Propagation of Loran-C signals in irregular terrain – Modelling and measurements Part II: Measurements

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ABSTRACT

This paper complements Part I by describing the methodology of measurement of LORAN C signal strength and ASF's and comparing those measurements to theoretical predictions. In February, 2000, the U. S. Coast Guard in co-operation with the University of Wales, NELS and MORS, and supported by the Norwegian Coast Guard made extensive measurements of LORAN C signal strength and Additional Secondary Factors (ASF's) along the western and southern coasts and in the fjords of Norway. These measurements were made both by a LOCUS™ LORAN C receiver using an electric field antenna and by a Coast Guard Academy produced receiver using a magnetic field antenna. Both receivers used a Hewlett Packard™ 5071 Cesium frequency standard. A Starlink™ DNAV212G DGPS receiver was used for ground truth latitude and longitude, and as a source of a UTC 1pps reference to the Coast Guard Academy receiver, which measured absolute Times of Arrival (TOA's) relative to the 1 PPS input. This enables the measurement of absolute ASF's and offsets from UTC of the LORAN signals. The LOCUS TOA's are referenced to an arbitrary point in time established upon initialisation and measure changes in ASF as the propagation paths change with vessel movement.

In the fjords, errors in predicting ASF's using Millington's method of 2.5usec or more are observed. The predictions based on the theory described in Part I are seen to significantly reduce this prediction error. `

Introduction

In co-operation with Northwest Europe LORAN System (NELS), MORS, and the Norwegian Coast Guard, LORAN data was collected in the fjords and along the coast of southern Norway during the week of 14 to 18 February 2000. The purpose of this effort was to validate and calibrate the numerical LORAN ASF predictions described in the companion paper [1]. ASF are defined as the additional phase shift relative to an all seawater path caused by the overland portion of the propagation path. Because the effects extreme terrain in the Norwegain fjords dominate measurement noise, we are better enables the validation and calibration of the models presented in Part I.

Figure 1 illustrates the proposed path of the sea trials. The Norwegian Coast Guard provided the services of the KV Lafjord and her crew to support the effort. The KV Lafjord is a 55 meter overall former offshore fishing vessel converted for use mainly in the regulation of the offshore fishing industry.

Measurement and Survey Equipment

Figure 2 shows a block diagram of the equipment used to make the measurements. The PC 104 H field receiver was developed primarily for urban warfare and law enforcement purposes and was previously described in [2]. As it was designed specifically to provide the LORAN measurements in a tightly coupled Kalman filter integration of GPS/LORAN, its TOA measurements are relative to an external strobe, usually provided by a GPS's one pulse per second (1 PPS). The receiver generates a Time Interval Counter (TIC) measurement based on the start of the 1pps and stops on the receiver's PCI roll over. Using the TIC value, H-field receiver TOA, and the survey position, absolute measurements of LORAN signal ASF can be made. The HP 5071 Cesium provides a stable clock source for both the H-field LORAN receiver and the LOCUS LORAN receiver. The Starlink DGPS receiver provides both a 1 PPS for the H-field LORAN.

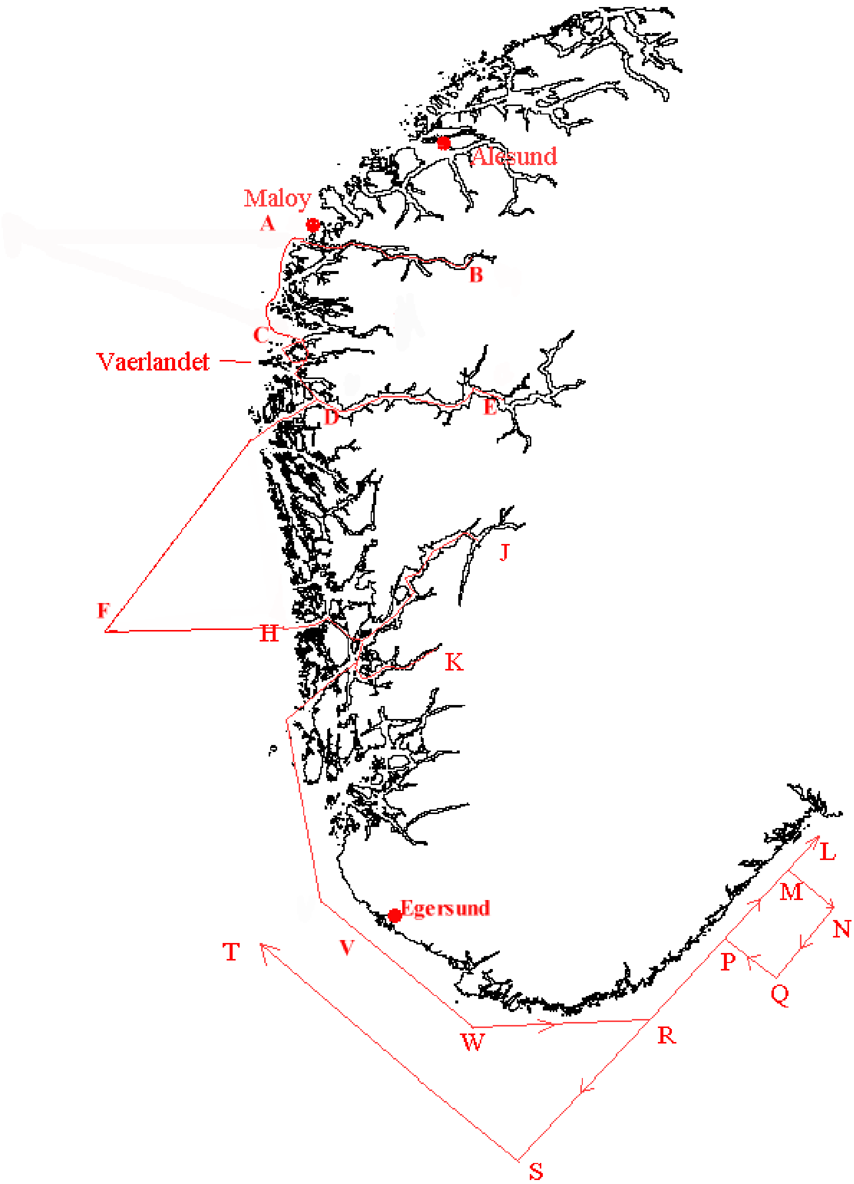

Figure 1. Route of sea trials.

receiver and a ground truth position. The DGPS position was used when the differential corrections were available. When not available, GPS position was used. The LOCUS receiver calculated its LORAN TOAs relative to an arbitrary point in the GRI based on receiver start up time. Using the LOCUS TOA information and the GPS/DGPS positions, only relative or changes in ASF were calculated

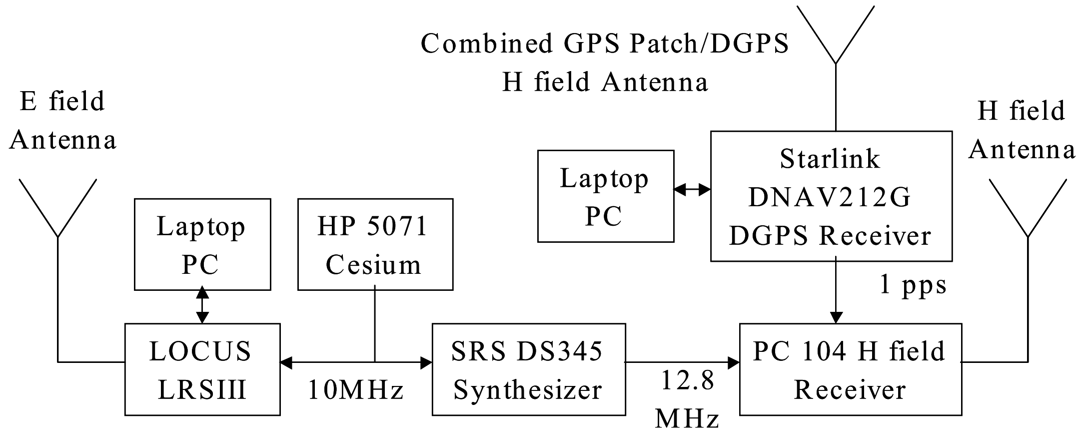

Figure 2. Measurement hardware block diagram.

Definition, measurement, and calibration of LORAN pulse relative to UTC

Reference [3] is the current USCG specification for the synchronization of the Master LORAN pulse and the UTC second; but is somewhat ambiguous in defining what point of the master pulse is coincident with a UTC second. In the earlier 1981 signal specification [4], in section 3.A, System Calibration Procedures, it states "TOC is defined as the UT second where the beginning of the master station's first pulse (phase code group A) is coincident with the occurrence of the UT second. The TOT measurements are made with respect to the Standard Zero Crossing (SZC), 30 microseconds after the beginning of the pulse." It later states the synchronization measurements are made using the transmitter antenna current waveform using a clamp-on transformer. For the purposes of receiver calibration, we use this 1981 definition. When calibrating the receiver, the master pulse is observed as voltage on an electric field whip antenna in the near far field. The voltage on an E-field antenna in the near far field is the derivative of the transmitter antenna current pulse, or a LORAN pulse in which the third positive going zero crossing is 2.4 usec earlier than the antenna current pulse plus the propagation delay. Figure 3 illustrates the antenna current and the near far field waveform. The start of the pulse is 27.6 usec before the third positive zero crossing on a pulse observed on an E-field whip in the near far field plus any propagation delay.

Figure 4 illustrates the method used to calibrate the H-field LORAN receivers. Using a strong LORAN signal and a common PCI reference point, the H-field LORAN receiver's calculated TOA is compared to an observed LORAN signal's TOA. The time difference is calculated and used as a the receiver calibration

As shown in figure 4, a Rubidium frequency standard is used as a stable clock source. An arbitrary PCI trigger is generated as a reference in the PCI signal. A 12.8 MHz signal is also generated for the H-field LORAN receiver. Using the HP 89410 Vector Signal Analyzer, the LORAN signal from the strongest station is observed using an E-field whip antenna in the near far field. The third positive zero crossing is identified and the time difference between this point and the PCI trigger is calculated (Tpci). Time of Arrival (TOA) referenced to the arbitrary PCI trigger in usec is calculated as

$$TOA_{observed} = Tpci - 27.6 \text{ usec}$$

The H-field LORAN receiver calculates a TIC value which is the time from an external one pulse per second (1 PPS) signal and what it uses as the "Start of Master". A GPS receiver normally supplies the 1 PPS signal so residuals for each LORAN signal can be computed. By using the PCI trigger, as the 1 PPS signal, the TIC value is the difference between the receiver's "Start of Master" and the arbitrary PCI trigger. The receiver also calculates TOAs for each station referenced to its "Start of Master". The receiver's TOA referenced to the arbitrary PCI trigger in usec is calculated as

$$TOA_{receiver} = TOA + TIC$$

The receiver's calibration is the difference between $TOA_{observed}$ and $TOA_{receiver}$. The receiver was carefully calibrated in New London, CT using Nantucket in GRI 9960 as the strongest signal. Using this method, calibrations of +/- 50 nsec were achieved.

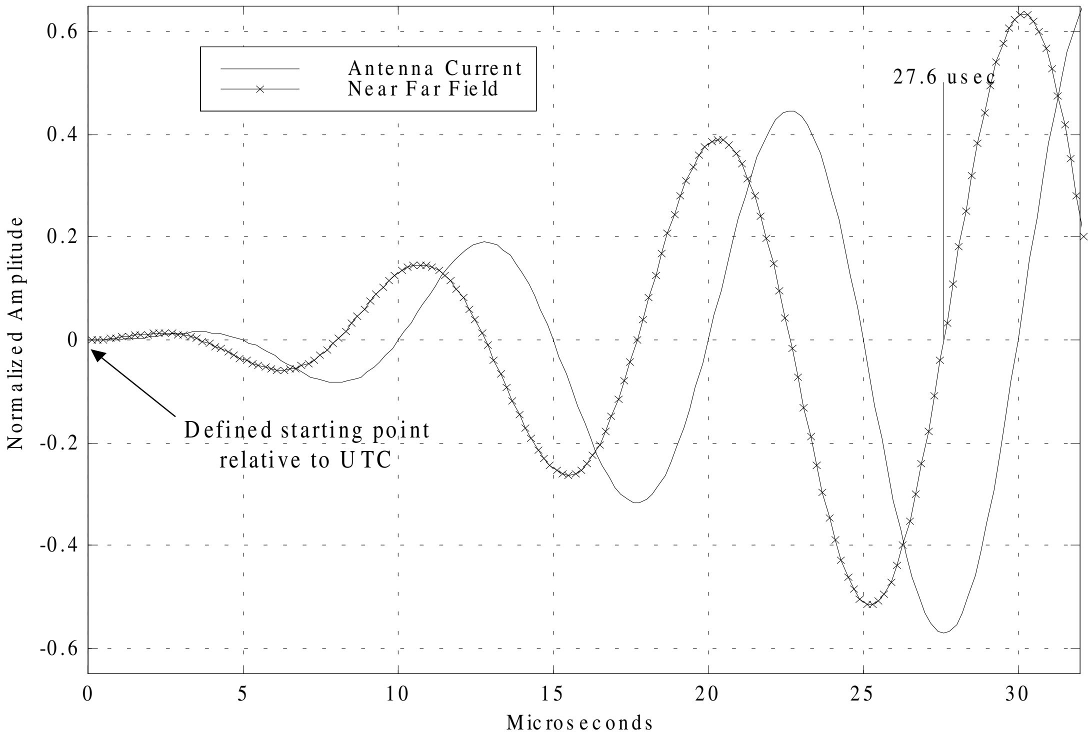

Figure 3. Definition of starting point on LORAN pulse for measurement relative to UTC used in this paper.

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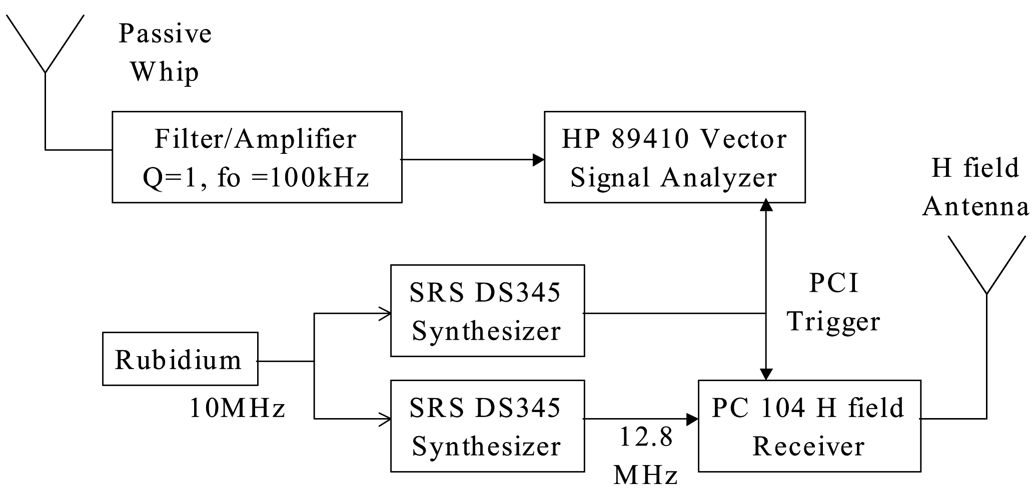

Figure 4. Block diagram of TOA calibration.

E field Data Analyses

Although data was collected for the entire trip, this section will focus mainly on the Wednesday and Thursday data in the interest of length. The path of the KV Lafjord for these days is shown in Figure 5.

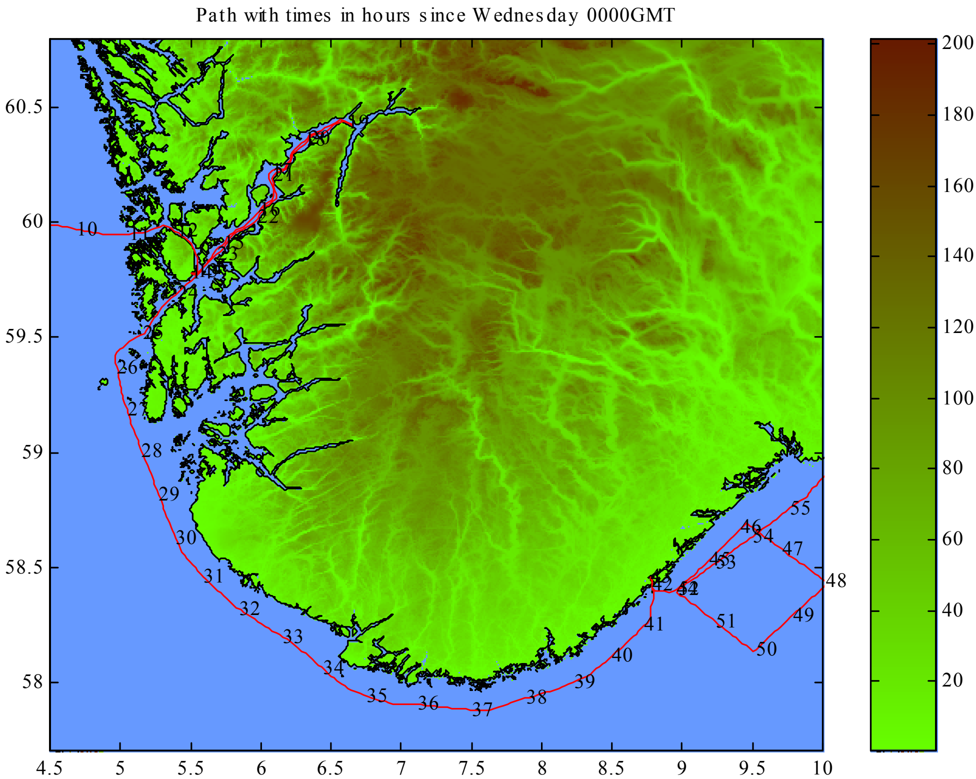

Figure 5. Path for Wednesday to Friday portion of trip. Elevation contours are in tens of meters.

Figure 6 shows the measured and predicted ASF's for Sylt for this period where the predictions are based on the method described in [1]. In the case of E field data from the LOCUS receiver, no absolute measurement of ASF is made and the measurements are adjusted such that the median of the difference is approximately zero. As can be seen, the change in ASF from the interior of Hardingerfjord Wednesday afternoon to an all seawater path during Thursday morning was predicted to be up to six microseconds and observed to be only three or four microseconds. It is interesting however to look in more detail at the measurements.

From 1600 to 1700 on Wednesday, the vessel was moving in the shadow of a large mountain. This track line can be seen in figure 7. As can be seen in Figure 8, there is a rapid change in ASF as the vessel moved from the shadow of the mountains to the south-southeast (in the direction of Sylt). At 1700, the propagation path does not have to refract nearly as much as earlier, and the ASF decreases by approximately two microseconds. As seen in figure 8, this change is predicted using the method in reference [1].

Figure 9 shows the predicted and measured E field ASF's over the same path as figure 5 for Ejde with the median of the difference forced to be zero. In this case the change in ASF from interior to the fjord to an almost all seawater path is predicted much better

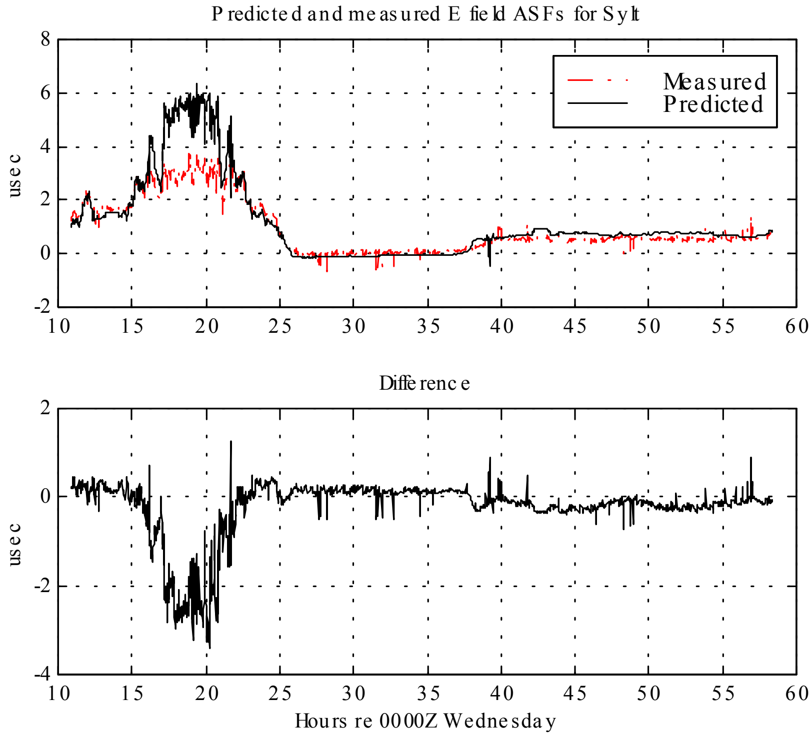

Figure 6. Predicted and measured E field ASF's for Sylt.

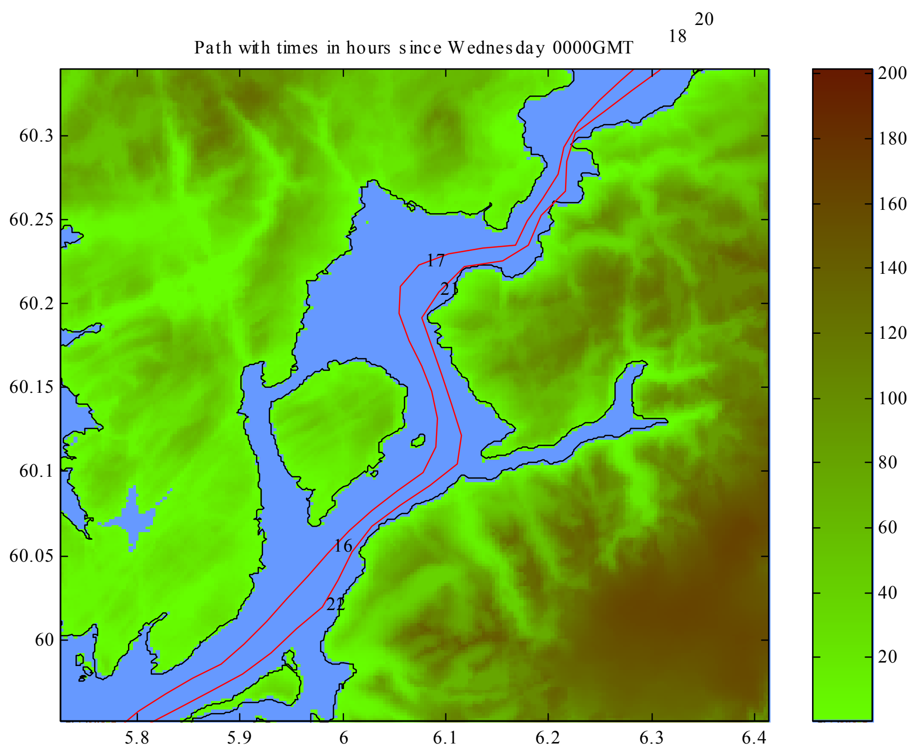

Figure 7. Path in the interior of Hardingerfjord. Elevation contours are in tens of meters.

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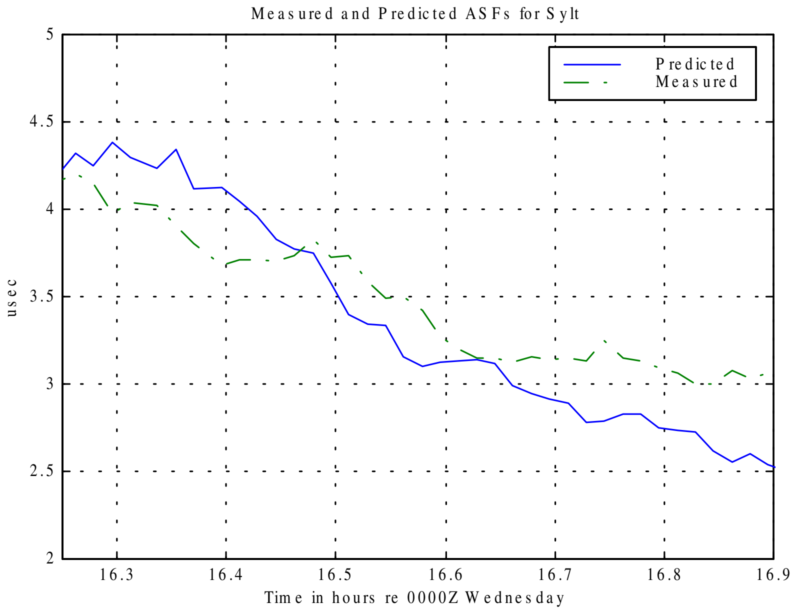

Figure 8. Change in ASF in the interior of Hardingerfjord.

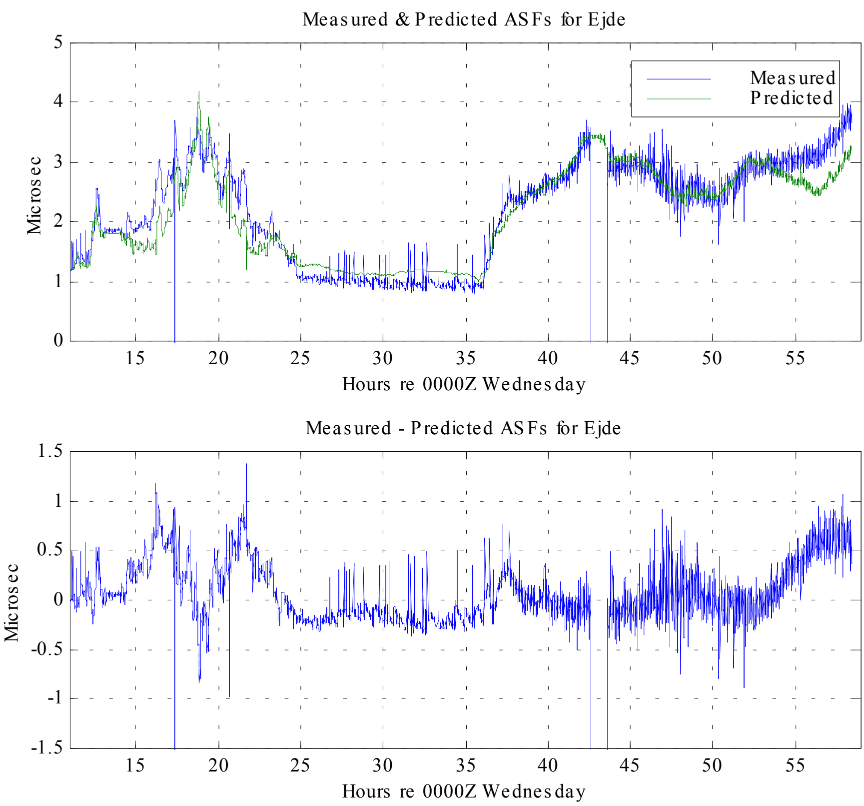

Figure 9. Predicted and measured E field ASF's for Ejde.

H field data analysis

In this case we can make absolute measurements of ASF. Figure 10 shows the H field measurements for Sylt. Again the measured changes in ASF from the interior of Hardingerfjord to the all seawater path southwest of Norway are much smaller than predicted. We also note an approximate 800 nanosecond difference for the all seawater path portion suggesting the possibility of Sylt being 800 nanoseconds late in transmissions using the definition for synchronization to UTC described earlier.

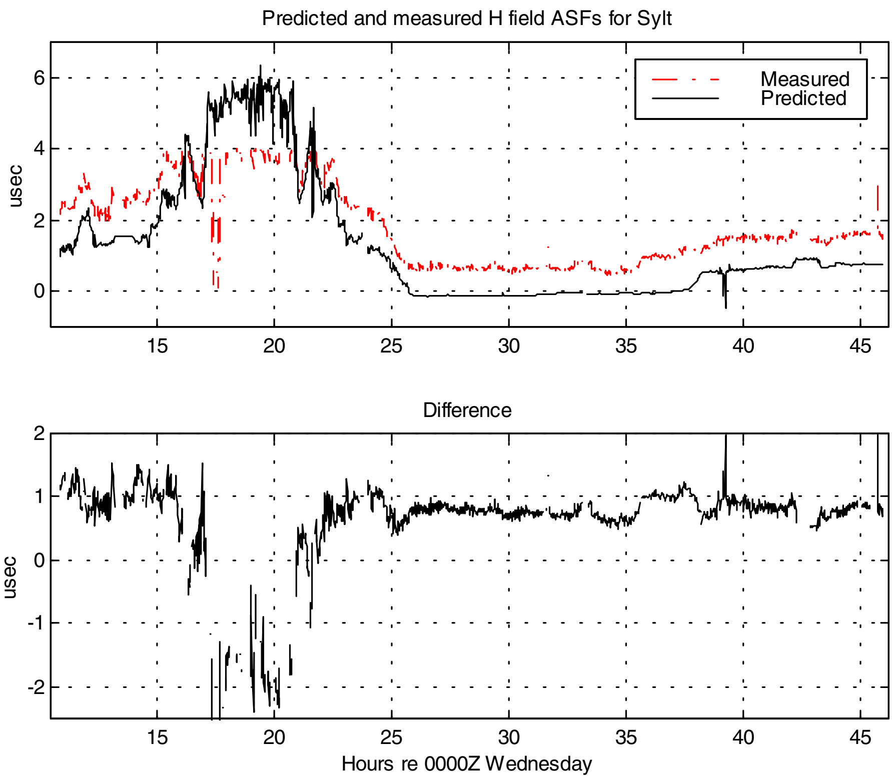

Figure 10. Predicted and measured H field ASF's for Sylt.

Figure 11 shows the measured ASF's for Ejde and the predicted ASF's using both the terrain model method [1] and a smooth earth model method [4]. The offset for Ejde is approximately 1.5 microseconds compared to terrain model predictions described in [1], and approximately 2.5 microseconds compared to smooth earth model predictions based on [5]. It can also be clearly seen that the terrain model method predicts the rapid changes in the measured ASF's far better than the smooth earth model.

Figure 12 shows the H field measurements for Vaerlandet for Thursday. Most of this data was collected offshore with varying amounts of the southwest portion of Norway in the propagation path. The measurements show very good agreement with predicted changes in ASF and approximately the same 1.5 microsecond offset as observed in the Ejde data. The Ejde and Vaerlandet data presented were from GRI 9007 signals and the Sylt data was from the GRI 7499 signal. However, it was noted that the two signals from dual rated stations were synchronized to each other and the offsets for each rate were the same.

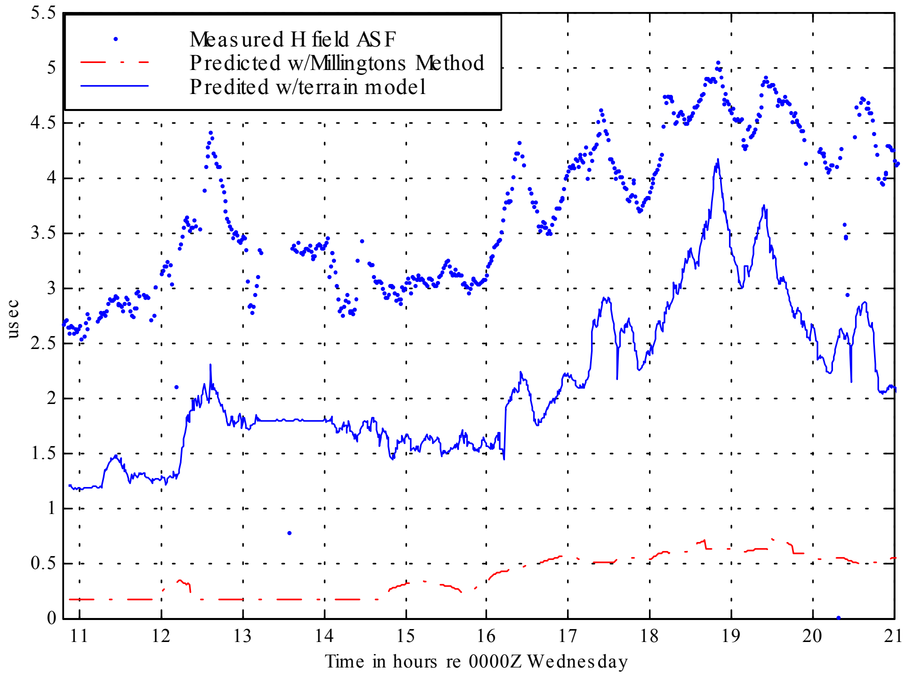

Figure 11. Predicted and measured H field ASF's for Ejde.

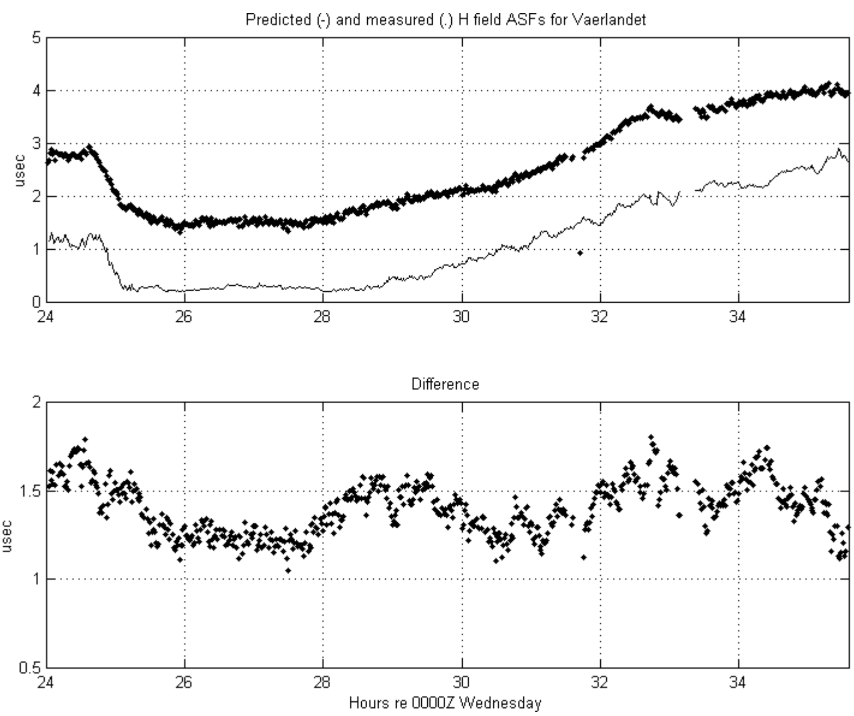

Figure 12. Predicted and measured H field ASF's for Vaerlandet.

Conclusions and directions for future effort

The method described in Part I, appears to predict changes in ASF much better than previous methods based on a smooth, inhomogeneous earth model. The extreme terrain in the Norwegian fjords enables the validation and calibration of the models presented in Part I. Using these methods combined with surveys such as done in this effort, predictions of ASF's in areas normally used for LORAN navigation to the 50 to 100 nsec level should be possible. We also know from previous efforts [6], that predictions of LORAN signal strength based on a smooth earth model are often greatly in error with propagation paths over rugged terrain. While these two papers have focused on the prediction and measurements of ASF's, validating the model used for prediction of signal strength should also be a worthwhile effort.

These measurements have suggested the potential that the NELS transmissions may be one to two microseconds late relative to the 1981 U. S. Coast Guard definition of the synchronization of LORAN to UTC. If LORAN TOA's are to be measured relative to the same strobe and combined with GPS pseudoranges in an integrated solution, it is important to have a clearly stated, internationally accepted, definition of synchronization.

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Author Biographies

Kenneth Dykstra is an independent consultant. He is a graduate of the U. S. Coast Guard Academy. He earned an MS in Electrical and Computer Engineering from Rensselaer Polytechnic Institute. He has co-authored several papers on digital LORAN receivers.

For biographies on David Last and Paul Williams, see part 1 of this paper

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-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 or the U.S. Department of Transportation.

Paul Williams