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Mr. Caspar K. Lebekwe was awarded the degree of MEng in Electronics and Communications Engineering at the University of Bath in 2008. He is currently a PhD candidate in the Department of Electrical and Electronics Engineering, sponsored by the General Lighthouse Authorities. His PhD project is focused on eLoran Service Volume Coverage Prediction.

Mr. George Shaw is a Principal Development Engineer working for the Research and Radionavigation directorate of the General Lighthouse Authorities of the UK and Ireland. He is responsible for strategy and systems studies that inform the future direction of maritime aids-to-navigation. His specialisation is in systems engineering and analysis of robust GNSS-based solutions for positioning and navigation across air, land and sea domains. He holds a MA in mathematics from the University of Cambridge, is a Chartered Engineer and a member of the Royal Aeronautical Society.

Dr. Nick Ward is Research Director of the General Lighthouse Authorities of the UK and Ireland, with responsibility for strategy & planning of research & development. His area of
specialisation is in radio-navigation and communications, including Automatic Identification Systems (AIS). He is currently vice chairman of the International Association of Marine Aids to Navigation and Lighthouse Authorities (IALA) e-Navigation committee. He is a Chartered Engineer, a Fellow of the Royal Institute of Navigation and a Member of ION.

Abstract
Resilient Positioning, Navigation and Timing (PNT) is an essential requirement for the successful implementation of the e-Navigation concept.

e-Navigation is defined by the International Maritime Organisation (IMO) and International Association of Marine Aids to Navigation and Lighthouse Authorities (IALA) as “the harmonized collection, integration, exchange, presentation and analysis of maritime information onboard and ashore by electronic means to enhance berth to berth navigation and related services, for safety and security at sea and protection of the marine environment”.

It comprises a number of structural components:

- electronic navigation charts;
- electronic positioning signals, supplemented by appropriate back-up systems;
- information on the vessel route, bearing, manoeuvring parameters and other status items in electronic format;
- transmission of positional and navigational information from ship to shore, shore to ship and ship to ship;
- clear, integrated display of the above information both on the shore and on the ship;

GNSS (in particular GPS) has become the primary means of navigation in many maritime applications. However, the vulnerability of GNSS to accidental or deliberate interference is well known and the need for more than one position input to e-Navigation is recognised. The requirement is for resilient PNT: it needs to be inherently reliable, secured against obvious external threats and capable of withstanding some degree of damage. A single, cross-sector solution that augments GNSS with an independent, dissimilar and complementary system is best for users. They will benefit from economies of scale to keep equipment costs low and existing networks - user, technology, business and regulatory - can be exploited. This will all lead to lower long-term average costs than other approaches.

eLoran is the only such complementary system that can be deployed in a timely fashion. This paper considers the vulnerability of GNSS, presents an overview of eLoran, discusses the drivers and requirements, briefly describes eLoran technology and projects being performed by the GLAs and reports on recent trials that demonstrate its performance.
1. INTRODUCTION. The Maritime Safety Committee of the International Maritime Organisation (IMO) has stated [1]:

*e-Navigation systems should be resilient and take into account issues of data validity, plausibility and integrity for the systems to be robust, reliable and dependable. Requirements for redundancy, particularly in relation to position fixing systems should be considered.*

Satellite navigation is now essential to the efficiency and safety of shipping. GPS drives ships’ electronic charts, stabilises radar displays, and indicates vessels' positions both to other ships and to the Vessel Traffic Management Services and Search and Rescue authorities ashore. GNSS are now regarded as a utility to be taken for granted and have become the major electronic aid to navigation used by all mariners; as such their use is advocated by the General Lighthouse Authorities (GLAs).

Yet GPS is lost from time to time due to a range of vulnerabilities that affect all satellite navigation systems: solar disturbances, satellite failures and, increasingly, unintentional radio interference or deliberate jamming. Thus GPS, even when supported by Galileo and other satellite navigation systems, simply cannot meet the IMO requirement for a resilient system to support e-Navigation [2].

However, various solutions could be postulated to address the requirements implied by the IMO statement above. These might range from enhanced provision of physical and radar Aids-to-Navigation (AtoN), through “hardening” of GNSS, to a complementary electronic navigation system, such as eLoran, presently being trialled in the UK.

2. DRIVERS, REQUIREMENTS AND ELORAN

2.1. The Vulnerability of GNSS. There is now broad agreement that GNSS (GPS, Galileo, GLONASS and Compass) are all vulnerable to unintentional and intentional interference. This includes natural phenomena, such as ionospheric effects. The use of GPS jammers, long foreseen in navigation circles [3], has become a reality as criminals employ them to overcome tracking systems and steal vehicles. Low-powered jammers are readily available over the Internet for as little as $150 and can block GPS reception in a vehicle’s vicinity. They can also block all mobile phone bands used in the area.

Today’s jammers are already configured to jam GPS, Galileo and GLONASS civil and military signals simultaneously on both the L1 and L2 frequencies. It would be trivial to add L5. Some of these jammers are powerful, radiating 2W on each frequency.

The GLAs held GPS jamming trials in 2008 [4] and 2009 [5] to understand the impact of a loss of GPS on the safety of navigation. The results are presented in another GLA paper at this conference, and will not be elaborated upon further here.

2.2. Extending GNSS Performance. Extending GNSS performance is a driver for some eLoran developments. Specifically, ST Microelectronics [6] is exploring integrated eLoran and GPS at the chip scale to give consumer GNSS receivers the extreme sensitivity needed to start up deep inside buildings, including concrete underground carparks.
2.3. Resilient PNT

*Resilient PNT* (positioning, navigation and timing) is today’s requirement not just for the maritime sector but for critical infrastructure (e.g. transport, telecommunications, power distribution, finance, emergency services etc.) in general [7].

The UK Centre for the Protection of National Infrastructure uses the following definition for resilience: the equipment and architecture used are inherently reliable, secured against obvious external threats and capable of withstanding some degree of damage.

O’Rourke [8] states that resilient physical and social systems must be ‘robust, redundant, resourceful and capable of rapid response’, where:

**Robustness:** The inherent strength or resistance in a system to withstand external functionality

**Redundancy:** System properties that allow for alternate options, choices, and substitutions under stress

**Resourcefulness:** The capacity to mobilize needed resources and services in emergencies

**Rapidity:** The speed with which disruption can be overcome and safety, services, and financial stability restored

2.4. The Requirement – GNSS Interference Detection and Mitigation

There is also a need for GNSS interference detection and mitigation that is being explored in the US [9] and UK [10]. In our safety-critical environment this needs to be available on board the ship. There are different ways of detecting interference, however, interference *mitigation* needs to ensure that a user’s operation is not disrupted.

The requirement should be to maintain the user’s concept of operations with a seamless transition from GNSS to a backup. This is what is really needed for e-Navigation. An inferior approach would provide a backup that does not maintain the user’s concept of operations and requires manual intervention.

2.5. A Systemic Backup

Users not only need resilient PNT, they also need it to be cost-effective and a systemic backup is the best solution. In this case, *systemic* means that the backup can be used within many user sectors – air, maritime, land, telecommunications, critical infrastructure etc.

Key benefits of a systemic backup include:

- **short-term economies of scale** – broad, cross-sector demand will ensure that cost of the systemic backup is very low. In practice, this means that chip-level integration with GNSS can be achieved swiftly and the cost to the user is small.

- **linking into existing GNSS networks** – these include technology research, product development and manufacturing, sales and marketing, user networks for retrofitting and regulation.
lower long-term average costs – the cost of a systemic backup should always be lower than sector-specific backups and should decrease over time. On this basis, systemic backups should decrease the long-term average costs for many stakeholders.

2.6. The Solution – eLoran. At the highest level, the requirement is for resilient PNT (Section 2.4). GNSS will undoubtedly be one of the sources of PNT. The requirements for a GNSS complement are to:

- enable resilient PNT for use by critical infrastructure applications including maritime transport.
- be readily integrated with GNSS at chip-level.
- support interference detection and mitigation.
- maintain the user’s concept of operations with a seamless transition to a complement when GNSS is lost.
- have the potential to be deployed world-wide.
- support maritime general navigation applications.
- be independent of GNSS.
- be dissimilar in terms of failure modes.
- provide similar levels of performance as GNSS

eLoran is the only system that can meet all these requirements in a timely fashion and support the development and implementation of e-Navigation. The GLAs firmly believe this and that is why the GLAs continue to encourage eLoran development, both cross-sector and cross-government within the UK and transnationally.

3. GLA ELORAN TECHNICAL PROJECTS

As a complementary, dissimilar and independent back-up for GNSS, eLoran can provide the resilient PNT information required by the future e-Navigation concept. The GLAs and others have shown this during various trials.

The GLAs are engaged in a number of technical projects aimed at developing the knowledge and processes required to establish eLoran services in their service areas. These will be presented briefly next. First of all, however, it is necessary to understand what defines maritime eLoran.

3.1 Defining Maritime eLoran. eLoran receivers are manufactured to assume that the ground-wave signals they receive have propagated over sea-water only. However, the propagation time of ground-wave signals varies with the type of surface over which the signal travels; fastest over sea-water, and more slowly over land. To account for any land along the propagation path, the receiver has built into it tables of propagation corrections called Additional Secondary Factors (ASFs). These tables are arranged in grid format and there would typically be a grid for each transmitter that the receiver is likely to use in a position solution in any particular geographical area – for example a harbour approach. ASFs are required for eLoran in the same way that tropospheric and ionospheric corrections are required in the GNSS receiver for GNSS signal propagation delays.
ASFs have a spatial component, which varies with geographical location (hence a grid of ASFs is published), and a time varying component, due to short-term weather variations and longer-term seasonal effects affecting ground conductivity. The time varying component affects the repeatable accuracy performance. Once the ASF grids have been published, and fixed in the mariner’s receiver, the time varying component will need to be mitigated through the provision of differential-Loran (dLoran) broadcasts, in the same way that differential-GPS is used to mitigate the time varying effects of the earth’s atmosphere on GPS; see Figure 1.

![Figure 1 – ASFs and differential-Loran.](image)

The eLoran temporal corrections may be transmitted to the user of the differential service using a data channel built into the Loran signal itself - the Loran Data Channel (LDC). In Europe this is likely to be Eurofix [11] – a data communications system based on the pulse positioning modulation of the last 6 pulses of the 8 pulse group transmitted from the station [11] - but the channel could equally be the US Ninth Pulse system [17].

e-Navigation’s data communication system is also a possible future mechanism for the dissemination of pseudorange corrections for both differential-Loran and DGNSS.

In summary then, maritime eLoran requires the following:

- All in view eLoran receivers, which can form a least-squares position solution from Time of Arrival (TOA), or pseudorange, measurements made from individual eLoran transmitters, rather than hyperbolic Time Difference measurements
- Databases of ASF grid data stored within the receivers
- Differential-Loran corrections to account for changes in ASF values, transmitter timing and atmospheric effects over time – broadcast over LDC or the communications segment of e-Navigation
The GLAs’ technical eLoran projects are aimed at understanding these components and more, with the aim of rolling out initial eLoran application services by mid-2013. We will now briefly outline some of the major GLA eLoran projects.

### 3.2 ASF Measurement and Processing Best Practice

It is possible that the GLAs will become responsible for measuring and publishing ASFs for their service areas. In order to gain experience in ASF measurement, and develop the technical expertise required, the GLAs have procured three ASF measurement systems. Each unit contains an eLoran receiver, a GPS receiver, a precise clock, a PC, glue logic and processing hardware to make the precise measurements required to compute ASFs.

The project is investigating best practice in performing ASF measurement and post-processing, so that we can ensure the integrity and quality of the ASF data produced. Once the raw ASF data has been measured, it will need to be processed to minimise measurement noise. Processing may be divided into the spatial and temporal domains.

- **Temporal Domain** – There will be apparent variations of the ASFs over time during the performance of the spatial ASF surveying. These variations are due to transmitter timing variations, passing weather fronts, and changes in ground-wave propagation conditions. These temporal variations will need to be processed out of the raw spatial ASF data before grid processing can be performed. Temporal processing can be performed in post-processing or in real-time during ASF surveys using data from a differential-Loran Reference Station established near to the survey location.

- **Spatial Domain** – Spatial processing performed on the geographically distributed ASF data, measured during a mobile survey. The goal of spatial domain processing is to produce an ASF grid for eventual publication within a mariner’s receiver. The spatial ASF measurements are made once-and-for-all at a particular date and time. In addition, the form that the ASF grid takes will affect the accuracy performance of the ASF data.

The GLAs are investigating the use of 2D surface interpolation of the ASF data. This allows the smooth transition from one grid point to the next as a vessel travels through the area.

It is not sufficient to simply publish ASF data, we also need to understand to what accuracy the ASFs are produced so that we can ensure integrity. It is therefore necessary to understand the contribution to the overall ASF error budget of each of the processes and techniques that we use. This will result in the generation of one or more error bounds on the ASF grid, which may be fed into a receiver’s integrity monitoring algorithm. Figure 2 shows an interpolated ASF grid produced from raw ASF data collected during our Orkney Island trial (briefly discussed later). Figure 3 shows a plot of the standard error of the data of Figure 2. Figure 4 shows a screenshot of the ASF survey and validation software developed by the GLAs.
Figure 2 - Interpolated grid of Anthorn ASFs (vertical scale in microseconds) measured in a part of the Orkney Islands.

Figure 3 - Plot of the interpolated standard error of the ASF grid.
3.3 Real Time dLoran Service. The GLAs plan to produce a fully operational differential-Loran service (outlined in Section 3.1). Our main aim in this project is to understand how many Reference Stations are required to cover the GLAs’ service areas. The answer to this question needs an analysis of such things as:

- The optimum update interval of the differential corrections to be broadcast. This depends on the radio frequency noise seen at the Reference Station site and the frequency of the variations typically seen in propagation measurements. It is very important to locate the receiving antenna of the differential Reference Station in an area of good Signal to Noise Ratio (SNR) and optimise the filtering of the differential measurements before they are broadcast.

- The degree of spatial decorrelation of the corrections from a Reference Station. The description of differential-Loran presented in Section 3.1 is an idealised situation. In reality there will be a degree of spatial decorrelation between the pseudorange variations seen at the reference station location and the variations seen by the mariner. This is because the signals received at the Reference Station travel over different land paths compared to the signals received at a user’s vessel. Spatial decorrelation creates a geographical range limitation on the validity of the pseudorange corrections generated by the Reference Station. The error residual due to these spatial decorrelation effects will also need to be accounted for and a bound for them may need to be built into the overall ASF error budget.

Figure 5 illustrates a plot of a set of ASFs measured at the Harwich dLoran reference station and a set measured a few hundred metres away. It is possible to measure the decorrelation between the two sets and compute the dilution of precision due to the
phenomenon. The effect is very much dependent on the configuration of land and sea paths from the transmitters to the reference station, and no two reference station installations will present the same level of spatial decorrelation.

Figure 5 - Correlation of ASF measurements between two separate but close locations.

Figure 6 - Possible locations of GLA dLoran reference stations at GLA AtoN.
The GLAs plan to undertake extensive measurement campaigns with monitors placed at a number of locations across the UK. This will enable us to gather evidence of long term seasonal variations and the degree of correlation at each end of the baselines defined by the locations of the monitor sites in a similar manner to that performed in the US [12].

The aim is to model the effect and build it into a coverage prediction model. Our eLoran coverage prediction capability (presented next) is being developed to include the effects of choosing the locations of differential-Loran reference stations. Figure 6 illustrates a possible future configuration of GLA differential-Loran reference stations. In this diagram, the red points represent differential-Loran reference stations located for convenience at GLA AtoNs – lighthouses and DGPS radio beacon sites. The red circles show an assumed 30km range of a reference station [12]. The blue diamonds represent an initial estimate of the ports and harbours able to support SOLAS class vessels and which will be required to be covered by differential-Loran. The diagram shows us constraining the reference station locations to GLA infrastructure. It can be seen, however, that in some circumstances this constraint may prohibit the coverage of some ports and either alternative locations would have to be sort or we would have to investigate whether a particular reference station’s corrections can be safely used beyond the initial 30km range limitation. Should either of these two solutions prove difficult the GLAs have plans to investigate networked differential-Loran solutions – interpolating differential corrections between reference stations to form virtual differential stations.

3.3 Service Volume Coverage Prediction

The bulk of the technical work on our Service Volume Coverage Prediction project is being performed by a PhD student sponsored by the GLAs. The purpose of the study is to develop a software tool for use by the GLAs to investigate the structure and performance of possible future European eLoran transmitter networks. The work would support optimising infrastructure placement, developing a new operational concept as well as testing and providing feedback on new eLoran standards for equipment and signals.

From a scientific perspective, eLoran service coverage will be assessed in terms of meeting user requirements (accuracy, integrity, continuity and availability) throughout a geographic area of interest.

A sensitivity analysis is being undertaken to determine the level to which different service parameters need to be modelled, including:

- network topology – transmitter locations, mast heights, amplifier power, differential Loran reference stations and integrity monitors;
- signal design – shape and stability, group repetition intervals and data channel performance (bandwidth and bit error rate);
- signal propagation – atmospheric (primary factor) and ground conductivity (secondary and additional secondary factors), atmospheric activity (troposphere and ionosphere); and
- user equipment – antenna performance as well as all-in-view data processing techniques including station selection strategies and digital filtering.
The work is beginning to produce some very useful results. The plots of Figure 7, Figure 8 and Figure 9 show accuracy, availability and continuity plots respectively for eLoran over the British Isles.

Figure 7 shows the repeatable accuracy available over the service area. This plot assumes that differential-Loran, and ASFs are available over the entire service area. In reality this will not be the case, and the final version of the software will include the effects of limiting differential-Loran to various locations for the harbour entrance and approach application, for example.

Figure 8 shows the system availability of the Loran over the British Isles as it exists today. The plot takes into account the signal availabilities from each Loran transmitter contributing to the fix at each coverage grid location. This data has been derived from two years’ worth of transmitter availability statistics obtained from the Loran Control Centre Brest (CCB), the operational centre for northwest European Loran based in France. The signal availabilities are then combined into a system availability statistic. It is important to realise that the performance figures here are meant as an illustration of coverage modelling capability and are not meant to represent true eLoran capabilities. The signal availability figures used in computing the system availability plots were obtained from measured statistical data for today’s modernised Loran-C, which is still currently run using the old NELS standard operating procedures. We still have a way to go before eLoran becomes fully implemented in Europe, at which point we expect availability performance to be much improved.

This is the first time that the ability to predict Loran system availability has been possible in the UK and Europe! This is also true of the continuity plot shown in Figure 9.

All three of these plots illustrate the poor coverage to the west of the British Isles and indicate a requirement for an additional transmitter somewhere in the west of Ireland.

![Figure 7 – Modelled accuracy contour plots.](image)
Figure 8 – System availability.

Figure 9 – Modelling of the continuity of the eLoran service.
3.4 GRI Selection and Crossrate analysis

The GLAs sponsor a second PhD student, Jan Šafář from the Czech technical University, who is focussing on some fundamental system design questions that arise when considering the introduction of new eLoran transmitter stations. The two main goals of the project are:

- to update existing Loran-C procedures for Group Repetition Interval (GRI) selection to reflect new eLoran standards
- to provide models of the effects of Cross-Rate Interference (CRI) between eLoran stations on the system’s performance

Cross-Rate Interference is due to the ‘collision’ of pulses from different transmitters, on different Loran rates, arriving simultaneously at a receiver. This is the worst type of interference to Loran. However, it is a predictable characteristic and modern receivers can mitigate the effect to a greater or lesser extent. Figure 10 shows the loss of pulses of GRI 6731 using one type of receiver based mitigation called Cross-Rate blanking. In this form of mitigation, pulses from GRI 6731 that are interfered with by pulses from Loran signals from all other chains, including those via skywave, are removed – blanked by the receiver and therefore are not integrated and used in the position computation. The resulting loss of ‘wanted’ GRI 6731 pulses reduces the signal-to-noise ratio of the tracked signal. This has the potential to increase the variance of the Time Of Arrival (TOA) measurements made by the receiver, which in turn will result in poorer positioning accuracy. However, this loss of performance is small when compared to the consequences of not mitigating the effect.

Figure 11 and Figure 12 show that cross rate introduces a bias and a variance in pseudorange measurements. Figure 11 shows a plot illustrating the effect of each of the full possible range of GRIs (along the x-axis) cross rating with GRI 6731. The effect can be seen to produce a pseudorange (TOA) bias of between 3m and 6m as the cross rating GRI decreases in value from the right to the left. GRIs create interference to each other to a greater or lesser extent depending on their mathematical relationship to each other. For example some GRIs combine with 6731 quite catastrophically, while others that are quite numerically close are fine. This is reflected in the ‘comb’ structure of plot. Figure 12 shows the effect on the variance of the pseudorange measurements. In both of these pictures the red circles represent simulation results produced by Šafář using signals generated using a numerical Loran simulator written in Matlab™ with the resulting digital ‘signals’ fed into a software receiver, also written by Šafář. In a separate study Šafář also investigated a theoretical, frequency domain, analytical approach to solving the same problem so that the effects could be built into our coverage software. The results of this are shown as the blue dots in the figures. The results of the two separate approaches are astonishingly close! The techniques can also include the effects of cross rate mitigation methods.

The analysis techniques developed during this work will be built into the coverage modelling software described in Section 3.3 and will be required if and when it becomes necessary to install additional eLoran transmitters, and optimise the selection of their GRIs; either full power transmitters to extend coverage, or lower power mini or micro Loran stations as coverage gap fillers.
Figure 10 – Blanking loss due to eLoran cross rate interference for the signal of the 6731Y Anthorn station.

Figure 11 – Modelling the effect on pseudorange bias of a cross rating Loran signal.
3.5 GAARDIAN and SENTINEL

Once we have rolled out our Core and Application Services, we would need to be able to monitor their availability and integrity, collecting long term performance data and generating integrity alerts as required. Hence we are interested in developing and monitoring the type of technology that would allow us to do this.

GAARDIAN is to be a network of data gathering and monitoring probes, to be located at the point of service for GNSS and eLoran timing, frequency and navigation users. It is the aim that the probes will provide detailed information on the availability and integrity of GNSS and eLoran signals to service providers through a web-enabled server interface. Users can access past and current data, and can be provided with alerts in real-time if and when service disruption occurs. In addition, the probes will be able to gather long-term data, which can be made available through the server for particular users.

The GAARDIAN project began as an initiative by the Technology Strategy Board (TSB), part of what is now called the Department for Business, Innovation and Skills (BIS) (previously DIUS). The Technology Strategy Board provides research funding to encourage the development of technology in areas that are considered vital to the future of the UK economy. The GLAs, as part of a consortium of seven organisations, led by Chronos Technologies Limited (CTL) submitted GAARDIAN as a proposal to the Technology Strategy Board to address the technology area ‘Data Gathering in Complex Environments’. The Technology Strategy Board awarded £2.2M funding to the project, and the project is almost complete, with the development of 15 prototype probes.

Under the work of the project the GLAs have been developing algorithms to detect potentially hazardous eLoran conditions and generate alarms as and when they occur, and collect summary performance data from these probes. We see the technology as a
potential prototype platform from which to develop a fully fledged integrity monitoring network.

SENTINEL is a proposed follow-on project to GAARDIAN that will research and develop a service to establish the extent to which Global Navigation Satellite Systems (GPS, GALILEO etc.) and eLoran Positioning, Navigation and Timing (PNT) signals can be trusted by users on a 24×7 basis. The SENTINEL service will be used to detect, quantify and locate accidental and deliberate GNSS interference (e.g. criminal jammers), natural PNT interference phenomena (e.g. weather, solar flares), at point of use, to enable decisions to be made on the degree to which a PNT service for safety/mission critical services with security or revenue generating impact can be trusted. This will provide alerts and be able to quantify and assess deliberate jamming to enable detection or mitigation by the appropriate agencies.

SENTINEL will build on the basic research being undertaken in the TSB funded GAARDIAN project and will be administratively lead by Chronos. The project will seek to deploy clusters of modified “GAARDIAN” probes up to a total of approximately 50 units deployed according to a strategy lead by ACPO ITS (Association of Chief Police Officers - Intelligent Transport Systems working group). The probes will be based on those being developed for the GAARDIAN project with an additional feature of RF signal detection. The team also includes members of the communications systems industry and academia. ACPO will bring interests from the wider governmental community to the project. The GLAs will further their eLoran algorithm development within the project and provide support for maritime trials of the system.

3.6 Standardisation

eLoran standardisation efforts began with a definition agreed by the International Loran Association [13] and in October 2007 the Radio Technical Commission for Maritime Services Special Committee-127 (RTCM-SC127) on eLoran systems was established. This Committee was set up to consider the need for the development of standards for eLoran position, navigation and timing (PNT) system components, including, but not limited to maritime eLoran receivers, and/or combined GNSS/eLoran receivers. Appropriate RTCM standards or reports are to be developed, addressing performance requirements, technical requirements, and/or test procedures, with a view to their use for the production of eLoran systems, and as the basis for eventual IMO, ITU and/or IEC recommendations or standards, as appropriate. The GLAs have recently taken over the chairmanship of the committee and are keen to encourage and progress standards development. The release of a draft RTCM eLoran Receiver Minimum Performance Standard (MPS) is imminent (November 2010).

3.7 eLoran Shipborne Monitoring

The aim of this project was to install automatic eLoran Monitoring Systems (LMS) aboard all six of the GLAs’ vessels; THV Patricia, THV Galatea, NLV Pole Star, NLV Pharos, THV Alert and ILV Granuaille.
Figure 13 shows the front and rear panels of the Loran Monitor System (LMS), six of which were procured from the Dutch Loran receiver manufacturer Reelektronika. The unit is a 3U 19 inch rack mountable unit containing a Reelektronika LORADD eLoran receiver, a u-Blox™ GPS receiver and a PC motherboard. Logging software running on the PC platform allows the automatic collection of data such as signal-to-noise ratio, pseudorange variations and positioning data, including standalone Loran, GPS-calibrated Loran, ASF corrected Loran with differential-Loran corrections, and GPS data.

The units are currently in operation aboard GLA vessels, working continuously to gather data automatically as the vessels perform their normal day-to-day business. In a future project R&RNAV engineers will gather the collected data, analyse it and write software to present the results in a convenient graphical form.

Figure 14 shows an example position plot of Anthorn signal-to-noise (SNR) data collected aboard THV Patricia during the month of September 2010. The data requires further post-processing in order to separate out day and night effects. In general an eLoran receiver should be capable of locking onto and tracking an eLoran signal down to an SNR of -10dB. The plot shows that this should be achievable from Anthorn off the east and southeast coast of the UK.
4. SOME TRIAL RESULTS

4.1 Anthorn

Since 2007 the GLAs have run a Loran transmitter at Anthorn, in Cumbria. The station’s day-to-day operation and maintenance is contracted out to Babcock. The transmitter is containerised and is run unmanned but monitored by staff at the Anthorn site, which is shared by other Babcock radio services. The station radiates 220kW and broadcasts as the ‘Y’ secondary of the 6731 chain (Figure 15).

Table 1 shows the monthly availability figures for Anthorn for the year up to September. These figures are the availability of the Loran signal from the transmitter and do not include authorised maintenance periods as agreed in the operating procedures of the Northwest European Loran System (NELS), the original organisation setup to run Loran-C in northwest Europe in the mid-1990s and which ran until the end of 2005. The outage of 1200 seconds in February was a single block of time and was traced to a problem with the X.25 data communications system in France. The figures correspond to an availability of 99.99% over the nine month period to September.
4.2 Differential-Loran Reference Station

In addition to Core Service provision through the provision of an eLoran transmitter, the GLAs also plan to develop a differential-Loran Application Service, as outlined in Section 3.3. A prototype differential-Loran reference station has been running in Harwich since 2007, and we have been using the system to inform our various development projects. The Harwich dLoran reference station sends Loran pseudorange corrections up to Anthorn via a Virtual Private Network (VPN) over the Internet. The data is subsequently broadcast over the Eurofix Loran Data Channel (LDC).

Table 1 – Anthorn availability figures for the first 9 months of 2010.

<table>
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<th>Seconds in month</th>
<th>Monthly Availability (%)</th>
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In computing the value of the eLoran pseudorange correction to broadcast, the reference station integrates, or averages, a number of corrections over a particular time period. The operator of the reference station can choose the length of this integration period. The reference station generates corrections, broadcasts them and then receives them back over the LDC so that post-broadcast integrity checking can be performed. In this way, the resulting positioning accuracy of differential-Loran can then be measured at the reference station.

Figure 16 shows the results of some of the analysis work that we have performed on archived data collected by the Harwich dLoran reference station. The figure shows the variation of the 95\%ile differential-Loran positioning accuracy, with differential-correction averaging (integration) interval and correction update transmit interval. This was produced from corrections determined at the Harwich reference station, collected from January 2009 to the middle of October this year.

The plot of Figure 16 shows that in general as the integration interval increases, for a fixed update interval, the static positioning accuracy at the Harwich reference station improves. For a fixed integration interval, as the update interval increases, so the positioning accuracy worsens. Our aim is to achieve an optimally performing service based on investigating the effects of varying the integration interval. We need to do further work on this because the picture seems to imply that if you keep integrating corrections that you get better and better performance for a given update interval, but this is not necessarily true because of the effects of lag between the timeliness of the corrections and the time constant of propagation phenomena that cause the static pseudorange measurements to vary. The effect of employing a fixed integration interval is shown in Figure 17, which show approximately a year’s worth of daily average positioning accuracy data collected at the Harwich reference station. With a fixed integration interval there appears to be an increase in positioning error in the winter because with this integration interval the broadcast pseudorange corrections are lagging the TOA variations due to the rapid propagation variations which are causing them. In the summer months the propagation variations are lower and the fixed interval results in lower lag. In order to obtain consistent corrections, and therefore a flat red line in Figure 17, the best approach may be to investigate the possibility of using a dynamic integration interval based on the variations of the pseudorange corrections measured over a particular period.
Figure 16 – Change in 95%’ile positioning error measured at Harwich reference station with time due to changing differential correction integration time and correction update rate.

Figure 17 – Approximately 1 year’s worth of daily averaged positioning accuracy data at the Harwich reference station. A fixed integration interval may not be appropriate for the entire year.
In addition we will need to further investigate the broadcast update interval and its compatibility with the integration interval and other filtering methods used to generate the correction data. The required update intervals from our reference stations will also have a bearing on the amount of data bandwidth available from the LDC, as shown in Figure 18.

The ASF units we described in Section 3.2 can also be run as differential-Loran reference stations, thus providing portable units for our trials. Figure 19 shows our Mobile Monitoring Unit (MMU) fitted out with a portable reference station and a satellite broadband unit for sending corrections up to Anthorn for broadcast. This unit has been used very effectively during our recent GPS jamming trials and during some eLoran performance trials we performed in the Orkney Islands, which are discussed next.
4.3 Orkney Island Trials

Researchers worldwide have already shown that eLoran can meet the accuracy, availability, integrity, and continuity performance requirements for aviation non-precision instrument approaches and maritime harbour entrance and approach [15].

The GLAs have been developing initial proof-of-concept systems, and testing them in challenging environments. To demonstrate performance in an archipelago, the GLAs performed eLoran trials in the Orkney Islands, off the northern coast of Scotland [16]. This is an area of excellent eLoran geometry and signal strength from the transmitters at Ejde, Vaerlandet and Anthorn. Three routes were followed on three separate days. The total distance travelled was some 230 nautical miles with a total steaming time of about 23 hours at 10kts, the biggest trial performed to date.

Figure 20 - Pre-operational eLoran system tested in the challenging environment of Orkney, an archipelago off the northern coast of Scotland.
To establish an eLoran system in the area for the duration of the trials, two things were required: a differential-Loran reference station and a map of ASFs stored within the receiver. A temporary differential-Loran Reference Station was installed at Kirkwall – the capital city of the Orkney Islands (Figure 20). ASFs were measured from the data collected during the performance of the routes. The most technically difficult part of the voyage occurred in the Hoy Sound (Segment D in Figure 21); a channel with complex land-sea signal paths. However, accuracies of 11m (95%) were achieved using eLoran. These accuracy levels are typical of those realised in widespread trials over the past four years.

The conclusion so far is that where there is good eLoran transmitter geometry and signal strength, and a maritime eLoran service has been established, complete with propagation correction maps (ASFs) and differential-Loran, there is no reason why eLoran should not provide close to (if not better than) 10m (95%) positioning accuracy. Other challenging areas include mountainous terrain and fjords, and these will need to be investigated in the near future. The GLAs have developed the capability to establish a temporary eLoran installation quickly and accurately for trial purposes, and to measure and analyse the system’s performance.
5. OTHER OPTIONS TO PROVIDE RESILIENT PNT

The GLAs have analysed other technologies and their potential to provide resilient PNT. These include the use of physical and radar aids to navigation and hardening existing GNSS technology.

5.1 Physical & Radar Aton

Recognising current trends in maritime user radar equipage, it might be possible to expand or enhance the physical AtoN infrastructure to support a fall-back mode of radar positioning. This would assume a continuation of existing approaches and technologies to mark hazards, channels and traffic separation schemes, enhanced by the increased use of synchronised and sequenced lights and a major expansion of radar aids to navigation (radar reflectors, enhancers and radar beacons) to provide complete coastal coverage.

This could be used in conjunction with New Technology radars to provide absolute positioning, sufficient to allow continuation of navigation in the event of loss of GNSS. This possibility is explored in more detail in [14], but it must be stated that considerable R&D would be necessary to establish the feasibility and cost of such a solution, as well as international coordination and cooperative action by ship-owners and radar manufacturers, all of which would take many years to bring about.

5.2 HARDENING OF GNSS

This approach is a development of interference detection and mitigation outlined in Section 2.4. It further assumes that all SOLAS vessels would be equipped with multi-constellation GNSS receivers, initially provided when their existing equipment needs replacing, but fully equipped by no later than 2020. It would also be assumed that over time the users’ GNSS receivers would incorporate more robust testing for the effects of interference and would alarm in an appropriate fashion if interference were detected.

Recognising the dependence of users upon GNSS based navigation, maritime authorities would need to undertake an infrastructure upgrade programme to enhance the capabilities of the IALA DGPS beacon infrastructure such that it supports multiple GNSS systems and various frequencies. Alternatively, or in addition, there would need to be a move towards international recognition of an integrated Satellite Based Augmentation System (SBAS) incorporating, for example WAAS, EGNOS, MSAS and GAGAN. There would also need to be increased R&D activities to support the standardisation of more robust user GNSS receiver equipment and to ensure its safe integration into future bridge systems.

This solution obviously requires concerted action from a wide range of stakeholders, coordinated through a number of international organisations, and would be a lengthy and perhaps costly process. National telecommunications regulators and their regional and international counterparts would need to ensure the adequate provision of means to deter, detect and respond to GNSS interference events. Finally, there would be a need for maritime authorities, including VTS operators and shipping organisations, acting through IMO, to develop reversionary procedures to which mariners can turn in the event of potentially hazardous GNSS interference.
6. CONCLUSIONS

The successful implementation of e-Navigation is dependent on resilient PNT. GNSS will undoubtedly be the primary source of that PNT, but to satisfy the requirement for resilience it will need complementary support. A GNSS complement must: enable resilient PNT for use by critical infrastructure applications including maritime transport; be readily integrated with GNSS at chip-level; support interference detection and mitigation; maintain the user’s concept of operations with a seamless transition to a complement when GNSS is lost; have the potential to be deployed world-wide; be independent of GNSS and dissimilar in terms of failure modes, but provide similar levels of performance.

In the opinion of the GLAs, eLoran is the only system that can meet all these requirements in the timescale required to support the development and implementation of e-Navigation. For this reason the GLAs continue to encourage the development of eLoran within their organisation and within the wider national and international community.

7. REFERENCES


