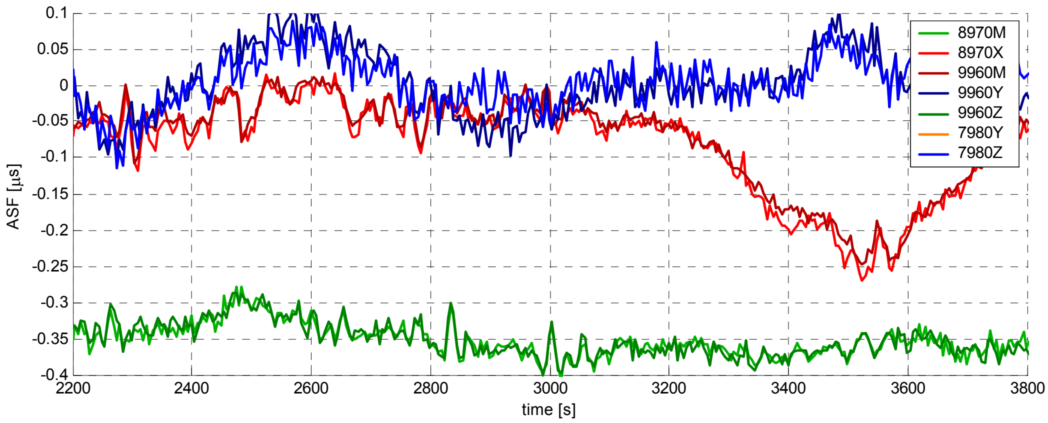

Figure 8: Close up of the ASF fluctuations measured by the E-field setup.

The level of agreement between the two rates from a dual-rated Loran transmitter provides direct insight into the tracking quality of the receiver. Flight-technical errors, reference position and time errors, antenna errors as well as propagation phenomena cancel as they are common on both rates. What remains is the receiver tracking performance and the transmitter timing control. The latter can be compensated for by the usage of a local reference station, leaving the receiver performance as the major contributor to the dual-rate difference.
Figure 9 shows the dual-rate differences for both E-field and H-field. Note that E-field and H-field have been measured consecutively, not simultaneously.

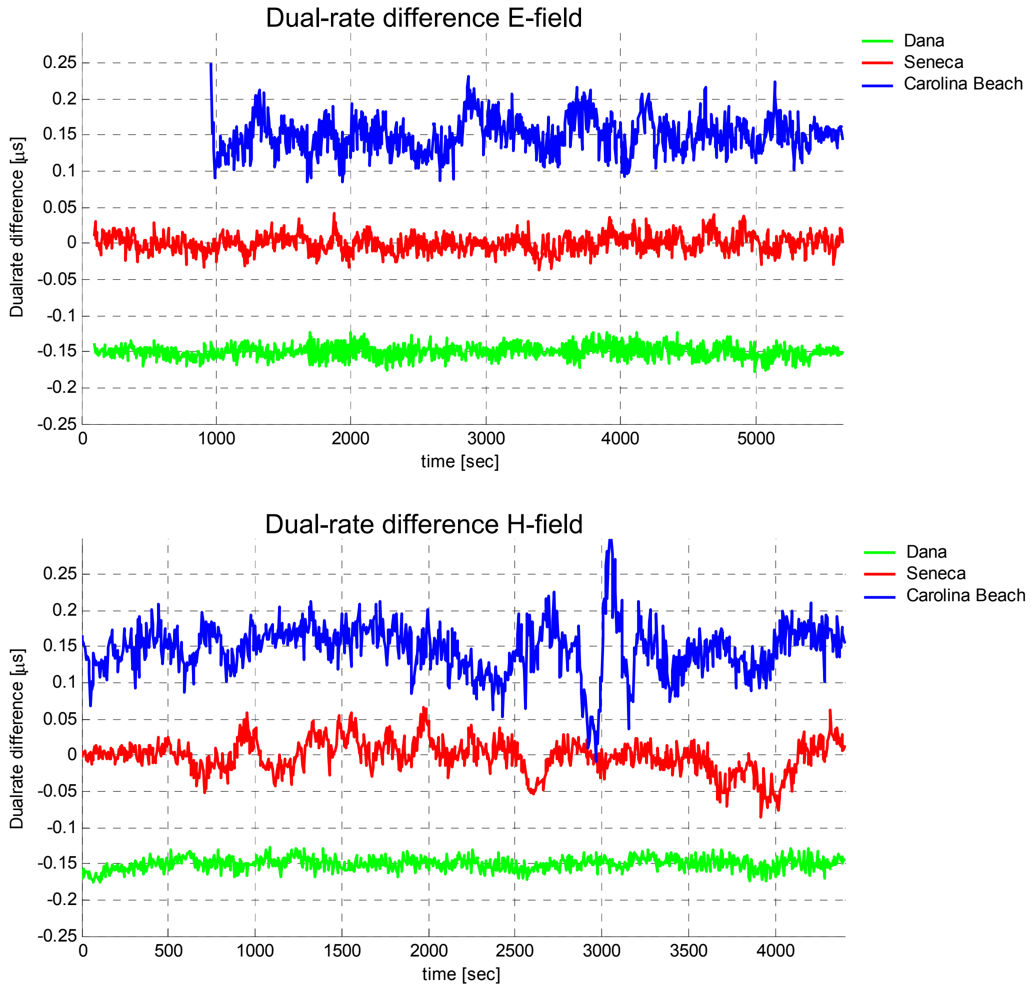

Figure 9: Dual-rate difference for E-field (top plot) and H-field (bottom plot)

Dual-rate differences should look noisy, without low frequency components. Unfortunately, in Figure 9 this is not always the case for the plotted dual-rate difference of the H-field setup (bottom plot). For example the dual-rate difference of Carolina Beach shows significant excursions around 3000 sec. The origin of these deviations is currently under investigation.
Table 1 shows the dual-rate differences quantitatively:

Table 1: Standard deviation of the dual-rate difference for E-field and H-field

Dual-rate difference	**Distance**	**E-field**	**H-field**
Dana (8970M – 9960Z)	377 km	9.4 ns	8.9 ns
Seneca (8970X-9960M)	632 km	12.3 ns	22.9 ns
Carolina Beach (7980Z-9960Y)	767 km	25.1 ns	36.0 ns

H-field antenna dependent error

The H-field antenna potentially suffers from heading-dependent errors. Several circles have been flown to assess the severity of these errors and the potential mitigation methods. Figure 10 shows the circles, Figure 11 the (uncorrected) amplitude and phase response of the antenna.

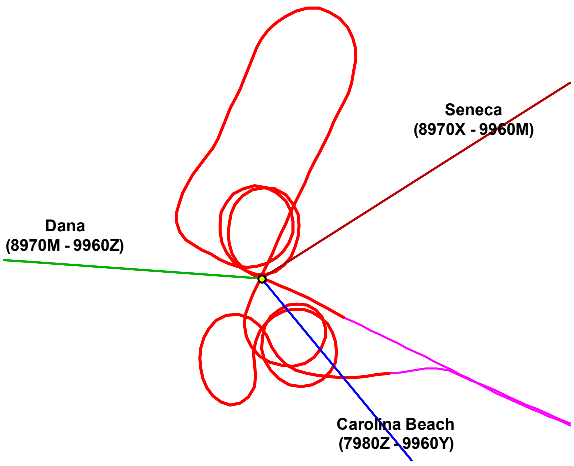

Figure 10: Circles flown with the H-field setup

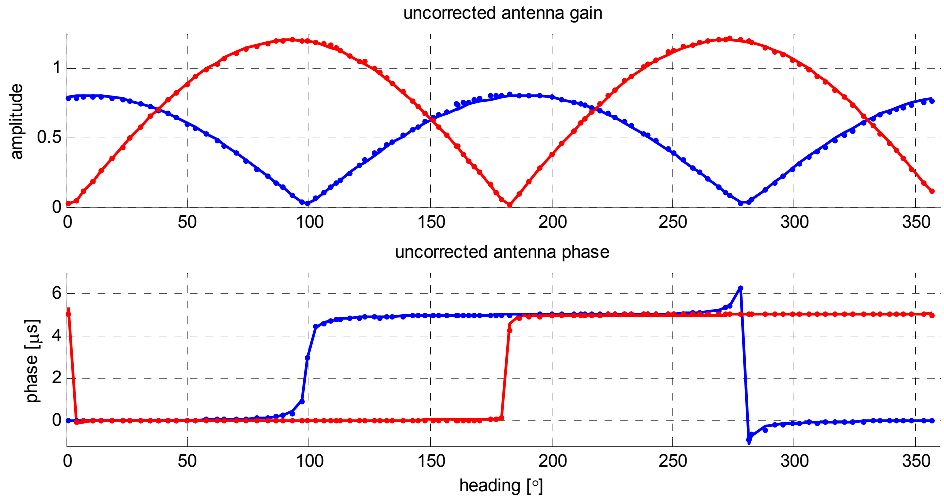

Figure 11: Uncorrected antenna gain and phase response (blue = loop 1, red = loop 2)

Most noticeable is the difference between the gain of loop 1 and loop 2. However, this difference is most likely caused by the significant banking of the airplane during the 2 minute, standard-rate turns. Furthermore, a gain difference between the two loops will not directly lead to an error in the TOA measurement. The less than perfect phase response of the antenna is of more importance. Especially loop 1 (blue) shows some deviations close to its null at 90 and 270 degrees. Without calibration these imperfections will lead to TOA and eventually to positioning errors. Figure 14 shows the H-field antenna response after calibration.

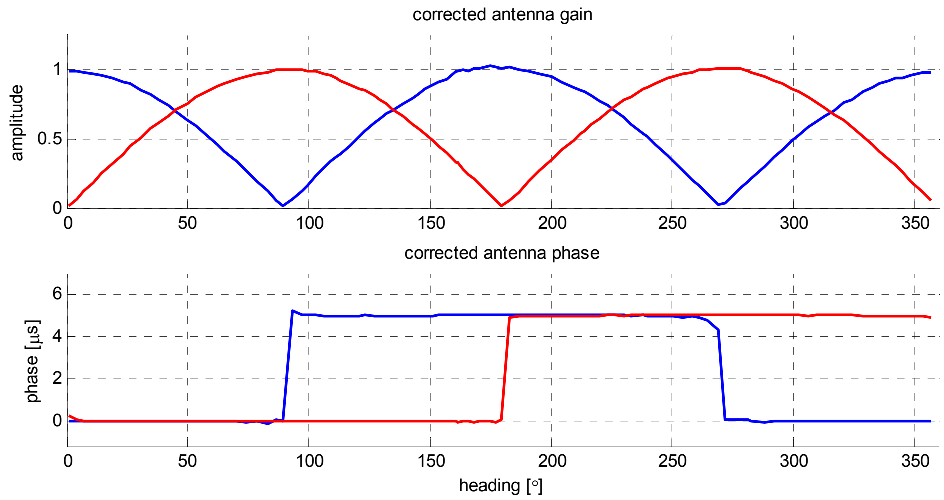

Figure 12: Corrected antenna response (blue depicts loop 1, red loop 2)

Run-to-run, dual-rate and E-field vs. H-field repeatability

The TMS performance is further analyzed by assessing the consistency between successive measurement runs, between E-field and H-field and between the two rates of dual-rated stations. For this, a track has been defined, starting at Circleville and heading to the north-west for approximately 47.5 km. Next, the measurements have been projected onto this track. Measurements further than 250 meters away from the track are ignored. Figure 13 shows the E-field (red) and H-field (blue) measurements with respect to the distance on the track. Per transmitter a single offset has been applied for displaying purposes.

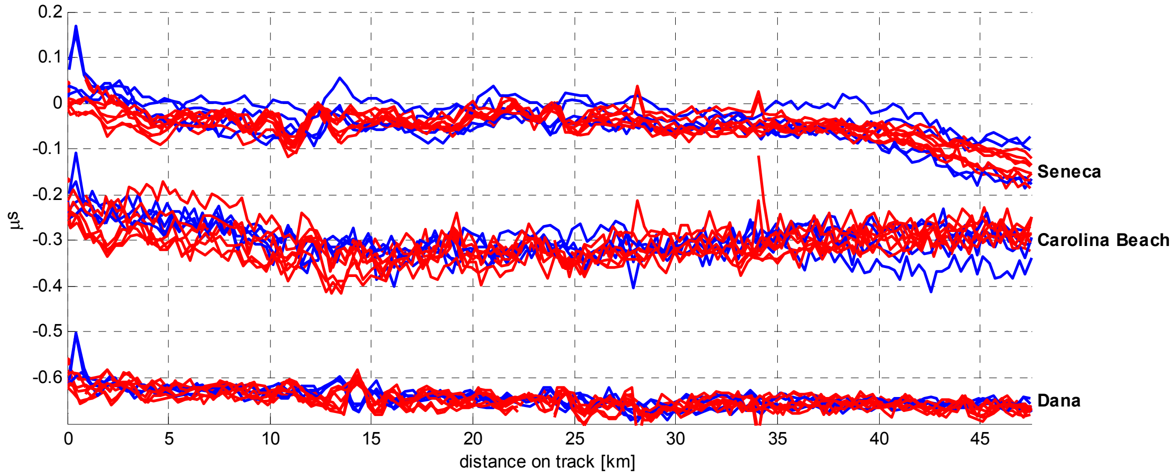

Figure 13: E-field (red) and H-field (blue) measurements projected on the 47.5 km long track

The repeatability shown in this figure reflects both the TMS performance and the flight technical error (FTE). In the measurement area the ASFs can fluctuate severely, as clearly visible in Figure 8. A slight deviation from the track can therefore lead to a significant reduction of measurement repeatability. A better TMS performance analysis at this measurement location will require reduction of the FTE which is very well possible under more favorable weather conditions and by using better guidance.

Note also the repeatable discrepancies between E-field and H-field, for example on the Dana measurements around 14 km. The fact that these measurements show run-to-run repeatability but disagreement between E-field and H-field indicates the presence of local propagation phenomena. From this it can be concluded that the far-field condition is not guaranteed for an airborne receiver at 2000 ft. Although scientifically most interesting, these local propagation phenomena conflict with the objectives of this measurement campaign as they reflect propagation phenomena rather than the TMS performance.

Position domain analysis

Whereas the TOA and ASF are of great interest for scientific purposes, for the user the positioning error is the parameter of most interest. For the position domain analysis, the ASFs as measured by the reference station have been subtracted from the mobile measurements. Therefore, the relative ASFs and the resulting positioning error displayed in Figure 14 should be, and they fortunately are, close to zero at the Ohio University Airport. After departure with the H-field setup, the position scatters to the south-west as a result of the changing ASFs over the hills. After passing Circleville, at approximately 2000 sec, the terrain is more flat resulting in more stable ASFs and Loran positions. While flying the 47.5 km track back an forth, the position scatter is stable with an offset of approximately 100 m to the north-west. At 4800 seconds the airplane has landed at Circleville and the H-field antenna is swapped for the E-field antenna. The E-field measurements precisely follow the excursions earlier measured with the H-field antenna. Note that the track has been flown four times (twice back and forth) with the E-field antenna. While closing in to Ohio University airport the E-field positioning error converges back to zero. There has been no noticeable difference between cross track and long track positioning errors, indicating correct synchronization between the GPS and Loran measurements.

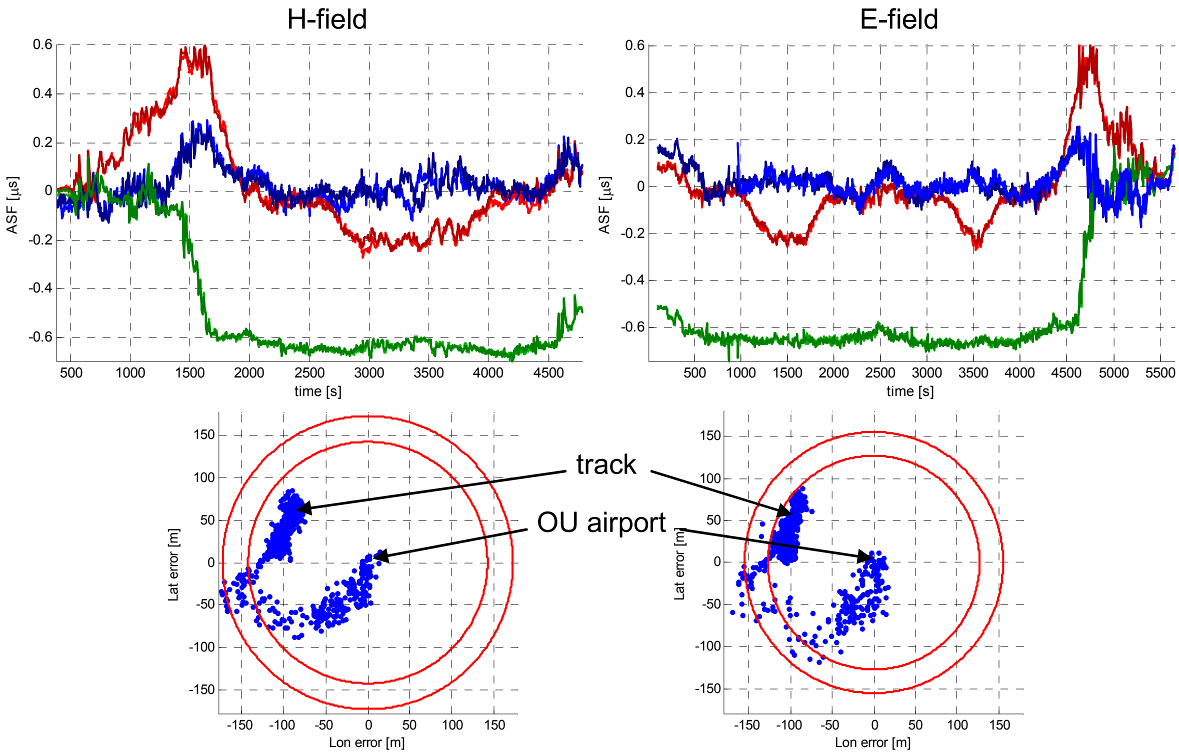

Figure 14: ASFs relative to the OU airport ASFs and the resulting positioning error for both H-field and E-field. The relative ASFs plotted in green are from Dana, red from Seneca and blue from Carolina Beach.

Conclusions

Hardware

The correct functioning of the TMS prototype hardware has been successfully validated. The final hardware, containing a custom FPGA design and the Loran signal simulator are currently being tested.

Software

The software modifications required for the TMS perform as expected. Finalization of the firmware is well underway and is expected to be finished late 2006, early 2007

System integration and testing

The TMS has operated successfully with a variety of antennas: the Reelektronika H-field, Locus H-field, Locus E-field and Apollo E-field. Tests have been conducted at static locations, in land-mobile environments, on water and in the air. Real-time analysis tools have proven valuable for in-flight quality monitoring and measurement campaign optimization.

Acknowledgments

This work was performed under Federal Aviation Administration contract DTFA01-01-C-0071 Technical Task Directive 2.1 – LORAN-C Analysis and Support. The authors would like to thank the Program Office manager, Mr. Mitchell J. Narins, for his assistance in making this research possible.