ASF Quality Assurance for eLoran

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eLoran has the potential to act as a cross-platform backup radio-navigation system to GPS to provide Position Navigation and Timing. As service providers of differential-eLoran for maritime navigation, the General Lighthouse Authorities of the UK and Ireland (the GLAs) must ensure that the system meets the internationally agreed standards for Accuracy, Availability, Continuity and Integrity.

For eLoran to provide accuracy better than 10m (95%), the user must have knowledge of the signal propagation Additional Secondary Factors (ASFs). The GLAs are charged with the measurement, validation and publication of accurate ASF tables for use within users’ receivers. To this end an extensive surveying campaign is required in order to measure the ASF tables for the nominated harbours and port approaches for eLoran IOC before 2014.

It is important that sufficient survey data is gathered to ensure high-quality ASF tables can be produced, but equally that surveying effort and ship-time are kept to a minimum to reduce costs. Making use of an ASF error-budget, novel processing techniques and an Integrity-based Quality Assurance methodology for ASF surveying have been created. This is designed to give the GLAs a real-time picture of the progress of an on-going survey, so surveying resources can be used effectively to maximise data quality.

As an additional benefit, ASF-table Quality figures can be fed into an eLoran Integrity equation to keep the mariner informed of the level of performance they can expect from the eLoran system. This will ensure that eLoran is used with an appropriate degree of trust during the various phases of a voyage for which it is used.

**Keywords-eLoran, maritime, ASF, Integrity, IMO**

I. OVERVIEW

To navigate a ship along an approach channel to enter a harbour a mariner must be able to fix their position to a high degree of accuracy. The International Maritime Organisation (IMO) has set out a list of requirements, which must be met by an electronic positioning system during the various voyage phases including port approach [1][2]. For eLoran to meet the IMO accuracy requirements, the receiver must be provided with accurate Additional Secondary Factor (ASF) measurements.

This report describes the efforts of the GLAs to measure and process eLoran ASF in order to obtain sub-10m (95%) accuracy from eLoran. Software applications have been written in MatLab™ to aid the gathering and processing of eLoran data, and the current state-of-the-art in recommended ASF measurement and processing is described.

II. INTRODUCTION

A user of eLoran will determine their position by a Least-Squares solution of a (preferably) over-determined set of pseudorange measurements made from all eLoran stations in view. A user’s receiver should be able to make use of any eLoran signal within about 800-1000km of their position with a signal-to-noise ratio (SNR) better than -10dB. In the GLAs service area there are typically between three and eight eLoran signals available to the user at any location.

A. Delay Factors

The eLoran signal propagates by groundwave across the surface of the Earth, as it does it accumulates a number of delays relative to the speed of light. These delays need to be accounted for when using measured pseudo-ranges to fix a position.

1) Primary Factor

Due to the refractive index of the atmosphere ($n_{pf}=1.000338$), the PF speed of the Loran signal through the atmosphere is given by:

$$c_{pf} = \frac{299,691,162}{n_{pf}} \text{m/s}$$

2) Secondary Factor

Due to the electrical conductivity and curvature of the surface of the Earth an additional delay is incurred. Seawater is the best conducting surface, and it is possible to model the SF contribution from seawater using the equations described by P. Brunavs [3], as shown in Fig. 1.

![Figure 1. Secondary Factor Delay from Brunavs’ equations](image-url)
3) Additional Secondary Factor

Any land encountered with a surface conductivity lower than seawater will delay the signal even further. This additional delay is termed the Additional Secondary Factor or ASF. Work has shown it is not viable to determine ASF by modelling with sufficient accuracy for navigation [4][5].

B. Provision of ASF

The current method for providing ASF data involves a comprehensive measurement campaign of an area, with the surveyed data then uploaded to the user’s receiver. This survey will have been carried out on a particular day to fix the ASF values once and for all.

Since ASF depends on the ground conductivity along the propagation path, any changes in conductivity will change the ASF. Likewise, changes in the temperature, pressure or moisture content of the atmosphere will alter the PF. Although this is technically not a change in ASF, it will appear so to the user, and PF variations are often lumped together with ASF variations.

To account for these, a differential-Loran service can be established to continually measure the ASF at a particular site and monitor any changes over time. These changes can then be broadcast to the user in the form of updates over the Loran Data Channel (LDC). The situation is analogous to the way that DGPS accounts for changes in the Ionosphere and Troposphere delay (see Fig. 2).

C. ASF Measurement

The ASF Measurement System developed by Reelektronika (www.reelektronika.nl) in the Netherlands is currently the best all-in-one unit for measuring ASF that has been used by the GLAs.

ASF is determined by calculating the PF and SF-corrected time-of-flight (TOF) of the signal to the user’s location and subtracting this from the value that is observed. The unit determines its location (ground-truth) using marine-beacon DGPS, and the expected TOF is given by (2)

$$\text{TOF}_e = \rho \frac{\text{HF}}{c} + \text{SF} (\rho)$$

(2)

The expected Time-of-Emission (TOE) of each signal is precisely maintained by the transmitter relative to UTC. By measuring the Time-of-Arrival (TOA) at the receiver relative to UTC, then the observed TOF can be calculated. ASF is then the difference between measured and expected TOF, this is the ASF Equation (4):

$$\text{ASF} = \text{TOF}_m - \text{TOF}_e$$

(4)

To synchronise the receiver’s clock to make UTC-referenced TOA measurements requires time-tagging hardware which uses a GPS-derived 1PPS signal as a UTC reference. In addition, a Loran simulator signal is injected into the reception antenna used to calibrate out any variable antenna / cable delays.

D. Temporal Variations

ASF changes with location, and varies gradually over time as described above. When conducting a survey, a roving ASF unit will measure both temporal and spatial variations of ASF. The temporal variations can be removed by making use of a differential reference-station, in much the same way as a user will make use of the station in their positioning. This process of removing DLoran corrections from an ASF survey effectively ‘ties’ a survey to a particular reference station.

With a DLoran station set up and broadcasting its corrections on the Eurofix LDC it is possible to remove the temporal ASF variations on-the-fly as an ASF survey is in operation. This removes the need for any post-mission processing and crucially can be used to assess the quality of the ASF measurements while the survey is still ongoing.

Figure 2. Changes in ASF for Loran are analogous to changes in atmospheric delay for GPS, and can be mitigated by a differential service in much the same way.

Figure 3. ASF Measurement System, courtesy Reelektronika
E. ASF Error Budget

By understanding precisely how the ASF is measured, it is possible to determine the accuracy of the measurements that are made, and the possible sources of measurement error picked up along the way. ASF is the combination of:

- TOA measurement
- UTC time-tagging
- differential-corrections
- eLoran-simulator calibration
- transmitter TOE jitter
- ground-truth ranging

Following simple error-propagation laws, the error in ASF is given by the addition of errors from each of these sources:

\[
\sigma_{ASF}^2 = \sigma_{TOA}^2 + \sigma_{TAG}^2 + \sigma_{DLoran}^2 + \sigma_{Sim}^2 + \sigma_{TOE}^2 + (\frac{2\pi}{\rho})^2 \sigma_{\rho}^2
\]  

(5)

Experimental evidence has provided figures for each of the error-components, as tabulated below:

<table>
<thead>
<tr>
<th>Error Source</th>
<th>Magnitude</th>
<th>Notes</th>
</tr>
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| \( \sigma_{TOA}^2 \) | Noise in Loran TOA measurements | 10-25ns (3-8m)  
| \( \sigma_{TAG}^2 \) | Time-tagging noise | 10ns (3m)  
| \( \sigma_{Sim}^2 \) | Simulator error | <5ns (2m)  
| \( \sigma_{TOE}^2 \) | Transmitter jitter | <10ns (3m)  
| \( \sigma_{\rho}^2 \) | Ground-truth ranging error | 3ns (1m)  
| \( \sigma_{DLoran}^2 \) | Differential corrections | <5ns (2m)  

Typically, a single ASF measurement from a strong station (SNR>+15dB) will only be accurate to about 15-20ns (4-6m) when all error sources are considered. It is for this reason that a large number of measurements must be collected to ensure the accuracy of the survey.

III. Surveying ASF for a Harbour Approach

It is impractical and would be extremely costly to perform an extensive ASF survey of all waters in the GLAs service area. It is for this reason that R&RNAV have chosen to concentrate their efforts on providing the highest quality ASF in areas where Robustness of PNT information is most safety and mission-critical.

As an example of ASF data-collection and mapping techniques the recent GLA survey of Harwich Harbour is presented.

A. Planning

Prior to planning the survey, TH Navigation Directorate provided R&RNAV with AIS data showing the routes sailed during the last year by SOLAS class vessels sailing into Harwich. This data showed the tracks most often taken by approaching vessels. To maximise the usefulness of the ASF data gathered, it was decided these areas would be surveyed most extensively.

B. DLoran Station in Harwich

The GLAs have operated a Differential-Loran station in Harwich since 2008. This station continually broadcasts differential corrections on the LDC from the GLA transmitter at Anthorn. This station was used to provide temporal corrections for the survey of Harwich and Felixstowe.
D. Gathered Data

In total about twenty thousand individual ASF measurements were made in the course of a surveying campaign that was performed over a number of consecutive days. As an example, the raw data gathered for the Anthorn (6731Y) transmitter is shown in Fig. 9 below:

These raw ASF measurements must be processed into a form appropriate to be loaded into a user’s receiver. The proposed data format is a ‘grid’ of spot values at regular spacing; one grid will be required for each eLoran transmitter used in positioning. These grids will be assigned the ID of the particular reference station they are ‘tied’ to.

Experimental work in the USA [6] has indicated that 500m grid spacing for the values is an optimal figure to be able to describe typical spatial variations accurately and the GLAs have verified this independently [7]. For ease of use, the grid lines follow the WGS84 lines of Latitude and Longitude. A spacing of approximately 0.005 degrees in latitude and an appropriate scaling in longitude provides a regular lattice of ‘cells’ at 500m spacing.

These grids or ASF Maps can be thought of in the same way as the grids of ionospheric delay provided by SBAS systems such as WAAS or EGNOS, but contain a greater density of information and remain static over time. They are used by the receiver to help derive a position fix in much the same way: the spot values are interpolated at the approximate position of the receiver.

1) The Interpolation Equation

At a particular location (X), given by the co-ordinates \((x, y)\), the geographical position of the receiver within a particular ASF grid cell can be expressed in terms of two parameters \(\alpha\) and \(\beta\).
Here \( x(i) \) and \( y(j) \) are the WGS84 co-ordinates of the grid cell, within which the receiver is currently located. The parameters \((\alpha, \beta)\) are then used to perform a two dimensional interpolation between the four nearest grid elements C1-C4:

\[
\alpha = \frac{x - x(i)}{(x(i+1) - x(i))} \quad (6)
\]

\[
\beta = \frac{y - y(j)}{(y(j+1) - y(j))} \quad (7)
\]

To generate an ASF grid, a method was first developed by G. Johnson and his team in the US [6] to reverse the Interpolation Equation (8) by least-squares, and so derive the grid values from the raw data. This technique, however, can be computationally difficult and does not always converge on a ‘sensible’ solution.

The GLAs prefer a mapping method akin to the de-noising filters used in image processing, such as the Photoshop ‘blur’ tool. This method uses a convolution of the raw data with a filter ‘kernel’ equation that ‘spreads’ each observation over a particular area.

A map can then be made by taking a series of sample-points \((x_0)\) and performing a sum of the data points \((y)\), weighted by the kernel equation \((k)\), with an appropriate re-normalisation constant \((A)\) as (9) below:

\[
\hat{y}(x_0) = A \int_{\mathbb{R}} y(x) k(x_0 - x) \, dx \quad (9)
\]

Here the kernel function is a radial exponential with a filter ‘width’ equal to \(d\):

\[
k(r) = \exp\left(-|r|/d\right) \quad (10)
\]

When applied to the raw data shown in Fig. 9 with a filter width of 500m, the resulting map shown in Fig. 11 is generated.

### E. Error Mapping

It is important to be able to assess the contribution of this mapping process on the overall ASF error budget. The kernel function used in the mapping is not arbitrary, but is selected based on a model of ASF error-propagation.

\[
\sigma_i^2 = \sigma_0^2 \exp\left(r_i/d\right) \quad (11)
\]

We have modeled the error in using an ASF measurement \((\sigma)\) at a distance \((r)\) from where it was measured as growing exponentially, \(\sigma_0\) is the accuracy of the raw measurement, as given by Equation (5). Taking the result that an ‘ideal’ filter should weight raw data by the inverse of its variance:

\[
W_i = 1/\sigma_i^2 \quad (12)
\]

We can ensure our filter is close to ‘ideal’ by carefully selecting the kernel function width \((d')\), a width equal to the grid spacing (500m) is optimal. By combining the image-filter processing (9) and the ASF Error-budget (5) it is possible to ‘map’ the error-contribution from the ASF measurements.
This image is an important driver of the ASF Survey process. It indicates which areas of the map have been precisely surveyed and can also indicate any gaps. The red areas indicate where the ASF values have not been observed directly, but are extrapolated from nearby measurements. When extrapolation is used we cannot guarantee the map accuracy.

It is the intention of the GLAs that the ASF data they provide shall be accompanied by such tables of error-measurements so the user will have a full understanding of the quality of the ASF data. Again, this is analogous to SBAS grid- ionospheric vertical error (GIVE) data and allows the inclusion of ASF error-contributions in the receiver’s Integrity Monitoring.

F. Use of ASF Error Map in Integrity Monitoring

The GLAs are developing an eLoran Integrity Equation. This is designed to offer a guaranteed level of performance for a user’s position fixing to enable them to use eLoran with an appropriate degree of confidence. The equation works by assessing the likely errors in the eLoran pseudo-ranging, and provides a Horizontal Protection Level to bound on the likely position error:

$$HPL = 3.3931 \sqrt{C_{xy}(1,1) + C_{xy}(2,2)}$$

The HPL is found using an estimate of the positioning Covariance Matrix ($C_{xy}$). This is found from the positioning design matrix ($G$) and pseudo-ranging covariance ($C_{PR}$):

$$C_{xy} = \left(G^T C_{PR}^{-1} G\right)^{-1}$$

Each eLoran pseudo-range is made up of a: signal time-of-arrival (TOA) measurement; a differential-Loran correction; and a mapped ASF. The $C_{xy}$ matrix is made by covariance addition from these three sources: TOA; DLoran and ASF.

$$C_{PR} = C_{TOA} + C_{DLoran} + C_{ASF}$$

Since ASF is so crucial to eLoran accuracy, if a user were to fix their position using an ASF map without any knowledge of its accuracy they would be unable to ascertain how precise their fix is. It is important, therefore, to be able to provide reasonable estimates of these covariance matrices. The GLAs are currently developing Integrity models for each of these components – by doing so eLoran can be provided with an Integrity guarantee.

It is vital for the system to be able to offer this guarantee, both in terms of user confidence and usability of the system. Fusion of navigation data will become increasingly important in an e-Navigation context, where robustness of PNT data will come from the integration of disparate navigation systems. For this integration to be done efficiently it is important for the integrator to be able to assess the reliability and quality of the input data. For all radio-navigation services it is suggested, pseudo-ranging covariance information should be the heart of this quality assessment.

IV. SUMMARY AND CONCLUSIONS

The work presented here is the current state of the art in ASF measurement and processing performed by the GLAs, to ensure that the ASF data we provide is of the highest quality.

A suite of measurement and processing software has been written that acts to oversee the GLAs surveying of ASF. This software uses a novel filtering technique based on image-processing and works to assimilate ASF measurements into a Map; and ASF errors into a Quality Map.

An eLoran positioning Integrity Equation is being developed to be able to incorporate these Quality statistics into an eLoran Horizontal Protection Level. The HPL is used to assess the Integrity of a derived eLoran position-solution, and is incorporated into the ASF Survey software.

REFERENCES

[1] Revised maritime policy and requirements for a future global navigation satellite system (GNSS), IMO A.915(22), 22 January 2002