

## IALA GUIDELINE

G1125

# THE TECHNICAL APPROACH TO ESTABLISHING A MARITIME eLORAN SERVICE

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# 1 INTRODUCTION

Service providers are opting to provide eLoran services as part of a robust PNT solution, as eLoran is dissimilar and complementary to GNSS services. The aim of this Guideline is to enable service providers to deliver, monitor and assess the performance of eLoran services in a common manner.

System performance is based on the assumptions that the system provider conforms to these Guidelines and that the user equipment meets the design and installation standards as specified in the referenced documentation.

## 1.1 PERFORMANCE REQUIREMENTS

IMO Resolution A.1046 (27) [1] details the requirements on World-Wide Radio Navigation Systems (WWRNS) considering vessels operating in the Ocean and harbour entrances, harbour approaches and coastal waters. The requirements are described by accuracy, integrity, availability, and continuity [2]. Table 1 summarizes the requirements specified in A.1046 (27), whereby the requirement on availability is given as signal availability describing the availability of radio navigation signals in the specific coverage area [3].

**Table 1** *Requirements for GNSS systems [based on IMO A.1046 (27) & IMO A.915(22)]*

Area	System Level				Service Level	
	Absolute Horizontal Accuracy (95%)	Integrity			Signal Availability (2 years)	Continuity (over 15 minutes)
		Alert Limit	Time to Alarm	Integrity Risk		
	m	m	s	%	%	%
Ocean	≤ 100	N/A	N/A	N/A	≥ 99.8	N/A
Harbour entrances, harbour approaches and coastal waters	≤ 10	25	10	1 x 10 <sup>-5</sup>	≥ 99.8	99.97

Receiver equipment for GNSS systems intended for navigational purposes on ships with maximum speeds not exceeding 70 knots shall meet the minimum performance requirements outlined in Table 1.

### 1.1.1 REQUIREMENTS FOR A BACKUP NAVIGATION SYSTEM

As stated in [4]:

‘Where the risk assessment concludes that a backup system (i.e. a system ensuring continued operation, but not necessarily with the full functionality of the primary system) is necessary, suggested minimum maritime user requirements (derived from IMO Resolution A.915(22)) for such a system are listed at Appendix A. It may however be impractical to expect backup systems to achieve some of these standards, such as global coverage in the ocean phase of navigation or metre level accuracy in the port phase. In these cases, it might be necessary to navigate the ocean phase by dead-reckoning, or delay port manoeuvres until the primary navigation system is restored. The argument for a backup system may be dependent on the perceived threat to the primary system and the likely duration of primary system outages.’

For convenience Table 2 illustrates the user requirements for a backup system as outlined in Appendix A of [4].

**Table 2** *Suggested minimum maritime user requirements for a backup system for general navigation [IALA Recommendation R-129]*

	System level parameters				Service level parameters			
	Absolute Accuracy	Integrity			Availability % per 30 days	Continuity % over 15 minutes <sup>3</sup>	Coverage	Fix interval (seconds)
	Horizontal (metres)	Alert limit (metres)	Time to Alarm <sup>2</sup> (seconds)	Integrity Risk (per 3 hours)				
Ocean	1000	2500	60	10 <sup>-4</sup>	99	N/A <sup>2</sup>	Global	60
Coastal	100	250	30	10 <sup>-4</sup>	99	N/A <sup>2</sup>	Regional	15
Port approach and restricted waters	10	25	10	10 <sup>-4</sup>	99	99.97	Regional	2
Port	1	2.5	10	10 <sup>-4</sup>	99	99.97	Local	1
Inland Waterways	10	25	10	10 <sup>-4</sup>	99	99.97	Regional	2

There are two main voyage phases of interest to the eLoran user community; Port Approach Phase, and Coastal Phase.

Port Approach Phase requires the highest achievable accuracy performance from eLoran, ~10 m (95%). This can only be achieved through bespoke Additional Secondary Factor (ASF) measurements and the installation and use of a Differential-Loran (DLoran) reference station at each port.

Coastal Voyage Phase requires 100 m (95%) accuracy. This can be achieved by eLoran without the use of differential-Loran reference stations and by computer modelling ASF data over a wide area and then calibrating the data with a sparse set of measured ASF data, which may most conveniently be collected automatically by vessels going about their everyday business –these vessels are referred to as ‘vessels of convenience’. Coastal ASF maps have been shown to be able to provide positioning accuracy on the order of 30 to 50 m.

These two statements, made without explanation of the key technical terms at this stage, cover the foundation of maritime eLoran service provision and the rest of this document describes the motivation and background and the methodology required to achieve this performance with eLoran.

## 1.2 AN OVERVIEW OF eLoran

Enhanced Loran (eLoran) is a low-frequency, long range Terrestrial Radionavigation System, capable of providing positioning, navigation and timing (PNT) service for use by many modes of transport, including maritime. eLoran transmits pulsed groundwave signals with a central frequency of 100kHz. This low frequency gives the signals their LONG RANGE Navigation capability from widely spaced transmitters. The receiver’s position is determined by the measurement of the times of arrival (TOA) (or pseudorange) of these pulses.

Pseudoranges from at least three transmitters are required to be measured to determine a position solution by trilateration. Measuring more than three transmissions (preferably five) provides the user with RAIM (Receiver Autonomous Integrity Monitoring) capability in addition to positioning accuracy.

An eLoran system includes the following elements:

- Several eLoran transmitters broadcasting a UTC synchronised and standardised eLoran signal [5];
- The signal incorporates a data message channel (the Loran Data Channel (LDC)), which may take several forms [6], [7];
- An identified service area, in which the signal propagation characteristic, represented by Additional Secondary Factors (ASF), have been measured or modelled through software and then calibrated [8];
- Where accuracy is required to support the Port Approach Voyage Phase, Differential-Loran (DLoran) Reference Stations should be installed;

These calculate differential corrections, which are sent to the mariner via the Loran Data Channel for reception using the same eLoran receiver used for positioning [9], [10];

- An infrastructure based integrity monitoring system that takes two main forms:
  - Alarms and alerts concerning the health and status of eLoran transmitters and their associated transmissions and the health and status of DLoran reference stations and their transmitted differential-corrections;
  - The capability to monitor the effects of solar weather is required to be installed in locations that are particularly prone to such effects (geomagnetic storms, proton events, coronal mass ejections etc.).

The effects on eLoran vary with the geomagnetic latitude of the user and the distance between the user and the transmitters. Integrity monitors of this kind remotely monitor the quality of the received signals and are able to interface to the Loran Data Channel in order to issue timely integrity warnings to the mariner. Integrity monitors may be co-located with DLoran Reference Stations where appropriate, however separate processing hardware may be required.

- A Control and Monitoring Centre, which provides a remote human/machine interface to the set of transmitters and/or DLoran reference stations deployed by the service provider. Its role is to control the system(s) and monitor alarm conditions;

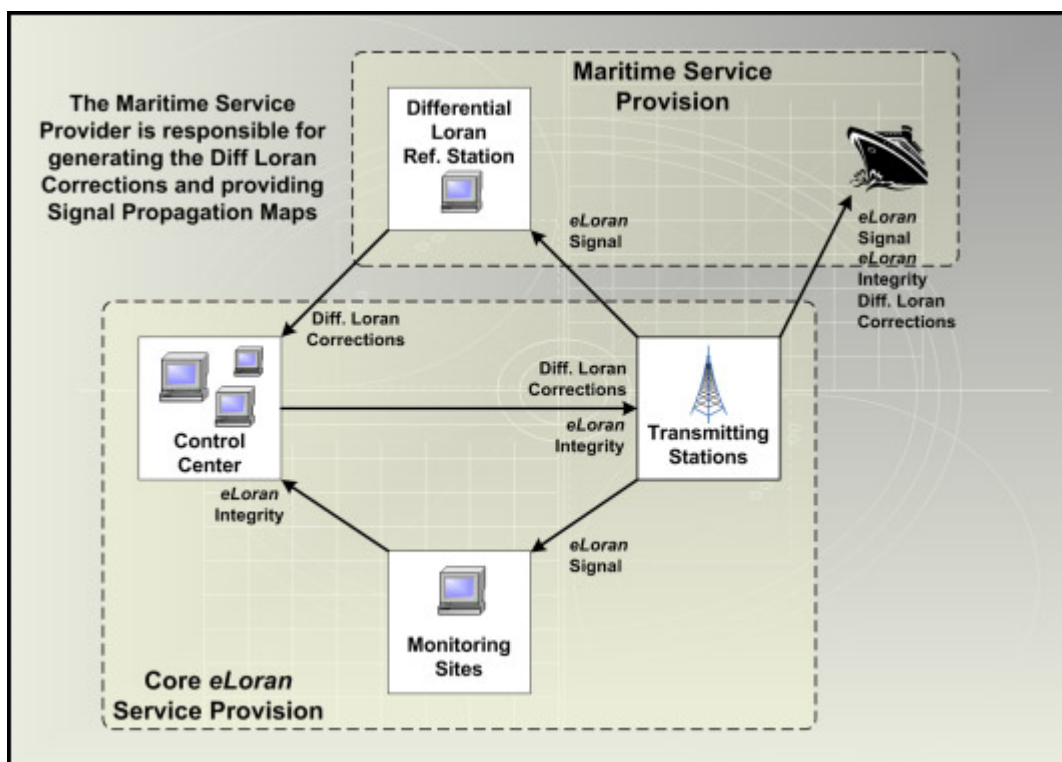
Control Centre personnel should have the power to deploy engineers to remedy any issues with equipment. It may be that the organisation that is responsible for the set of transmitters is not the same organisation that is responsible for the DLoran reference stations, in which case the eLoran transmitter Control/Monitor Centre may be separate from the DLoran Reference Station Control/Monitoring Centre.

- A data communications backbone is required for the various components of the system to communicate with their respective Control Centres, and to link DLoran reference stations with transmitters.

Such data communications include such items as control messages, differential correction information, integrity alerts, UTC time dissemination etc. The data backbone will usually be implemented using Internet Protocol, and may run on a private network, or via the public Internet. In the latter case, it is appropriate to implement one or more Virtual Private Networks (VPN) for data security purposes.

Figure 1 illustrates an overview of the eLoran system for maritime applications.



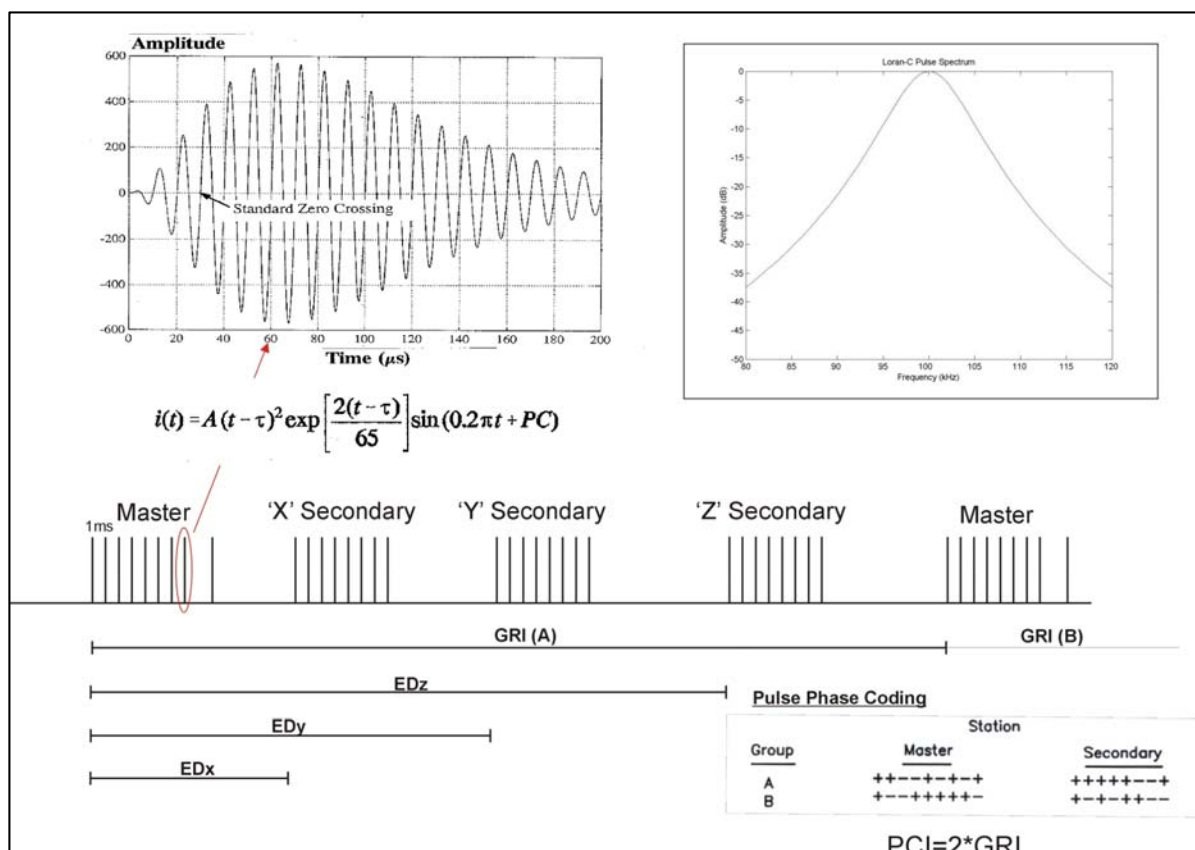


**Figure 1** *The service architecture for eLoran and the components required. After ‘eLoran Definition Document’, V1.0, October 2007, International Loran Association*

### 1.3 eLoran SIGNAL STRUCTURE

Figure 2 shows the signal structure and frequency spectrum of the eLoran signal [5]. The figure is divided into three sections. In the top left of the diagram is shown the individual Loran pulse. It has a specially designed shape (given by the equation underneath the plot) with a centre frequency of 100 kHz. At such a low frequency, the main mode of propagation is by a very stable radio frequency groundwave. The front edge of the pulse is carefully designed to provide high signal strength at the tracking point within a receiver, while the tracking point is early enough in the pulse to avoid early arriving skywave (an unwanted reflection of the groundwave pulse off the ionosphere). The pulse duration is approximately 250  $\mu$ s. The tail of the pulse is not defined, however the transmitter suppresses it sufficiently to maintain 99% of the energy of the eLoran signal within the band 90 kHz to 110kHz as shown in the frequency plot in the top right of the figure.

A transmitter broadcasts a group of 8 of these ‘navigation’ pulses, transmitted at 1 millisecond spacing. The additional 9th pulse (actually in 10<sup>th</sup> pulse position!) shown in the Master pulse group in the diagram is now obsolete for eLoran, being a legacy of Loran-C. However, 9th and 10th pulses may be added in order to implement the Loran Data Channel.



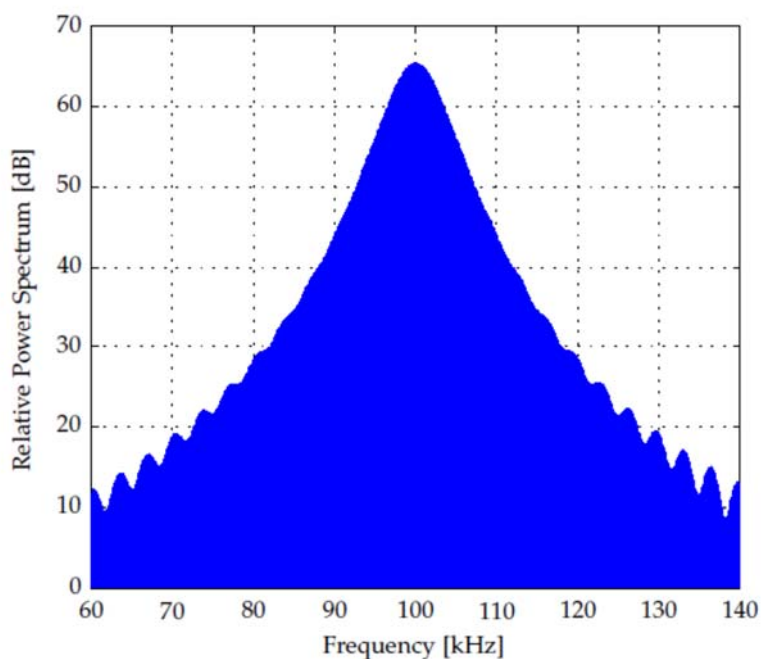
**Figure 2** eLoran signal structure and frequency spectrum

All eLoran transmitters transmit at the same frequency, so they cannot all transmit at the same time. Instead one transmitter, designated the **Master**, transmits a group of pulses followed a set time later by one of several successive **Secondary** transmitters. The time delay between the Master transmission and a Secondary is called the Emission Delay (ED) of that Secondary. The time interval between successive Master station transmissions within the same group is called the Group Repetition Interval (GRI), also sometimes referred to as the 'rate'.

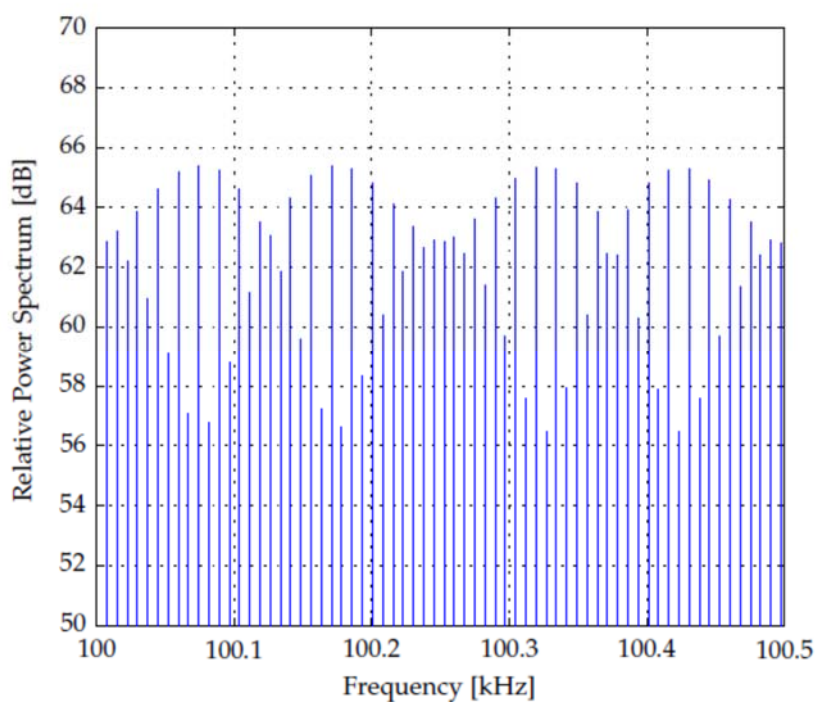
A Secondary transmitter's Emission Delay includes the signal propagation delay between the Master and the given Secondary, and a Coding Delay (CD) intended to position the Secondary transmissions within the GRI such that nowhere in the coverage area do the transmissions overlap. Careful design of the GRI and selection of Coding Delays are a vital part of system design.

The pulses of each GRI have an alternating Phase Coding according to the diagram shown in the lower right of Figure 2, and the PC term in the equation. A Phase Code Interval (PCI) is made up of up two GRIs (A and B) the phase coding of GRI A is different to that of GRI B. A '+' sign indicates a shift in phase of the pulse by 180°, while a '-' indicates a 0 phase shift. Phase coding is provided to mitigate the effects of long-delay, multi-hop skywave by employing correlators in the user's receiver.

Figure 3 shows the 'total' spectrum of the eLoran signal (provided through computer modelling). The spectrum of the pulse shown in Figure 2 is convoluted with the spectrum of the rate structure shown at the bottom of that figure. The effect of this rate structure can be seen in Figure 4, which shows that the eLoran spectrum is made up of a large number of finely separated spectral lines, each separated by  $1/(2 \times \text{GRI})$ .

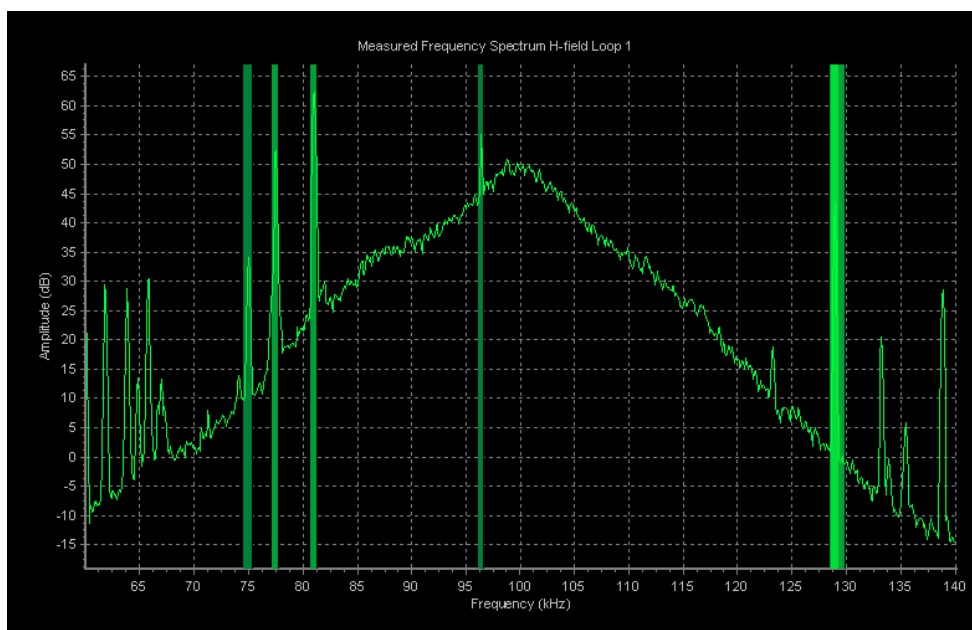


**Figure 3** *A model of the power spectrum of an eLoran signal*



**Figure 4** *Zoomed in view of the power spectrum shown in Figure 3*

Finally, Figure 5 shows real-life measurements of the eLoran spectrum made using an eLoran receiver's Fast Fourier Transform (FFT) algorithm. The peaks seen in the spectrum are continuous wave interfering (CWI) signals appearing in and around the frequency band; the green bands are notch filters implemented by the receiver to mitigate this CWI.



**Figure 5** *Real-life, off-air signal measurements*

## 1.4 RECOMMENDED READING

Table 3 contains a list of standards and other documentation that should be ‘required reading’ by a service provider intending to provide eLoran services and as background to the understanding of the implications of the rest of this IALA Guideline. Other references and relevant background reading can be found in Section 6 of this document.

**Table 3** *eLoran required reading for service providers*

Topic	Document(s)
eLoran evolution and recommendations	‘Loran’s Capability to Mitigate the Impact of a GPS Outage on GPS Position, Navigation, and Time Applications’, Prepared for the Federal Aviation Administration Vice President for Technical Operations Navigation Services Directorate, March 2004
System Definition	Enhanced Loran (eLoran) Definition Document, International Loran Association, 2007
eLoran Signal Specification	Enhanced Loran (eLoran) LORIPP/LORAPP Draft Specification of the eLoran System, Rev. 4.0
Receiver Minimum Performance Specifications	Minimum Performance Standards for Marine Loran Receiving Equipment, RTCM Special Committee 127
Loran Data Channel	Tri-State (e.g. Eurofix) - ITU-R Recommendation M.589-2*, Technical characteristics of methods of data transmission and interference protection for radionavigation services in the frequency bands between 70 and 130 kHz  9 <sup>th</sup> Pulse - ‘Enhanced Loran for Maritime Harbor Entrance and Approach’, Benjamin Peterson <i>et al</i> , Institute of Navigation National Technical Meeting 2004.

## 1.5 THE DEVELOPMENT OF eLoran

eLoran is an enhanced version of the original Loran-C system.

Any discussion of the difference between Loran-C and eLoran is complicated because Loran-C has been modernised at different times and to different extents in different areas of the World. The definitions in Table 4 are used to assist the comparison.

**Table 4** *Definitions of different generations of Loran*

<b>USCG Loran-C</b>	The original version of Loran-C (c. 1960s) based on tube transmitters, Service Area Monitor (SAM) control, ASF look-up tables and hyperbolic navigation, requiring large numbers of people on site. Typical accuracy: 460 m (95%).
<b>Modernised Loran-C</b>	The original version of the Northwest European Loran System (NELS) (c. 1990s) based on solid-state transmitters, time-of-emission control, ASF software modelling, hyperbolic or rho-rho navigation, and requiring very few people on site. Typical accuracy: 100 m (95%).
<b>Prototype eLoran<sup>1</sup></b>	The UK General Lighthouse Authority's system (c. 2008) based on modernised Loran-C together with (i) Eurofix as the LDC, (ii) all-in-view navigation, (iii) precise ASF surveys, and (iii) differential-Loran reference stations for maritime use. Typical accuracy: 10-20 m (95%).
<b>eLoran<sup>1</sup></b>	This is based on (i) updated station equipment to improve timing stability, (ii) mitigation of vulnerabilities to ensure high availability, (iii) LDC at all stations, and (iv) modernised control/monitoring capability at a Control Centre. Typical accuracy: 10-20 m (95%).

### 1.5.1 POSITIONING MODE AND ELORAN RECEIVERS

Loran-C was a hyperbolic system and the user measured the Time Differences (TD) between the arrival times of Loran-C signals from pairs of transmitters (typically the master and one of the secondary stations) within the same group. Measuring all points on the earth where the same TD is measured and plotting those points on a navigation chart it would be seen that the points all lie along a hyperbolic curve defined by the location of the pair of transmitters. Measuring another TD, using the same master but now a different secondary, derives another hyperbolic curve – where the two hyperbolic curves cross is the observer's position. With hyperbolic navigation, each station's transmission does not have to be synchronized to a precise clock – as long as the TD measured between the pairs of stations is constant at a given location the system is considered to be stable.

Control of this synchronisation was performed by installing a Service Area Monitor (SAM) somewhere in the coverage area. The SAM would be configured with a nominal set of TDs determined at the SAM's location. The Master station of each pair was not synchronised to any external source of time and was allowed to drift; however, the secondary stations were adjusted by measurements made at the SAM to maintain the constant TD at that location. This has the implication that the stability of the hyperbolic lines was only precisely maintained at the location of the SAM, other locations within the coverage area may witness accuracy degradation because of the distance from the SAM calibration point.

This ensures that Loran System Time is maintained and is based on the assumption that all Master transmitters began transmitting at midnight on 1st January 1958 (the Loran Epoch). Each transmitter's broadcast is therefore synchronised to UTC, although Loran System Time implements no leap-seconds. This method of control is referred to as Time of Emission (or Transmission) (TOE, or TOT) control. UTC messages can be broadcast over the Loran Data Channel, which include a figure for the current number of leap-seconds between Loran System Time and UT1 (mean solar time). This implies that eLoran can be used to provide timing users with a precise source of time independent of satellite systems.

<sup>1</sup> All generations of Loran support Stratum 1 frequency for telecommunications. Prototype eLORAN and eLORAN support UTC time of day. eLORAN will support sub-50ns precise timing.

To use eLoran, users should operate a receiver capable of calculating an eLoran position in accordance to the technical specifications set out [2], [11] and incorporating an up-to-date ASF correction database.

Earlier generation Loran-C receivers will be able to utilise any core Loran signals received, but will not be able to benefit from ASF mapping or the eLoran LDC messages.

### 1.5.2 THE LORAN DATA CHANNEL

The principal difference between Loran-C and eLoran is the addition of an LDC by pulse position modulation (PPM) of the eLoran signal. There are two main LDC techniques in development. One is Eurofix, based on a standardised, balanced tri-state PPM [6]. This is the modulation of the last 6 pulses in a station's 8 pulse group transmission, so the pulses used for Position, Navigation and Timing can also be used to transmit data. The other LDC concept is 9<sup>th</sup> Pulse [5], [7], which is again a pulse position modulation scheme, using an extra pulse added to the end of the transmitted 8-pulse groups. It is also possible to add a 10<sup>th</sup> and even an 11<sup>th</sup> pulse to the broadcast as long as there is space in the GRI. For maritime services the use of tri-state PPM and N<sup>th</sup> Pulse is not mutually exclusive.

The data channel conveys corrections, warnings, and signal integrity information to the user's receiver via the Loran transmission. The data transmitted may not be needed for all applications but will include at a minimum:

- The identity of the station;
- Almanacs of Loran transmitting and differential monitor sites - making it possible to change systems without rendering previous eLoran receivers obsolete;
- Absolute time based on the Co-ordinated Universal Time (UTC) scale;
- Leap-second offsets between eLoran system time and UTC;
- Warnings of anomalous radio propagation conditions including early skywaves;
- Warnings of signal failures, aimed at maximizing the integrity of the system;
- Messages that allow users to authenticate the eLoran transmissions;
- Official-use only messages;
- Differential Loran corrections, to maximize accuracy for maritime and timing users;
- Differential GNSS corrections may also be broadcast as an option depending on the available bandwidth of the LDC.

### 1.5.3 ADDITIONAL SECONDARY FACTORS (ASF)

eLoran receivers calculate their position by measuring how long it takes the system's 100 kHz groundwave radio signals to reach them over the surface of the earth from the transmitters. The measured propagation times are called 'pseudoranges'. eLoran receivers measure the pseudoranges of a number of signals from transmitters placed around the coverage area.





**Figure 6** *Example of all-in-view positioning using Anthorn, Lessay and Sylt. With all-in-view mode signals need not belong to the same GRI and more than three signals are employed in the positioning solution in order to provide integrity*

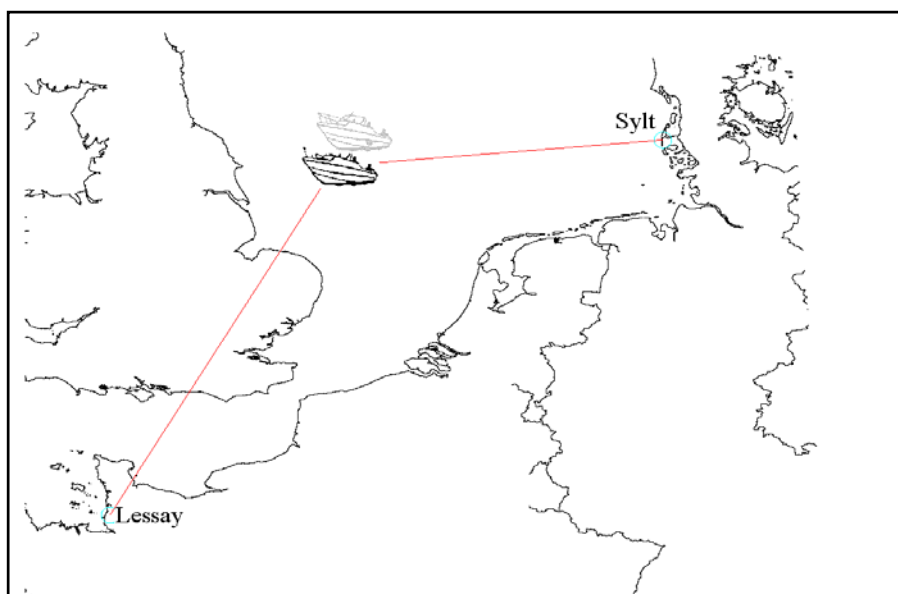
Figure 6 shows an example of some lines of position (circles) with the transmitters at Sylt (Germany), Anthorn (United Kingdom) and Lessay (France) at the centres. The reception of signals from three stations is sufficient to compute a position but more signals are typically employed in the positioning solution in order to provide integrity. Signal received need NOT belong to the same GRI.

The receiver measures these time delays and, by assuming a value for the propagation speed of the signal, the position relative to the transmitters can be computed. The speed of a ground-wave radio signal depends on the electrical conductivity of the surface over which it travels. For example, it travels slowest over ice, deserts and mountains, a little more quickly over good farm land and quickest of all over sea water.

eLoran receivers compute their position in two stages. Firstly, they assume that the entire earth's surface is covered in sea-water and they therefore employ a sea-water propagation model for the speed of propagation [2]. This model is based on a set of standard parameters adopted by the United States Coast Guard and models propagation over sea-water in earth's atmosphere very accurately.

In the second stage, the delays due to land paths are taken into account by adding them to the pseudorange measurements. These delays are called Additional Secondary Factor (ASF) delays. Their values are expressed as microseconds of propagation delay, and are typically supplied to users as a database built into their receivers. ASF are the dominant propagation phenomenon affecting the accuracy of positioning and navigation with eLoran.

If ASF are not taken into account they appear as a bias, or offset, in the measured pseudorange of an eLoran signal. Figure 7 illustrates this; the position of the vessel determined by the eLoran receiver is offset from its true position because of the land in the propagation path from the eLoran transmitter at Lessay.



**Figure 7** *ASF due to Lessay results in a position offset if it is not taken into account.*

ASF data will be required to be provided to the mariner. There are two main voyage phases that require to be supported:

- 1 Port Approach Voyage Phase – data will be measured through bespoke measurement campaigns at each port approach as discussed above.
- 2 Coastal Voyage Phase – data will be modelled to the best of the service provider’s ability. The modelled data will be calibrated using a small amount of ASF measurements gathered through the operation of ‘vessels of convenience’.

eLoran receivers may be integrated with GNSS, and such ‘Resilient PNT’ receivers are available. These receivers can be employed not just for navigation purposes but for automatically measuring and logging ASF data, since they already have a GNSS receiver ‘built in’.

#### 1.5.3.1 Determining ASF Values

The eLoran service provider is responsible for producing maps of Additional Secondary Factors for its operating region. There are several ways to produce ASF data:

- 1 Measure ASFs directly using an ASF measurement system.
- 2 Model ASFs using computer software.
- 3 Combine modelled data with a set of measurements measured using vessels.

#### 1.5.3.2 Measuring ASFs

The simplest, and most accurate, way to map ASF is by measuring them using special equipment aboard a survey vessel. The true position (the ground-truth) is typically determined using differential GNSS, which has a horizontal accuracy of approximately 1m (95%). If the ground-truth position is compared to the position given by an eLoran receiver with a sea-water only propagation model, the position offset would be due to ASF. However, ASF measurement is expensive in terms of ship time, and so this method is reserved for bespoke surveys for areas requiring the greatest positioning accuracy available from eLoran – Harbour Approaches.

For vessel-mounted receivers used to measure ASF, it is important to use an E-Field eLoran antenna to remove any heading-dependency that may result from interaction between the vessel’s metal superstructure and an H-Field eLoran antenna. When using an E-Field antenna, it is important to mount the antenna element high up, and on the end of a conducting antenna-mount to maximise E-field concentration and thus improve eLoran signal



reception. Establishing an electrical Earth is also critical, as often a ship's on-board mains power Earth is insufficient. Ideally a direct electrical connection made to the metal hull of the vessel, which in turn is in electrical contact with the sea-water, is necessary for vessel installation of an E-Field antenna.

Figure 8 shows an example of an ASF measurement system. The unit consists of an eLoran receiver; a GPS receiver to provide 'ground-truth' position and a precise time-tag against which to measure the eLoran signals' times of arrival; custom electronics, and a PC in one convenient 19inch rack mountable unit. ASF surveying software runs on this system and is used to process and validate the ASF data collected [8]. During bespoke surveys the equipment is typically monitored by a human operator and the success of the ASF measurement process, and the quality of the resulting data can be determined in real-time lending the possibility of re-surveying areas should a problem be found. Installing an eLoran antenna on a vessel, performing an ASF Measurement survey and operating the ASF Measurement System are not trivial tasks.



**Figure 8** *An example of an ASF Measurement System*

### 1.5.3.3 Modelling ASFs

Measurement is only practical for small regions such as harbour approaches where methods of surveying have evolved that take into account the physics of eLoran signal propagation and the characteristics of ASF as they build up over land along the signal propagation path from the transmitter to the mariner's vessel. For larger areas, it is more appropriate to model the ASF data using computer software.

There are sophisticated methods available for modelling eLoran propagation and producing software generated ASF maps. These techniques take into account the electrical ground conductivity of the surface of the earth (land or sea), terrain elevation and coastline, using a set of databases. ASF maps are produced in grid format and at required grid densities for a given coverage area. In this way, large ASF maps, one for each eLoran transmitter within the coverage area can be produced; as has been done for the waters around the United Kingdom and Ireland [10]. Such maps, following calibration with measured ASF data, are suitable for use during the Coastal Voyage Phase, where the mariner may be far away from a DLoran Reference Station. Interpolation is used to determine the ASF for a vessel's location when between grid points [2].

### 1.5.4 DLORAN

To get the highest accuracy from eLoran, a service called DLoran will need to be provided in those regions requiring 10 m (95%) accuracy – for example during a harbour approach. DLoran works in a similar way to Differential GNSS, in that a DLoran Reference Station is set up to cover a specific service area.

During the establishment of the service area precise ASF measurements would be made along the harbour approach and the data processed ahead of eventual publication. However, ASF measurements are only valid for the day on which they are made because the electrical characteristics of the land change with rainfall and season of the year.

eLoran Reference Stations continuously measure the propagation time of the eLoran signals to the service area and compute the differences between the nominal measured ASF stored within the reference station, and the current value of the ASF measured by the eLoran receiver at the reference station. This correction is broadcast to the user via the LDC; and the corrections used to obtain the best positioning accuracy possible. Variations in TOA of the signals also include components due to transmitter timing variations and atmospheric effects; these are automatically lumped together with the ASF variation in the computed differential correction.

Setting of Nominal ASFs at a Reference Station must be done very carefully to link a Reference Station to a particular ASF Map. Differential corrections from the Reference Station must be subtracted from measured pseudo-ranges recorded during the ASF survey, and these relative ASFs mapped. This is done so that when an eLoran receiver makes use of the ASF Map, adding the current Differential Correction to the mapped ASF should yield the current value for the ASF for the signal in question.

#### 1.5.5 TIME AND FREQUENCY EQUIPMENT

New eLoran transmitters contain up to three caesium clocks. The increased timing stability and integrity of the eLoran signal means that the signal can be used as a precise source of time and frequency for telecommunications applications, power grid synchronization, financial transactions etc. UTC can be recovered to an accuracy of 50 ns or better from an eLoran transmission, and the frequency stability is in the order of  $10^{-12}$  or better.

eLoran signals should be synchronised to Universal Co-ordinated Time (UTC).

The Signal Performance Standard [5] requires:

- The 10 second exponential moving average of all navigation pulses (not modulated) shall be within 25 ns of UTC;
- The 1 second exponential moving average of all navigation pulses (not modulated) shall be within 100 ns of UTC;
- The peak to peak variation of the 5 second exponential moving average of all navigation pulses (not modulated) shall be less than 10 ns within a 20-minute period.

Time of Emission adjustment is performed by frequency steering of the driving Caesium oscillators, rather than making integer time adjustment steps [12].

#### 1.5.6 BENEFITS OF ELORAN

eLoran is an aid to navigation that is complementary to GNSS, providing continuation of Position, Navigation and Timing (PNT) service provision when GNSS becomes unavailable for any reason. eLoran receivers may be integrated with GNSS receivers providing a seamless backup.

eLoran meets the position accuracy requirements for non-precision approach for aviation; the harbour entrance and approach requirements for the maritime sector; and the timing and frequency requirements of communications system providers. It is a system that has no failure modes in common with GNSS. It is complementary in the following way:

- eLoran is Low Frequency while GNSS is Ultra High Frequency;
- eLoran has transmitters on the earth while GNSS has space-based transmitters;
- eLoran is high power while GNSS is very low power.

### 1.6 STANDARDS PROCESS

This section sets out the roles of the various international bodies involved in standardisation of Position, Navigation and Timing equipment and systems.

### 1.6.1 INTERNATIONAL REGULATORY BODIES

The International Maritime Organisation (IMO) is the United Nations specialized agency with responsibility for the safety and security of shipping and the prevention of marine pollution by ships. IMO sets the performance standards for systems and onboard equipment, based on established user requirements.

The International Telecommunication Union (ITU) is the UN specialized agency for information and communications technologies. ITU determines the technical characteristics and radio spectrum requirements for radio-determination systems.

The International Electrotechnical Commission (IEC) is the international standards and conformity assessment body for all fields of electrotechnology. IEC provides the requirements and test specification for the onboard user equipment, based on the output from IMO and ITU.

The Radio Technical Commission for Maritime Services (RTCM) is an international non-profit scientific, professional and educational organization. RTCM prepares recommendations for maritime radio equipment and services, which may be used in IEC specifications.

### 1.6.2 THE STATUS OF LORAN DOCUMENTATION

There are existing IMO, ITU, RTCM and IEC standards and recommendations for Loran, but these are for Loran-C and relate to outdated technology.

#### 1.6.2.1 ILA & RTCM

The International Loran Association (ILA – now defunct) produced documentation for eLoran. In 2007, the ILA published an eLoran Definition Document and this is the starting point for preparing performance standards and an interface control document.

RTCM established Special Committee 127 (SC-127) for eLoran and a new RTCM performance standard is being developed, including a final signal specification for DLoran correction characteristics. The draft receiver standard has been adopted by SC-127 and may provide input to an IEC document.

RTCM also set up Special Committee 131 (SC-131) on Multi-system Shipborne Navigation Receivers. New draft Performance Standards for Multi-system Navigation Receivers were finalised and approved by IMO in June 2015 for implementation in 2017. SC-131 has also prepared a specification to be provided to IEC as a draft Requirements and Testing standard.

#### 1.6.2.2 ITU – Technical Characteristics & Spectrum Requirements

Recommendation M.589-3 (08/01) already provides technical characteristics for tri-state data transmission and interference protection. It requires revision and the addition of an annex giving more detail of the modulation system to be adopted.

#### 1.6.2.3 IMO – Performance Standards & WWRNS Recognition

IMO Resolution A.818(19) contains performance standards for Loran-C, based on long out-of-date technology. A new resolution is required before a World Wide Radio Navigation System (WWRNS) submission could be made.

The IMO Performance Standards for Multi-system Receivers contain a reference to PNT Guidelines, which mainly refer to onboard systems and have yet to be fully developed.

#### 1.6.2.4 IEC – Equipment Test Standards

IEC document 61075 Ed. 1.0 (1991-07) 'Loran-C receivers for ships – Minimum performance standards, methods of testing and required test results' is based on an RTCM standard from the 1980s and is not relevant to modern Loran.

#### 1.6.2.5 IALA – Operational Standards for Service Providers, Database of stations & GRIs

The database of transmitting stations and GRIs, maintained by IALA, should be updated as an S-200 series Product Specification as new data is produced or changes are made to almanacs.

IALA is likely to be involved in developing guidelines for PNT infrastructure that could include terrestrial systems as backups to GNSS.

## 2 THE PROCESS OF ESTABLISHING AN eLORAN SERVICE

This section provides an overview on how a maritime service provider could establish an eLoran service. Essential background to this process can be found in the essential reading list of Table 3, other required reading material is also identified to orientate the service provider or its contractor to the technology.

Consideration must be given to the following aspects:

- transmitters – location, number, GRI, size of antennas and Effective Radiated Power (ERP). Also the physical security of the sites; and repair / maintenance duties;
- Control Centre(s) – location, duties, Time of Emission (TOE) control;
- Differential-Loran (DLoran) Reference Stations – location, number and LDC data bandwidth requirements;
- data communications backbone for transmitters and DLoran reference stations – architecture, design and security;
- infrastructure based integrity monitoring – ‘early skywave’ effects, transmitter and reference station health and status monitoring and reporting;
- additional Secondary Factor (ASF) surveys for Port Approach Voyage Phase;
- additional Secondary Factor data for Coastal Voyage Phase;
- ASF database publication and updates;
- transmitter and DLoran reference station almanac publication;
- LDC - including message types, structure, encryption and data bandwidth requirements;
- development of standards (both National and International) including equipment requirements for vessels operating in Service Provider’s national waters;
- Engagement of user-groups, educational and publicity output to establish a user-base.

As a guide for further investigation each of the steps involved is outlined below:

- 1 System coverage prediction and analysis:
  - a Obtain/develop software or consultancy to perform coverage prediction.
  - b Determine the ERP required for the transmitters to support the intended application.
  - c Analyse the resulting predictions of accuracy, integrity, availability and continuity and determine their adequacy.
  - d Consider additional or alternate transmitter configurations and iterate the process from point b as required.
- 2 Use coverage predictions to identify candidate locations for the establishment of new eLoran transmitters:
  - a Ensure that proposed transmitter sites are able to support the size of antenna structure required to provide the desired ERP; also consider site infrastructure, power, data communications, security, land availability etc.
- 3 For the set of transmitters, select an operating GRI and a set of transmitter designators:
  - a eLoran stations may in future operate only on a single GRI, thus reducing Cross-Rate Interference (CRI).
  - b Establish the Emission Delays of each of the secondary transmitters.

- c Note that for one or two additional transmitters there may be space available in the GRI of an existing set of transmitters covering the region.
  - d Consider the interoperability of neighbouring GRI to minimise the effect of CRI.
- 4 Install transmitters:
- a Establish contracts with site providers.
  - b Procure transmitters and maintenance contracts.
  - c Install transmitters.
  - d Establish an eLoran Control/Monitoring Centre if required or make arrangements for transmitters to be integrated into an existing regional control/monitoring centre.
- 5 Establish Applications - Voyage Phase Requirements:
- a Identify the Voyage Phase required for specific regions around the service provider's territory; Port Approach Voyage Phase or Coastal Voyage Phase.
  - b For Port Approach Voyage Phase (requiring ~10 m accuracy):
    - i Identify Ports to be served.
    - ii Identify locations for the installation of differential Loran reference stations.
    - iii Plan an ASF measurement survey based on the extent of the port's VTS (Vessel Traffic Service) coverage area, or vessel confluence zone, and the expected vessel traffic density. In some cases the range of the reference-station (nominally 30km) will limit the coverage area.
    - iv Establish the DLoran reference station(s) and incorporate the generated differential corrections into the LDC.
    - v Perform ASF measurement survey ensuring all transmitters are on air.
    - vi Process the ASF data.
    - vii Perform validation of the ASF data, by assessing the performance of DLoran for each port approach.
    - viii Publish data to receiver manufacturers.
  - c For Coastal Voyage Phase (requiring not better than 10 m accuracy):
    - i Identify coverage region.
    - ii Produce ASF data using modelling software.
    - iii Establish a programme of automatic eLoran shipboard monitoring using service providers' own vessels, or vessels of convenience owned by other ship operators that operate within the coverage area.
    - iv Gather sufficient sparsely measured ASF data with which to calibrate the modelled ASF data.
    - v Perform validation of the calibrated modelled data using further data measured by the shipboard eLoran monitoring receivers.
    - vi Publish the ASF data for the Coastal Voyage Phase region to receiver manufacturers.

The following sections discuss the above in further detail.

## 2.1 SYSTEM COVERAGE PREDICTION AND ANALYSIS

The first step in identifying a system configuration is to perform computer software based coverage modelling. Service providers are recommended to obtain or develop software for this purpose, or obtain consultancy from experts in this area. Coverage predictions should allow the estimation of the geographical area over which the eLoran service will meet the application requirements outlined in Table 1 and Table 2. The provider should start with estimates for the number and locations of required transmitters. As a starting point, certain heuristics can

be applied; for example, assuming a 250 kW ERP transmitter has an approximate range of 1000km, and that at least 3 transmitters are required to allow positioning, with 5 required to be received to provide full RAIM-type integrity within a user's receiver. Coverage prediction should be made for accuracy, integrity, availability and continuity.

## 2.2 IDENTIFY LOCATIONS FOR TRANSMITTERS

The analysis of coverage estimates will allow the provider to estimate the ERP required for each transmitter. Knowing the required ERP will allow the provider to determine the type and size of antenna needed to be installed at a proposed transmitter site, and that will determine the location and size of the site itself. The ERP of the transmitter may be constrained by the size of site available, in which case further coverage analysis will be required to confirm service performance resulting from the use of the proposed site.

The analysis of coverage estimates will allow the provider to estimate the ERP required for each transmitter. Knowing the required ERP will allow the provider to determine the type and size of antenna needed to be installed at a proposed transmitter site, and that will determine the location and size of the site itself. The ERP of the transmitter may be constrained by the size of site available, in which case further coverage analysis will be required to confirm service performance resulting from the use of the proposed site. Table 5 illustrates some example data regarding transmitter output power versus antenna height and type. It can be seen that the selection of antenna type and height is not linear with desired power, but needs to take into account other factors. It is recommended that service providers liaise with an organisation offering expertise in the field of antennas.

**Table 5** *Example (historical) antenna heights versus power and type*

Transmitter	ERP (kW)	Antenna Height (m)	Antenna type
Bo, Norway	165	192	Guyed mast
Anthorn, UK	220	150	T-antenna
Williams Lake, Canada	400	190	Guyed mast
Grangeville, LA, USA	800	213	Guyed mast
Cape Race, Canada	1000	260	Guyed mast
George, WA, USA	1400	211	Array of four T-antennas on for 211m masts, over a 442 m <sup>2</sup> area

## 2.3 SELECT GROUP REPETITION INTERVAL(S)

One or more GRI will need to be assigned to the transmitters. Techniques are available to achieve this, which may be computerised. Then Emission Delays should also be selected for each of the transmitters.

The Emission Delay (ED) is the time difference, in microseconds, between when a master eLoran station transmits and a given secondary station transmits. The ED is equal to the sum of the baseline travel time of the signal plus the secondary's Coding Delay (CD). EDs are chosen so that there is no overlap in transmissions from the different transmitters covering the service area.

Where the provider is adding one or more new transmitters to an existing set of transmitters it is appropriate to consider assigning the new transmitters to the already existing GRI(s) by an appropriate choice of ED (s); this will avoid creating any additional CRI.



## 2.4 INSTALL TRANSMITTERS

It is recommended that intended eLoran service providers liaise with their nation's radio service providers who may have a capability to provide a location and assist in the installation of the eLoran transmitter. eLoran service provision typically involves international cooperation and coordination to run the system, for example as with NELS and FERNs. In these scenarios, there will invariably be a requirement for a Control Centre, whose day to day duties include monitoring the eLoran signal and transmitter performance, coordinating maintenance activities and providing notices to users of authorised and unauthorised transmitter off-air events. New eLoran transmitters that are to be integrated to an existing set will need to also be integrated into Control Centre operations. The Control Centre should be tasked with maintaining synchronisation of the eLoran transmissions to UTC, and controlling the access to the LDC of customers requiring access to the data channel without navigation services. UTC synchronisation and LDC data tasks may, alternatively, be handled by organisations more suited to the work. For example, national standards agencies (NPL in the UK; the USNO in the USA; KRISS in South Korea) may handle UTC synchronisation; national security agencies may handle the LDC client data.

To transmit an eLoran signal, a mast of 200 m is recommended, with a significant number of top loading elements and an appropriate earth mat that may extend up to a 300 m radius around the mast. The transmitter output power shall be in the region of 200kW-1MW. For the Loran Data Channel, and control and monitoring the local infrastructure must provide reliable power and broadband Internet connectivity with the appropriate security. It may be a requirement to provide separate Internet access for each of the LDC and monitoring and control. In either case, redundant data communications systems should be provided, with spatial diversity of the redundant data links given a high priority.

For redundancy, it is normal practice to duplicate the transmitter, timing and control units and power supply. The use of Uninterrupted Power Supplies to prevent outages in the event of short term loss of power supplies is strongly recommended.

The performance of the LF transmitter and its antenna can be affected by weather conditions and an automatic Antenna Tuning Unit (ATU) should be used to minimise such effects. Lightning protection techniques are highly recommended.

Service providers are recommended to contact eLoran transmitter vendors for more information and installation options.

Information on the format of eLoran transmitter almanac data may be obtained from RTCM SC-127 [2]. Transmitter almanac information should be published in IHO S-200 series format; see section 3.4.

## 2.5 ESTABLISH APPLICATIONS - VOYAGE PHASE REQUIREMENTS

The service provider should identify performance requirements around the provider's coastal territory. Providing ports and harbours with Port Approach Voyage phase capability will require the installation of one or more differential-Loran Reference Stations and ASF surveys. Coastal Voyage phase will require the production of ASF data through modelling and calibration with measured ASF data.

### 2.5.1 PORT APPROACH VOYAGE PHASE

A DLoran Reference Station will be required to be installed for each port or harbour to be provided with 10 m (95%) positioning accuracy capability. The typical geographical range of validity of the differential-corrections computed by a DLoran reference station is limited by an effect called 'spatial decorrelation', the effect of which is dependent on the difference in propagation paths between the eLoran transmitter and the user, and the eLoran transmitter and the reference station. The usable range of a DLoran reference station may be limited by spatial de-correlation to less than 30 km. Numerous DLoran reference stations will be required to cover a large region.

### 2.5.1.1 Reference Station Installation

A suitable building will require to be found to house the reference station, with power, Internet connection, roof space for the eLoran antenna and access available for maintenance activities. Legal and financial compensation agreements will need to be made with port authorities and licences or leases may be required.

When surveying the likely location of the reference station, it is recommended that the service provider perform a radio frequency 'noise survey' of candidate buildings to ensure the quality of reception of the eLoran signals at the location. Certain electrical equipment can affect the signal-to-noise ratio of the eLoran signals depending on proximity. For example, power supplies to LED lighting, elevator motor equipment, air-conditioning plant, switch mode power supplies of radar, radio and satellite receiving equipment and computer monitor screens can all have a detrimental effect on eLoran signal quality if such equipment is too close (1 metre or so) to an eLoran receiver antenna. For each port, the DLoran reference station should be installed and put into operation before the ASF measurement survey of the port is performed, as the reference station will need to be operating to take account of any signal propagation changes that might occur during the ASF survey.

Excessive local noise at the reference-station will have a detrimental effect on the quality of the broadcast differential-corrections. Also, Integrity monitoring and post-broadcast validation of the corrections requires the reference-station to be able to perform accurate pseudo-range measurements and be able to de-modulate the LDC. As a guideline, all received eLoran signals should have a Signal-to-Noise ratio (SNR) greater than 0dB, and any stations implementing a data-channel will need an SNR greater than +7dB at all locations where the LDC is required to be received and reliably demodulated. Ideally all eLoran signals used in positioning should be received at the reference-station site at never less than +10dB SNR. Intermittent noise may be present for short time-intervals during a day – an example would be air-conditioning plant which operates intermittently as required by daytime temperatures. Once a site is selected for DLoran installation, a long-term noise survey should be conducted to ensure no such intermittent noise exists.

The reference station should be provided with a unique identification number for automatic use by receivers. Information on the format of DLoran Reference Station almanac data may be obtained from RTCM SC-127 documentation. DLoran Reference Station almanac information should also be published in IHO S-200 series format; see Section 3.4.

### 2.5.1.2 Planning ASF measurement Surveys

An ASF database will be required for each port or harbour approach. Since the area covered by a port approach is limited, it is appropriate to obtain the required data by measurement rather than modelling. The resulting data will be the highest quality.

Only the sea-areas accessible by shipping need to be surveyed. Analysis of historic AIS data showing vessel-traffic density, and published Nautical Charts of the area should be considered when planning a survey. Survey vessel tracks should be planned in advance and issued to the survey vessel operators.

Using processing techniques and knowledge about the physics of eLoran signal propagation and ASF build-up over land it is not necessary to perform grid type surveying, as used to establish bathymetry. Rather, ASF measurements are made around the edges of the area to be covered and the data is then post-processed using interpolation and extrapolation to cover those areas not directly measured. ASF build-up over land depends on the terrain conductivity and is often unknown, but once the signal propagates out over sea-water the behaviour of ASF delay over distance is much more predictable. Expending surveying effort near to coastlines and between islands and archipelagos is more important than measuring ASF far out to sea, where its behaviour can be predicted with much more accuracy.

### 2.5.1.3 Perform the ASF Survey

The service provider should ensure that the local DLoran Reference Station is operating correctly before and during the survey. In addition, the provider should ensure that all eLoran transmitters intended to be used for position fixing in the area by users, are operating correctly and that there is no transmitter maintenance planned during the survey that will either take the transmitter off-air, or affect the performance of the transmitted signal.



Vessels should traverse around the edges of the VTS service area and along heavily-trafficked approach channels. Depending on the extent of the VTS area, it may be appropriate to traverse other lines within the area. The aim is to gather as much high quality data in the most efficient manner possible to save ship time, personnel time and fuel. It is recommended that, for Port Approach ASF, data is gathered and monitored in real-time with an operator sat at the measurement equipment. The software should be able to provide information on the quality and amount of data gathered, and decision can then be made whether to re-survey areas that are of poorer quality than others. ASF measurement equipment may be purchased from an appropriate vendor.

#### **2.5.1.4 ASF Data Processing**

Once the survey has been completed the data will need to be processed to interpolate and extrapolate data to those regions where data was not measured. The data should be output in a grid format, most conveniently a rectangular grid of individual ASF cells for each transmitter intended to be used for position fixing in the area. The ASF data cells should be spaced no more than 500 m apart. Interpolation and filtering techniques are available that take into account the physics of ASF to optimise the accuracy of the generated ASF grid.

At the same time as producing the ASF data grids an equivalently sized grid of ASF measurement errors, one error value per ASF grid cell, should be produced. This should be published alongside the ASF data for use within a user's receiver. The ASF error data will be used in RAIM type integrity equations as one component of a Horizontal Protection Level (HPL) computation. Depending on the amount of Interpolation, or Extrapolation required to produce the ASF Map (and the distances over which the extrapolation is performed) certain areas of the Map will contain high-accuracy ASF values, and certain areas will contain low-accuracy ASF.

It is important to define a Service Area for Port Approach voyage phase of eLoran. This is the region of the map for which ASF data has been surveyed to high accuracy, and can be used for precise eLoran positioning. Typically the Service Area will be the region contained within the interpolation (i.e. bounded on all sides by the 'tracks' run by the survey vessel) and extrapolated a distance no more than about 500m outside the survey 'tracks'.

The quality of the ASF Map outside this Service Area cannot be guaranteed, as this data is based on extrapolation techniques which are known to be inaccurate. High-accuracy eLoran positioning cannot be guaranteed in regions outside the Service Area, so it is important to plan survey tracks well in advance of the measurement campaign.

#### **2.5.1.5 ASF Data Validation**

Once the final output ASF data has been produced it is recommended that the service provider validate eLoran positioning in the area of interest. This validation should employ the ASF map and the local DLoran Reference Station. ASF Data Validation should be carried out only in areas where high-accuracy ASF data is provided, i.e. strictly within the ASF Map Service Area as defined above.

#### **2.5.1.6 ASF Data Publication**

The ASF (and ASF error) data grids should be converted into RTCM SC-127 format ready for use by receiver manufacturers. It should also be handed to IALA for conversion to IHO S-245 format; see section 3.4.

### **2.5.2 COASTAL VOYAGE PHASE**

This phase of navigation is assumed to take place outside of harbour approach areas at greater distance from a DLoran reference station where the differential-corrections are not valid. The Coastal Voyage phase does not require as high accuracy positioning as the Port Approach Phase (see Table 2). eLoran using ASFs alone has been demonstrated to be capable of providing 30 m to 50 m positioning accuracy at the 95% probability level.

#### **2.5.2.1 Identify the Coverage Region**

The service provider should identify the coverage region within which Coastal Voyage Phase performance from eLoran is required. The service provider may need to consult coverage maps to verify that coverage within this region is feasible.

### 2.5.2.2 Produce ASF Data Using Modelling Software

The coastal voyage phase, by definition, covers a much greater geographical area than the harbour approach. ASF data is most efficiently produced through software modelling and subsequent calibration using a much smaller set of measured data. Sophisticated ASF modelling software is available, which accounts for the electrical conductivity of the earth's surface, coastline data and terrain elevation data.

### 2.5.2.3 eLoran Shipboard Monitoring

Measured ASF data may be gathered by 'vessels of convenience', or crowd sourcing. Once vessels have been fitted with multi-source receivers containing one or more GNSS and an eLoran receiver then this can be a source of ongoing measurements against which to calibrate and monitor the performance of the service provider's ASF data. The shipboard monitoring equipment may also serve to provide the service provider with validation data on the performance of its eLoran service.

### 2.5.2.4 ASF Data Processing and Calibration

Measured ASF data, or the data that can be used to derive measured ASF, should be collected from the service provider's shipboard eLoran monitoring vessels regularly, and the modelled data re-calibrated with it and republished. In this way, the service provider ensures that the mariner is provided with the latest data. The re-publication of data may be achieved using an e-Navigation service providing data through the IHO S-245 format. This could be an automated process to ensure timeliness of updates.

### 2.5.2.5 ASF Data Validation

Once the final output ASF data has been produced it is recommended that the service provider validate eLoran positioning in the area of interest. This validation should employ the calibrated ASF map and 'vessels of convenience', or crowd sourcing of an agreed set of validating users.

### 2.5.2.6 ASF Data Publication

The ASF (and ASF error) data grids should be converted into RTCM SC-127 format ready for use by receiver manufacturers. It should also be handed to IALA for conversion to IHO S-245 format; see section 3.4.

## 3 OPERATIONAL ASPECTS

Aspects of service providers' operations are presented here, with some detail found in [12].

### 3.1 CONCEPT OF OPERATIONS

Taking into account that:

- eLoran stations are unmanned and fully automated;
- each station contains an Uninterruptible Power Supply (UPS) to minimise outages due to power failure.

An eLoran service provider should:

- continuously monitor the service and manage any disruptions;
- inform users of important properties of the service and communicate warnings about service disruptions to the user;
- manage any maintenance work or changes to the service in such a way where service disruption is minimized and the users are provided with advance warning;
- verify the service is performing according to specifications and provide such information to users;
- Exchange information with users about achieved performance.

## 3.2 REFERENCE DATUM

There is a need to ensure the interoperability of ASF data measured within different service providers' territories. The eLoran datum employed in a region will ultimately be derived from the position reference used to survey ASF data (related to the ground-truth system employed, for example WGS84 for DGNSS). The datum used should be stated in each of the service provider's publications, however, it is recommended that WGS84 should be employed directly, or ASF and almanac data converted to WGS84 prior to publication.

## 3.3 MONITORING

On-site monitors should be provided at each transmitting station, to check the transmitted signal and the data content.

Additional signal monitoring is recommended using receivers placed at sites within the coverage area, to validate broadcast site RF and signal performance. Communication lines to a central control and monitoring centre may link integrity monitors. Data may either be logged at the integrity or reference station and downloaded periodically or passed directly to the central control and monitoring centre. It is recommended that this data be archived for a period sufficient to meet local litigation requirements.

Information on each DLoran reference station or integrity monitor shall be provided to a control and monitoring centre. The information will include:

- identity (ID) of the Reference Station;
- integrity alert and type of alert as deemed necessary.

## 3.4 PUBLICATION OF INFORMATION

Individual Service Providers are encouraged to publish service descriptions, including coverage predictions and system performance statistics.

In addition to the information contained in the standard LDC message types notice of current or planned signal unavailability should be provided to users through the appropriate service (e.g. coastal radio station, VTS, Navtex, SafetyNet, etc.).

Wherever practicable, information on scheduled and unscheduled off-air periods should be promulgated to users as shown in Table 6:

**Table 6** *Information on maintenance and outages to be promulgated to users*

Event Type	Date and Time Period	Provision of Notice to Users
Scheduled maintenance	Date and expected downtime	One month in advance is recommended, but at least 1 week in advance is mandatory
Unscheduled outages	Expected downtime	As soon as practicable and not more than 1 hour after the occurrence

IALA Guideline 1016 on Bilateral Agreements and Inter-Agency MoU on the Provision of DGNSS services in the frequency band 283.5 kHz– 325 kHz contains examples of guidance on the information that should be exchanged between co-operating agencies and, where appropriate, the circumstances and timing for it to be exchanged. Those guidelines can be extended to eLoran by analogy.

IALA will maintain a master list of eLoran transmitters and reference stations on the Internet. Input to the master list will be prepared by each Service Provider. IALA will provide an electronic template that should be used for initial entry of station data and assembly of the complete Service Provider submission. After initial submission,

the Service Provider will be responsible for updating their own sections of the IALA master list. The process to incorporate changes will require each Service Provider to provide a complete, updated section of the list for all the eLoran sites that they operate. Each complete submission will appear exactly as submitted.

The service provider is recommended to publish that they follow IMO Resolutions and IALA Recommendations for the provision of eLoran, giving emphasis to the provision of integrity information.

The service provider is required to tell the user at which ports, or within which areas, they can expect to receive eLoran signals and where they can expect the service to achieve specific performance.

eLoran transmitter and almanac information shall also be made available in IHO S-200 format, which will then afford the data's provision by e-Navigation service. The current S-200 series designations for eLoran are:

- S-245: ASF (Additional Secondary Factor) data;
- S-246: eLoran transmitter almanac data;
- S-247: Differential-Loran Reference Station almanac data.

### 3.5 PERFORMANCE VERIFICATION

It is recommended that the service provider monitors the performance of the service continuously in order both to detect service disruptions and to determine if the performance requirements are being met over an extended period. In this way, the service provider can verify the accuracy, integrity, availability and continuity of the service.

Performance should take account of the declared eLoran service coverage area. To maximize the combined performance service providers should follow the guidelines outlined in section 3.1.

#### 3.5.1 GENERIC REQUIREMENTS FOR SERVICE VERIFICATION

Published coverage diagrams are normally based on software modelling predictions and should be verified by measurements. Coverage modelling should include predictions for accuracy, integrity, availability and continuity.

The modelling process can be quite complex and difficult, especially over mixed land/sea paths. Advice regarding modelling can be sought through IALA, and background technical information is available as described in Section 2.1; providing guidance and references to accomplish a capability in coverage prediction.

Measurements to verify eLoran Coverage can be gathered from **static** monitors at fixed and known locations, or **dynamic** monitors hosted aboard 'vessels of convenience', which may be the service provider's own vessels or vessels belonging to other regional partners. In either instance, data should be recorded and stored locally by the monitoring receiver for later analysis and processing. At a minimum, the following data should be recorded:

- eLoran position-fix data at intervals of no more than 5 seconds;
- Integrity information relating to each eLoran position-fix, indicating whether RAIM is possible, and if so, whether the fix is declared good ('green-light') or bad ('red-light');
- Ground-truth location of receiver (either the precisely surveyed location of a static receiver, or the current differentially-corrected GNSS location of the vessel);
- The precise (UTC) time of the eLoran position-fixing. For dynamic verification on-board a vessel, the UTC time of the ground-truth position-fixing is also required.

eLoran position-fixing shall be by a Weighted Least Squares All-in-View solution of ASF-corrected and differentially-corrected pseudo-ranges, as described in RTCM SC-127 eLoran Receiver Performance Specifications [2]. Integrity algorithms should obey all external integrity alerts, including early-skywave warnings and do-not-use flags when selecting the sub-set of eLoran pseudo-ranges used for position-fixing.

Internal Integrity (RAIM) by hypothesis-tested Solution-Separation (as described in [2]) shall be applied after the position-fix has been calculated to determine whether the fix is declared good ('green-light') or bad ('red-light').

If Integrity cannot be determined, the receiver should declare this to be the case ('yellow-light'). A Horizontal Protection Level (HPL) shall be calculated based on the estimated accuracy of the pseudo-ranges used in solution, including the error contributions from the underlying ASF map and broadcast differential-corrections. If this HPL exceeds the pre-set Alert Limit an Integrity 'red-light' should be declared and presented to the user within the specified Time to Alarm.

Alternatively, an Integrity technique that can be shown to be mathematically not worse than Solution-Separation RAIM in terms of Integrity performance can be employed.

If for any reason the eLoran receivers used for the verification are not compliant with SC-127 performance specifications (for example, if the receiver does not output RAIM or HPL information, or does not perform all-in-view positioning, or does not obey early-skywave warnings) then this processing can be done 'offline' in post-processing for validation purposes.

In the following sub-sections, the additional requirements for the verification of each of the individual navigation performance parameters are presented.

#### 3.5.1.1 The Amount of Measurement Data Required for Successful Verification

It is recommended that in what follows data is measured and logged over a period of at least 12 months for **accuracy**, **availability** and **integrity** verification; and 2 years for **continuity** verification.

The service provider is free to decide to use a shorter measurement period, but the consequences of this need to be understood. ANNEX A to this document provides guidance on the effect of using shorter measurement periods for service verification.

#### 3.5.2 ACCURACY VERIFICATION

Where differential eLoran corrections are provided e.g. in Port and Port Approach areas, the absolute horizontal accuracy should be better than 10 m at the 95% probability level within the published coverage area; for Coastal Voyage phase areas the accuracy should be better than 100 m at the 95% probability level. Future eLoran receivers will form one component of a multi-source receiver unit. Under normal operations this allows the possibility to measure the performance of eLoran against one or more GNSS (including DGNSS).

##### 3.5.2.1 Accuracy Verification Method

Accuracy assessment for eLoran Service verification is done by considering all 'green-light' position-fixes output by the monitor receiver. The horizontal accuracy of these is determined by calculating their geographical distance (in meters) from the known ground-truth. The absolute magnitude of these horizontal errors are ranked in order from smallest to largest, and assembled into accuracy 'bins' in order to produce a Cumulative Distribution Function (CDF). The Service Accuracy is given as the 95<sup>th</sup> percentile horizontal error (i.e. the error on the fix for which 95% of all fixes lie closer to the ground-truth).

#### 3.5.3 INTEGRITY VERIFICATION

Integrity is defined by the IMO as:

***The ability to provide users with warnings within a specified time when the system should not be used for navigation.***

For a service to provide integrity it must be possible to monitor error thresholds set by the service provider, and provide alerts to users of the service should those thresholds be breached. The alerts should be provided within a specified time to alarm (defined below).

Numerically, integrity is often specified as **Integrity Risk**, which is defined by the IMO as:

***The probability that a user will experience a position error larger than the threshold value without an alarm being raised within the specified time to alarm at any instant of time at any location in the coverage area.***



These and other definitions and terms used for defining integrity are used by analogy to the ICAO GNSS SARPs (GNSS Standards and Recommended Practices) [18], as have been adopted for aviation WAAS (Wide Area Augmentation System), including EGNOS [19], integrity analysis.

There are two forms of integrity monitoring that the service provider should be aware of:

- Infrastructure (External) based integrity monitoring;
- User Receiver (Internal) based integrity monitoring.

### 3.5.3.1 Infrastructure Based Integrity Monitoring

System status information will be vital to maintaining knowledge of integrity and positioning accuracy. eLoran integrity alerts shall be generated by an infrastructure (external) based integrity monitoring system. There are two different types of alert that require to be monitored:

- Core eLoran Signal-in-Space;
- Differential-Loran.

#### 3.5.3.1.1 Core eLoran Signal-in-Space

To alert the user to poor quality eLoran signal conditions, or a signal outage. In addition, external integrity monitoring may be required to monitor for the existence of rare 'early skywave' events [12]. Early Skywave is an effect whereupon a copy of the 'wanted' groundwave signal pulse arrives by skywave reflection when the ionosphere is particularly low in altitude owing to strong solar activity. The magnitude of the effect depends on the distance between a user and the respective eLoran transmitter, and the user's geomagnetic latitude. Where necessary 'early skywave' monitors should be installed at suitable locations [16], [17].

#### 3.5.3.1.2 Differential-Loran

Alerting the user to any reduction in the performance capability of the broadcast differential corrections.

In both types of monitoring, the eLoran integrity information is disseminated by the Loran Data Channel (LDC). On the rare occasions when strong sky wave interference is likely, or there is likely to be a transmitter or differential correction data outage, users should be notified within a time-to-alarm period (typically 10 seconds according to IMO requirements).

The IMO [3] defines Time to Alarm as:

***The time elapsed between the occurrence of a failure in the system and its presentation on the bridge.***

### 3.5.3.2 User Receiver Based Integrity Monitoring

eLoran is unusual amongst radio-navigation services (particularly when compared to GNSS) in that the majority of Integrity risks depend upon the proper functioning of a User's receiver at a particular time and at a particular location. Infrastructure-based Integrity monitoring cannot guard against:

- low signal-to-noise ratio (SNR) due to noise local at the receiver;
- Continuous Wave Interference (CWI) from local noise-sources;
- poor signal-tracking;
- incorrect 100kHz cycle-selection;
- cross-rate interference (CRI).

These form the bulk of the Integrity Risk inherent in eLoran position-fixing. The majority of the error-mitigation and Integrity Monitoring work must be done by the user's receiver.

#### 3.5.3.2.1 Horizontal Alert Limit (HAL) and Horizontal Protection Level (HPL)

Associated with each set of requirements and voyage phase is a Horizontal Alert Limit (HAL) (see Table 2), which is the limit (in metres) of positioning error tolerable by the given application. Typically, HAL is 2.5 times the 95%

Accuracy requirement. A mariner's Navigation System Error (NSE) is not observable as it typically does not have access to a 'ground-truth' system, so it must be estimated; this is accomplished by computing a Horizontal Protection Level (HPL).

All errors contributing to the HPL are expressed as uncertainties. These uncertainties are summed in quadrature (in other words no correlation is assumed between pseudo-range measurement errors, ASF map quality, and differential-correction errors) and transformed into the positioning domain. The resulting two-dimensional position error may be represented as an error ellipse. The error ellipse is then linearly scaled to a positioning probability level corresponding to the desired integrity risk level; for example,  $10^{-5}$  integrity risk, which indicates that there is a 1 in 100,000 chance that a fix lies outside the error ellipse.

Aboard ship, should the computed HPL breach the HAL ( $HPL > HAL$ ), the system should be declared unavailable and an alarm generated within the receiver. A multi-system Receiver can then switch sources of PNT to one that is available, i.e. demonstrating an HPL that is lower than the HAL. In a multi-system receiver, containing both eLoran and GNSS based receivers, each should independently verify their own Integrity at the levels set down by the IMO for electronic position-fixing at sea [1], [3]. Receiver integrity algorithms are available for eLoran [2].

### 3.5.3.2.2 Receiver Autonomous Integrity Monitoring (RAIM)

The HPL is only an estimate of positioning accuracy and is used as a 'best guess' that the system can deliver the performance that is required. There will be cases where sufficient signals are received at high SNR, and with accurate ASF corrections but positioning accuracy is poor. These cases are usually due to one of the issues identified at the start of section 3.5.3.2 and cannot be mitigated by Infrastructure-based Integrity monitoring.

RAIM assesses the individual pseudo-range measurements to determine if there are any obvious outliers which do not agree with the other measurements, so are likely to be in error. RTCM Receiver Performance specifications [2] suggest a Solution-Separation RAIM algorithm be employed for this purpose. Each eLoran pseudo-range observation is individually removed from solution, and a fix is generated using the remaining subset of eLoran signals. This fix is compared to the 'all-in-view' solution made up using all available pseudo-ranges. If the distance between the 'all-in-view fix' and the 'reduced-subset fix' is particularly large then this is an indication that the excluded pseudo-range is probably in error.

The separation threshold that is needed for the error to be considered statistically significant will depend on the estimated accuracy of the all-in-view fix, and the contribution made by each individual pseudo-range measurement. Setting threshold values must be done extremely carefully, and the process is described in the Receiver Specification [2].

Occasionally RAIM will falsely indicate a pseudo-range measurement to be in error when, in fact, it is perfectly accurate. These Integrity 'false alarms' can harm service Availability and so the RAIM algorithm needs to be designed accordingly. Assigning an Availability 'budget' allows for managing of these false-alarms and so maintaining a high Availability. The table below is an example of how a 99.8% Availability 'budget' can be allocated.

**Table 7** *Example of how a 99.8% Availability 'budget' can be allocated*

Item	Time Budget
Service is available for use	99.8%
Loss of position-fixing due to off-air transmitters	0.18%
Loss of positioning due to Integrity false-alarms	0.02%
<b>Total</b>	<b>100%</b>

A probability of false-alarm of 0.02% is recommended for use when 99.8% Availability is required from eLoran position-fixing. It is expected that the large majority of the 0.2% 'un-available time' will be due to transmitters

off-air for routine maintenance. 0.18% corresponds to approximately a 90-minute Maintenance Outage once a month.

In some cases, RAIM cannot identify an erroneous pseudo-range, and so an Integrity Risk is incurred. The output from the RAIM algorithm is to identify which pseudo-ranges can be trusted, and the amount of residual risk inherent in the position-fix. If this risk is greater than the allowed Integrity level for the Voyage Phase in question (for example IMO A.915 specifies  $10^{-5}$  for Port Approach procedures) then Integrity cannot be guaranteed at the required levels and a 'yellow-light' warning indicating the inability to perform sufficient Integrity Monitoring should be issued. This is particularly important for Service Continuity, as loss of Integrity Monitoring is as bad as loss of position-fixing for a safety-of-life application that requires high Integrity.

If the RAIM algorithm has determined that a particular pseudo-range should be excluded then the all-in-view position fix should be discarded and the corresponding reduced-subset fix used instead. This is the correct functioning of Fault Detection (FD). The resulting fix is likely to be less accurate, and have reduced Integrity as it makes use of fewer eLoran pseudo-ranges. The RAIM and HPL calculations should be run for a second time on this reduced-subset fix. If a pseudo-range is excluded from solution, and the resulting reduced-subset fix still meets the required Accuracy and Integrity targets then Fault Detection with Exclusion (FDE) has been effected.

#### 3.5.3.2.3 Multi-System Integrity

Tight multi-system integration at the level of pseudorange measurements has several benefits, including greater accuracy; improved availability of solution; the ability to calibrate cross-system biases; and increased coverage or better HDOP by combining signals from several systems. However, for safety-of-life navigation where a high level of integrity is required any multi-system integration or calibration process risks introducing faults from one system into another. Likewise, the use of Kalman Filtering or any other type of multi-epoch smoothing propagates Integrity Risk from one epoch to the next.

As a general rule, for high-Integrity applications cross-system calibration and cascaded filtering should be avoided whenever possible [15] to maintain the level of system-separation needed to 'quarantine' the Integrity Risk.

#### 3.5.3.3 Integrity Verification Method

Integrity verification performed by the service provider relies on the provision, by the service provider, of monitoring receivers positioned at suitable locations throughout the eLoran coverage area. These monitor receivers may be static (within the service area of a DLoran reference station), or dynamic (installed on 'vessels of convenience' employing crowd sourcing techniques).

##### 3.5.3.3.1 Infrastructure Based Integrity Verification

There is currently no specified performance target for Infrastructure-based Integrity Monitoring in eLoran, save for the 10-seconds Time to Alarm (TTA). Times to alarm data are difficult to verify by the service provider since they do not have direct access to users' receivers. However, DLoran reference stations and 'early skywave' monitors should be able to log historic data, and monitoring and control centres should be able to log historic alarms. It is recommended that at least 3 years' worth of storage capacity be available for this (this capacity would also facilitate **availability** and **continuity** verification).

The budget for TTA is typically made up of the following latencies and delays:

- detection of fault at monitoring receiver site e.g. 5 seconds;
- transmission of alarm via Internet VPN to transmitter for broadcast over LDC (typically 200 ms 'ping' delay plus negligible time for a small alarm message at 1Mbit/s);
- message scheduling delay at eLoran transmitter, e.g. 2 seconds for Anthorn on 6731Y;
- LDC message transmission time at LDC bit rates, e.g. 2 more seconds;
- reception, decoding and presentation at the user's receiver (typically  $\ll$  1 second).



If the Integrity Alarms are broadcast from an eLoran transmitter with a GRI of longer than 8330 (83300 micro-seconds per Group Repetition Interval), then message scheduling and transmit times will be longer than 2.5 seconds (applying Eurofix LDC). Allowing for 5-second pseudo-range integration at a reference-station site, this exceeds the 10-seconds Time-to-Alarm typically required. Broadcasting Infrastructure Integrity Alerts on a higher bit-rate data-channel (shorter GRI or alternative LDC) should be considered.

The monitoring receivers used in the verification of the service should obey all Infrastructure-based Integrity Alerts, including early-skywave warnings and 'do-not-use' flags issued by the DLoran reference-station for eLoran pseudo-ranges that are determined to be out-of-tolerance. A monitoring receiver could detect a problem, issue an alert, transmit it via the LDC and receive it back. An indication of TTA can then be calculated and stored at the monitor site along with the alert. Alternatively, a methodology can be established whereby the alarms detected at monitoring receivers are logged and regularly (perhaps on a 6-monthly cycle) reconciled with alarms logged at the control centre.

**Infrastructure Integrity** verification for the DLoran service may be accomplished by post-processing and analysis of the logged data, identifying those alarms and conditions under which the TTA was **not** met. This would provide the service provider with the opportunity to improve the system should it be found to be operating incorrectly or inefficiently.

#### 3.5.3.3.2 Service Provider Verification of User Based Integrity

All infrastructure based monitoring receivers should operate at a level of fidelity such that a User's experience of Integrity is within the specified Integrity Risk for the particular voyage phase they are undertaking.

Service provider owned **statically** located monitoring receivers can compute a value for the NSE (Navigation System Error) by comparing the eLoran computed position against the monitor's precise position. Service provider owned **dynamically** located monitoring receivers may also compute NSE because, unlike the general mariner user, the service provider could employ a differential-GNSS service as a measure of ground-truth with which to compute the NSE for verification purposes.

**Integrity Failure** is defined as a position-fix with a position error (NSE) that is greater than the pre-determined Horizontal Alert Limit (HAL), which is presented to the user without an appropriate Integrity alert ('green-light' presented incorrectly, when it should be 'red-light'); this is called **Hazardously Misleading Information (HMI)**. In this case:

$$NSE > HAL \text{ when } HPL < HAL.$$

Recall that HPL is an estimate of the user's NSE.

The NSE of each 'green-light' eLoran position-fix (when  $HPL < HAL$ ) is found by comparing the eLoran fix to the known ground-truth. The number of these exceeding the HAL is then divided by the total number of epochs. This gives the level of Integrity at the monitor site:

$$I = \frac{\sum \text{Integrity\_Failures}}{\sum \text{Positioning\_Epochs}}$$

#### Equation 1 Level of Integrity

Note that the monitor must be installed at a location with high signal-to-noise ratio to prevent local noise effects from damaging the assessment of the System performance.

#### 3.5.3.4 Integrity Hazards

Hazards to integrity and service availability include the following.

##### 3.5.3.4.1 eLoran Transmitter Derived

- Time of Emission control out of tolerance;
- Transmission outage;

- Signal amplitude out of tolerance;
- Envelope-to-Cycle Difference (ECD) out of tolerance;
- Loran Data Channel message failure;
- Loran Data Channel message corruption.

#### 3.5.3.4.2 Propagation Channel Derived

- Excessive early skywave;
- Re-radiation based signal multipath;
- Crossrate interference out of tolerance.

#### 3.5.3.4.3 DLoran Correction Sub-system Derived

- DLoran correction data out of range or tolerance;
- Failure of VPN based data communication backbone;
- DLoran reference station outage due to hardware failure or power failure;
- DLoran software failure;
- DLoran reference station improperly configured;
- Integrity failure at DLoran reference station.

#### 3.5.3.4.4 User Receiver Derived

- SNR out of tolerance;
- Pseudorange measurement variance out of tolerance (equivalent UDRE);
- Incorrect transmitter or reference station almanac;
- Out of date, incorrect, or misconfigured ASF database;
- Continuous wave interference;
- Poor signal tracking;
- Receiver algorithm failure.

#### 3.5.3.4.5 Control Centre Derived

- Control software failure;
- Loss of data communication.

### 3.5.4 AVAILABILITY VERIFICATION

The availability standard adopted for an eLoran service is related to the techniques used in planning and implementing the service.

Availability is defined in IMO Resolution A.915 (22) [14] as:

***The percentage of time that an aid, or system of aids, is performing a required function under stated conditions. The non-availability can be caused by scheduled and/or unscheduled interruptions.***

Availability should include the ability to provide positioning accuracy with 'green-light' integrity; for the system to be available, the system's integrity monitor (IM) must declare that the system is usable.

Availability can be calculated for a given monitor receiver by counting the number of position-fixing epochs for which a valid eLoran position-fix is generated, and the integrity monitor declares that fix is good ('green-light') and dividing this number by the total number of epochs:

$$A = \frac{\sum \text{Green\_light\_fixes}}{\sum \text{Positioning\_Epochs}}$$

### Equation 2    Availability

**Signal availability** is defined as the availability of a radio signal in a specified coverage area. Mathematically this can be written as:

$$A = \frac{\text{MTBO}}{\text{MTBO} + \text{MTSR}}$$

### Equation 3    Signal availability

Where:

**MTBO** = Mean time between outages;

**MTSR** = Mean time to service restoration.

This accounts for scheduled and unscheduled service interruptions, i.e. preventative and corrective maintenance. MTBO and MTSR can be obtained based on a 30-day averaging period, which provides a monthly signal availability figure.

\* Alternatively expressed as UP TIME/TOTAL TIME where TOTAL TIME = 30 days

### 3.5.5 CONTINUITY VERIFICATION

The IMO define **continuity** as:

***The probability that, assuming a fault-free receiver, a user will be able to determine position with specified accuracy and is able to monitor the integrity of the determined position over the (short) time interval applicable for a particular operation within a limited part of the coverage area.***

Inherent in a radionavigation service is the capability to provide accurate position fixing and integrity information without interruption during a specified period (normally short term). Interruptions to eLoran deny vital information to the users and, if frequent, erode user confidence in the ability of the service to provide that information. The frequency of unusable events, not the length of the usable periods, determines continuity performance.

In the event that a healthy and monitored eLoran transmitter or reference station begins to experience intermittent failures (i.e. failures separated in time by a period less than one continuity time interval (CTI)), the period of intermittent operation would be counted as a single failure event for continuity purposes.

**Continuity** is based upon the mean time between failures as measured over a two-year period. It is the probability of a Continuity Failure within any given Continuity Time Interval (CTI), the IMO definition of the CTI is 15 minutes.

**Continuity Failures:** All unscheduled unusable events described in the availability section are considered failures. Unlike availability, continuity does not count scheduled maintenance events as failures. Since public notices are provided for all scheduled maintenance events, users should be aware of such planned outages and plan the voyage accordingly. Nor should Continuity count momentary (single epoch) Integrity monitor 'red-lights' as continuity failures, as these may still constitute correct functioning of the Service. Outages of more than a few epochs are more likely to constitute a system wide issue, for example, transmitter outage. See ANNEX A section A 5.1.

Only a complete loss of positioning, or loss of Integrity Monitoring for any reason without adequate warning (scheduling) is classed as a Continuity Failure.

### **Approximation of Continuity**

If we assume that, for any epoch, the probability of the system going offline is equal to some probability value  $p_{fail}$ . On average failures will occur with a Mean Time Between Failures (MTBF) equal to:

$$MTBF = \frac{\Delta t}{p_{fail}}$$

#### Equation 4 Mean Time Between Failures

Where:

$\Delta t$  is the time in seconds between positioning epochs.

At a certain point ( $t_0$ ) the system is available for use and functioning correctly. The next epoch ( $t_1 = t_0 + \Delta t$ ) the probability of it still being available for use is:

$$p_1 = (1 - p_{fail})$$

The probability of it being available at the next epoch ( $t_2$ ) is:

$$p_2 = p_1(1 - p_{fail})$$

$$p_2 = (1 - p_{fail})^2$$

Thus the probability of  $N$  consecutive epochs without a failure can be written as:

$$p_N = (1 - p_{fail})^N$$

Re-writing  $(1 - p_{fail})$  as an exponential gives:

$$(1 - p_{fail}) = e^{\ln(1 - p_{fail})}$$

Such that:

$$p_N = e^{N \cdot \ln(1 - p_{fail})}$$

Expanding the natural log gives:

$$\ln(1 - x) = -x - \frac{x^2}{2} - \frac{x^3}{3} - \frac{x^4}{4}$$

Since  $p_{fail}$  is (should be!) extremely small, terms in  $p_{fail}^2$  and greater can be neglected, thus:

$$p_N = e^{-N \cdot p_{fail}}$$

Replacing  $N$  discrete epochs with a continuous time-variable  $t$ , and substituting back in the values for MTBF, the probability that the system is still functioning after time  $t$  is:

$$C = e^{\left(\frac{-t}{MTBF}\right)}$$

This is the standard expression for reliability and excludes scheduled outages, assuming that planned outages will be notified and the operation will not take place.

The probability that the service will be available after a time CTI (the continuity) is then:

$$C = e^{\left(\frac{-CTI}{MTBF}\right)}$$

If MTBF is very much greater than CTI, this can be approximated to:

$$C = 1 - \frac{CTI}{MTBF}$$

#### Equation 5 MTBF much greater than CTI

Where:

MTBF is the Mean time between failures; based on a 2 year averaging period

CTI is the Continuity time interval; in the case of maritime continuity equal to 15 minutes.

For eLoran Service verification purposes the figure that needs to be calculated from the data output by the monitoring receiver is MTBF. This is found by counting up the lengths of all the periods of continued operation and taking an average. Starting at the first Epoch for which an eLoran position-fix is available and Integrity monitoring green-light indicates that it is valid (allowing for receiver cold-start time, and time to acquire DLoran corrections), successive valid epochs are counted up until a Continuity Failure occurs. At this point a single observation of Time Between Failures (TBF) has been made, this TBF figure should be stored, and the count begun again at zero.

Recalling that planned maintenance does not count as a Continuity Failure, upon commencement of a planned maintenance outage the TBF count does not reset but is held frozen and continues to count up again after the end of the planned maintenance. Recalling also that successive Continuity Failures within one CTI do not count as separate incidents, any TBF count not greater than the CTI is ignored, and a new count begins again at zero.

MTBF is the arithmetic mean of all stored TBF counts in the data-collection period. By definition, this period should be two years, and Continuity figures derived over shorter time-frames than this are subject to inaccuracy.

## 4 DEFINITIONS

The definitions of terms used in this IALA Guideline can be found in the International Dictionary of Marine Aids to Navigation (IALA Dictionary) at <http://www.iala-aism.org/wiki/dictionary> and were checked as correct at the time of going to print. Where conflict arises, the IALA Dictionary should be considered as the authoritative source of definitions used in IALA documents.

## 5 ACRONYMS

ASF	Additional secondary factor(s)
ATU	Antenna Tuning Unit
CD	Coding Delay
CRI	Cross-Rate Interference
CTI	Continuity Time Interval
CWI	Continuous Wave Interfering
dB	deciBel
DGNSS	Differential Global Navigation Satellite System
DLoran	Differential Loran
ECD	Envelope-to-Cycle Difference
ED	Emission Delay
EGNOS	European Geostationary Navigation Overlay Service
ERP	Effective Radiated Power
FD	Fault detection
FDE	Fault detection and exclusion
FERNS	Far East Radio Navigation Service
FFT	Fast Fourier Transform
GLA	General Lighthouse Authority(ies)
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
GRI	Group Repetition Interval
HAL	Horizontal Alert Limit
HDOP	Horizontal Dilution of Precision



HMI	Hazardously Misleading Information
HPL	Horizontal Protection Level
IALA	International Association of Marine Aids to Navigation and Lighthouse Authorities – AISM
ICAO	International Civil Aviation Organization
ID	Identity
IEC	International Electrotechnical Commission
IHO	International Hydrographic Organization
ILA	International Loran Association (now defunct)
IM	Integrity monitor
IMO	International Maritime Organisation
ITU-R	International Telecommunication Union-Radiocommunication Sector
kHz	kilohertz
km	kilometre
kW	kilowatt
LDC	Loran Data Channel
LED	Light-Emitting Diode
LORAN	LOng Range NAVigation
LORAPP	LORan Accuracy Performance Panel
LORIPP	LORan Integrity Performance Panel
m	metre
Mbit/s	megabits per second
MoU	Memorandum of Understanding
MTBF	Mean time between failures
MTBO	Mean time between outages
MTSR	Mean time to service restoration
MW	megawatt
N/A	Not applicable
NELS	Northwest European Loran System
NSE	Navigation System Error
PC	Personal Computer
PC	Phase Code
PCI	Phase Code Interval
PFA	Probability of false alarm
PNT	Position, Navigation & Timing
PPM	Pulse Position Modulation
RAIM	Receiver Autonomous Integrity Monitoring
rho-rho	Rho-Rho (range-range) navigation system (navigation using two precisely synchronised transmissions and a precise on board clock)
RTCM	Radio Technical Commission for Maritime Services
SAM	Service Area Monitor
SARP	Standards and Recommended Practices (GNSS)
SC	Special Committee (RTCM)



SNR	Signal-to-Noise ratio
TBF	Time Between Failures
TD	Time Difference(s)
TOA	Time of arrival
TOE	Time of emission
TOT	Time of transmission
TTA	Time to Alarm
UDRE	User Differential Range Error
UPS	Uninterruptible Power Supply
USA	United States of America
USNO	United States Naval Observatory
UTC	Universal Time Co-ordinated
UT1	Mean solar time
VPN	Virtual Private Network
VTS	Vessel Traffic Service(s)
WAAS	Wide Area Augmentation System
WGS84	World Geodetic System 1984 (Reference co-ordinate system used by GPS)
WWRNS	World-Wide Radio Navigation Systems
μs	microsecond

## 6 REFERENCES

- [1] IMO Resolution A.1046 (27) – ‘Worldwide Radionavigation System’
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## **ANNEX A**    **PERFORMANCE VERIFICATION USING SHORT TERM MEASUREMENT DATA**

It is assumed that an eLoran system has been installed, including transmitters; DLoran reference-stations; ASF maps; monitoring receivers and all associated ancillary equipment and services. Service providers will wish to determine whether the system they have installed meets their requirements; these are assumed to be (Table 2 of the main Guideline):

**Table 8**    **Suggested minimum maritime user requirements for a backup system for general navigation [IALA Recommendation R-129]**

<b>Voyage Phase</b>	<b>Accuracy (95%)</b>	<b>Availability (%)</b>	<b>Continuity (% over 15 minutes)</b>	<b>Horizontal Alert Limit (HAL)</b>	<b>TTA</b>	<b>Integrity Risk (%)</b>
Port Approach	10m	99	99.97	25m	10s	$10^{-4}$
Coastal Navigation	100m	99	N/A	250m	10s	$10^{-4}$

It is assumed that *static* monitor receivers have been installed at known locations within the service area of a DLoran reference-station, and therefore that nominal ASF values and local differential-corrections are available. It is also assumed that *dynamic* monitoring receivers have been installed on vessels taking part in the performance verification and that they are sailing within the service-area of the DLoran reference-station. The process outlined below assumes that data is collected and processed, including eLoran position-fixing and Integrity information.

### **A 1. HYPOTHESIS TESTING AND CONFIDENCE LEVELS**

The service provider needs to gather some data from a monitor receiver (static or dynamic) and use it to demonstrate a particular aspect of system performance; accuracy, availability, continuity or integrity. Two potential outcomes may occur: either a system parameter meets its performance target, or it does not. It is not possible to know if the system performs to the levels required because it is only ever possible to see the short data-window that has been collected. The fact is that the system may not actually meet its targets, but by sheer chance the data collected could indicate that it does.

Two hypotheses are defined:

H0 = The requirement has not been met;

H1 = The requirement has been met.

To err on the side of safety, it is always assumed that the requirement has not been met.

This is called the ‘null hypothesis’ (H0). To reject this idea and adopt the ‘alternative hypothesis’ (H1) it must be shown that the data that has been collected that could not have reasonably been collected under the assumption of the null hypothesis.

The method outlined below uses the principle of assuming a confidence level, which indicates the probability that a result has been arrived at purely by chance. For example, specifying a confidence level of 2.5%, indicates that H0 is not rejected unless the probability of obtaining the sample data by pure chance is less than 2.5%.

This probability is always calculated under the assumptions laid down in H0, and is based on the actual data collected, not an assumed distribution in the population.

## A 2. ACCURACY VERIFICATION

Radial error is the root sum of the square of the errors in 'y' and 'x' co-ordinates (or Latitude and Longitude), which for eLoran we assume to be normally distributed random errors. The assumption for now is that the error is approximately circular, so the expected errors in 'x' and error in 'y' are about equal and there is no correlation between the two. The radial error follows a Rayleigh probability distribution.

In navigation system analysis, it is traditional to take a finite sample of position-fixes and determine their 95<sup>th</sup> percentile error. Unless mistakes have been made in measuring the data, this value should be an unbiased estimate of the 95<sup>th</sup> percentile of the Rayleigh population. The issue is that taking a finite number of measurements subjects this 95<sup>th</sup> percentile estimate to some error. It may just be that more than 95% of the sample observations happen to lie below the Rayleigh 95<sup>th</sup> percentile, and the population error has been underestimated, or vice-versa.

A hypothesis test is established to determine the significance of the sample that has been gathered. The null hypothesis is that eLoran has failed to provide sufficient accuracy, its 95% error exceeds (but only just) 10 m.

H0: Accuracy of eLoran is just 10 m (95%) (accuracy = 10 m (95%))

H1: Accuracy of eLoran is better than 10m (95%) (accuracy < 10 m (95%))

Note that if it is assumed in H0 that the error is much larger than 10m (say, 30 m) then significance will be easier to prove. H0 sets the conditions for a 'fail' i.e. accuracy is not less than 10 m, but makes the conservative assumption that it is as hard as possible to prove otherwise (accuracy is just 10 m, no less and not much more).

H1 is accepted only if the sample 95<sup>th</sup> percentile is significantly below 10 m, i.e. the upper tail of the confidence bound (at, say 2.5%) does not include the 10 m threshold. To determine the confidence bound, first accept H0, that the population 95% error is indeed 10 m, and that each sample error has exactly 0.95 probability of being below 10 m, and 0.05 probability of being above 10 m. It is then required to know how many sub-10m fixes are needed before H1 is considered plausible.

Suppose one hour of data has been collected. This comprises 720 individual fixes (assuming 5 seconds per independent fix), and it is to be expected that the population 95th percentile error be equal to the error on the fix with the 684th smallest error. The number 684 is actually the expectation value of a Binominal distribution (each fix either lies below the 95% level with 0.95 probability, or above it with 0.05 probability).

The confidence bound can be calculated by integrating the Binomial distribution up to the Confidence level (one tail, 2.5%). To make this integral easier the Binominal distribution can be approximated to a Normal distribution. The number of samples here is  $n=720$ , and  $p=0.95$ , giving:

$$\begin{aligned}\mu &= np = 684 \\ \sigma &= \sqrt{np(1-p)} = 5.85\end{aligned}$$

It is possible to calculate how many sub-10m fixes would significantly indicate H1 is true. The confidence level has been chosen at 2.5%. The one-tail integral of the Normal distribution up to 2.5% is given as 1.96-sigma, the threshold is then:

$$\mu + 1.96\sigma = 684 + 5.85 * 1.96 = 695.4622$$

Rounding up, only if the 696<sup>th</sup> smallest position error in one-hour of data is below 10 m do we accept H1. The 696<sup>th</sup> error corresponds to 96.7% of the one hour's worth of data. Our significance test for a one-hour data-sample is that 96.7% of all fixes are below 10 m. So this has made the accuracy 'target' harder to hit, and so the system will have to perform better than required in the hour.

If it is assumed that the sample population is Rayleigh distributed, a 96.7% accuracy of 10 m corresponds to a population with standard-deviation 3.83 m, and the corresponding 95% accuracy of this population would be 9.38 m.

In essence, by taking a short window of fixes (one hour) it is required to prove 95% accuracy at the 9.83 m level to be confident that 10 m accuracy has been demonstrated with Confidence better than 2.5%. The more data collected, the less stringent the confidence requirement is. Below is a table of the length of time for which data may be gathered showing the fix number that corresponds to 2.5% confidence, which percentile that fix number is for a Rayleigh distribution, and what the effective 95% accuracy of that sample distribution would have to be.

**Table 9** *Duration of measurement period versus statistical significance for effective accuracy target to demonstrate 10m (95%) (assuming 5 seconds per fix)*

Length of Time	Number of Fixes	Confidence Level	Effective Percentile	Effective Accuracy Target
1 hour	720	696	96.7%	9.38m
2 hours	1440	1384	96.12%	9.60m
6 hours	4320	4132	95.65%	9.78m
12 hours	8640	8248	95.46%	9.85m
24 hours	17280	16472	95.32%	9.90m
7 days	120960	115061	95.12%	9.96m
30 days	518400	492788	95.06%	9.98m
1 year	6.3M	6.0M	95.02%	9.99m

By taking more sample data, the requirements are asymptotically equivalent to showing 95% of the sample population lies below 10 m, which is as expected.

In reality, the limitation of using a small data-window is not the statistical significance of the observation, or the number of fixes expected to exceed the target accuracy by sheer chance. The issue is that eLoran position-fixing is dependent on precisely calibrating out the bias in ASF. This value varies throughout the day on a 24-hour cycle and is highly seasonal, showing greater variability in winter than in milder summer months.

In reality, a year's worth of data (or smaller samples taken at intervals spanning 12 months) would be needed to rigorously prove the accuracy performance of the system under all seasonal conditions.

### A 3. AVAILABILITY VERIFICATION

The Null hypothesis (H0) is that the system fails to meet the availability target, the probability of each fix being 'Available' for use is less than (but only just less than) our requirement. The alternative hypothesis is that this probability is higher (the Availability exceeds the target).

H0: Probability of fix availability = 0.99

H1: Probability of fix availability > 0.99

The individual availability of each fix is a Binomial distribution, with  $p=0.99$ . A large number ( $n$ ) of observations is gathered in a sample. The Binominal distribution is again approximated to a Normal distribution.  $\mu=np$ ,  $\sigma^2=np(1-p)$ . The confidence level (at 2.5%) can then be assigned to this distribution.

For example, for one day of data, has  $n=17280$ ,  $\mu=17107.2$ ,  $\sigma=13.1$  (again assuming 5 seconds between fixes). The confidence level (at 2.5%) is mean plus 1.96 times sigma. This is 17132.8, so it is required that there are at least 17133 'available' fixes this day for the result to be significant. This is an Availability figure for the day of 99.15%.

Again, there is a relation between the amount of data gathered, and the 'effective' availability that must be shown to be statistically significant. This is very similar to the Table 9 for accuracy and the required effective

availability is asymptotically (in the number of fixes) equal to the system requirement. With a very large amount of data collected in the sample, proving 99% Availability would require demonstrating 99% sample-availability.

There are limitations with this treatment of Availability – since most of the un-available time is expected to be due to transmitter down-time and maintenance. If the data-collection window in question contains no transmitter-outages then the data is not representative of the ‘long term’ behaviour of the system. 12 months of data would be recommended in order to include a significant number of monthly transmitter maintenance periods.

## A 4. INTEGRITY VERIFICATION

Integrity of  $10^{-4}$  requires that the probability of Integrity failure is less than 0.0001.

H0: Probability of Integrity failure equals 0.0001.

H1: Probability of Integrity failure is less than 0.0001.

The number of Integrity failures in the sample follows a Binomial distribution. For the example of one-day of data,  $n=17280$ ,  $p=0.0001$ ,  $\mu=1.7$ . In this case it is likely that it is not possible to use the Binominal to Normal approximation, as  $\mu$  is less than about 5. A statistical significance test shows that, given H0, a full day of ‘good Integrity’ (i.e. zero integrity failures in the day) can occur purely by chance with probability  $P_0$ :

$$P_0 = (1 - p)^n$$

$P_0$  is equal to 0.1776, so there is a 17.76% chance that, even though the Integrity Risk of the system is just  $10^{-4}$ , a whole day goes by without an Integrity failure. There is no way this can be considered statistically significant, and considerably more data is required to verify Integrity.

For higher levels of Integrity this statistical significance becomes even more demanding. If the system must satisfy  $10^{-5}$  Integrity, a whole two-weeks of data without an Integrity failure can be expected to occur purely by chance with a probability of 8.9% (using the  $P_0$  formula above).

Integrity, if anything, is more suited to this kind of analysis since fault-detection is done by a user’s receiver largely based on a statistical process involving assumptions about pseudo-ranging accuracy. Transmitter off-airs and outages are more likely to impact availability and continuity, since a critical loss of geometry is more likely to result in loss of RAIM rather than Integrity failures (‘yellow light’ Integrity loss rather than ‘green light’ HMI failures).

The only caveat is that loss of minor transmitters (those a long way from the user, or available at low SNR, or those transmitters less critical for position-fixing geometry) are more likely to leave a user still able to use RAIM, but at a lower level of fidelity. In these cases, the assumption that the Integrity risk (probability ‘ $p$ ’) is constant is unlikely to be valid. However, the population Integrity risk will never improve with loss of transmitters. Integrity risk always increases when pseudo-ranging information is lost, so the test will prove, if anything, an overly pessimistic indication of true system performance.

The following table indicates the amount of data-collection required and what can be determined of Integrity.

**Table 10** *Duration of measurement period versus statistical significance for effective Integrity Risk target to demonstrate  $10^{-4}$  Integrity Risk (assuming 5 seconds per fix)*

Length of Time	Number of Fixes	Notes
1 day	17280	All-clear can occur with 17% probability, no way to verify Integrity.
2 days	34560	All-clear can occur with 3.2% probability. One failure will occur with 11% probability. We would need 100% all-clear to suggest that Integrity is better than $10^{-4}$ at 5% Confidence.
7 days	120960	All-clear would occur with 0.00056% probability. One failure would occur with 0.007% probability. Two-failures at 0.04%. Three-failures at 0.16%. Four failures at 0.5%. Five failures at 1.2%. Six at 2.4%. We would probably accept up to five Integrity failures in a week and still determine that Integrity is better than $10^{-4}$ . Five failures in 120k fixes is $4 \times 10^{-5}$ Integrity.
14 days	241920	Would accept up to 14 Integrity failures for 2.5% Confidence. This is effectively $5.8 \times 10^{-5}$ Integrity.
30 days	520k	37 failures allowable at 2.5% Confidence. Effectively $7 \times 10^{-5}$ Integrity.
1 year	6.3M	Can use Normal Distribution approximation. Would ordinarily expect 630 failures in a year. Our Confidence requirement is to have less than 581, which is an effective Integrity of $9.2 \times 10^{-5}$ .

A large amount of data (>1 year) is recommended to be collected, by shortening the data-collection time a price is paid that a more stringent level of Integrity must be demonstrated for the result to be significant. One year's worth of data still pays this price, but  $9.2 \times 10^{-5}$  Integrity is probably an achievable result.

## A 5. CONTINUITY VERIFICATION

Continuity may be dealt with in one of two ways. Either assume a given probability, for each position-fix, that continuity will be lost (loss of positioning, or loss of RAIM) or deal with each Continuity Time Interval (CTI) as a single block, and assume a fixed probability for these intervals.

The second option is probably the most reliable way to handle Continuity, in part because of the calculation that needs to be done for a fixed probability per position-fixing epoch results in highly implausible figures. For example, if it is assumed that each epoch has chance ' $p$ ' of losing continuity. The requirement 99.97% continuity over 15 minutes means 180 consecutive epochs (15 minutes at 5-second epochs) have to preserve continuity with probability 0.9997, the calculation for  $p$  is:

$$(1 - p)^{180} = 0.9997$$

Solving for  $p$  results in  $p = 1.7 \times 10^{-6}$  chance of Continuity loss. This is much more stringent than even our Integrity requirement. The implication is that it would be preferable to see HMI than get an Integrity 'yellow light', which is clearly nonsense!

The 'sense' emerging from this is that Continuity losses are more likely to be due to transmitter off-air, where loss of position-fixing geometry (reducing the number of transmitters down to 3, for instance) means RAIM becomes unusable. These losses will be grouped together in outage intervals, so perhaps should not be thought of as events occurring at random on each epoch. A better statistical treatment of Continuity is to consider each CTI as individual 'units' and treat these with the Binomial distribution. Even so, the assumption is being made

that these are independent blocks, and (unrealistically) that a transmitter outage would not span more than one block.

H0: Probability of continuity in each CTI is 99.97%.

H1: Probability of continuity in each CTI is better than 99.97%.

Assuming H0, it is expected that one in every 3333 CTIs will have a continuity failure – this is approximately once a month. At a minimum, it is required to gather a month's worth of data to determine Continuity with any degree of confidence. Apply the Binomial distribution, assuming  $p = 0.9997$  to find out how many CTIs need to show continuity to be considered significant. The results are outlined in Table 11:

**Table 11** *Duration of measurement period versus statistical significance for continuity verification (assuming 5 seconds per fix)*

Time Interval	Number of CTI	Notes
1 month	2880	42% chance of all-clear under H0, no chance of significance.
2 months	5760	17.8% chance of all-clear under H0.
1 Quarter (3 months)	8640	7.5% chance of all-clear.
6 months	17280	0.56% chance of all-clear. 2.9% chance of one failure. 7.5% chance of two failures. We would accept 6 months of all-clear as significant at 2.5%, and allow one continuity outage at 5% confidence.
12 months	35k	0.0027% chance of all-clear. 0.028% for one outage. 0.15% for two outages. 0.53% for three outages. 1.38% for four outages. 2.91% for five outages. At 2.5% significance, up to four continuity outages in a year would probably be allowed. This is 99.99% continuity.
24 months	70k	Probably allow Normal approximation for 2 years of data. 21 outages would be expected in this time-period under H0. 2.5% significance would be fewer than 12 outages in total. This is 99.983% 'effective' continuity.

Note that there is a significant gain to be had by increasing the period of data-collection. In the first six months of a year it would be appropriate to only consider declaring continuity had been met with an all-clear (or possibly one outage). Taking the next six months in isolation, again an all-clear (or possibly one outage) would be required. However, combining the two half-years into one continuous data-collection period of 12 months, would allow up to four outages in total. Doubling the monitoring period again allows up to 12 outages (rather than two lots of 4 if the two years were treated as being separate).

Continuity is by far the most difficult requirement as the specification stands. Two years' worth of data are required to demonstrate results with any degree of significance. Even so, the continuity level needed for significance is approximately twice our requirement. The 'budget' for significant non-continuity is 0.0172% at the two years' worth of data level. Compare that to the base requirement of 0.03% non-continuity.



## A 5.1. COMPATIBILITY WITH INTEGRITY REQUIREMENT

A by-product of the toughness of the Continuity requirement is in how Integrity warnings (and HMI) must be handled by the Continuity calculation. In two years' worth of data, we expect 21 Continuity outages to occur. It is easy to see that if HMI and Integrity 'red lights' are also counted as Continuity failures that this is an almost impossibly difficult requirement to place on any system. At  $10^{-4}$  Integrity 1261 incidents of HMI would be expected. In the same period, if 0.02% of the Availability 'budget' were to be allocated to the Integrity Monitor, roughly 2500 Integrity false-alarms would be expected.

It might be reasonable to accept that HMI usually occurs when transmitters go off-air (as accuracy and integrity are reduced) so it can be allowed that most of these 1200 HMI incidents will group together into the 21 Continuity outage periods, corresponding to unplanned transmitter outages.

It is a harder prospect to insist that Integrity False-Alarms also occur only when there are transmitter outages. It would have to be insisted that the probability of integrity monitor false alarm when the system is operating without fault be almost zero. Certainly, if these 21 outages are allocated as being either due to a transmitter off-air, or due to an Integrity false-alarm, roughly 50% of each might be allowed. Ten (10) Integrity false-alarms in 2 years corresponds to a probability of  $8 \times 10^{-7}$  or significantly lower even than our Integrity requirement of  $10^{-4}$ . It does not make any sense that HMI is a considerably more favourable outcome (by a factor of about 120) than False-Alarm.

Faced with this requirement, the only conclusion is that the only rational Integrity Monitor is one where the green light is wired 'on' permanently, and the red light is disconnected permanently, any incident of HMI simply to be absorbed into the  $10^{-4}$  budget. This setup would no-doubt get closer to the requirements than any algorithm attempting to detect Integrity hazards!

**It is proposed that further work is required to establish the compatibility between the required performance parameters integrity and continuity and their respective IMO definitions.**

## A 6. CONCLUSIONS

### A 6.1. ACCURACY

To achieve statistical significance for Accuracy, the system must effectively demonstrate a tighter level of accuracy than the base requirement. The degree to which the demonstration must 'over shoot' its target depends on how much data is gathered, longer data-collection windows allow for an 'easier' target.

In reality, this is not going to be the biggest issue. The practical task of verifying eLoran accuracy has more to do with demonstrating that the seasonal variations in signal-propagation and ASF do not adversely affect the positioning accuracy throughout the year. It would be difficult to choose a 'worst month' to verify in advance without knowing which month that is.

### A 6.2. AVAILABILITY

The statistical treatment of Availability is much like accuracy, and gathering a short data-collection set effectively makes the target Availability requirement higher.

Again, as with accuracy the issue is probably not going to be statistically significant, but to do with the fact that eLoran availability should be demonstrated in all seasons, and under varying signal propagation conditions. A short data-set may 'demonstrate' Availability under the stated conditions, but would not be particularly believable to an eLoran engineer, who would know to expect significant seasonal variation.

### A 6.3. INTEGRITY

If a short data-collection window is used then the ‘target’ Integrity performance needed to declare significance is increased greatly. Even allowing for a year’s worth of data-collection, a system requirement of  $10^{-4}$  Integrity means the data-sample must over-shoot its target by about 10% and show  $9 \times 10^{-5}$  Integrity in order to be considered statistically significant. This is plausible and would be a reasonable way to test the system.

#### A 6.3.1. CONTINUITY

Continuity is a very difficult requirement, and again there is the same dependency between the length of the data-collection window and difficulty of the target. If the collection window is too short then even a ‘perfect record’ does not significantly indicate the system meets the requirement.

Even with a 2-year data-record, the data-sample must demonstrate 99.983% Continuity to verify the system meets the requirement at 2.5% Confidence. Note that this is a higher requirement than the base IMO requirement of 99.97%.

#### A 6.3.2. RESULTS

It is recommended that at least 12 months of data is collected to verify eLoran system performance under varying seasonal conditions. Arguments may be made regarding the statistical significance of Accuracy and Availability data gathered over shorter periods of time, but these neglect underlying physical properties of the system.

Verifying Integrity and Continuity at a reasonable confidence level will require a long data-set no matter how the argument is phrased. One year is recommended as a minimum. It is probably not possible to verify eLoran Continuity at the level of the stated IMO performance-requirements with anything less than 2 years of data or more.