eLoran Initial Operational Capability in the United Kingdom – First results

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BIOGRAPHIES

Dr. Gerard Offermans is Senior Research Scientist of the UrsaNav LFBU engaged in various R&D project work and product development. He supports customers and operations in the European, Middle East, and Africa (EMEA) region from UrsaNav's office in Belgium. Dr. Offermans is one of the co-developers of the Eurofix data channel concept deployed at Loran installations worldwide. Dr. Offermans received his PhD, with honors, and Master's Degree in Electrical Engineering from the Delft University of Technology.

Erik Johannessen is Vice President of LF Business Development at UrsaNav. He is responsible for leading the Low Frequency Business Unit (LFBU) in business development, and also provides technical and operational expertise with LF Business Unit systems, services, and products.

Steve Bartlett is Vice President of Operations for the UrsaNav LFBU. He is responsible for all aspects of business operations including manufacturing, engineering, quality control, program management, and project delivery. Steve served as an active duty officer in the U.S. Coast Guard and retired from the U.S. Coast Guard Reserve. He earned his BS in Electrical Engineering from Northeastern University and an MS in Electrical Engineering from North Carolina State University.

Charles Schue is co-owner and President of UrsaNav, Inc. He champions providing Low Frequency Alternative Positioning, Navigation, Time and Frequency, and Data solutions for "sky-challenged" users. He served in the U.S. Coast Guard, where his expertise included radio navigation systems, and was the first Commanding Officer of the Coast Guard's Loran Support Unit. He holds Masters Degrees in Electrical Engineering, Engineering Management, and Business Administration. He is a Fellow of the Royal Institute of Navigation.

Andrei Grebnev is Principal Engineer at UrsaNav, Inc. and is responsible for the design of new products for LF systems and eLoran user equipment technology. He received BS and MS degrees in Radioelectronics Engineering from Moscow Aviation Institute. He worked at the same Institute as Senior Research Engineer and later as Chief of Receivers Laboratory. Mr. Grebnev holds patents pertaining to the use of magnetic loop antennas for Loran and has authored several papers on the subject.

Martin Bransby is the Manager of the Research and Radionavigation Directorate of the General Lighthouse Authorities of the UK and Ireland. He is responsible for the delivery of its project portfolio in research and development in such technical areas as AIS, eLoran, e-Navigation, GNSS and Lights. He is a Fellow of the Royal Institute of Navigation, and holds memberships of the Institute of Engineering & Technology and the US Institute of Navigation. He is also a member of the International Marine Aids to Navigation and Lighthouse Authorities' (IALA) Aids to Navigation Management Committee.

Dr. Paul Williams is a Principal Development Engineer with the Research and Radionavigation Directorate of The General Lighthouse Authorities of the UK and Ireland, based at Trinity House in Harwich, England. He is currently the technical lead of the GLA's eLoran Work Programme. The work involves planning the GLA's maritime eLoran trials and work on a wide range of eLoran related projects. He holds BSc and PhD degrees in Electronic Engineering from the University of Wales, is a Chartered Engineer, a Fellow of the Royal Institute of Navigation, and is chairman of the Radio Technical Commission for Maritime Services Special Committee 127 on Standards for Enhanced Loran (eLoran) Systems.

Chris Hargreaves is a Research and Development Engineer with the Research and Radionavigation Directorate of The General Lighthouse Authorities of the UK and Ireland, based at Trinity House in Harwich, England. His work is focused on the GLA's eLoran project in particular measurement trials, software development and data analysis. He holds an MSci degree in Mathematics and Physics from the University of Durham, and an MSc in Navigation Technology at the University of Nottingham and is a member of the Institute of Navigation and the Royal Institute of Navigation.

ABSTRACT

There is an increasing awareness in the Maritime world that no single system can provide Position, Navigation, and Time (PNT) resiliently under all circumstances. At this moment GPS (with augmentations) is used on most commercial vessels, and in many cases integrated into systems we did not expect would need or use GPS derived

position or time. Even though the introduction of Glonass, Galileo, Beidou and other GNSS systems will provide some resilience, the underlying (satellite) technology remains the same, only providing relatively weak signals from space at mostly the same frequencies for compatibility and inter-operability.

The International Maritime Organization (IMO) recognizes the need for multiple PNT systems on board. The organization developed the e-Navigation concept to increase maritime safety and security via means of electronic navigation, which calls for (at least) two independent dissimilar sources of positioning and time in a navigation system to make it robust and fail safe. As a follow on, IMO's Navigation, Communications and Search and Rescue Committee (NSCR) is considering Performance Standards for Multi-System Shipborne Navigation Receivers, which includes placeholders for satellite, augmentation and terrestrial systems.

The most viable terrestrial system providing PNT services that meet IMO's requirements is eLoran. With three eLoran transmitters in good geometry, eLoran can provide sub-10 meter (95%) horizontal positioning accuracy and UTC synchronization within 50 ns, sufficient to be the co-primary PNT solution next to GNSS. The General Lighthouse Authorities of the United Kingdom and Ireland (GLA) have installed Differential eLoran Reference Stations to provide the world's first Initial Operational Capability (IOC) eLoran system. Together with Loran transmitters in England, France, Germany and Denmark, the Differential eLoran Reference Stations provide better than 10 meter positioning accuracy at seven ports and port approaches along the English and Scottish East Coast. Initial Operational Capability was declared by the end of October 2014 with Full Operational Capability planned for 2018. Other nations have begun similar projects.

The paper describes the IOC eLoran system in the UK, consisting of Differential eLoran RSIMs covering seven major ports in England and Scotland. ASF maps for the port and harbor approaches are published by the GLAs for integration into maritime user equipment. The paper provides initial static (zero-baseline) and dynamic measurement results at the harbor and harbor approach areas.

INTRODUCTION

The General Lighthouse Authorities of the United Kingdom and Ireland (GLA) comprise Trinity House, The Commissioners of Irish Lights and The Northern Lighthouse Board. Between them, they have the statutory responsibility to provide marine Aids-to-Navigation (AtoNs) around the coast of England and Wales, all of Ireland and Scotland, respectively. AtoNs take many forms, from the more traditional lighthouse to radio navigation systems, including the use of new Global Navigation Satellite Systems (GNSS) when they become available.

It is recognised that GPS, or more generally GNSS have become the primary means of obtaining Position, Navigation and Timing (PNT) information at sea, and there is no doubt that GNSS will form the primary source of PNT for e-Navigation.

An aim of the International Maritime Organisation (IMO) is to develop a strategic vision for e-Navigation, integrating existing and new navigational tools in an all-embracing system, contributing to enhanced navigational safety and environmental protection, while reducing the burden on the navigator. One of IMO's requirements for e-Navigation is that it should be resilient - robust, reliable and dependable [1]. Requirements for redundancy, say the IMO, particularly in relation to position fixing systems, should be considered.

But GPS is vulnerable to intentional and unintentional interference [2, 3], while at the same time it is used in many ship's systems. Its output is displayed on the ECDIS; is transmitted to other vessels using AIS; is used to calibrate the gyro compass; in the RADAR; connected to the digital selective calling (DSC), its reported position transmitted at the push of the emergency button for search and rescue; the vessel data recorder; the dynamic positioning system; surveying equipment; the ship's entertainment system for aiming the satellite dish and it even synchronises the ship's clocks!

In 2010 the GLA followed the UK Treasury methods to produce the GLA's eLoran Business Case [4, 5]. This comprehensive document presented and analysed various options for providing 'Resilient PNT' in UK and Irish waters. It was clear that if the GLA chose to implement eLoran it could rationalise its physical AtoN infrastructure, removing some lights and other physical aids, and on balance actually reduce costs by implementing eLoran. Indeed, compared to other possible resilient PNT options such as GNSS hardening, radar absolute positioning, increasing physical AtoN provision, eLoran would save the GLA millions of pounds over a nominal system lifespan of 10 years from the introduction of e-Navigation services in 2018 to 2028.

So, the GLA opted to provide differential Loran services in selected ports on the East coast of the UK, in what they elected to call its Initial Operational Capability (IOC). This paper will discuss the role out of these services in detail.

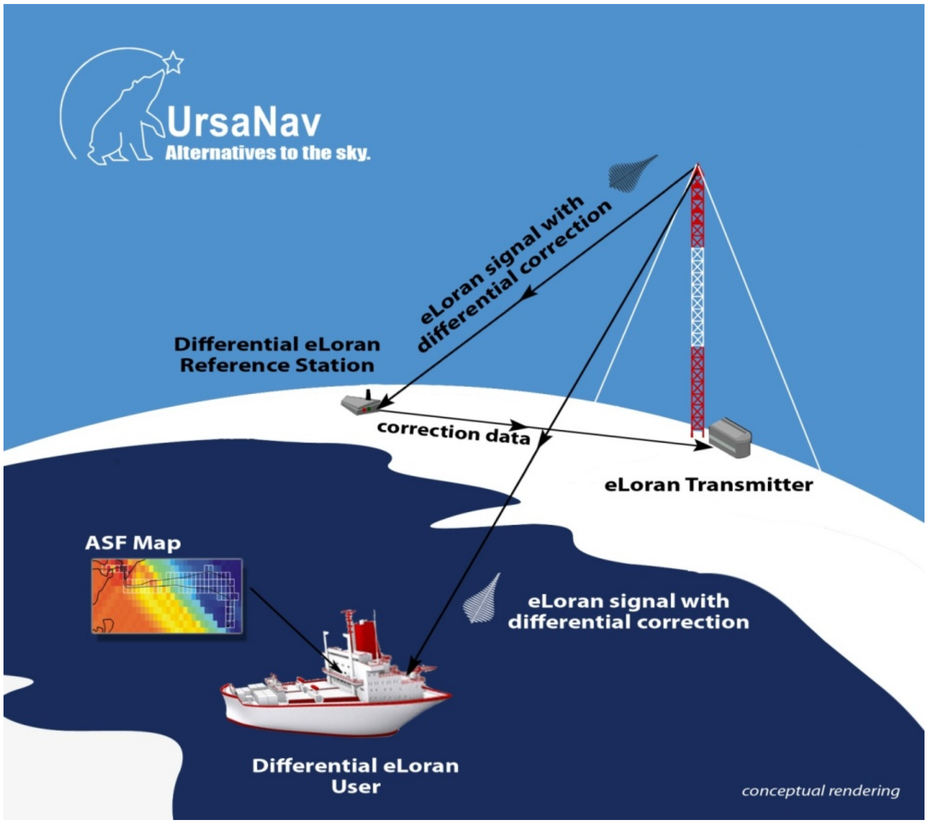


Figure 1. Differential eLoran for Maritime Applications

ELORAN FOR MARITIME BASICS

eLoran is a high-power, low-frequency, long range radionavigation system that provides similar Position Navigation, Time and Frequency services as GNSS, without the same failure modes as GNSS. It uses pulsed signals at a frequency of 100 kHz. The pulses are designed so as to allow the receiver to distinguish between the groundwave and skywave components in the received composite signal. This way, the eLoran signals can be used over very long ranges without fading or uncertainty in the time of arrival measurement related to skywaves.

The eLoran system has been designed to meet maritime harbor entrance and approach requirements. System specifications and numerous trials over the past decade have shown that eLoran meets the 10 m (95%) accuracy as stipulated by IMO's A.953 requirement for future GNSS systems.

An eLoran receiver measures the Time of Arrival (TOA) of the eLoran signal:

$$TOA = T_{TOR} - T_{TOT} = PF + SF + ASF + \Delta Rx \qquad (1)$$

where:

- TOR - Time of Reception
- TOT - Time of Transmission
- PF - Primary Factor (propagation through air)
- SF - Secondary Factor (propagation over sea)
- ASF - Additional Secondary Factor (propagation over land and elevated terrain)
- ΔRx - Receiver and cable delays

The Primary and Secondary factors are well defined delays and can be calculated as a function of distance. The Additional Secondary Factor delay is mostly unknown at the time of installation. Fortunately, the ASFs remain stable over time. Any changes in fine ASF over time may be compensated by a Differential eLoran Reference Station providing corrections over the Loran Data Channel.

When eLoran is used for positioning, a minimum of three eLoran stations are needed in order to calculate a two-dimensional position fix and time. Any additional measurements provide a means to improve the solution's accuracy (weighted least squares) or protect the solution's integrity (RAIM).

In order to achieve the highest accuracy levels in a maritime environment, the user receiver corrects its TOA measurements with the published ASF values for the harbor (approach) and differential eLoran corrections

Figure 2. GLA Differential eLoran Initial Operational Capability Configuration

received through the Loran Data Channel. ASF maps for specific geographic areas are distributed to users in a receiver independent data format as being standardized by RTCM's Special Committee SC127. The ASF map data is published by the maritime service provider responsible for Aids to Navigation.

As described before, the measured ASF values remain stable over long periods of time. Any small changes of the published ASFs due to changes in propagation path characteristics or transmitter related delays will be compensated by differential corrections. For this, a Differential eLoran Reference Station is deployed on shore, close to the area of interest. The Reference Station compares its measured ASFs against the published values and broadcasts corrections to the users through the Loran Data Channel. Figure 1 shows the principle of Differential eLoran positioning in a maritime environment.

eLORAN IN EUROPE

In Europe, there is an existing Loran-C infrastructure with nine transmitters located in the UK (Anthorn), France (Lessay and Soustons), Germany (Sylt), Denmark (Ejde, Faroe Islands), and Norway (Vaerlandet, Boe, Jan Mayen, and Berlevag). The UK station at Anthorn is prototype eLoran, with a Loran Data Channel capability providing UTC and differential corrections for navigable waters off the east coast of the UK.

The GLA have installed differential eLoran reference station and integrity monitor (RSIM) equipment to provide an Initial Operational Capability (IOC) high accuracy eLoran service at seven harbors along the Scottish and English East coast, shown in Figure 2. From north to south the RSIMs are installed at Aberdeen, Leith, Humber, Harwich, Sheerness, and Dover. Two Monitor and Control Stations (MCS) are installed at Harwich and Edinburgh. Initial Operating Capability of the eLoran system was declared at the end of October 2014. Full Operational Capability is expected to follow in 2018.

DIFFERENTIAL eLORAN TECHNOLOGY

UrsaNav developed technology and products for both system and user segments. The UN-154 differential eLoran RSIM series is built upon the 10x15 cm UN-151 OEM module and is shown in Figure 3. The receiver uses an external eLoran E-field or H-field antenna that is connected to the UN-151 eLoran engine using a single antenna connector and runs off of a single 5V power supply. The eLoran engine is the basis for UrsaNav's eLoran solutions ranging from timing or navigation receivers to Differential eLoran Reference Stations, monitor or scientific receivers.

To further improve the accuracy of ASF corrected eLoran positioning and provide system integrity, differential

Figure 3. UN-154 Differential eLoran RSIM

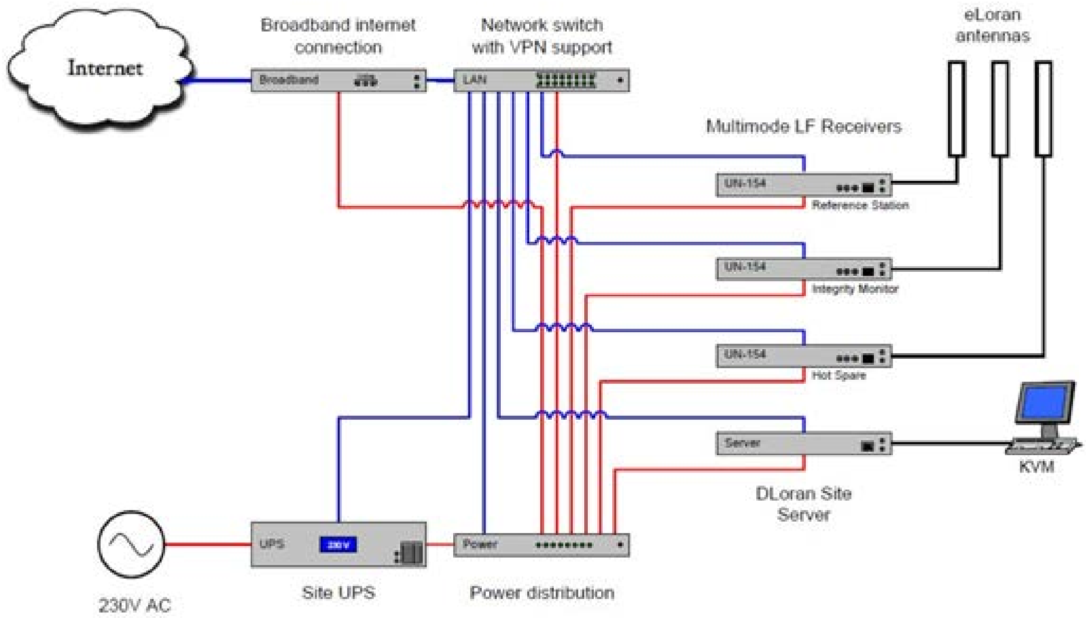


Figure 4. DLoran Reference Station Site System Block Diagram

eLoran Reference Station (RS) and Integrity Monitor (IM) equipment can be installed. The lessons learned through RTCM SC104 in the marine radio beacon DGPS system are equally applicable to eLoran. Today's powerful processing platforms allow smaller form and greater functionality. The UrsaNav model UN-154 is capable of being an RS or an IM or a hot standby with automatic failover and with no loss of data. A set of three is sufficient to provide differential corrections, integrity monitoring and redundancy at a differential eLoran site.

As shown in the DLoran Reference Site System Block Diagram, that is Figure 4, the UN-154 Multimode Receiver is the basis for all Differential eLoran reference data generation and integrity monitoring. The Multimode Receiver has the capability to provide *relative* ASF measurements with respect to an internal clock disciplined and synchronized to UTC using eLoran TOA measurements from one or multiple eLoran rates. It can also generate *absolute* ASFs with respect to an external UTC-synchronized clock, perform self-diagnostics to identify equipment failure and then activate appropriate alarms.

One Multimode Receiver is configured and operates as a Differential eLoran *Reference Station*. The Differential eLoran Reference Station Receiver accepts commands to configure the parameters for correction generation and monitoring, such as surveyed position, Differential eLoran ID, eLoran rates to monitor and their nominal ASFs, Eurofix message schedule, monitoring thresholds, and observation times.

A second Multimode Receiver is configured and operates as a Differential eLoran *Integrity Monitor*. As its primary function, the Differential eLoran Integrity Monitor Receiver ensures the provided Differential eLoran service meets all performance requirements and initiates alarms if service errors are detected. Integrity monitoring is performed both pre-broadcast and post-broadcast.

The third Multimode Receiver is configured and operates as a Differential eLoran *Hot Standby*. The Differential eLoran Hot Standby Receiver is capable of switching from standby to online automatically in the event of failure of either the Reference Station or Integrity Monitor.

For a full Differential eLoran service in a harbor, harbor entrance, or harbor approach, four elements are required. First, basic eLoran signals at appropriate signal levels, with sufficiently good geometry, provided by a minimum of three eLoran transmitters typically closest to the harbor. The installed eLoran transmitters provide this element. Second, a Differential eLoran Reference Station located close to the area of Differential eLoran operation. In a similar fashion as a Differential GPS Reference Station, the Differential eLoran Reference Station provides corrections to the nominal Additional Secondary Factors (ASF) caused by diurnal, seasonal, or weather related ASF changes. The corrections are broadcast to the user via the Loran Data Channel from one or multiple eLoran transmitters. Third, an ASF map for the harbor and harbor approach area providing the nominal ASFs for each eLoran transmitter of interest for the harbor. The ASF map is provided as an overlay grid

Figure 5. UN-2000 Differential eLoran Reference Station

with ASF values for each cell in the grid. This element results from an ASF survey, which needs to take place once before a Differential eLoran Service is operational, and at regular survey intervals (e.g., annually). Finally, the Differential eLoran user has a capable eLoran receiver, which accepts the published ASF map.

Besides the three eLoran receiver components, a complete Differential eLoran Station installation further contains a DLoran Station Server to display and archive status, measurements and alarms, an Uninterruptable Power Supply (UPS) and Power Distribution Unit (PDU), a network switch and broadband internet access. The network switch maintains Virtual Private Network (VPN) connections with the eLoran station which broadcasts the correction data to the users over the Loran Data Channel (LDC), and with the two Monitor and Control Sites (located in Edinburgh and Harwich). Figure 5 shows the full Differential eLoran Reference Station rack and Figure 6 shows a screen shot of the ELEGANT Viewpoint Monitor and Control software suite.

INSTALLATION

The GLA awarded a contract in 2013 to UrsaNav to deliver the equipment for seven Differential eLoran stations and two Monitor & Control Sites, with spares. The equipment was Factory Acceptance Tested (FAT) in April 2014 in the US before being shipped to Harwich (UK). The tests were performed with full simulation of the network and with simulated Loran signals. In May 2014, the first Differential eLoran Station and Monitor & Control Station were installed in Harwich. Over the past six months, the GLA have installed equipment at the other six harbor sites, and a second Monitor & Control Station in Edinburgh.

The GLA have selected sites for the installation of Differential eLoran equipment and mounting of antennas at buildings close to the area of operation in the harbor. All sites have commercial power and broadband internet access (ADSL or satellite). To provide resilience in communications, back-up internet access is provided by 3G or 4G mobile communications. The network router can use either internet connection to set-up its VPN and switches automatically in case of primary communications failure.

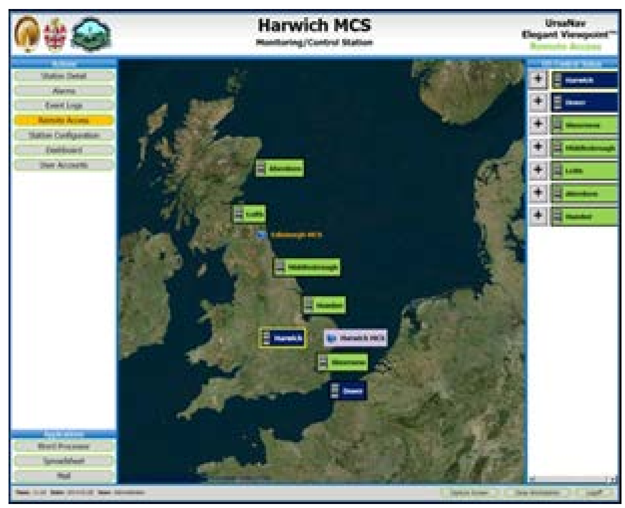
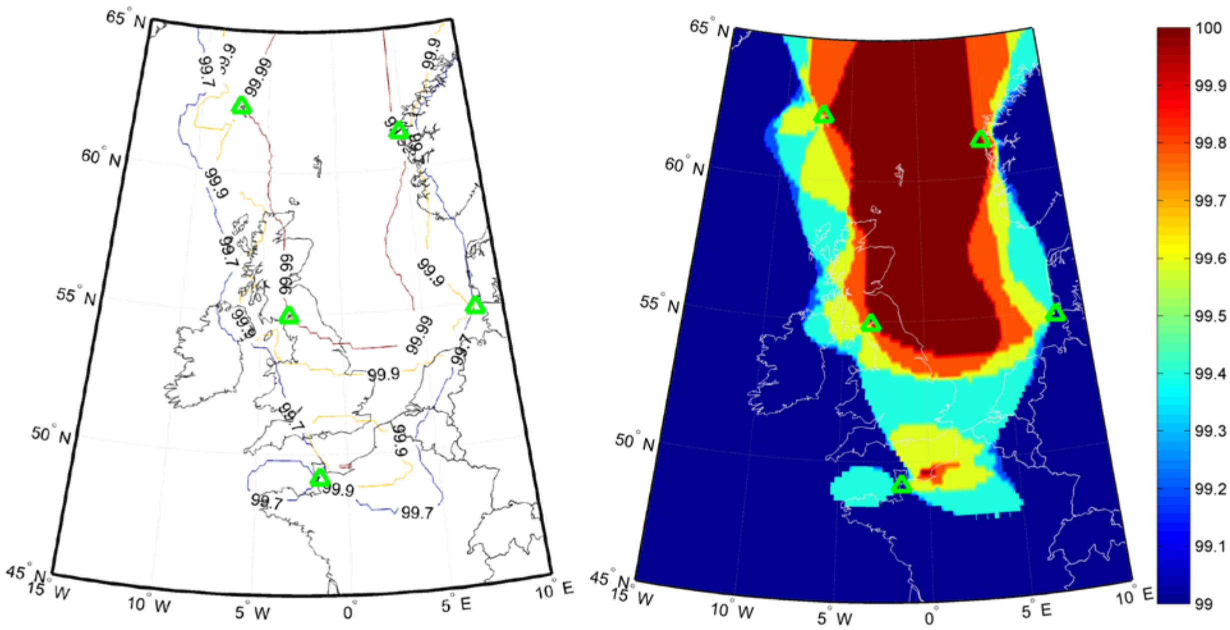


Figure 6. ELEGANT Viewpoint Monitor and Control software

THEORETICAL eLORAN ZERO-BASELINE HORIZONTAL ACCURACY PERFORMANCE AT DIFFERENTIAL eLORAN SITES

The GLA have developed a comprehensive software suite for modeling eLoran system performance. The model to be effective must include the natural phenomena that are inherent to and affect the processing of eLoran signals in space. Principal among these, the GLA model accounts for 100 kHz ground wave propagation over non-homogenous terrain, atmospheric noise, skywave expected strengths and delays, and Differential eLoran



Continuity contour plot Availability color surface plot

Figure 7 – Typical GLA model outputs

errors due to spatial decorrelation. Fortunately, there is a fair amount of source data at LF and MF frequencies available from the International Telecommunication Union (ITU). Specific sources for the model are shown in the following Table 1.

There are several outputs of interest to eLoran system planners including the four primary specifications for accuracy, availability, continuity, and integrity. The format of the plots can be set as either contour plots or as color surface/color gradation, examples of which are shown in Figure 7.

It is also possible to identify "hot spots", that is locations where for example, the accuracy or integrity performance can be improved by in-filling with an additional station. This is often the case at the "corners" of a coverage area where there are geometry limitations or in existing coverage areas where baseline distances may exceed that necessary to meet the highest accuracies of Differential eLoran. Modeling of Differential eLoran accuracy is possible including a calculation of the theoretical Zero-Baseline (ZBL) accuracy (Figure 8); and accompanying accuracy positioning ellipse axes and eccentricity parameters.

For each IOC site a modeled accuracy ellipse was calculated, with actual measured Differential eLoran positioning data obtained during the week 14th August – 5th September 2014. Based on geometry and expected signal strengths, different subsets of transmitters are used at each site as follows: Harwich, Sheerness and Dover use Anthorn, Sylt, Lessay and Soustons. Humber, Middlesbrough, Leith and Aberdeen do not use Soustons, but make use of Vaerlandet and Ejde stations. Each site has identical Differential eLoran setup parameters, 5 seconds TOA integration, 600 seconds DLoran correction integration, Differential eLoran update rate of one pair of corrections per 120 seconds. The Integrity Monitor (IM) provides a post-broadcast position-fixing check on the Differential Corrections generated by the Reference Station (RS) and transmitted over the Loran Data Channel: this is what is presented in the 'Measured Accuracy' performance results.

Table 1. Sources of LF Propagation Data

Data	Source	Notes
Ground Conductivity	ITU-R P.832-3	Digitised and rebuilt in places using DTED
Groundwave	ITU-R P.368-9	8th order polynomial fitting of groundwave output
Skywave	ITU-R P1147-4	Proprietary conversion of sky-field to TOA error
Background Noise	ITU-R P.372-6	Median converted to arithmetic mean power
Receiver Performance	GLA	RTCM SC-127 MOPS & IEC

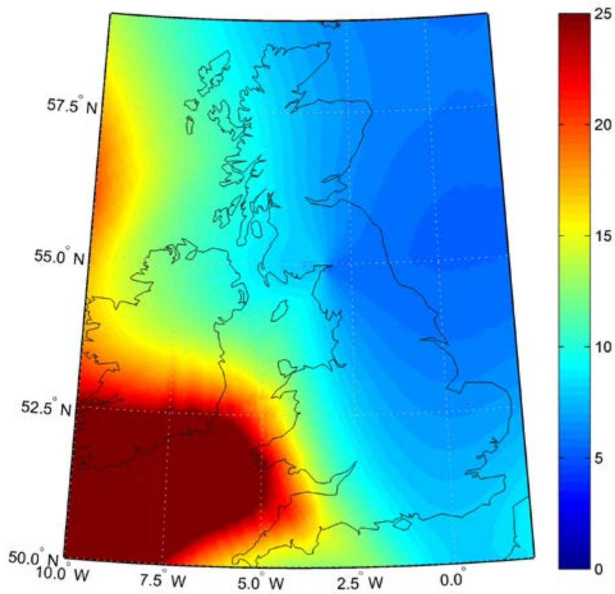


Figure 8 – Theoretical eLoran ZBL accuracy in meters

ZERO-BASELINE PERFORMANCE AT DIFFERENTIAL eLORAN SITES

As mentioned before a Differential eLoran Station hosts a Reference Station (RS), and Integrity Monitor (IM) and a Hot Standby (HS). The hardware and basic measurements for all three units are the same; however they differ in how their measurement data is used. The Reference Station calculates differential corrections for a set of eLoran range measurements and broadcasts them in messages of two corrections to the users. The message update time is 120 seconds, taking typically 360-480 seconds before a complete set of differential corrections from one Differential eLoran Station is refreshed. The

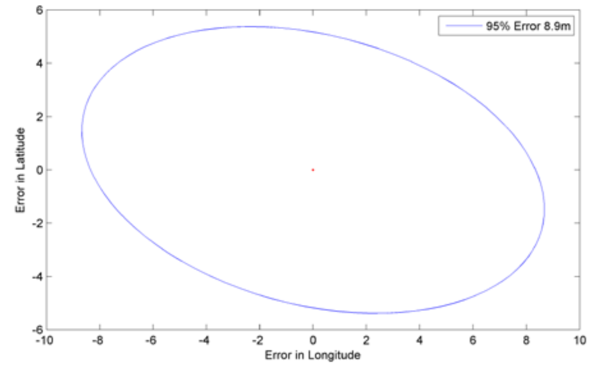


Figure 9. Modeled accuracy performance at Harwich using Loran stations Lessay, Anthorn, Sylt and Soustons.

Integrity Monitor compares the differential corrections from the Reference Station with its own set of corrections (on a 10 seconds basis) and raises an alarm if the difference between the corrections at RS and IM exceeds a threshold. Additionally, the IM applies the corrections it receives over the Loran Data Channel to its Time of Arrival Measurements and calculates a Horizontal Position Solution. If the difference between the calculated position and the surveyed position exceeds the Horizontal Protection Limit (set at 25 m), an alarm is raised and the Differential eLoran Service cannot be used. We have used the reported IM position solutions to evaluate the positioning performance of each Differential eLoran Station in the pictures below.

Figure 9 shows the modeled accuracy performance for Harwich and Figure 10 shows the measured zero baseline performance, measured over approximately one week of data. Figure 11 and 12 show the modeled and measured performance at Humber, respectively.

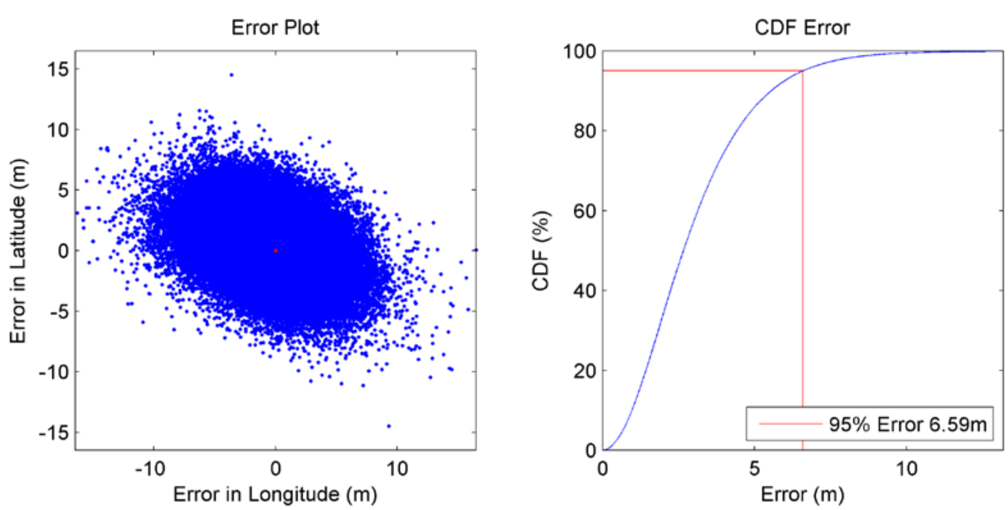


Figure 10. Measured accuracy performance at Harwich using Loran stations Lessay, Anthorn, Sylt and Soustons.

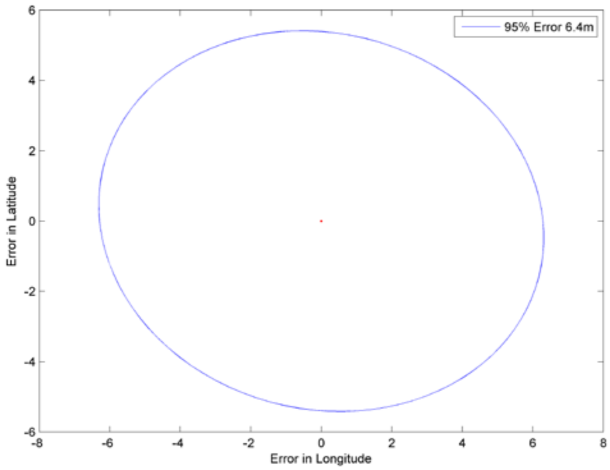


Figure 11. Modeled accuracy performance at Humber using Loran stations Lessay, Anthorn, Sylt, Vaerlandet and Ejde.

Table 2 summarizes the performance assessment of all seven sites to date. Presently, Middlesbrough has no measured data performance as the communications infrastructure still needs to be installed. With one minor exception, the measured performance exceeds the modeled performance. The measured performance at four sites exceeds the modeled performance by 15% to 32%. The antennas at these sites: Harwich, Dover, Sheerness, and Leith are raised above the roof or platform. It is particularly interesting that Aberdeen and Humber both have their E-field antennas mounted on the side of the building, so they get no height-gain from the structure. These sites agree most with the modelled accuracy, and give performance on a par with the old H-field antenna.

FIELD PERFORMANCE RESULTS

In order to collect data, the GLA plan to exploit "vessels of convenience" by fitting them with the UrsaNav UN-155 multi-source navigation receiver. The UN-155 combines a GNSS receiver, a marine beacon differential receiver, an eLoran engine, and processing platform. The

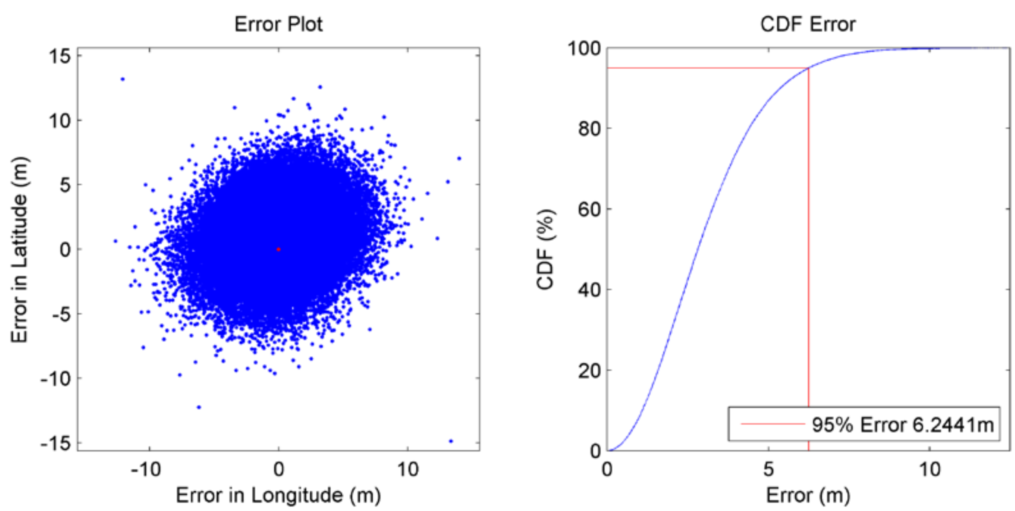


Figure 12. Measured accuracy performance at Humber using Loran stations Lessay, Anthorn, Sylt, Vaerlandet and Ejde.

Table 2. Predicted and Measured zero-baseline performance at Differential eLoran Sites

Differential eLoran Station	Predicted Horiz. Accuracy (95%)	Measured Horiz. Accuracy (95%)	Difference vs Model
Harwich	8.90 m	6.59 m	**25.9 % better**
Dover	10.20 m	6.87 m	**32.6% better**
Sheerness	9.30 m	7.78 m	**16.3% better**
Middlesborough	5.80 m	No data yet	tbd
Leith	8.40 m	7.14m	**15.0% better**
Aberdeen*	7.20 m	7.33m	**1.8% worse**
Humber*	6.40 m	6.24 m	**2.5% better**

Figure 13. UN-155 Resilient PNT Receiver

receiver (Figure 13) was delivered as part of the ACCSEAS program to demonstrate the benefits of resilient PNT. The UN-155 is connected to two antennas, one for GPS and a combined E-field antenna for the 100-kHz eLoran and 300-kHz radiobeacon. The first installation was completed on the ferry “Pride of Hull”, which sails between Hull, UK, and Rotterdam, the Netherlands, in the fall of 2014 as shown in Figure 14.

As part of the ACCSEAS demonstration work, the GLA prepared an ASF Map for the approaches to Hull, Immingham and the Humber river. To make sure the position-fixing was accurate for the trial it was necessary to ‘tie’ the existing map the GLA had surveyed back in 2013 to the new IOC Reference Station. A method for measuring ASF data was developed by the GLA using the UN-155 multi-system receiver.

The following Figures 15 and 16 are two plots; the first one showing the ASF Survey sailed on the THV Alert using a prior ASF Measurement kit. The second is processed output from the UN-155. The data shows the vessel tracks where data was measured and is colour-coded according to the ASF value in micro-seconds, scale

Figure 14. Antenna Installation on the Pride of Hull (eLoran on the left, GPS on the right)

shown at the side. Obviously it is encouraging that the data both agree very well with each other.

Figure 17 shows the difference in positioning of the eLoran engine using the surveyed ASF map (Figure 15) and corrections from the Differential eLoran Reference Station, the location shown as a star in Figure 17. The data was taken by the UN-155 receiver on board the Pride of Hull on the October 17th, 2014.

Figure 18 shows the scatter plot and cumulative error distribution of the dynamic run of Figure 17. The figure shows that Differential eLoran and DGPS agreed to within 7.84 m in for 95% of all measurements.

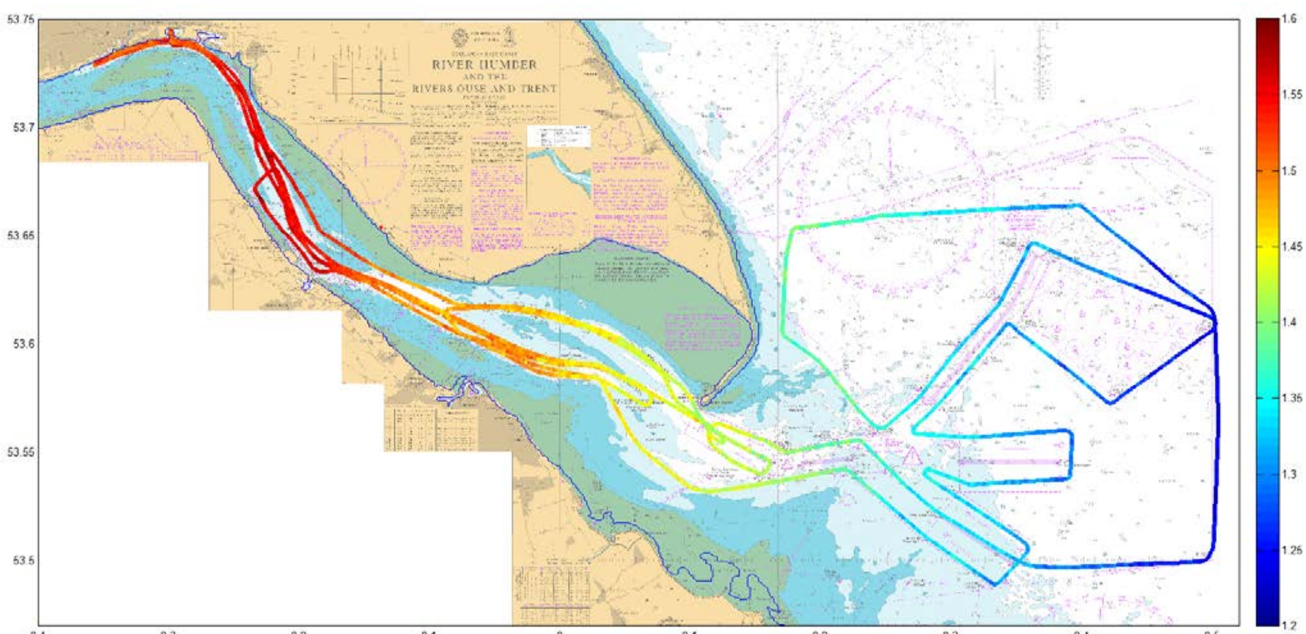


Figure 15. ASF Measurement Survey from 2013 (scale in µs)

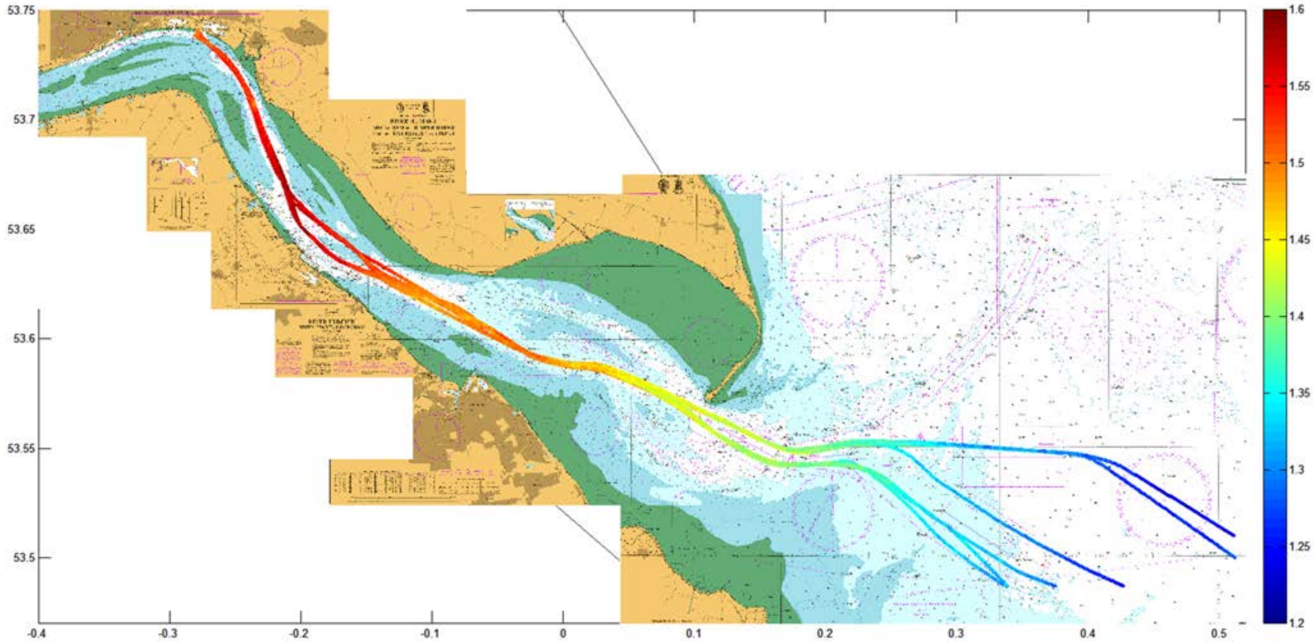


Figure 16. ASF Measurement Output of UN-155, October 2014 (scale in µs).

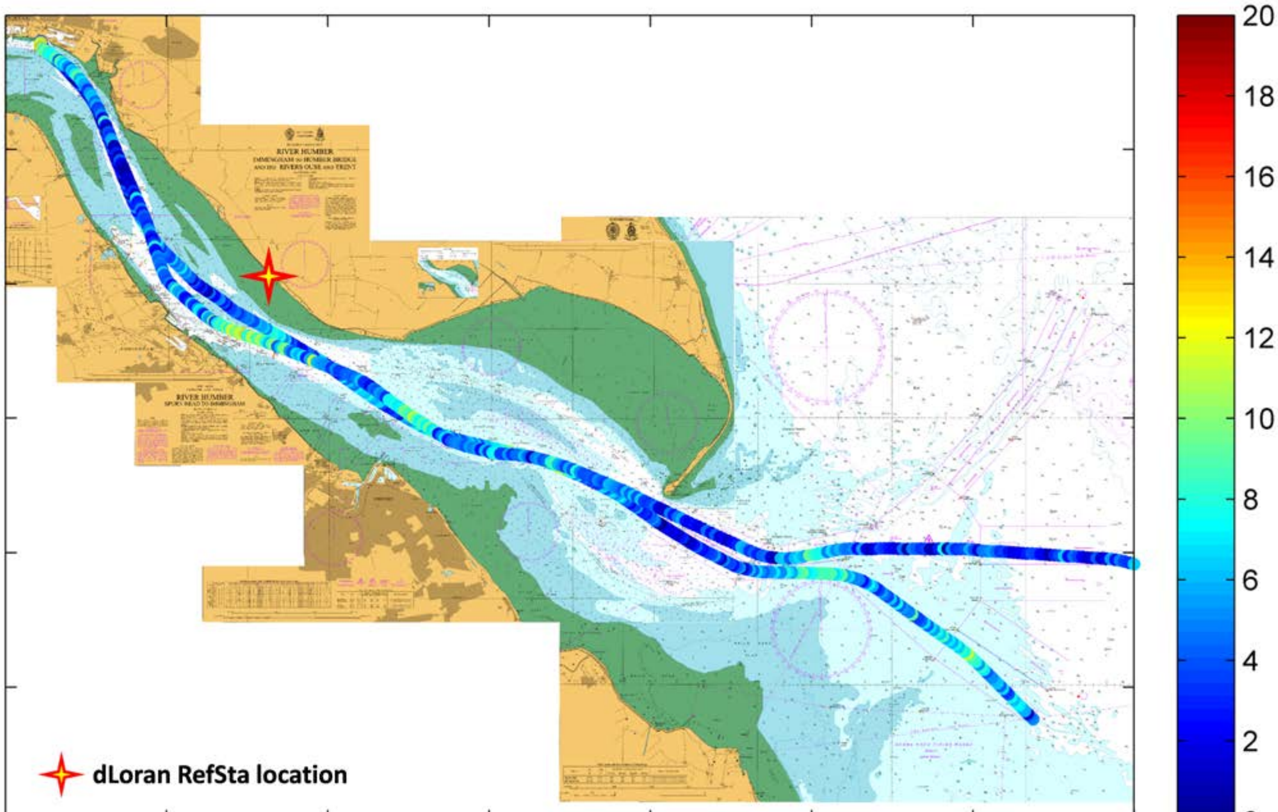


Figure 17. Difference in positioning between Differential eLoran and DGPS on the Pride of Hull (scale in m).

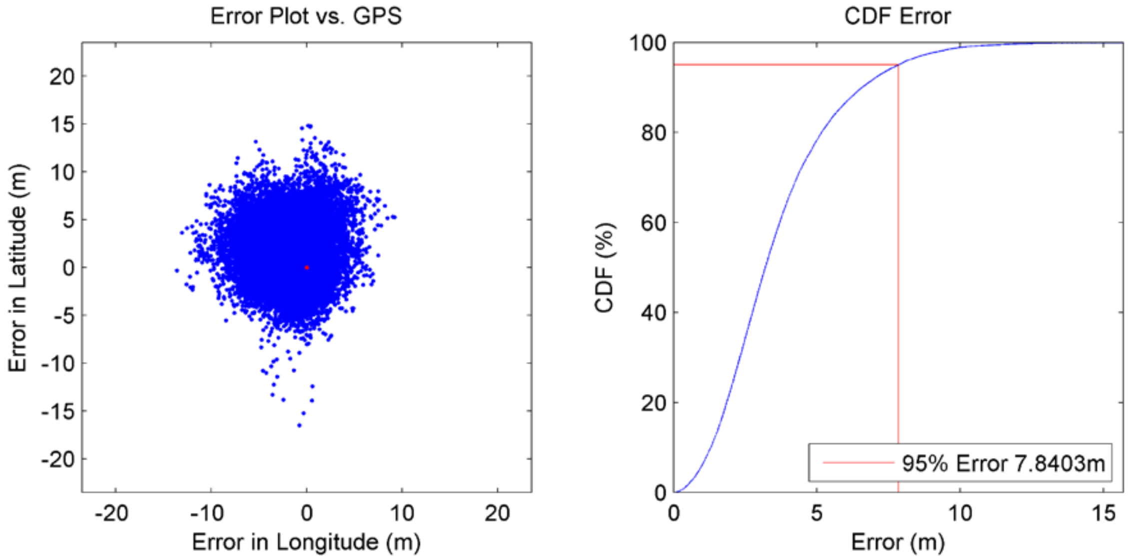


Figure 18. Measured accuracy performance on board the Pride of Hull.

CONCLUSIONS AND FURTHER WORK

The initial testing to date has verified that the measured performance is on par or better than the predicted performance. It is clear that the collected data will benefit the GLA model and that the model is particularly useful in being able to predict the accuracy at a given location. This will be of great value as a system planning tool and collected actual data will help to certify the efficacy of the model.

One Differential eLoran site remains to be connected to the data network and that site is predicted to have the highest accuracy, potentially sub-5 meters. There is sufficient flexibility in the RSIM architecture to be able to change the parameters such as averaging intervals and update rates that could be explored in future data collection efforts. The major next step will be collection of data in the field. Measurements will be taken to verify assumptions on spatial decorrelation, validate dynamic user performance, and measure the capability of the system to disseminate precise time, frequency, and phase.

We showed in this and in previous papers that an eLoran system (transmitter and receiver) can provide accurate positioning services with comparable performance to GPS. This is particularly important for maritime applications where IMO's e-Navigation concept requires two independent sources of position and time. The United Kingdom has deployed an Initial Operational Capability differential eLoran service, the first of its kind. The GLA of the UK and Ireland have shown in earlier publications that such a differential eLoran service in harbors on the east coast of England and Scotland can meet IMO's A.593 requirement for GNSS systems.

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