40th ILA(International Loran Association) Annual Convention and Technical Symposium

Tutorial

Haeundae Centum Hotel, Busan, KOREA
November 17-19, 2011

Organized by

International Loran Association

Sponsored by

Maritime Industry Research Institute

BUSAN CONVENTION & VISITORS BUREAU

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KOREA ASSOCIATION OF AIDS TO NAVIGATION

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GMT

Tutorial of 40th ILA (International Loran Association) Annual Convention and Technical Symposium

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Program of 40th ILA Annual Convention and Technical Symposium

Thursday, November 17, 2011

08:00 am Registration/Information Desk Open

09:00 am Booth Setup / Open (closing time : 17:00 pm, November 18)

09:20 am Welcome Remarks
Mr. Ha Pan-do(Director of Maritime Traffic Facility Department, Ministry of Land, Transport and Maritime Affairs)

09:30 am Keynote Speech
Dr. Kenneth C. Crawford(Vice-Administrator, Korea Meteorological Administration)
- The Marine Weather Services of Korea : Improvements Coming, More needed"

10:20 - 10:40 am **Photo time & Morning Break**

10:40 - 12:00 am **Session 1: World Status Updates**
Chairman : Mr. Charles Schue

10:40 am **Status of eLoran in the UK**
Mr. Chris Hargreaves, Mr. George Shaw, Dr. Paul Williams and Prof. David Last, GLAs

International Trend and Status for eLoran and Its Application in Korea
Prof. Dr. Gug Seung-Gi, KMU

Norway - observer's report
Ms. Kirsten Ullbaek Selvig , Norwegian Ministry of Fisheries and Coastal Affairs

Present Status of Chayka in the Russian Federation
Mr. Vadim ZHOLNEROV, The Russian Institute of Radionavigation and Time

Confirmation of the Accuracy Performance of North-West Pacific Loran-C Chain
Mr. Kazuyuki TANAKA, JCG

12:00 - 13:30 pm **Luncheon** - *18F Executive Lounge*

13:30 - 15:00 pm **Session 2: eLoran Technology I**
Chairman : Prof. Dr. Gug Seung-Gi

13:30 pm **Alternative Positioning, Navigation, and Timing (PNT) for Korea and the World**
Mr. Charles Schue, Mr. Chris Stout, Dr. Arthur Helwig, Dr. Gerard Offermans, UrsaNav

14:00 pm **The Operation Status and Expectation of Loran-C in the Republic of Korea**
Mr. Kim Hyun, Mr. Gu Ja-heon MLTM

14:30 am **Deriving Stratum-1 Time-of-day and Frequency using a Pulsed Low-Frequency System: Design and Test Results of an eLoran Timing Receiver**
Dr. Arthur Helwig, UrsaNav

15:00 - 15:30 pm **Afternoon Break**

15:30 - 17:30 pm **Session 3: eLoran Technology II**
Chairman : Mr. Tamotsu Ikeda

15:30 pm **Alternative Configurations for Co-located eLORAN and DGPS Antennas**
Mr. John Pinks, Nautel

16:00 am **Low Frequency Solutions for Alternative Positioning, Navigation, Timing and Data (PNT&D)**
Mr. Chris Stout, Dr. Arthur Helwig, Dr. Gerard Offermans and Mr. Charles Schue, UrsaNav

16:30 pm **GPS Jamming Accidents and its impact in the Korean Peninsula**
Mr. Bae, Yong Chan, MLTM

17:00 am **Differential eLoran Trials in France**
Dr. Gerard Offermans, Dr. Arthur Helwig, UrsaNav
Jean-Francois Grall, and Thierry Denaes, DCNS

17:30 pm - 18:20 pm **ILA Board Meeting**

18:20 - 20:00 pm **Banquet** - *4F Zeus Hall*
Prof. Dr. Kwak Kyu-seok, President, KINPR
Mr. Ryu Young-ha, President, KAAN
Dr. Sally Basker, President, ILA

Friday, November 18, 2011

08:00 am **Registration/Information Desk Open**

09:00 - 12:00 am **Session 4: Tutorial**
Chairman : Prof. Dr. Gug Seung-Gi

09:00 am **Investigating eLoran Integrity**
Mr. Chris Hargreaves & Dr. Paul Williams, GLAs

eLoran Receivers Tutorial
Dr. Arthur Helwig, UrsaNav

Next Generation LF Transmitter Technology for eLORAN Systems Tutorial
Mr. Tim Hardy, Nautel

12:00 - 13:30 pm **Luncheon** - *18F Executive Lounge*

13:30 pm **eLoran Signal Specification Tutorial**
Dr. Gerard Offermans, UrsaNav

14:30 - 15:00 pm **Afternoon Break**

15:00 - 16:00 pm **ILA Annual Convention**

18:00 - 20:00 pm **ILA Convention Dinner** - *4F Zeus Hall*

Saturday, November 19, 2011

Technical Tour - *Korea Maritime University (KMU)*

09:00 am Departure from the *Lobby, Centum Hotel*

10:00 am Simulation Center of KMU

10:45 am Maritime Museum

11:15 am MV HANBADA (Training Ship)

12:00 - 13:30 pm **Luncheon** - Korean BBQ

14:00 pm International & Fish Market (Nampo-dong)

17:00 pm Arrival at Centum Hotel

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SESSION 4

Tutorial

Investigating eLoran Integrity

Mr. Chris Hargreaves and Dr. Paul Williams

(General Lighthouse Authorities, R&RNAV)

Mr. Chris Hargreaves is a Development Engineer with the Research and Radionavigation Directorate of The General Lighthouse Authorities of the UK and Ireland, based at Trinity House in Harwich, England. His main area of work for the GLAs is in project delivery of their eLoran Work Programme, wherein he takes part in trials, develops software and data analysis techniques. He holds an MSci in Maths and Physics from the University of Durham, and an MSC in Navigation Technology at the University of Nottingham. He is a member of the Royal Institute of Navigation.

Dr. Paul Williams is a Principal Development Engineer with the Research and Radionavigation Directorate of The General Lighthouse Authorities of the UK and Ireland, based at Trinity House in Harwich, England. As the technical lead of the GLA's eLoran Work Programme, he is involved in planning the GLAs' maritime eLoran trials and works on a wide range of projects. He holds BSc and PhD degrees in Electronic Engineering from the University of Wales, is a Chartered Engineer, and an Associate Fellow of the Royal Institute of Navigation.

INTRODUCTION. eLoran is a terrestrial radio-navigation system, born out of Loran-C, that consists of a number of high-powered radio transmitters that operate by emitting a series of precisely timed pulses of energy centred at 100kHz. In addition, eLoran includes reference stations that are able to broadcast differential-corrections to a user on a data channel modulated directly onto the Loran pulses themselves.

The GLAs have argued that eLoran possesses the capability to act as a national, and international, backup to GPS for maritime navigation. The GLA have demonstrated that provision of accurate ASF data and a DLoran service can enable the mariner to fix their position using eLoran with a 95% accuracy of better than 10m. Long-term monitoring of the eLoran transmissions has demonstrated that the required levels of signal availability can be met by the service. However, doubts remain over the ability of eLoran to provide the required integrity, and no long-term eLoran Integrity monitoring campaign has been undertaken in Europe.

This paper presents work undertaken to develop and test an Integrity Equation for eLoran. Some of the results of testing are presented, with a few conclusions and suggestions for future work.

BACKGROUND. The basic method of providing positioning Integrity is to perform an assessment to validate each position-fix as it is made. This assessment typically takes the form of a Horizontal Protection Level (HPL) and provides an estimate of the maximum likely error of the fix. If this error is below a specified Horizontal Alert Limit (HAL) then the fix is validated as 'good', if the HPL breaches the HAL then the fix is designated 'bad'.

Statistically speaking it would be impossible to guarantee that *any* level of accuracy can be obtained 100% of the time, so an accepted margin for error is specified. This is the Integrity Level, or the percentage of fixes validated as 'good' that may be allowed to breach the HAL. Such fixes are designated as Hazardously Misleading Information (HMI) and are considered a danger to navigators, so their occurrence should be minimised at all costs.

For maritime navigation by electronic means the IMO standards [1] have set the required Integrity Level at 10^{-5}, so the HPL equation must bound the positioning errors 99,999% of the time (at the 'five-nines' level).

USE of HPL. The advantage of using a HPL is that a navigator can be provided with information regarding the reliability of their position-fix: this ensures that the system is used with an appropriate degree of trust. Over-reliance on a system may occur if position fixes are assumed to be much better than they are, and conversely mistrust may be engendered if a system often reports erroneous positions without first issuing a warning.

An additional benefit of HPL-based Integrity will be realised in an e-Navigation context, through data-fusion and integration of multiple navigation systems. The benefits of having a suite of independent position-fixing technologies (for example GNSS; Inertial; Radar; eLoran) are most easily attained through the coupling of navigation data in software, this is readily done with a Kalman Filter. The key to optimising system Integration and Kalman Filter performance is to have reliable input data and good *a-priori* estimates of the accuracy of the various systems being integrated, the HPL can provide these.

DEFINING HPL. The basic method for generating a HPL consists of modelling the expected positioning errors, and developing a method for bounding these errors at the required Integrity Level. In practice the most challenging aspect is determining what error-model to use, there are a number of options available:

Probability Distribution Function (PDF). An approach to creating an HPL equation is to model the errors on the navigation signal measurements (or pseudoranges) by a given PDF, it is usual practice to apply the Central Limit Theorem to ranging errors and assume a Normal Distribution applies. This distribution has the advantage that a single parameter (the standard-deviation) is all that is needed to describe the positioning-error and to be able to integrate this PDF up to a required Integrity Level to provide the HPL.

Using a Normal Distribution for pseudo-range errors for eLoran we assume that the standard-deviation is directly related to the quality of the signal-tracking, which itself is dependent on the Signal-to-Noise Ratio (SNR) of the tracked signal. A suitable equation can be used to calculate standard-deviation from SNR.

Error Bounding. It may not always be possible to assume a Normal Distribution for error-sources, and it may be more beneficial to establish an absolute limit that over-bounds any error that might reasonably be expected.

In their evaluation of eLoran for aviation NPA, the FAA team in the USA developed an Integrity equation based on a method of bounding expected errors based on long-term observations of ASF data [2] This practice was essential to guarantee the stringent 10^{-7} (seven-nines) Integrity Level required for aviation.

For maritime use the required accuracy performance for eLoran is significantly higher, so this may not be a beneficial technique, as the leeway for over-bounding error sources is significantly lower. In addition, the reduced Integrity requirement for maritime means such a strict bounding is not as essential.

LEAST-SQUARES POSITIONING. We have assumed that eLoran position-fixing is derived using an over-determined Least-Squares solution of pseudorange observations. Some mathematical understanding of this procedure is needed to relate pseudo-ranging covariance to positioning accuracy. Since groundwave geodetic range measurements are not linearly related to position, we linearise the pseudorange equation, at an estimated position (x_0) to give the linear matrix equation:

$$\underline{l} = G\underline{x} \quad (0.1)$$

Where G is the Jacobian of the observables, $\underline{x}$ is a change in position coordinates and $\underline{l}$ is the vector of corresponding changes in measured pseudorange:

$$G = \left.\frac{\partial l}{\partial x}\right|_{x0} \quad (0.2)$$

$$G = \begin{bmatrix} \sin(\alpha_1) & \cos(\alpha_1) & 1 \\ \vdots & \vdots & \vdots \\ \sin(\alpha_n) & \cos(\alpha_n) & 1 \end{bmatrix} \quad (0.3)$$

$$l_i = \left(TOA_o - TOA_e\right)_i \quad (0.4)$$

Given an observation vector l, the optimised Least-Squares estimate of the parameter update $\underline{x}$ is given by:

$$\hat{\underline{x}} = \left(G^T W G\right)^{-1} G^T W \underline{l} \quad (0.5)$$

Where W is the pseudorange weighting matrix. A solution is attained by iteration, for this solution to be optimal, W should be approximately equal to the inverse of the covariance of the pseudorange measurements:

$$W = \left[\left\langle \underline{l} - \underline{\mu}_l \right\rangle^2 \right]^{-1} \quad (0.6)$$

$$W = C_{PR}^{-1} \quad (0.7)$$

Propagating this covariance, we can derive the covariance of the position estimate as:

$$C_x = \left(G^T W G \right)^{-1} \quad (0.8)$$

Provision of an HPL for position-fixing is then dependent only on having a good estimate of the pseudorange covariance (C_{PR}), and calculating the position-bound at the five-nines level.

PSEUDORANGE ERROR EQUATION. As described above, the eLoran team in the USA developed an HPL Equation for aviation NPA [2] which relied on error-bounding to guarantee Integrity. The equation is shown (1.9), here β, γ and *PB* relate to correlated; uncorrelated; and Positional ASF bounds respectively.

$$HPL = \kappa_{RNP} \sqrt{\sum_i K_i \alpha_i} + \left| \sum_i K_i \beta_i \right| + \sum_i \left| K_i \gamma_i \right| + PB \quad (0.9)$$

The first term in (0.9) implies (for a position fix using N transmitters) a summation of the N pseudorange variances (α_i), weighted by the appropriate column in the Least-Squares projection matrix K. The projection matrix and TOA variance estimations are given by:

$$K = \left(G^T W G \right) G^T W \quad (0.10)$$

$$\alpha_i^2 = c_1 + \frac{337.5^2}{N_i \cdot SNR_i} \quad (0.11)$$

This equation was also used as the backbone of the Loran Coverage and Availability Simulation Tool (LCAST) [3]. For this reason we term it the LCAST equation. As mentioned before, a method of absolute-bounding of errors may not be appropriate for maritime eLoran, but we may make use of the TOA variance equation.

The second term in (0.11) was derived theoretically using the Loran frequency and the ideal antenna/ receiver bandwidth, N is the number of pulses integrated over and SNR is the Signal-to-Noise Ratio. The first term c_1 is an empirically observed offset for timing errors at the transmitter. A nominal figure of $(6m)^2$ was used for c_1, although work done by the GLA has suggested this is perhaps too pessimistic, and $(4m)^2$ is probably a better choice.

HPL EQUATION. For the purposes of this work, we have used the LCAST variance equation, but with our own HPL equation derived from covariance propagation(0.8):

$$HPL = \kappa_{HEA} \sqrt{C_x(1,1) + C_x(2,2)} \quad (0.12)$$

$$C_x = \left(G^T C_{PR}^{-1} G \right)^{-1} \quad (0.13)$$

Where C_{PR} is the covariance matrix of the receiver's pseudorange measurements taking into account all sources of error. The eLoran pseudorange is made up of a Time-of-Arrival (TOA) measurement, plus an applied correction for ASF, provided by tabulated Spatial ASF plus local differential-corrections, we have:

$$PR = TOA + ASF + DLoran \quad (0.14)$$

$$C_{PR} = C_{TOA} + C_{ASF} + C_{DLoran} \quad (0.15)$$

Each of which will have to be measured, or estimated, and provided to the receiver so that each source of error can be accounted for. This paper only investigates the contribution of C_{TOA}, the first term in Equation(0.15), the error due to time-of-arrival phase measurements made by the receiver. Under normal operation this term is expected to be the largest contributor to position error, and is the most critical component of the HPL equation.

METHOD. A differential-Loran Reference Station was first established in Harwich in 2008, and has operated almost without interruption since the winter of 2009. There are to date some 700 day's worth of eLoran data recorded by the machine. The unit continually measures the incoming eLoran signals and, by time-stamping the measurements relative to GPS time, determines a true range-measurement and range-correction for each signal. These corrections are averaged over a given time-interval to remove noise and then broadcast via the Loran Data Channel (LDC) from Anthorn. The unit also makes use of these corrections to form a zero-baseline differential-eLoran position fix as a post-broadcast check.

To test the candidate HPL equation, all of the data recorded by the reference station was processed according to the method below:

1. At each epoch, the observed Signal-to-Noise Ratios (SNRs) of the navigation signals used from Harwich (Anthorn, Lessay and Sylt) were passed to the TOA error-estimation equation.
2. The equation then returns the expected ranging standard-deviations and five-nines bound (HPL).
3. The actual positioning error at each epoch was then calculated by comparing the zero-baseline eLoran fix with the surveyed location of the station's antenna.
4. A Stanford Diagram comparing HPL with positioning accuracy was populated to show the performance of the equation being tested.

The Stanford Diagram plots positioning accuracy against HPL as a histogram, and is used to assess the performance of an HPL equation, the diagram itself is divided into four regions, as shown below:

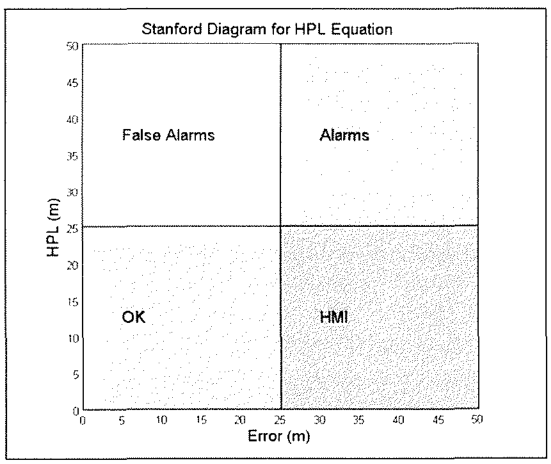

Figure 1 - Diagram for 25m HAL

Error<HAL and HPL<HAL: Is the 'OK' region, this is where the vast majority (>99.8%) of fixes should occur.

Error<HAL and HPL>HAL: 'False alarms', the HPL has breached the limit and declared the fix unusable, but the accuracy is good. Too many fixes in this region and the system Availability begins to suffer.

Error>HAL and HPL>HAL: 'Alarms', this is what we want the HPL equation to do - when the fix is in error, the equation successfully flags it as such.

Error>HAL and HPL<HAL: Hazardously Misleading Information 'HMI' - the fix is bad but the user has been told it is good, this is the one situation that must be avoided, our limit for this region is 0.001%..

Pre-Processing. Under normal operation it is expected that there will be some variation in the quality of signal-tracking and the accuracy of TOA measurements. This may be due to local interference or momentary outages or disruptions to the service at the transmitter. Such events may count towards system unavailability or even HMI on the Stanford diagram, but are an accepted hazard of eLoran.

However, from time-to-time a transmitter may have to be taken off-air for maintenance or switched into 'blink' mode to indicate that the signal should not be used due to a fault. This is important for Integrity, and blinking signals should not be used in a position-solution. To account for this, the reference-station data underwent some pre-processing to identify and remove any signals demonstrating blink. Fortunately such periods are easy to identify and are also recorded and published by CCB [4].

It is assumed that a user's receiver shall be able to detect the presence of blink in a timely manner and will automatically remove off-air and blinking signals from the positioning solution, in accordance with the minimum operational standards [5].

RESULTS. The results are presented in two ways, the Stanford Diagram, together with the statistics of each quadrant; Availability and Integrity.

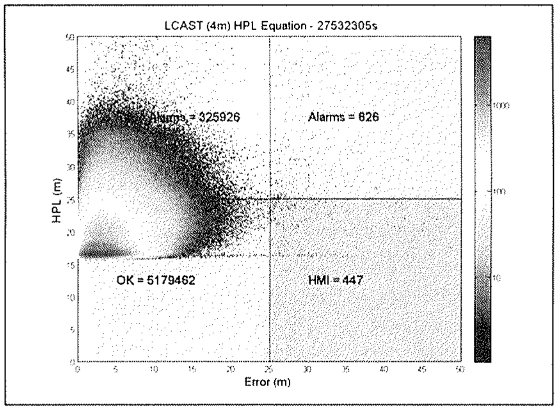

Figure 2 – Stanford Diagram for LCAST (4m) HPL Equation

Region	Number of Epochs	Percentage of Total
Normal Operation	5179462	94.0615%
Alarms	626	0.0114%
False Alarms	325926	5.9190%
HMI	447	0.0081%
TOTAL	**5506461**	**100%**
System Available	5179909	94.0679%
Integrity OK	5506014	99.992%

Table 1 – Statistics for Figure 2

50m HAL. The possibility was considered that for the purposes of guaranteeing high Integrity, it may be necessary to raise the Horizontal Alert Limit from 25m to 50m. The results of doing this are presented below:

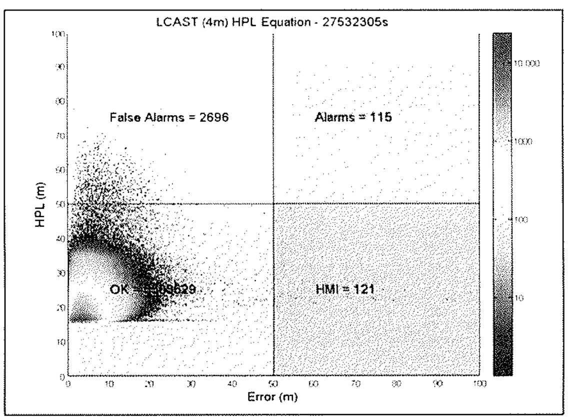

Figure 3 – Stanford Diagram for LCAST (4m) HPL Equation using 50m HAL

Region	Number of Epochs	Percentage of Total
Normal Operation	5503529	99.947%
Alarms	115	0.0021%
False Alarms	2696	0.049%
HMI	121	0.0022%
TOTAL	**5506461**	**100%**
System Available	5503650	**99.949%**
Integrity OK	5506340	**99.998%**

Table 2 – Statistics for Figure 3, using a 50m HAL

INITIAL SUMMARY. The HPL equation gives reasonable Integrity performance at the four-9s level, but sacrifices Availability slightly. Raising the HAL limit from 25m to 50m lessens the performance requirements sufficiently to allow both Availability and Integrity to be within reach.

INVESTIGATION. As described above, the HPL equation performs two separate tasks:

1. The quality of the signal TOA measurements are assessed using observed signal-quality statistics (such as SNR), and an equation is used to generate the expected TOA-standard-deviation.
2. The accuracy of the TOA measurements is then related to positioning accuracy using a second equation. This provides a protection level that should bound a given percentage of fixes (in our case 99.999%).

The performance of the HPL equation will depend on how well each of these tasks is performed.

TOA ERROR ESTIMATION. It was thought that further investigation should be carried out to determine how well the equations work in predicting TOA standard-deviation, and also to determine if the Normal distribution is the ideal PDF to model TOA measurement errors.

As can be seen in Figure 2, the error estimation equation is quite pessimistic in predicting the positioning errors, and as a result the Availability figures appear reduced.

To investigate the relationship between TOA standard-deviation and SNR, the reference-station data was processed again, using the method below:

1. A long-period exponential average (15-minute period) was passed through each signal's TOA data, forwards-and-back filtering was used to remove filter lag. This was to account for any long-term trend in ASF or drift in the local clock (GPS disciplined Rb oscillator)
2. The TOA errors were then given as the residuals of the measurements from this exponential-average.
3. The corresponding SNR value for each TOA error was found.
4. A histogram was populated by assigning the TOA-error and SNR values at each epoch into particular 'bins' at regular spacing. This histogram is shown in Figure 4,Figure below.

The standard-deviation of the histogram for each SNR 'bin' was calculated using the following result from statistics:

$$\sigma = \sqrt{\frac{\sum_i x_i^2 \cdot f(x_i)}{\sum_i f(x_i)}} \qquad (0.16)$$

Where x is the centre value of a particular TOA-error bin and $f(x)$ is its occupancy. The histogram bin standard-deviations are shown in figure 4:

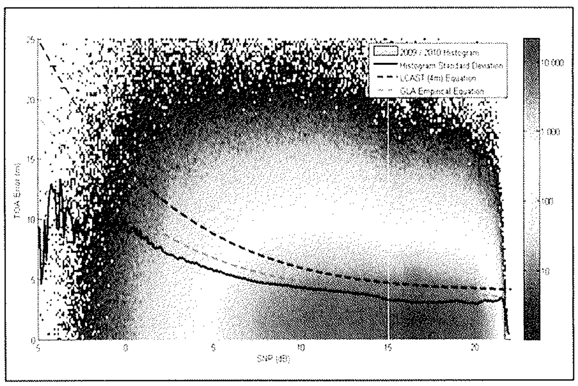

Figure 4 – Histogram of TOA errors vs. Signal-to-Noise Ratio (SNR)

It can be seen that the equation over-bounds the histogram standard deviation by up to 25-30%, and there appears to be quite good correlation for the stronger signals (SNR +15 to +25). However, the model does not work as well for weaker signals.

A modified form of the equation is also shown; this is not based on any theory but is an attempt to modify the existing equation to fit the observed data better. The changes made are:

1. Reduction of the transmitter-related noise from 4m to 3.5m to better fit the accuracy of the stronger signals.
2. Reduction of the coefficient in the second term of the equation to reduce how steeply the errors build up for weaker signals, while still bounding the real standard-deviation at all SNR.

TOA Error PDF Validity. In addition to predicting the standard-deviation correctly, the HPL equation must also use a reasonable model of the pseudo-range error Probability Distribution Function (PDF). The PDF we have chosen for the TOA-error model is a Normal Distribution, or one-sided Gaussian.

$$f(x) = \frac{1}{\sqrt{2\pi}\sigma} \exp\left(\frac{-x^2}{2\sigma^2}\right) \qquad (0.17)$$

To check the validity of this assumed PDF, a vertical slice through Figure 4 was taken at +15dB SNR and is plotted below in Figure 5, with the corresponding Normal distribution shown:

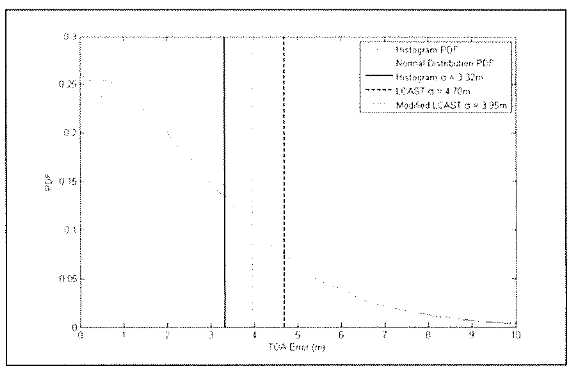

Figure 5 – Vertical 'slice' through Figure 4 at +15dB SNR, actual and modelled TOA standard-deviations are shown.

There is a slight discrepancy between the expected PDF (Normal Distribution) and the raw data histogram as shown in Figure 5. This discrepancy means that the assumed relationship between the number of standard-deviations and the bounding percentile may not be valid, and a Gaussian Distribution may be a poor description of the PDF.

To confirm this a Chi-Squared test was performed for each SNR 'bin' to test how accurately the assumed Normal Distribution fitted the histogram population. This test provides the percentage chance that the deviation from a Gaussian could have happened by random chance.

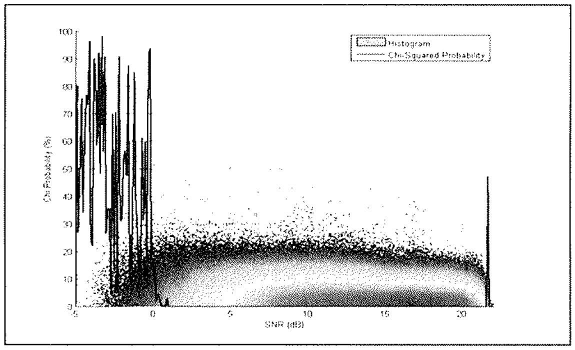

Figure 6– Chi Squared Test probability shown against TOA/SNR Histogram, probability is ~zero for most of the data

The large number of observations in the centre of the histogram means that even the small deviation from the Normal distribution, seen in Figure 5 is significant and produces an extremely unlikely Chi-Squared Statistic. Chi probability is almost zero between +1 and +21 dB SNR, indicating without a doubt that the distribution of TOA errors is not Normally Distributed. The larger chi probabilities towards the low end of the SNR scale (<0 dB SNR) are likely due to the uncertainty of having relatively few number of measurements made here.

Positioning Error PDF Validity. The second task of the HPL equation as described above is concerned with converting the expected signal measurement (pseudo-range) errors into a position bound.

The model that has been used assumes a symmetric (uncorrelated or 'circular') 2D Normal Distribution. The result is that it is assumed that the radial positioning error follows a Rayleigh Distribution:

$$f(r) = \frac{r}{\sigma^2} \exp\left(\frac{-r^2}{2\sigma^2}\right) \qquad (0.18)$$

It is known that in many locations the eLoran positioning distribution takes an elliptical form, in the case of a highly eccentric position-ellipse, this 'circular' model will break down. This model is therefore used with caution, as the eccentricity of the positioning ellipse could make the assumed distribution of errors incorrect.

Taking Figure 2, for example, the distribution of radial positioning errors for a given HPL value can be found by taking a horizontal 'slice' through the histogram and plotting the radial error PDF:

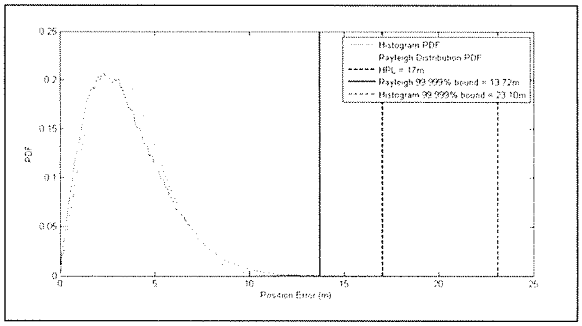

Figure 7 – Horizontal 'slice' through Figure 2 at HPL=17m

Using results from statistics, the value of σ can be found above that fits the raw data (blue line) to the Rayleigh equation. The distribution that best fits the raw data is shown above (red line). Note that the HPL bound lies above the theoretical 99.999% bound for this PDF. This indicates that the HPL equation is successfully providing a five-nines bound on the theoretical PDF. However, the actual 99.999% bound for the positioning-error histogram lies somewhat above both the HPL and Rayleigh distributions. This suggests that the theoretical PDF does not accurately bound positioning errors at the higher percentiles. It is possible that a new PDF may be needed to model eLoran position-fixing.

PDF Percentile	PDF (#σ)	Model (m)	Histogram (m)
39%	1	3.54	2.6
50%	1.18	4.17	3.1
86%	2	7.09	5.9
99%	3	10.63	9.6
99.9%	3.72	13.17	12.5
99.97%	4	14.17	13.9
99.999%	4.7985	17.0	23.1

Table 3 – Expected and Actual PDF Percentiles for Figure 7

Table 3 shows the levels at which various percentiles are bounded by the distribution shown in Figure 7. It is significant that the measured errors (Histogram PDF) are only bounded by the model up to 4 standard-deviations, at our 99.999% Integrity level the theory no longer bounds the errors (shown in red), indicating a chance of HMI at the higher percentiles.

For each HPL 'bin' in the histogram in Figure 2, the same processing shown in Figure 7 was performed: the Rayleigh standard-deviation was found from the raw data and a theoretical 99.999% bound plotted. Also, the HPL bound is plotted as a dashed black line, and the histogram 99.999% bound is shown in dashed blue, as above.

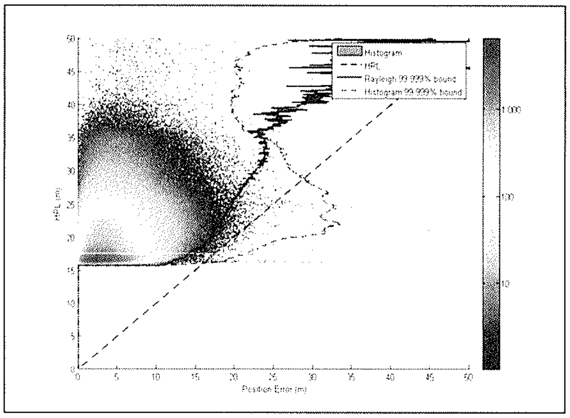

Figure 1 – Predicted (HPL), Modelled (Rayleigh, black line) and Actual (Histogram, blue line) five-nines positioning bounds

The white line shown in Figure 8 indicates where we took a slice through the histogram at HPL=17m, as shown in Figure 7. It can be seen that the HPL equation does over-bound the theoretical PDF for every HPL bin, but does not adequately bound the observed measurement errors.

CONCLUSIONS. All of the conclusions drawn from this report are summarised below:

TOA-Variance Equations. The LCAST Equation works better at predicting TOA errors when used with a nominal transmitter-related error of 4m.

This equation also over-estimates TOA-σ for low-SNR signals, and a modification may improve its performance (Figure 4).

TOA-Error Distribution. TOA measurement errors are likely not to be Normally Distributed (Figure 5 and Figure 6).

Error-clipping, as prescribed in [6] through signal-processing techniques or RAIM may be a way to mitigate this poor PDF 'tail' behaviour.

HPL Equation. The HPL equation works very well in bounding the 99.999% level for the *assumed* PDF (Figure 8)

The actual 99.999% bound is often higher than the theoretical bound and also, crucially, is higher than the HPL in the region of HMI (Figure 8).

Again, the failure of the assumed PDF to bound the errors is present at higher percentiles (Table 3)

Positioning-Error Distribution. The number of Integrity breaches (HMI in Figure 2) is likely due to the inadequacy of the Rayleigh distribution to provide a bound for the positioning errors at high percentiles (Table 3).

A better distribution model for TOA errors and positioning-fixing error may improve things here, but 'clipping' the tail of the distribution would be best.

Significance for eLoran System. Using the HPL equation described, we can only guarantee eLoran Integrity up to four-nines (99.99%), assuming a 10m (95%) accuracy target (Table 3).

To help with system Availability, we will be able to use a less conservative HPL equation, but only once the aforementioned Integrity issue is solved. Raising the bar to 20m Accuracy (95%) with 50m HAL is an option here (Figure 3).

Additional signal processing or the use of a RAIM algorithm may be required for eLoran receiver performance to meet the IMO Integrity specifications.

Extra eLoran transmitters will always help in terms of: improved accuracy; greater redundancy in position-fixing; and more powerful error-mitigation through RAIM.

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[4] European Loran-C Website, http://www.loran-europe.eu

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[6] Walter, Enge, Hansen, "Integrity Equations for WAAS MOPS" Stanford University

Investigating eLoran Integrity

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Dr. Paul Williams

General Lighthouse Authorities of the United Kingdom and Ireland

ILA 40 – Busan, Korea

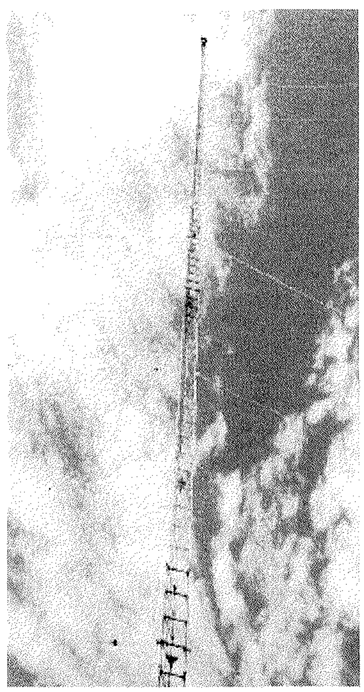
18th November 2011

Introduction - eLoran

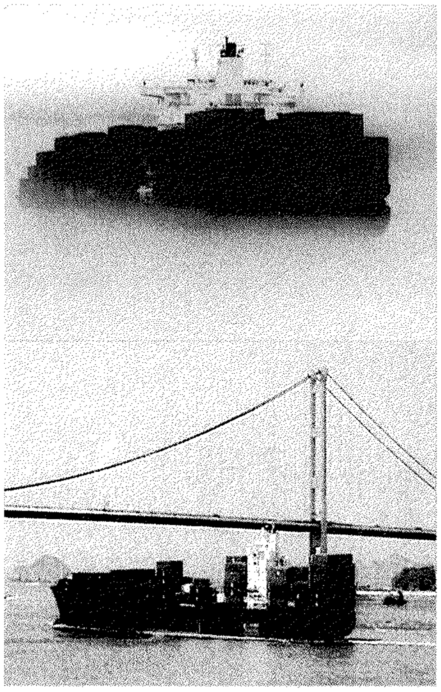
- High power (400 kW)
- Low Frequency (100 kHz)
- **Lo**ng **Ran**ge (1000 km)

- Also
  - 3x Cs. Clocks at each Station with TWSTT
  - Solid State Transmitters
  - Network of Reference Stations
  - Loran Data Channel
  - Digital Maps of ASF

- GLAs business case selects eLoran as best GPS backup



IMO Performance Standards



- Accuracy 10m (95%)
- Availability 99.8% (over 30 days)
- Continuity 99.97% (over 3hours)
- Integrity 99.999% (25m Alert Limit)

- GLAs trials show 10m Accuracy

- Transmitter availability >99.95%

- System Availability depends on meeting Integrity

Why is Integrity Important…

Importance of Integrity

- Integrity is a measure of Trust

- Appropriate level of confidence:
  - Too much – can lead to over reliance
  - Too little – engenders mistrust / disuse

- eLoran will be offered as added-value to GNSS receivers
  - Integrity helps GNSS / eLoran Integration

- System needs to stand on its own
  - eLoran must be able to validate its own position fixes

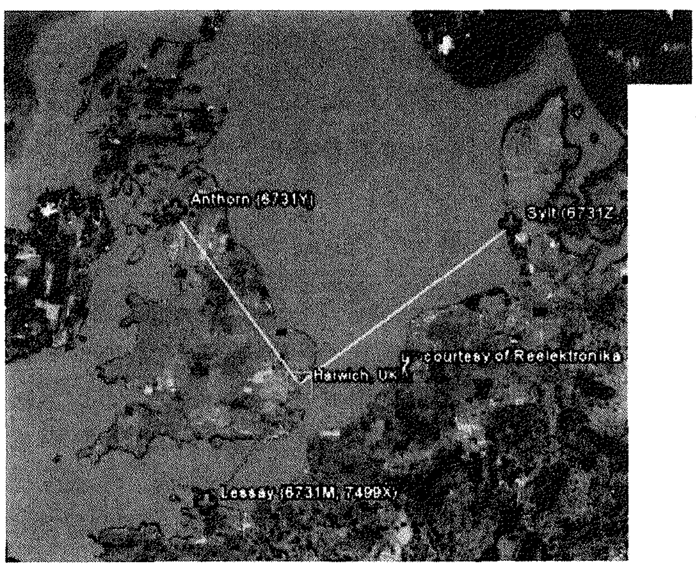
How to provide Integrity…

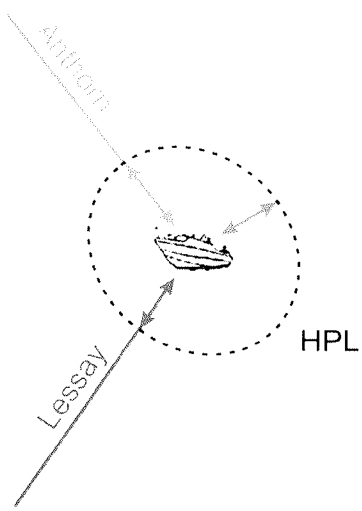
Horizontal Protection Level (HPL)

- HPL is a Position Bound
  - Expect 99.999% of all fixes to lie within HPL
- Horizontal Alert Limit (HAL) provides limit for HPL
  - Integrity alarm when HPL > HAL
- System must alarm within 10seconds
  - DLoran reference stations can provide warnings
  - Integrity hazards are mainly local to the receiver
  - User's receiver must do most of the work

How to we find HPL…

To Find HPL





What goes into an HPL…

Components of eLoran Positioning and HPL

Position Solution	=	Pseudo Ranges	+	Differential Corrections	+	ASF Value from Map
⇕		⇕		⇕		⇕
Horizontal Protection Level (HPL)	=	Pseudo Range Errors	+	Differential Correction Errors	+	ASF Errors from Quality Map

Model Pseudo-Range Errors…

Pseudorange Error Equation

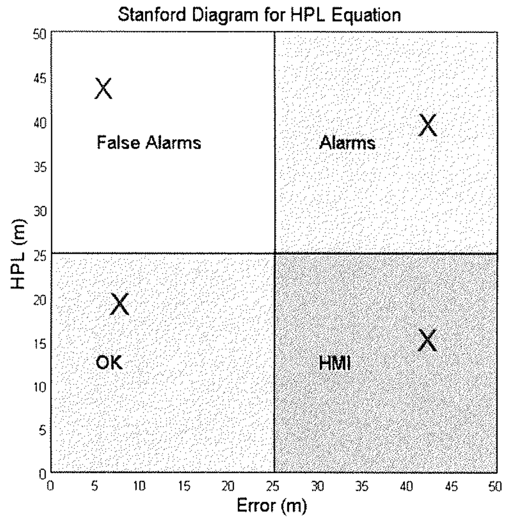
$$\sigma^2 = c_1^2 + \frac{337.5^2}{N \cdot SNR}$$

- Developed from work done at Stanford University
  - Originally a model for Aviation
- Uses Signal-to-Noise Ratio (SNR) and Number of eLoran pulses (N) received
- Stanford aviation model used c_1=6m, we use c_1=4m

To Test HPL Performance…

Stanford Diagram

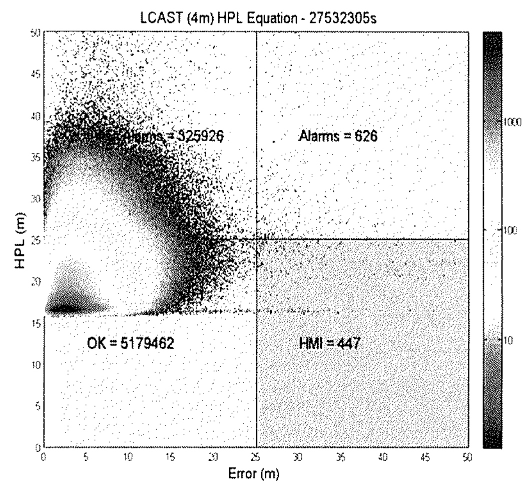
- Plot of Position Error vs. HPL
- Alarm when HPL > HAL (25m)
- False Alarm if accuracy is good
- If large Error occurs and alarm does not sound
  - Hazardously Misleading Information (HMI)



And the Results are…

Results of Testing

- Played back a year of recorded data (2010 - 2011)
- 626 Alarms
  - <1 hour in a Year
- 447 HMI
  - <40 minutes in a Year
- Most alarms were not needed
  - Error Equation is Pessimistic
  - eLoran is more accurate than we think it is

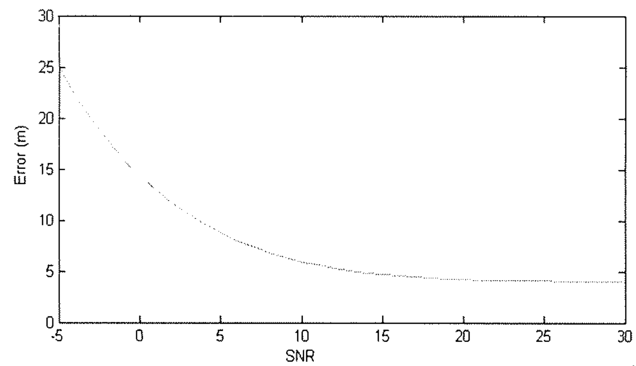


Take a look at the Error Equation…

eLoran Pseudo-Range Error Equation

$$\sigma^2 = (4m)^2 + \frac{337.5^2}{N \cdot SNR}$$

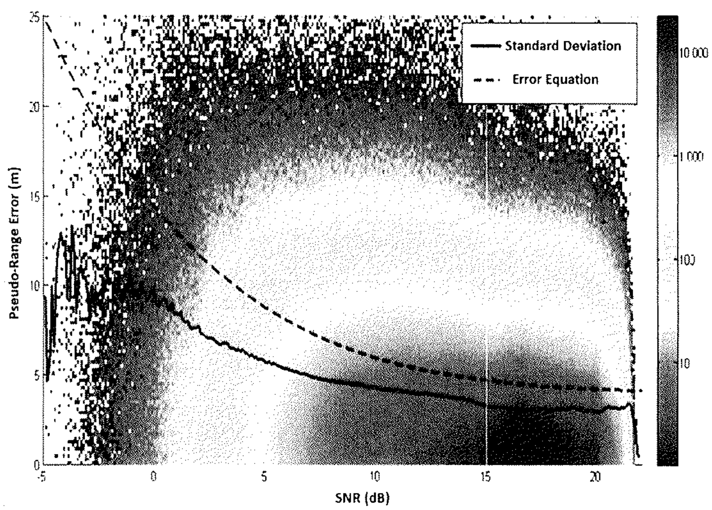
- Designed for Aviation
  - Lower Accuracy
  - Very stringent Integrity
- Probably too Pessimistic
  - 15m error at 0dB is unlikely
- Know eLoran Pseudo-Ranges usually <4m



Compare actual Pseudo-Range errors...

TOA Histogram – GLA data for 2010-2011

- eLoran Pseudo-Range Error vs. SNR
- Calculated standard-deviation from histogram
- Error Equation appears overly conservative
  - Reason why so many False Alarms



Conclusions...

Conclusion

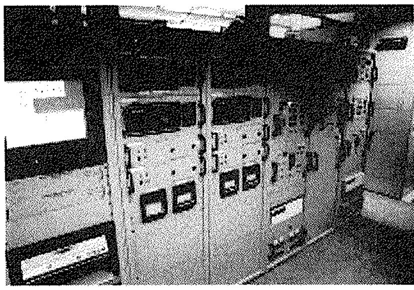
- Integrity is an important part of eLoran
- GLA have begun developing the tools to assess Integrity
  - Continuing work started at Stanford University
- Pseudo-range error equation is quite conservative
  - eLoran works better than the Equation predicts
- HPL is also conservative – Most alarms were unnecessary

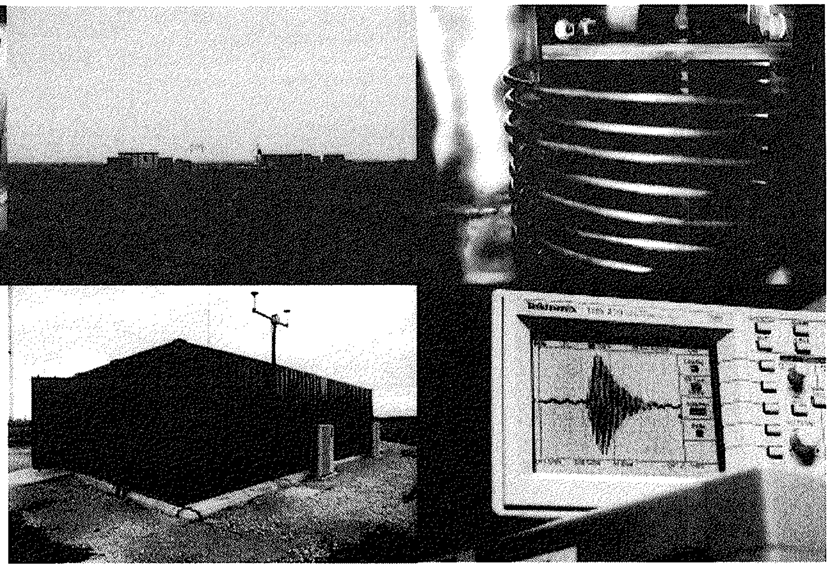
What's next…

Future Work

- Look at less conservative Error Equations
- Receiver Autonomous Integrity Monitoring (RAIM)
- Integrity on mobile platform
  - eLoran data gathering onboard the GLA ships
- Consider errors on ASF / DLoran
  - Update Standards to include Error / Variance data

Thank you!





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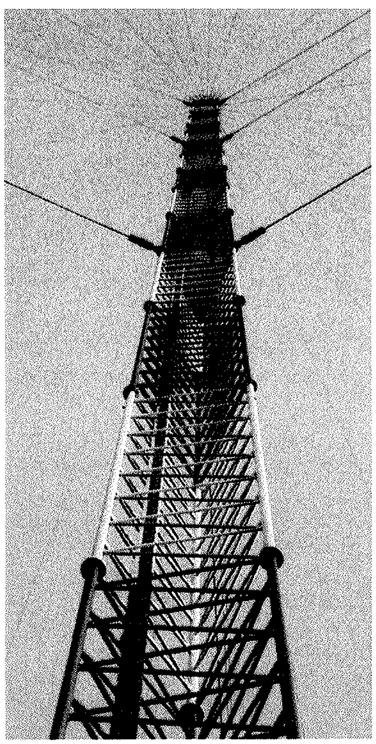
Shared interest in a more productive tomorrow.

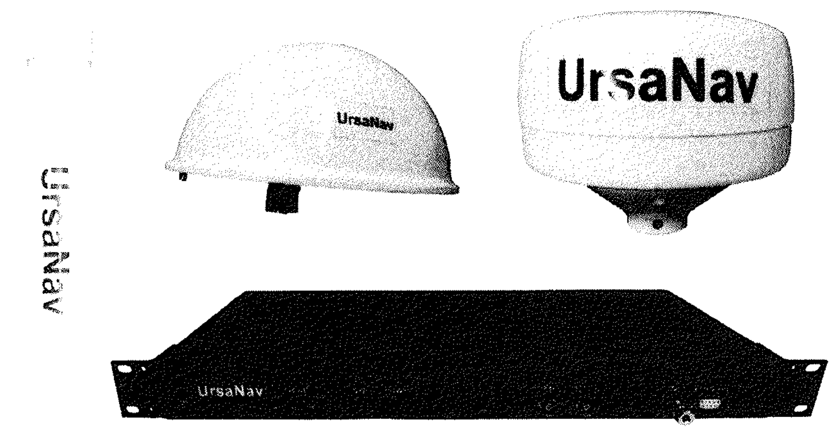
eLoran Receiver Technology
Tutorial

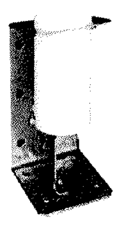
Presented by:
A. Helwig, G. Offermans, C. Stout, C. Schue (UrsaNav)

International Loran Association (ILA-40) – November 2011

UrsaNav

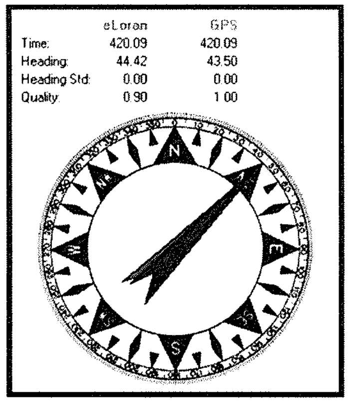






eLoran receiver technology

- Automatic eLoran receiver independent from GNSS
- Modern DSP technology
- Small form factor
- Easy integration with GNSS
- Independent heading determination (even static)
- Accuracy better than 10m*



* Differential mode

- Requirements for a “modern” eLoran receiver:
  - Multichain all-in-view Loran signal tracking
  - Fast acquisition (<30 seconds)
  - Interference mitigation
  - Integration with GPS
  - ASF and Differential Loran capabilities
  - Data demodulation
  - Regular position updates (e.g. every 5 seconds)

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Signal Clean-up - solutions

Interference source		Mitigation method	Performance
Continuous wave		Detect and notch	Good
Atmospherics	low amplitudes	Averaging	Moderate
	big amplitudes	Detect and drop	Good
Cross-rate		Beam Steering	Fair
		Detect and drop	Good
		Estimate and repair	Fair
		Frequency domain Comb filtering	Good
Skywave separation		Tracking early in pulse	Good
		GW/SW separation	Good
Local Interference		Detect and drop	Moderate
		Estimate and repair	Good
Additional Secondary Factor		Models	Moderate
		GPS Calibrated	Good
		Differential eLoran	Good

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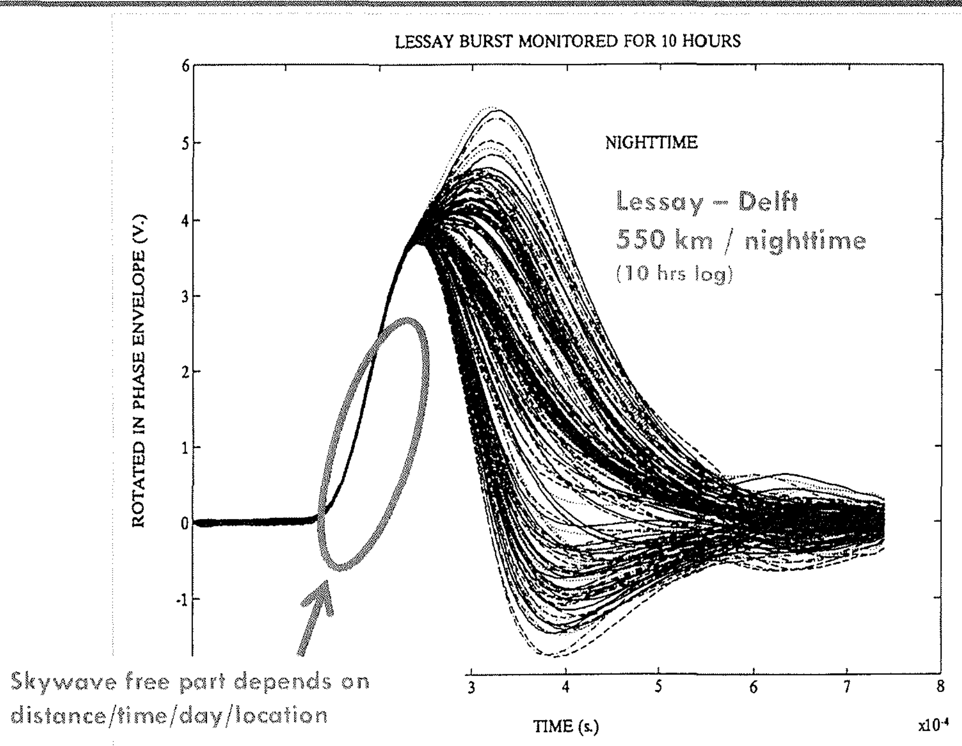
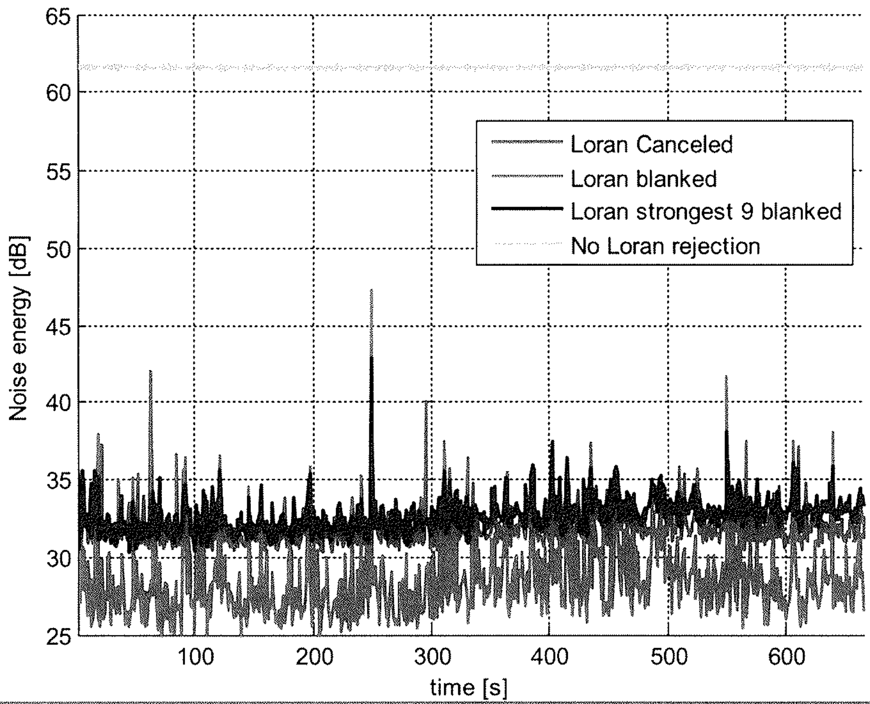
Skywave Interference



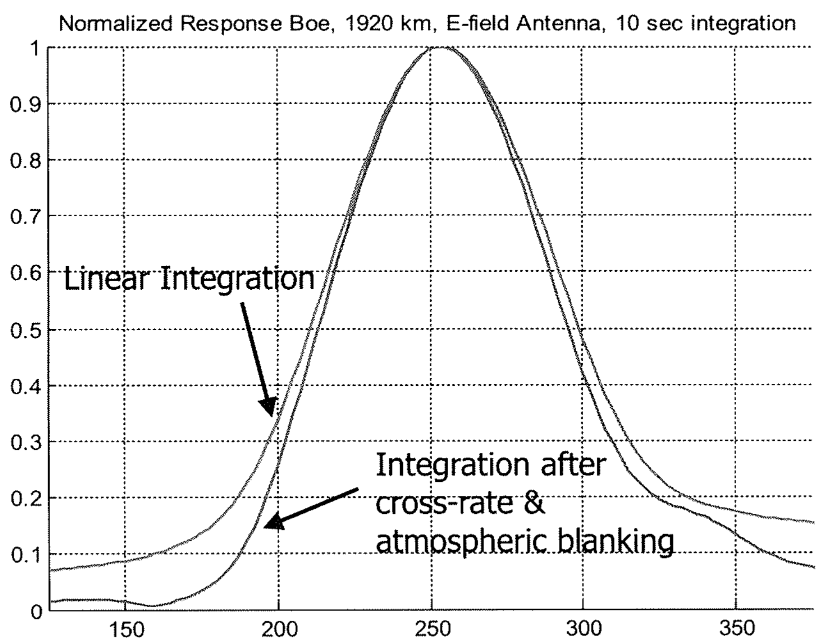
Van Nee - 1995

Noise levels: Atmospheric noise



Signal Clean-up

Cross-rate & Atmospherics filtering



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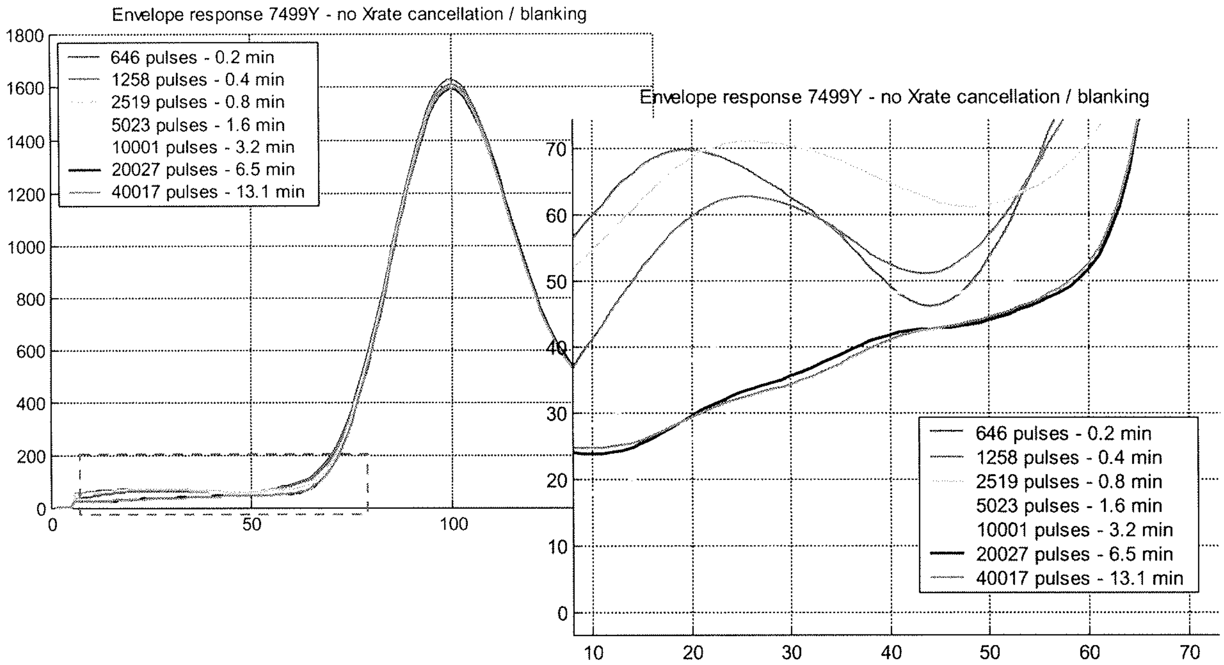
Cross-rate mitigation by averaging



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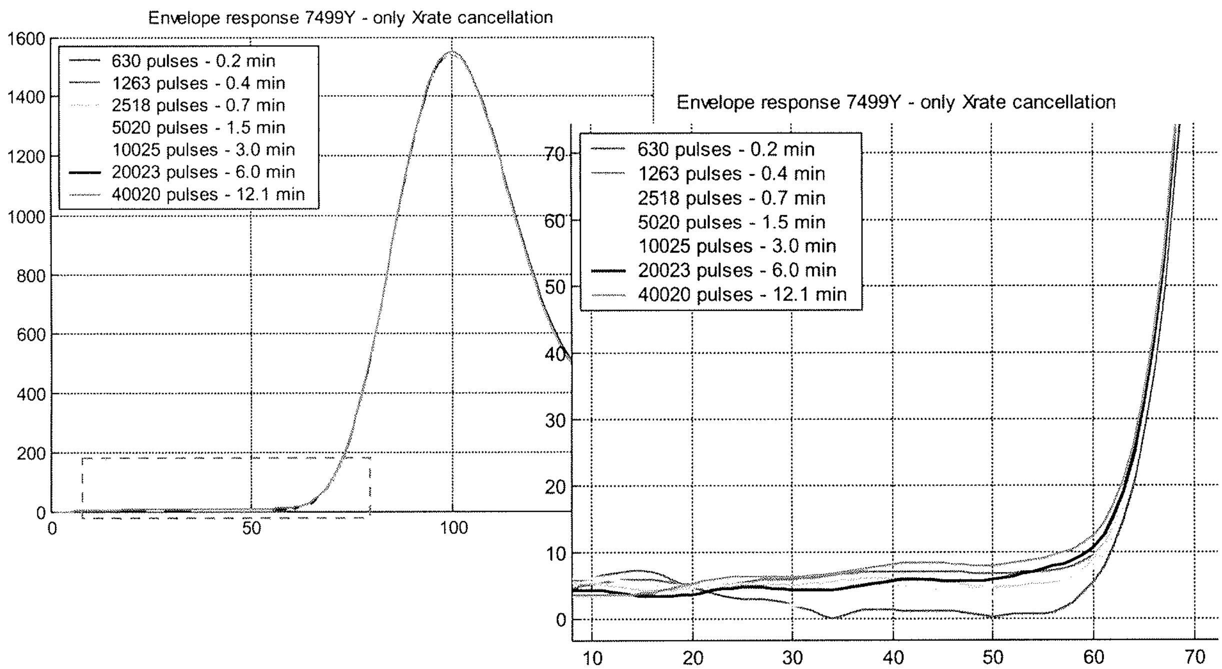
Cross-rate mitigation by cancelation



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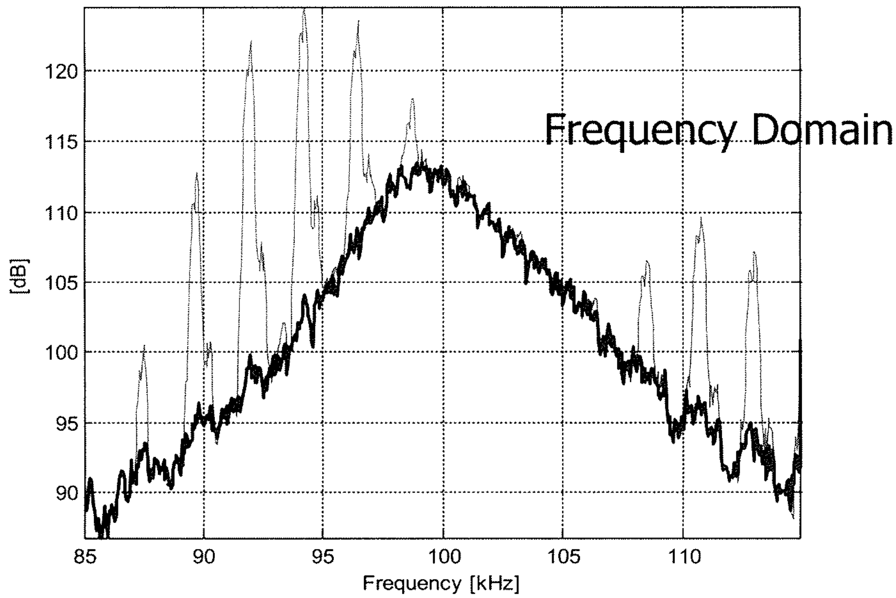
Signal Clean-up
Local interference suppression



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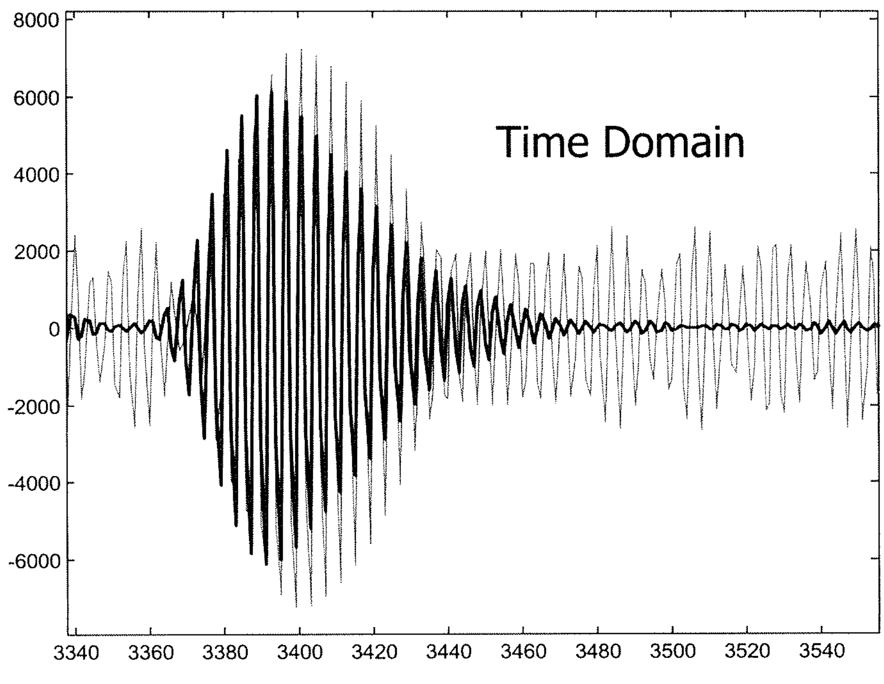
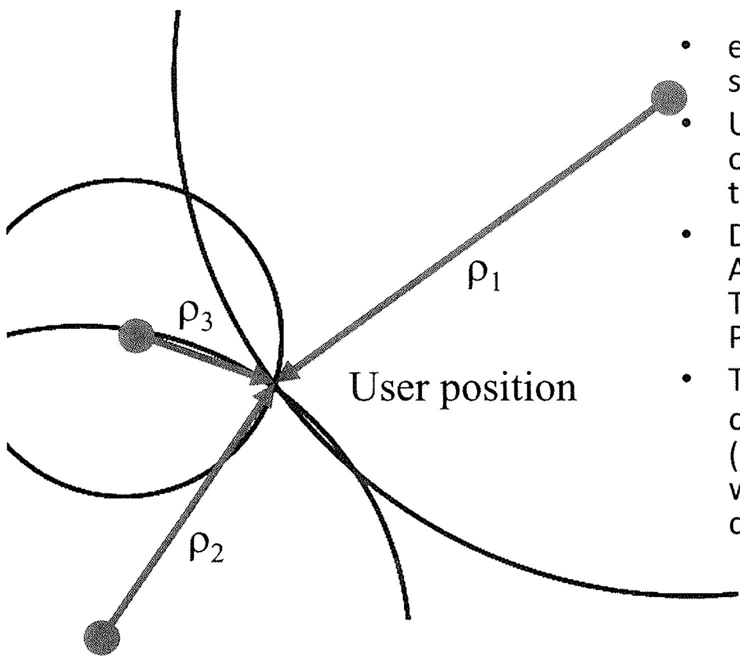
Signal Clean-up
Local interference suppression



Positioning using eLoran



- eLoran transmissions synchronised to UTC
- User receiver measures Time of Arrival to three (or more) transmitters
- Difference between Time of Arrival and Time of Transmission is the Propagation Delay T_{Prop}
- T_{Prop} (in seconds) needs to be converted to a pseudo-range ρ (in meters) by multiplication with the speed of light (*c*) to calculate the user position

eLoran Signal Propagation

$$\rho = R + PF + SF + ASF + \delta + \varepsilon + B$$

Where

R = true range (what we want to know)

PF = Primary Factor

SF = Secondary Factor

ASF = Additional Secondary Factor

δ = variation in PF, SF and ASF

ε = remaining measurement errors

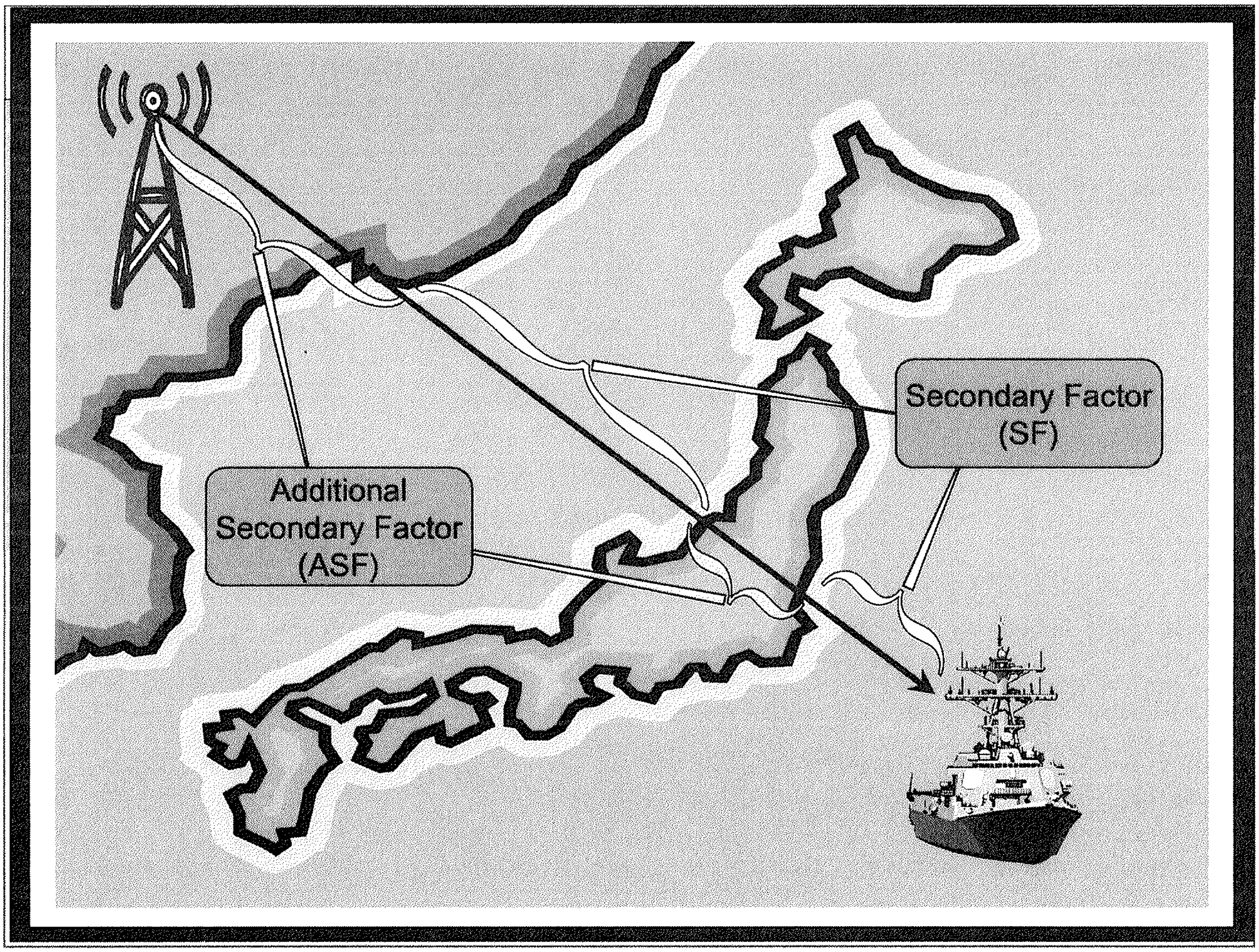
B = the receiver clock bias

Primary & Secondary Factor

- The Primary Factor delay is the difference between propagation of the signal in the earth's atmosphere as opposed to in free space
- The Secondary Factor delay accounts for signal propagation over sea-water
- PF and SF are known and considered constant, the receiver uses a model to calculate the delays

Additional Secondary Factor

- The Additional Secondary Factor is the delay caused by signal propagation over land and elevated terrain as opposed to over sea-water
- The ASF delay build-up depends on the type of soil
- The ASF delay is the total cumulative delay the signal experiences of sections with different ground conductivity
- Not taking ASFs into account may result in positioning errors of several kilometers



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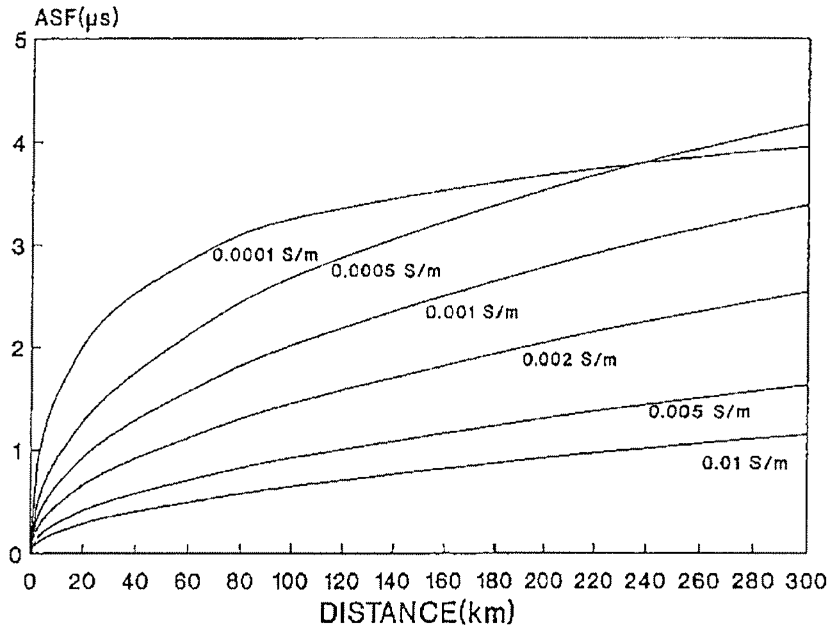
ASF as a function of ground conductivity

BRUNAVS' FORMULA-B PROPAGATION CALCULATION

Enter the propagation distance in kilometers: 1000

Sigma	Eps	Prop-time(us)	PF(us)	SF(us)	ASF(us)	Remarks
5	81	3338.55	3335.64	2.91	0.00	Sea-water
2E-2	15	3340.20	3335.64	2.91	1.65	Clay
1E-2	15	3340.91	3335.64	2.91	2.36	Marsh & sea-ice
2E-3	15	3343.49	3335.64	2.91	4.94	Moor
1E-3	15	3344.67	3335.64	2.91	6.12	Dry earth
5E-4	15	3345.17	3335.64	2.91	6.62	Sandy desert
1E-4	15	3344.16	3335.64	2.91	5.61	Snow and ice

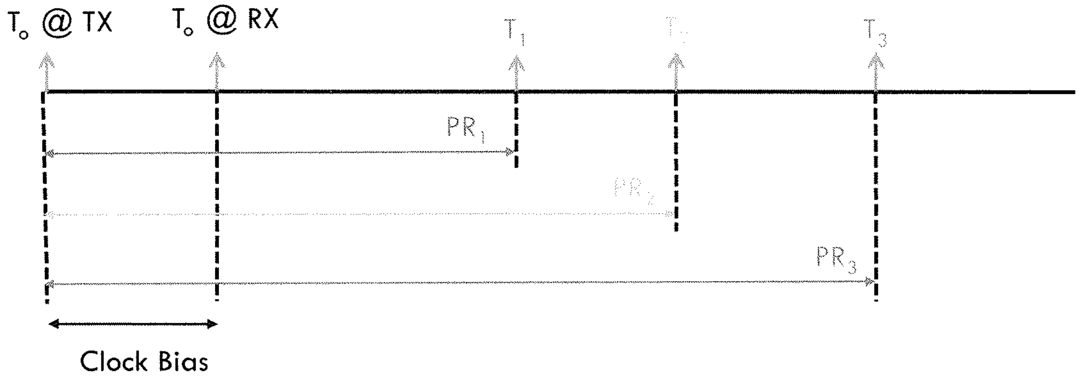
Note: 1 μs time error corresponds to 300 m range error



Variation in PF, SF and ASF

- Any variation in PF, SF or ASF due to weather, water vapor, air pressure, seasonal influences is captured in δ
- δ also contains any misalignment of the transmitter timing wrt UTC
- δ is unknown, but can be measured by a reference station at a known and fixed location
- In differential eLoran, these corrections are broadcast to the users to improve their positioning and UTC time accuracy

2D Pseudorange Positioning-1



- All received eLoran stations send wrt common time reference (T_0 @ TX)
- (T_0 @ RX) - (T_0 @ TX) = Receiver Clock Bias which is common to all used pseudo-range measurements
- Here, the pseudo-ranges PR_n are corrected for PF, SF and ASF

2D Pseudorange Positioning-2

What remains is:

Pseudo-range = True Range + Clock Bias + Noise

$$PR_n = R_n + B + \varepsilon_n$$

where

PR_n = measured pseudorange from user to TX_n

R_n = true range from user to TX_n

B = range (clock) bias to TX_n common to all PR_n

ε_n = remaining measurement noise

- Three unknowns must be found
  - latitude λ
  - longitude φ
  - clock bias B
- Three pseudoranges may solve position and clock bias
- Four or more pseudoranges additionally offer integrity and/or improved reliability

Linearised set of three pseudorange equations gives

$$\underbrace{\begin{pmatrix} \Delta PR_1 \\ \vdots \\ \Delta PR_3 \end{pmatrix}}_{\text{Measurement matrix}} \cong \underbrace{\begin{pmatrix} \frac{\delta PR_1}{\delta\varphi} & \frac{\delta PR_2}{\delta\lambda} & \frac{\delta PR_3}{\delta B} \\ \vdots & \vdots & \vdots \\ \frac{\delta PR_1}{\delta\varphi} & \frac{\delta PR_2}{\delta\lambda} & \frac{\delta PR_3}{\delta B} \end{pmatrix}}_{\text{Geometry matrix}} \cdot \underbrace{\begin{pmatrix} \Delta\varphi \\ \Delta\lambda \\ \Delta B \end{pmatrix}}_{\text{Correction matrix}}$$

φ = latitude
λ = longitude
B = range (clock) bias
PR_n = PseudoRange to TX_n

or

$$\begin{pmatrix} \Delta PR_1 \\ \Delta PR_2 \\ \Delta PR_3 \end{pmatrix} \cong \begin{pmatrix} \cos(h_1) & \sin(h_1) & 1 \\ \cos(h_2) & \sin(h_2) & 1 \\ \cos(h_3) & \sin(h_3) & 1 \end{pmatrix} \cdot \begin{pmatrix} \Delta\varphi \\ \Delta\lambda \\ \Delta B \end{pmatrix}$$

h_n = bearing from user to TX_n

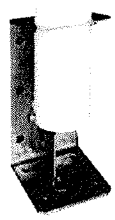
Iteration procedure

- Estimate user's position U_e (ϕ and λ) and clock bias B
- Compute ranges from U_e to all transmitters
- Measure pseudoranges from U_e to all transmitters
- Calculate ΔU_e with differences of computed ranges minus measured pseudoranges
  - Limit ΔU_e to sensible value to avoid divergence
- Stop iteration after updates are acceptably small
  - Update values may approach zero

- Modern eLoran receivers are software defined radios
- Analogue antenna, gain and anti-aliasing filter, A/D converter
- Digital processing on DSP or dedicated hardware
- Firmware upgradeable for improved or new functionality

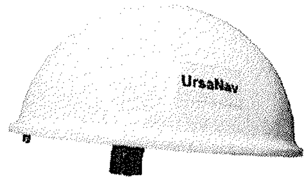
E-field Antenna

- E-field antenna based on short antenna element and low-noise amplifier
- Input wideband
  - Risk of overloading from out of-band signals
- Antenna omni-directional sensitive
- Precipitation risk
- No compass capability
- Ground required
- Simple production
- Size 25 x 3 cm

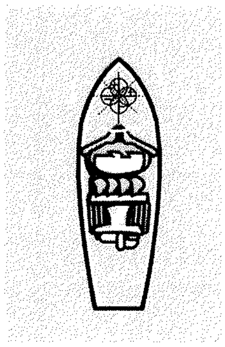


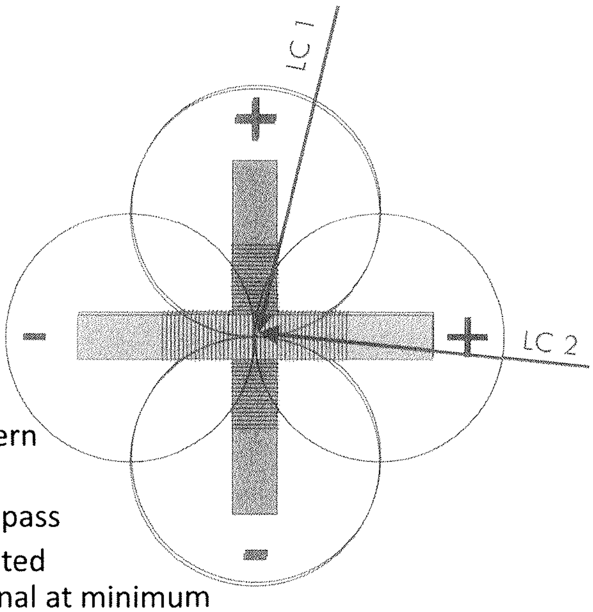
H-field Antenna

- H-field antenna based on four ferrite loops in a square
- Synthetic omni-directionality
- Beam steering feasibility



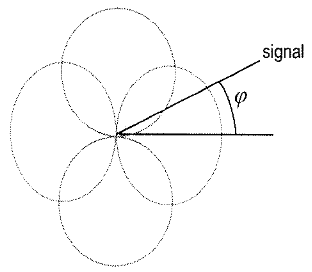
- Very low-noise amplifiers required
- Input bandwidth limited, so less risk of overloading by out-of-band signals
- True north compass
- No precipitation problem and no ground required
- Size 15 x 15 x 10 cm





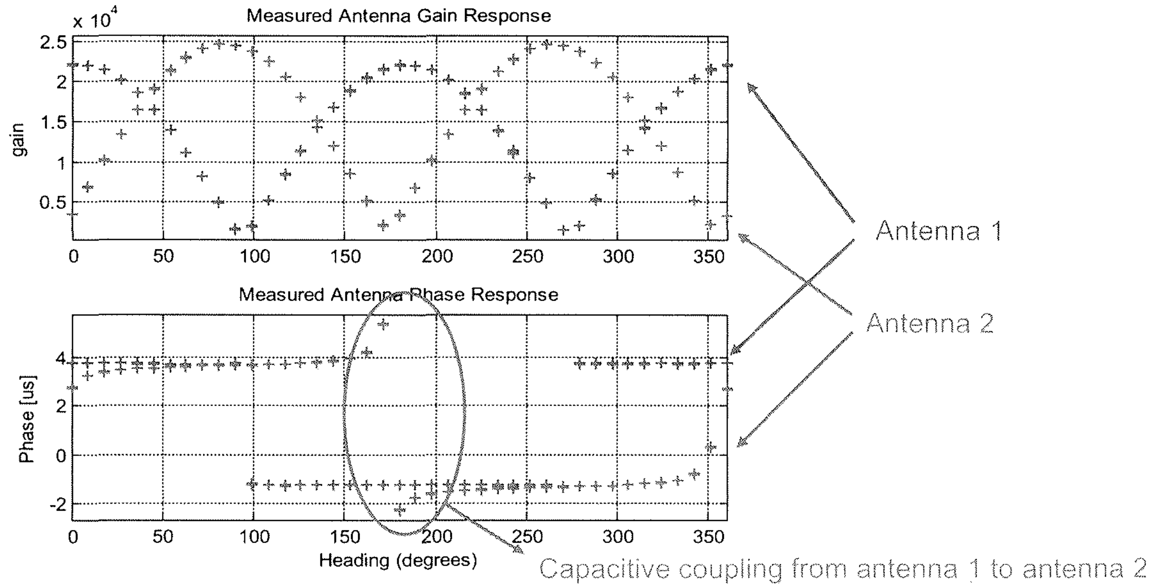
- Two H-field antenna loops needed for an omni-directional radiation pattern
- Two H-field antennas offer capability of an accurate eLoran true-North compass
- Figure-8 can be rotated such that wanted signal is at maximum or unwanted signal at minimum

- The two loops of the H-field antenna influence each other by capacitive and inductive coupling, resulting in a heading-dependant phase and amplitude error

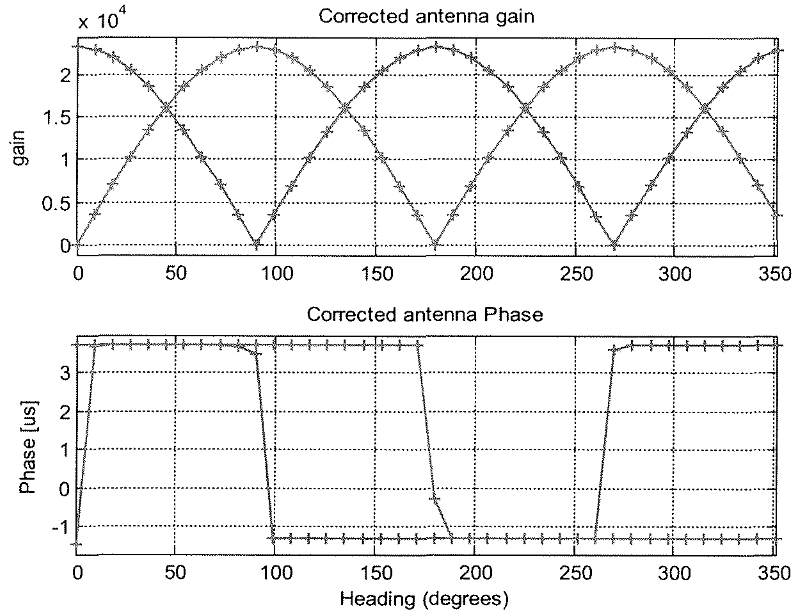


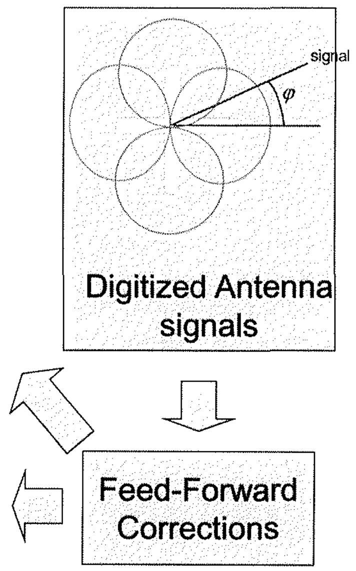
- The ideal double figure-8 pattern is not always realized due to antenna imperfections and installation specific effects (influence of metal on a vessel)
- Through a calibration measurement (sailing a circle) the influence of the effects can be modelled and provided as calibration parameters to the receiver
- Each set of parameters is only valid for one specific antenna at one specific location and heading.

- Measured Antenna Response

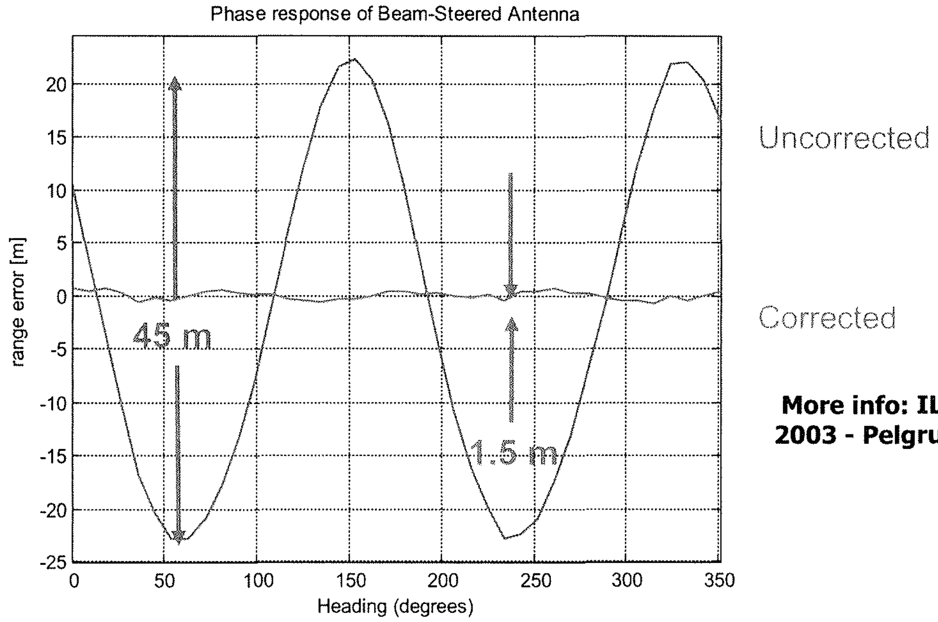


- Feed Forward Correction of Antenna





- Comparison of Uncorrected and Feed-Forward Corrected Response



More info: ILA 2003 - Pelgrum

Shared interest in a more productive tomorrow.

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OUR capabilities, improve YOUR capabilities.

eLoran System Definition and Signal Specification Tutorial

Presented by:
A. Helwig, G. Offermans, C. Stout, C. Schue (UrsaNav)

International Loran Association (ILA-40) – November 2011

UrsaNav

Overview

- eLoran basics
- eLoran System requirements
  - Maritime, Aviation, Land-mobile, Timing
- eLoran System Overview
  - Core eLoran service provider
  - Application service provider
- eLoran Signal in Space
  - Loran pulse shape
  - Timing control
  - Loran Data Channel (LDC)
- eLoran vs. Loran-C
- Maritime Harbor Entrance and Approach

- Enhanced Loran is an internationally-standardized positioning, navigation, and timing (PNT) service for use by many modes of transport and in other applications. It is the latest in the longstanding and proven series of low-frequency, LOng-RAnge Navigation (LORAN) systems, one that takes full advantage of 21st century technology.
- *eLoran* meets the accuracy, availability, integrity, and continuity performance requirements for **aviation** non-precision instrument approaches, **maritime** harbor entrance and approach maneuvers, **land-mobile** vehicle navigation, and location-based services, and is a precise source of **time and frequency** for applications such as telecommunications.
- *eLoran* is an independent, dissimilar, complement to Global Navigation Satellite Systems (GNSS). It allows GNSS users to retain the safety, security, and economic benefits of GNSS, even when their satellite services are disrupted.

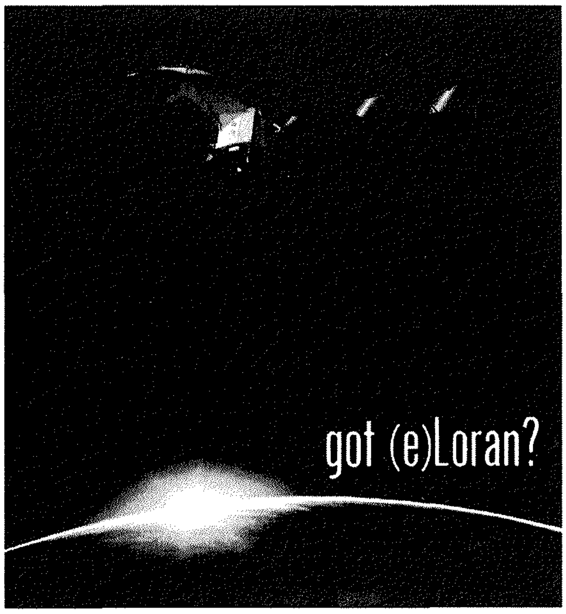
From eLoran Definition Document
International Loran Association November 2006

- The core *eLoran* system comprises modernized control centers, transmitting stations and monitoring sites. *eLoran* transmissions are synchronized to an identifiable, publicly-certified, source of Coordinated Universal Time (UTC) by a method wholly independent of GNSS. This allows the eLoran Service Provider to operate on a time scale that is synchronized with but operates independently of GNSS time scales. Synchronizing to a common time source will also allow receivers to employ a mixture of *eLoran* and satellite signals.
- The principal difference between *eLoran* and traditional Loran-C is the addition of a data channel on the transmitted signal. This conveys application-specific corrections, warnings, and signal integrity information to the user's receiver. It is this data channel that allows *eLoran* to meet the very demanding requirements of landing aircraft using non-precision instrument approaches and bringing ships safely into harbor in low-visibility conditions. *eLoran* is also capable of providing the exceedingly precise time and frequency references needed by the telecommunications systems that carry voice and internet communications.

From eLoran Definition Document
International Loran Association November 2006

- eLoran technology is built upon the foundation of Loran-C
- eLoran has been developed over the past decade as a response to the recognized vulnerability of GNSS, by international government agencies, industry and academia
- eLoran transmitter and receiving equipment makes full use of 21st century technology
- eLoran is recognized and recommended by the International Association of Lighthouse Authorities (IALA)
- eLoran receiver Minimum Performance Standards are being developed by the Radio Technical Commission of Maritime services (RTCM) Special Committee 127

- eLoran is <u>NOT</u> Simply Modernized Loran-C



- requires a different timing strategy, control strategy, and new equipment to meet more stringent requirements
- specifies tighter timing tolerances
- transmissions are synchronized with respect to UTC (not SAM)
- employs a data channel for broadcast of application specific data
- includes Differential eLoran monitor stations and ASF maps to provide optimum accuracy in key areas (e.g. marine ports or airports)
- PROVEN TECHNOLOGY

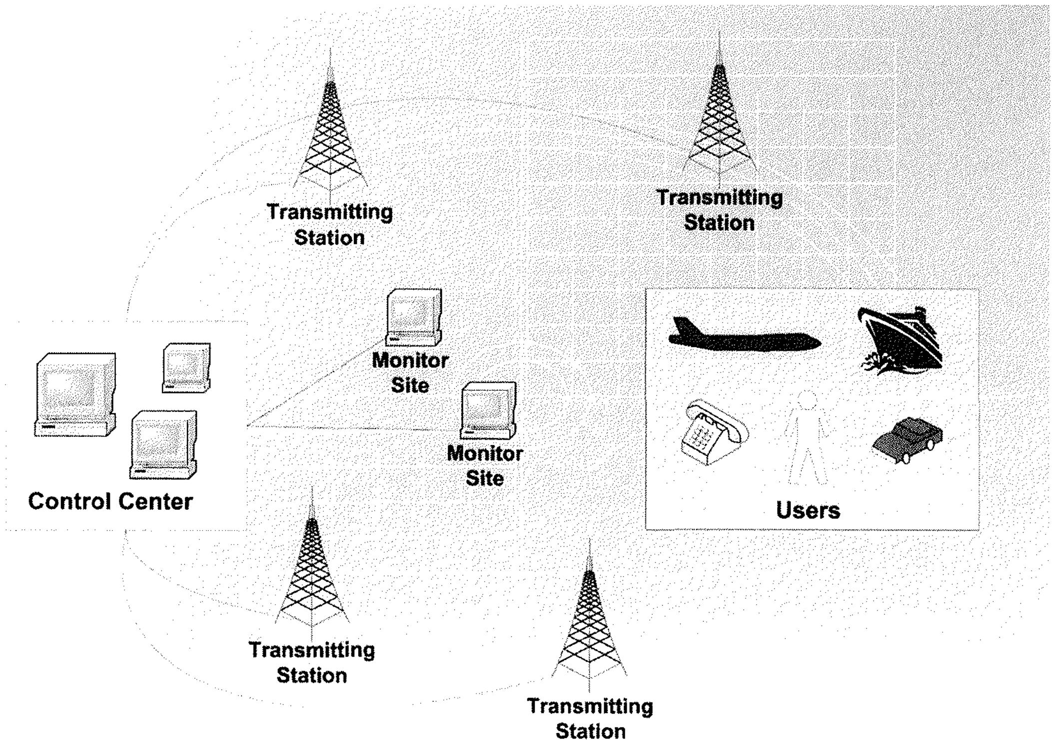
Unaided Loran-C can <u>never</u> achieve the accuracy and integrity inherent in eLoran.

- A properly configured and installed eLoran system can meet the following requirements

Application	Accuracy	Availability	Integrity	Continuity
Maritime Harbor Entrance and Approach (HEA)	**20 meters (95%)**	**0.998 over 2 years**	**10 seconds Time to Alarm**	**0.9997 over 3 hours**
Aviation Non-Precision Approach (RNP 0.3)	**0.3 Nautical Mile (556 meters)**	**0.999 – 0.9999**	**1 x 10^{-7} per hour**	**0.999 – 0.9999 over 150 seconds**
Timing	**Stratum-I frequency stability; timing to +/- 50 ns from UTC**			

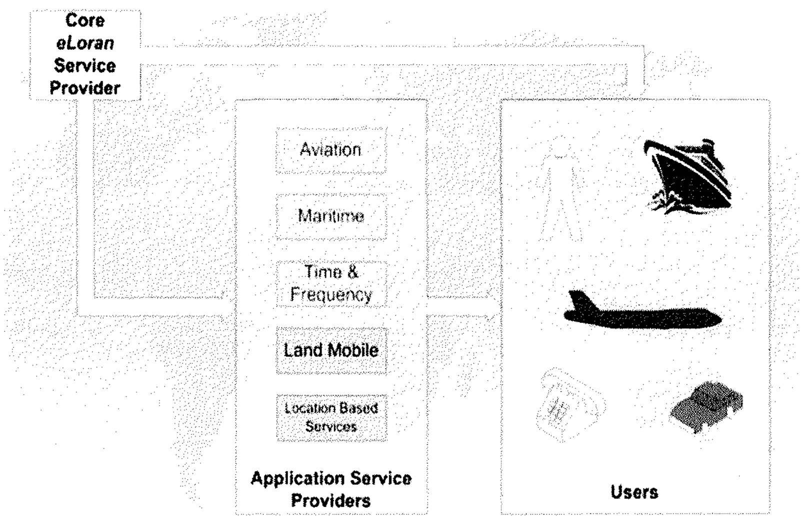
- Maritime
  - Harbor Entrance and Approach
  - Coastal navigation
- Land-mobile
  - Vehicle navigation (security)
  - Tracking of goods
  - Location based services
  - First responders (police, fire brigade, ambulance)
- Timing
  - UTC time recovery (50 ns)
  - Stratum-1 frequency standard
- Aviation
  - Non-precision approach
  - En-route
- Military & High profile events
  - PNT in a GNSS denied environment
  - Tactical mobile eLoran solutions available

eLoran System Overview



eLoran System Overview (cont.)

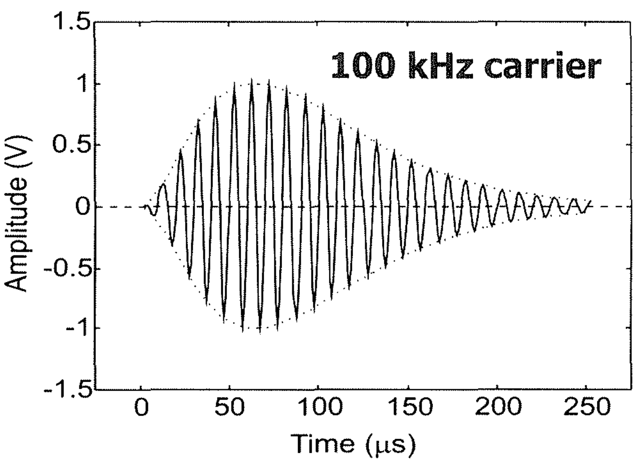
- In many nations, the core and application service provider will be the same agency



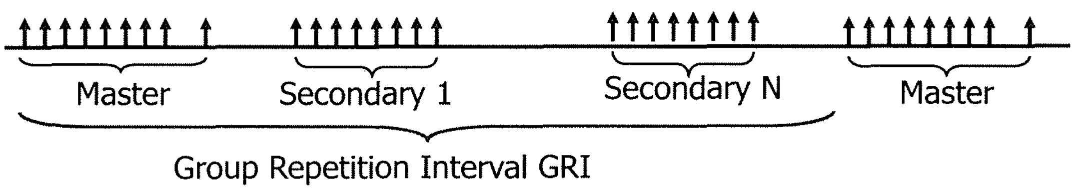
- Core eLoran service
  - eLoran transmitters provide a highly stable eLoran signal
  - eLoran transmitters are autonomous, unmanned, self-controlled, self-supporting
  - Signals are synchronized to an identifiable source of UTC (no SAM control)
  - Monitor sites and Control centers do not interfere with the timing control of the transmitted signal
- eLoran application service
  - To improve accuracy and/or integrity application specific monitor stations provide augmentation data
  - Application data is broadcast to the users over the Loran Data Channel (e.g. maritime differential corrections or aviation early skywave warnings)
  - Application data are treated as corrections or integrity warnings and will not influence the delivery of the core eLoran service

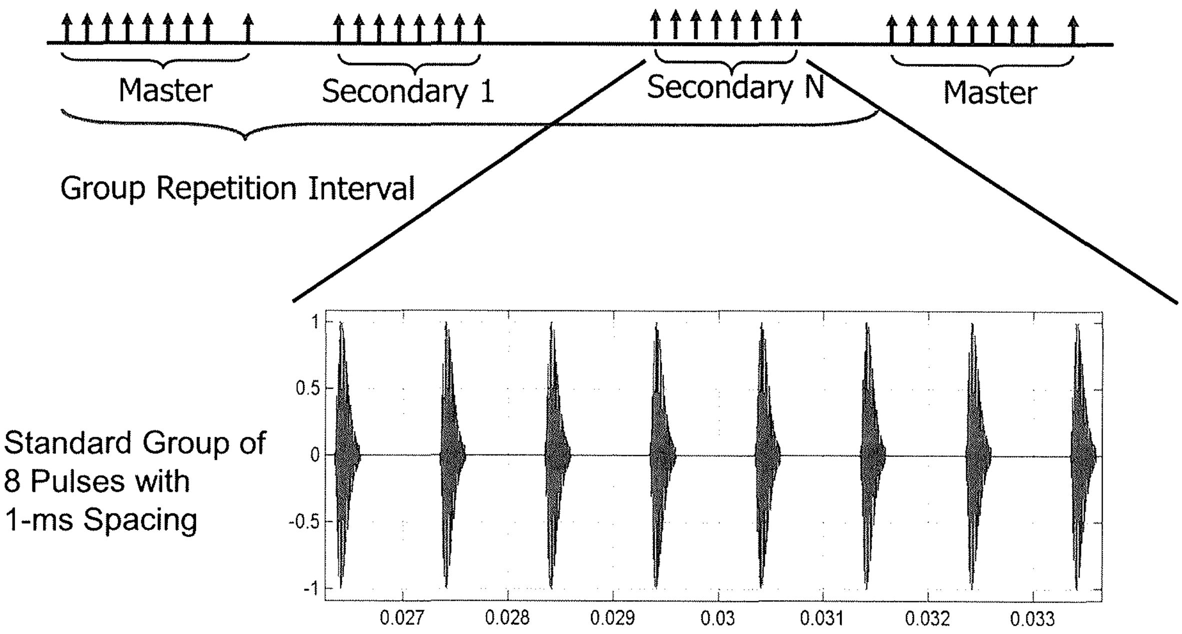
- The core eLoran service needs to provide signals with good geometry and signal strength in the maritime coverage area
- The Maritime Application service provider publishes an ASF map for the maritime coverage area, providing grid data with nominal propagation corrections per transmitter
- The Differential eLoran Reference Station provides real-time corrections on the nominal published ASFs for each transmitter through the Loran Data Channel
- The maritime user applies the ASFs from the map and differential corrections from the LDC to improve its positioning accuracy to better than 20 m (95%)
- The eLoran Integrity Monitor monitors the resulting eLoran accuracy and issues integrity warnings over the Loran Data Channel in case the service exceeds the horizontal protection limit

- The eLoran Signal in Space for the most part follows the specified Loran-C signal as published by the USCG, differences include:
  - eLoran specifies tighter synchronization to UTC, tighter timing tolerances between GRIs, between pulses and between zero-crossings in a pulse.
  - eLoran specifies tighter tolerances with respect to pulse shape
  - Time and frequency equipment apply phase corrections in a continuous manner instead of Local Phase Adjustments (LPA) of 10 or 20 ns steps.
  - eLoran uses Time of Transmission (synchronization to UTC) for all stations instead of Service Area Monitoring (SAM) timing control.
  - eLoran does not apply Blink anymore to indicate an out-of-tolerance condition. Integrity messages are conveyed through the LDC. In case of serious and harmful loss of synchronization, the transmitter will be take of the air.

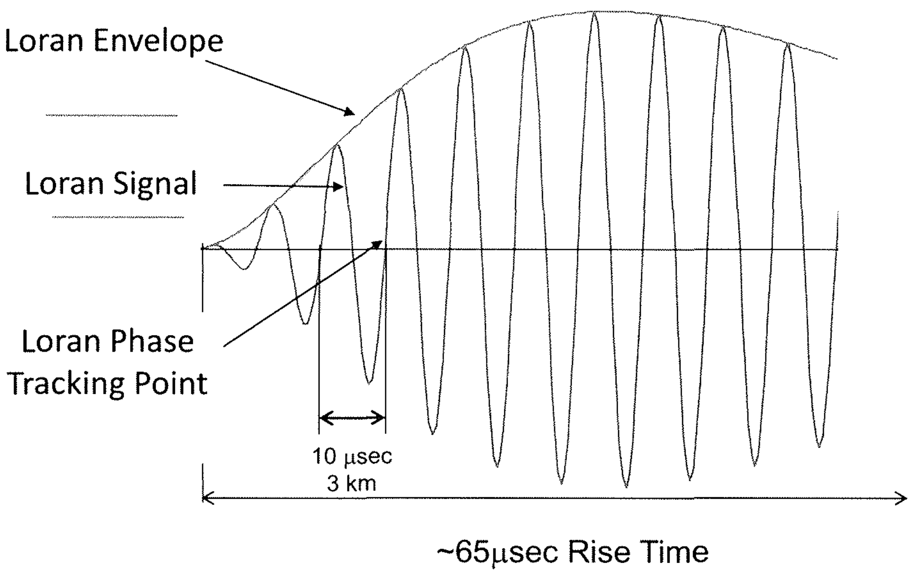


- 90-110 kHz frequency band
- Pulsed signal with 100-kHz carrier frequency
- Groups of 8 pulses 1-ms spaced in TDMA structure
- Transmission of groups repeats every Group Repetition Interval (GRI)
- Up to 5 stations may share same GRI to form a chain



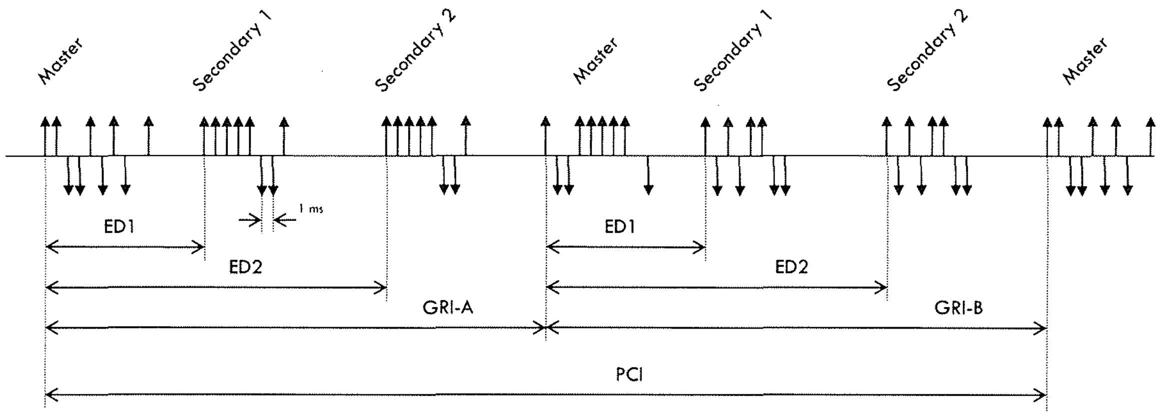


- Known Loran envelope shape used to identify reference zero-crossing, which is synchronized to UTC.



eLoran Signal Structure (cont.)

- The transmitted signals are phase coded (0 or 180°) for Master/Secondary identification and rejection of multiple hop skywaves.



↑ = 0° Carrier Phase

↓ = 180° Carrier Phase

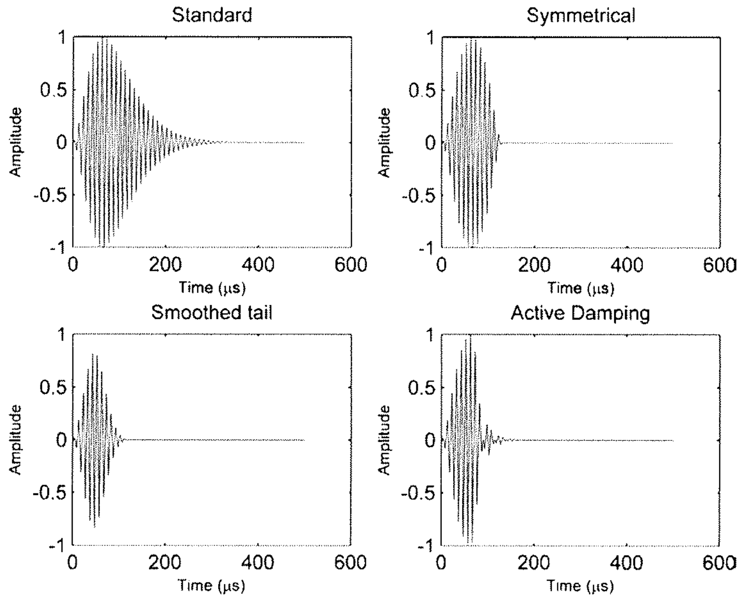
ED = Emissions Delay (=Coding Delay + propagation time from Master to Secondary)
GRI = Group Repetition Interval (40 – 100 ms)
PCI = Phase Code Interval (80 – 200 ms)

eLoran Signal Improvements

- Improved phase codes
  - Phase codes should average to zero.
  - Pseudo-Random Noise (PRN) based phase codes will allow unique identification of a station in a group and will reduce cross-correlation of signals from other stations.
- The 9th Master pulse in the 10th pulse slot is no longer needed for identification and can be removed. This improves cross-rate interference and frees up the slot for the LDC.
- Waveforms can be improved over "standard" Loran-C.
- Shorter pulses allow for more navigation pulses, or room for more data. Navigation function is not degraded.
- Shorter pulses reduce negative cross-rate and skywave effects.

eLoran Signal Improvements (cont.)

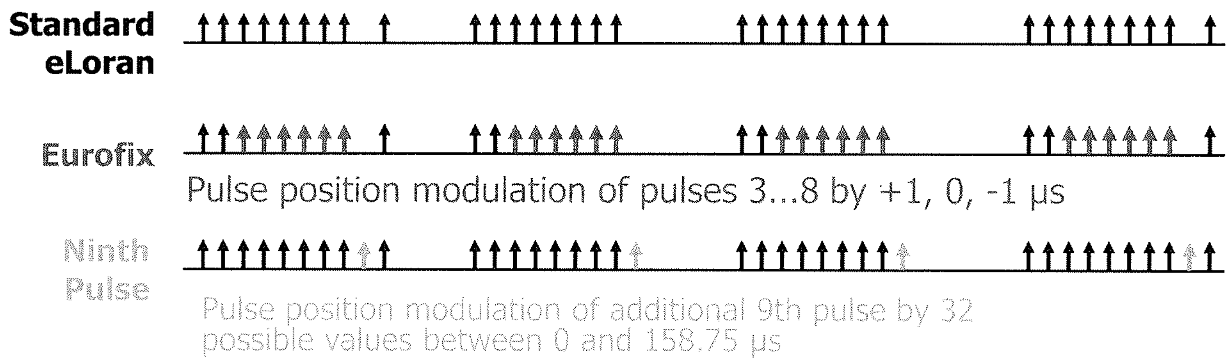
- Shorter pulses reduce the output power at the same levels of navigation signal power at the standard zero crossing.
- Shorter pulses are feasible and have been transmitted on air.



eLoran Data Channel

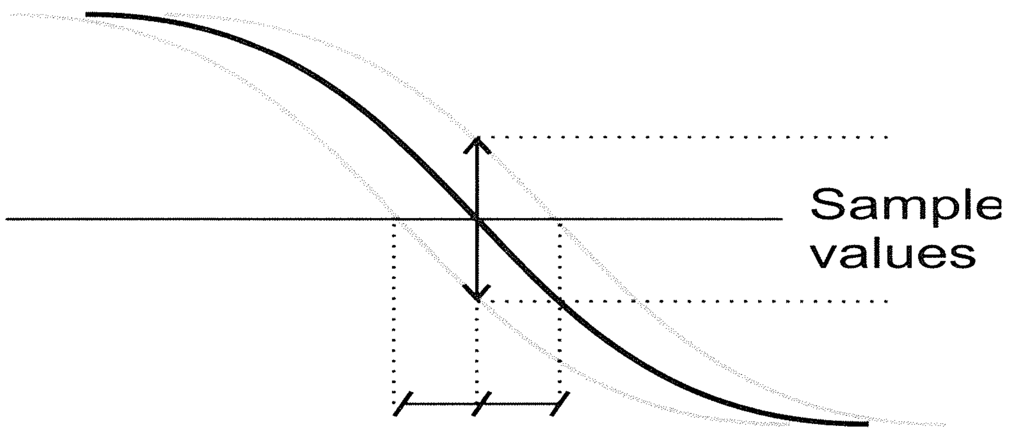
- Major difference between Loran-C and eLoran is the Loran Data Channel
- Data Channel carries
  - Differential eLoran Correction
  - UTC Time of day and date information
  - eLoran Integrity information
  - Differential GPS information
  - GPS integrity information
  - Other data
- Two implementations exist:
  - 3-state Pulse Position Modulation (Eurofix)
    - Standardised by RTCM and ITU
  - 9th Pulse Modulation

- Both systems provide equal data bandwidth (approx. 20 – 50 bps)
- Both systems protected by Reed-Solomon forward error correcting code to counter the effects of cross-rate and noise



- Eurofix and Ninth Pulse broadcast data at about 30 bps
- Eurofix and Ninth Pulse **simultaneously applicable**
- Receivers can handle multiple data channels from different transmitters at the same time

- Data channel by 3-level 1 us pulse position modulation (1 us advance, prompt or 1 us delay)
- Last 6 of 8 pulses modulated (balanced each GRI) results in 7-bit symbols



1 µs PPM modulation

Eurofix Modulation / Encoding

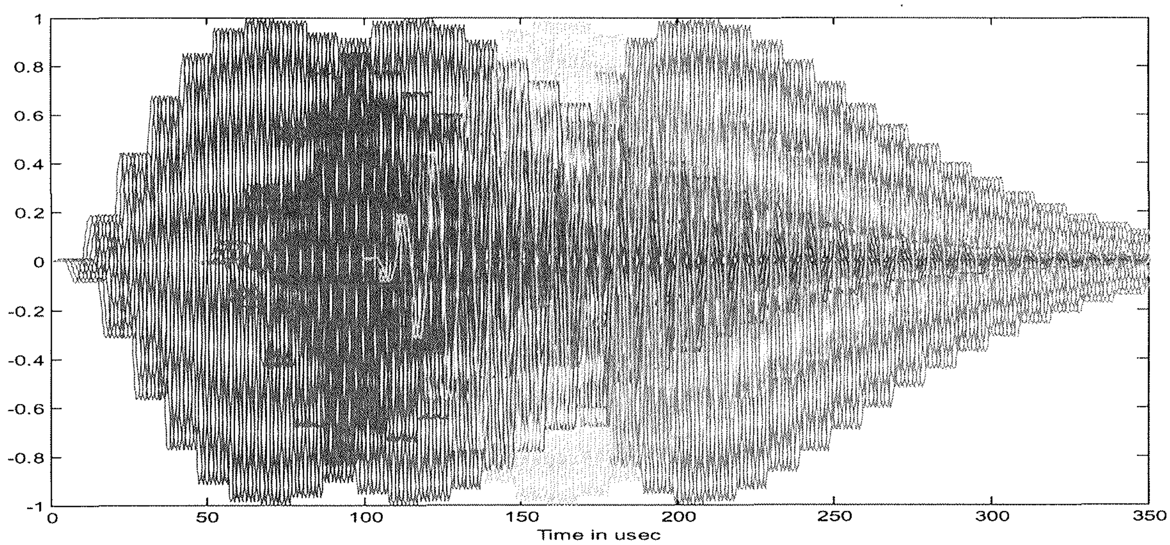
- 56 bits DGPS message
- 14 bits Cyclic Redundancy Check (datalink integrity)
- <u>140 bits</u> Reed-Solomon Parity
- 210 bits = 30 GRIs of 7 bits per message means 1.2 – 3 sec per message

DGPS Message → Encoding → DGPS Message | CRC | Reed-Solomon

Bits	0100101	0001011	1011000	1010001	0011101	0010110	0111001	0011010	1001110
Modulation	↓	↓	↓	↓	↓	↓	↓	↓	↓
Pulses	00+-+-	+-00-+	0-00+0	-+++--	0-0+00	+0--0+	+--0+0	-00+00	0+00-0

eLoran Data Channel – 9th Pulse

- 9th pulse Pulse Position Modulation (PPM)
- 32 state PPM, 5 bits/GRI (3 bits phase, 2 bits envelope & phase)



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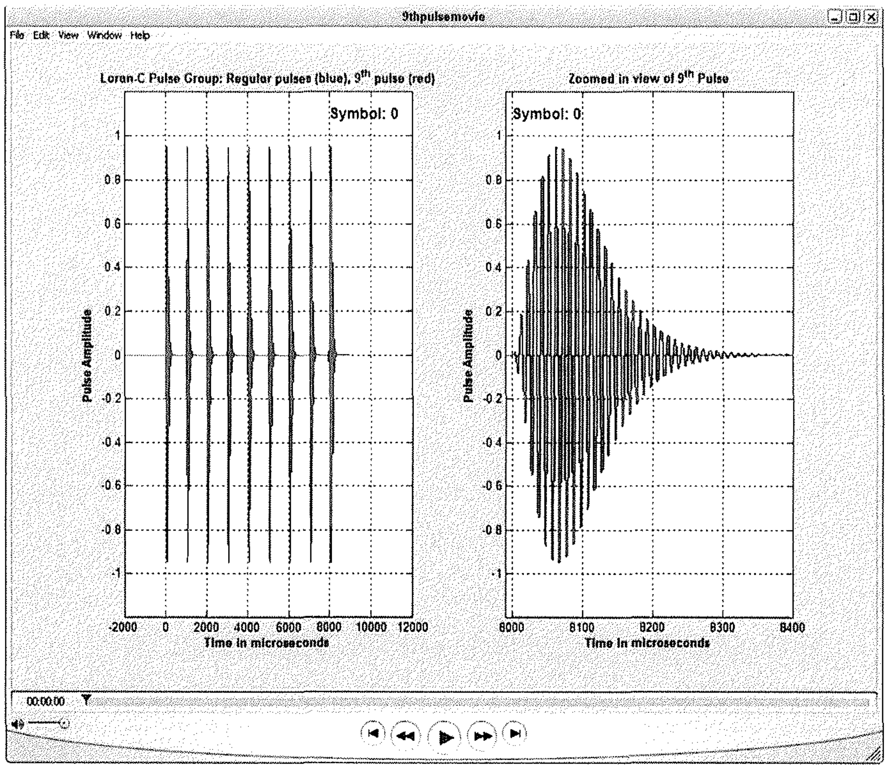
9th Pulse Demo



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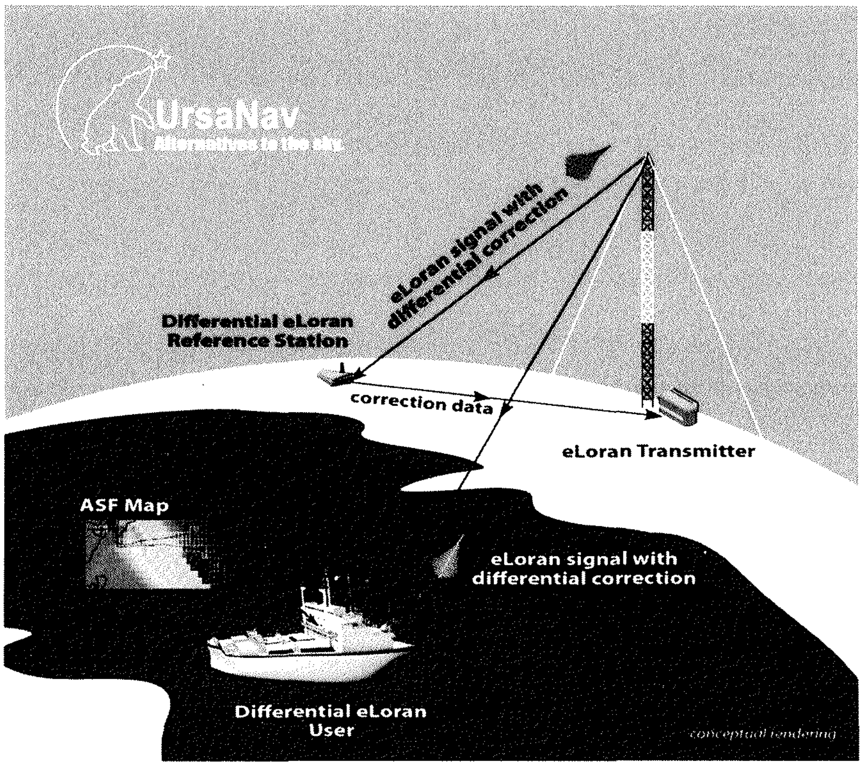
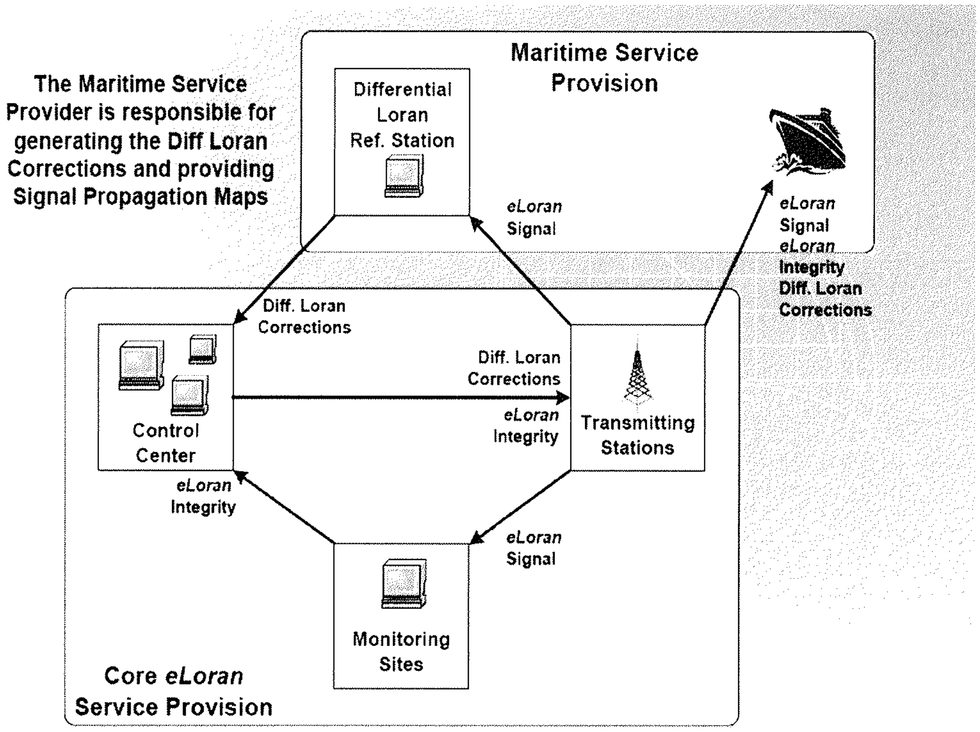
Differential eLoran - Application

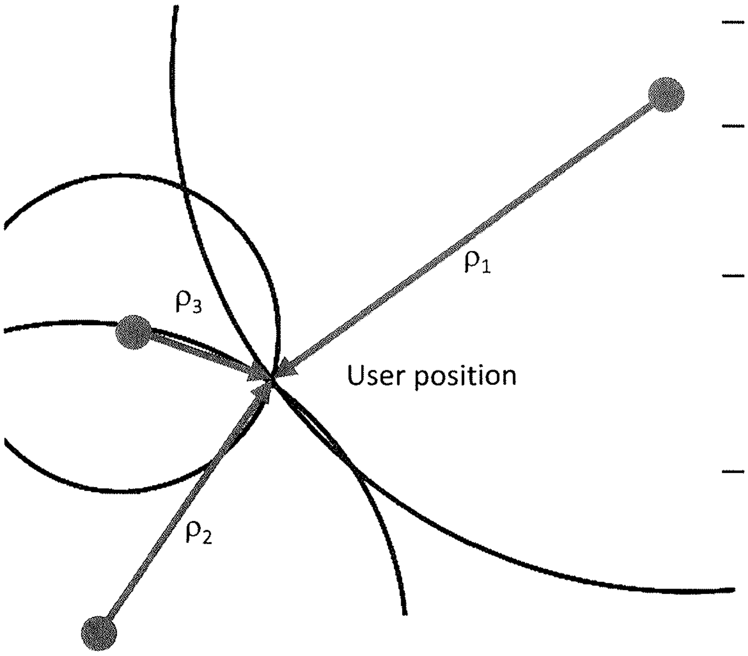


eLoran Service for Maritime Users



eLoran for Maritime Uses

- To explain maritime ASF we need to understand:
  - Positioning using eLoran
  - eLoran signal propagation
  - Concept of ASFs and the ASF map
  - Concept of differential corrections



- eLoran transmissions synchronised to UTC
- User receiver measures Time of Arrival to three (or more) transmitters
- Difference between Time of Arrival and Time of Transmission is the Propagation Delay Tprop
- TProp (in seconds) needs to be converted to a pseudo-range ρ (in meters) by multiplication with the speed of light (c) to calculate the user position

- A position calculation is based on 3 (or more) pseudoranges to 3 (or more) transmitters
- The receiver measures arrival times, which convert to pseudoranges by multiplication with the signals' propagation velocity
- This velocity is not equal to the speed of light in vacuum, but depends on the medium the signals travel in and over!

$$\rho = R + PF + SF + ASF + \delta + \varepsilon + B$$

Where

R = true range (what we want to know)

PF = Primary Factor

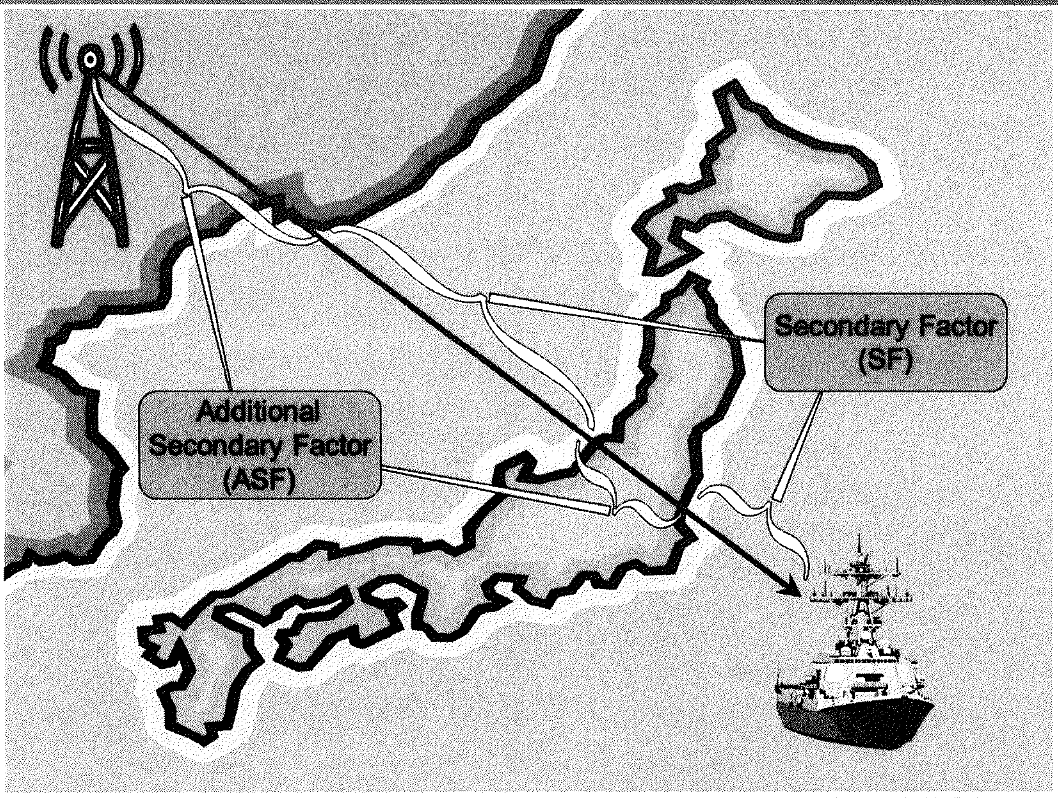
SF = Secondary Factor

ASF = Additional Secondary Factor

δ = variation in PF, SF and ASF

ε = remaining measurement errors

B = the receiver clock bias, solved in the position calculation



Primary and Secondary Factor

- The Primary Factor delay is the difference between propagation of the signal in the earth's atmosphere as opposed to in free space
- The Secondary Factor delay accounts for signal propagation over sea-water
- PF and SF are known and considered constant, the receiver uses a model to calculate the delays

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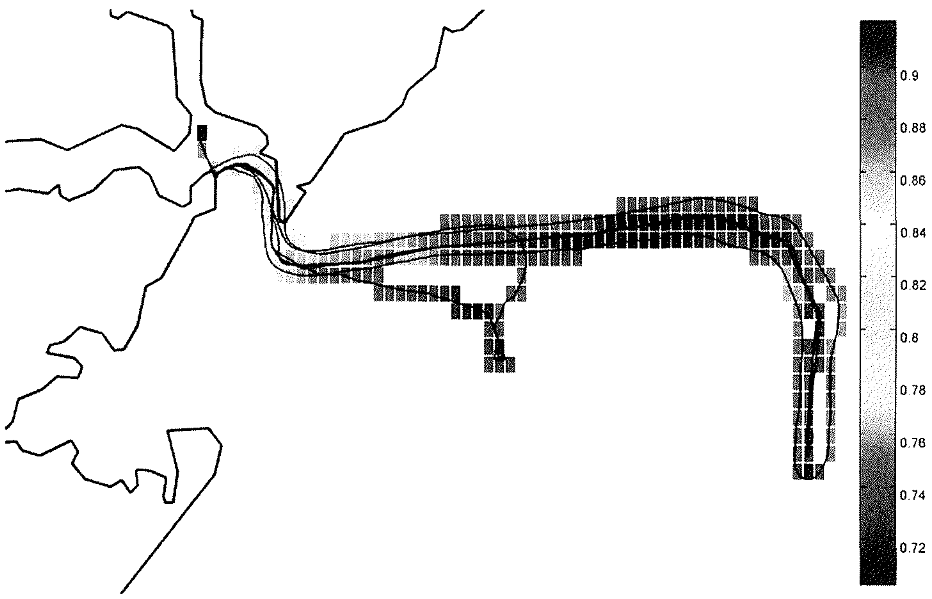
Additional Secondary Factor

- The Additional Secondary Factor is the delay caused by signal propagation over land and elevated terrain as opposed to over sea-water
- The ASF delay build-up depends on the type of soil
- The ASF delay is the total cumulative delay the signal experiences of sections with different ground conductivity
- The Maritime service provider publishes an ASF map for the operating area as a grid with surveyed nominal ASFs for each transmitter
- Not taking ASFs into account may result in positioning errors of several 100 meters to kilometers

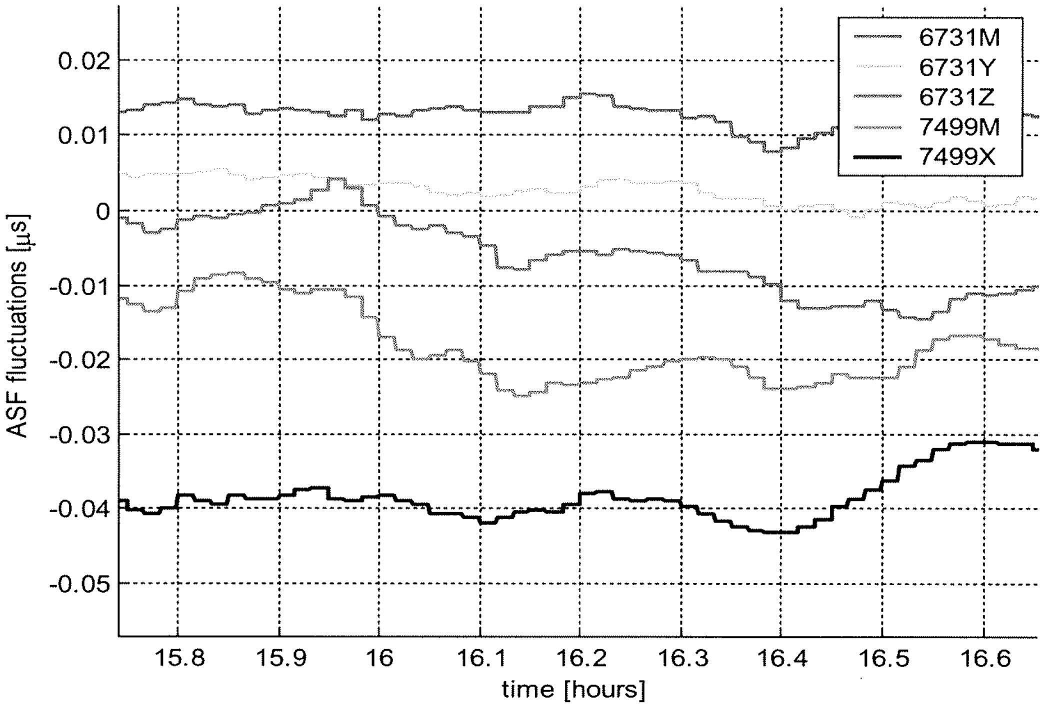
- ASFs are published as a map with an ASF grid for each transmitter

picture courtesy of the General Lighthouse Authorities of the UK and Ireland



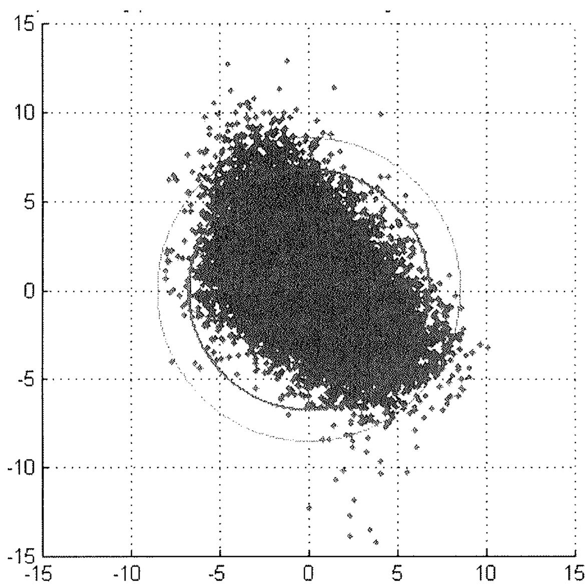
- ASFs are relatively constant in time
- Any variation in ASF due to weather, water vapor, air pressure, seasonal influences is captured in δ
- δ also contains any misalignment of the transmitter timing wrt UTC
- δ is unknown, but can be measured by a reference station at a known and fixed location
- In differential eLoran, these corrections are broadcast to the users to improve their positioning and UTC time accuracy

Differential eLoran Reference Station Corrections

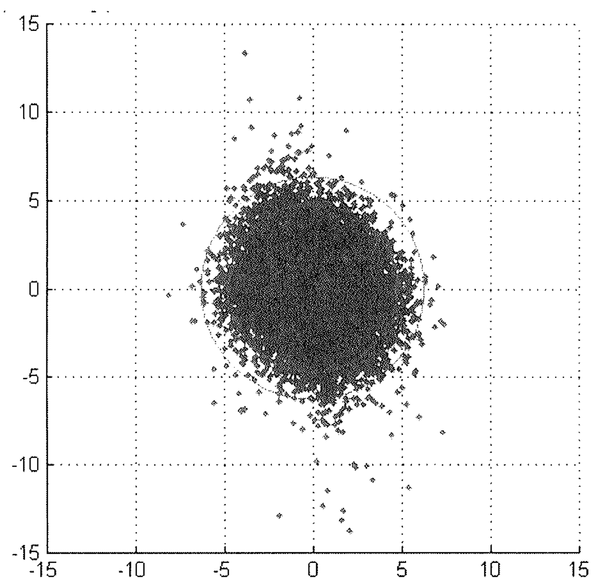


picture courtesy of the General Lighthouse Authorities of the UK and Ireland

Application of Differential Corrections (Static)



No differential eLoran corrections
Accuracy: 6.8 m (95%)



With differential eLoran corrections
Accuracy: 4.8 m (95%)

- The Differential eLoran user calculates position based on:
  - eLoran range measurements
  - Corrected with modeled PF and SF
  - Corrected with ASF map values for the estimated location
  - Corrected with differential corrections coming from eLoran Reference Station broadcast from eLoran transmitter
    - Differential corrections compensate for changes in ASF map data and possible transmitter timing errors

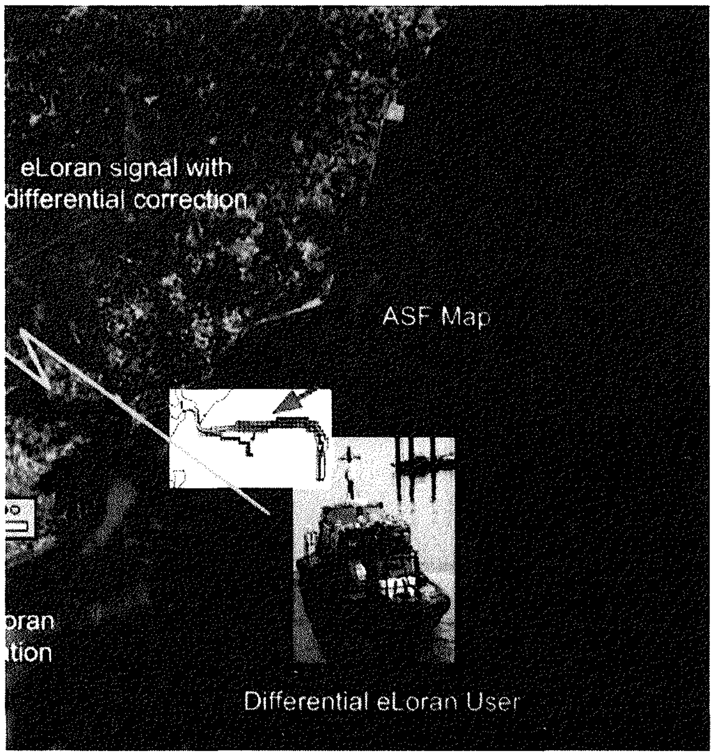
$$R + \varepsilon = (\rho - PF - SF - ASF - \delta - B)$$

Where

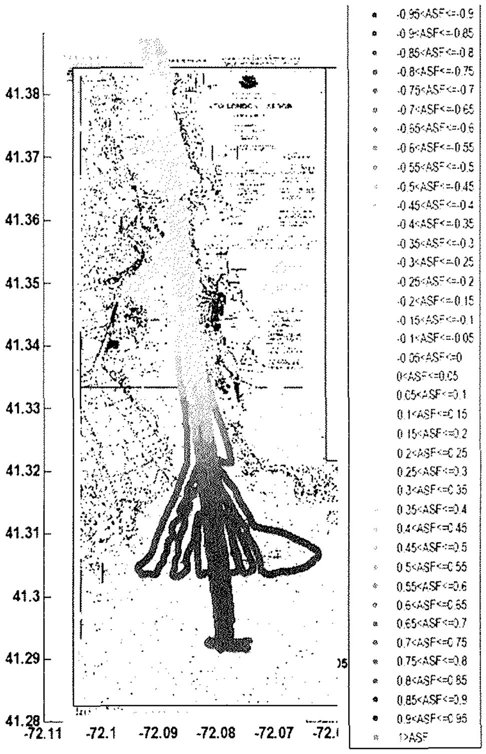
R = true range (what we want to know)
PF = Primary Factor (modeled)
SF = Secondary Factor (modeled)
ASF = Additional Secondary Factor (published)
δ = differential correction (broadcast)
B = clock error bias (solved in positioning)
ε = remaining measurement errors

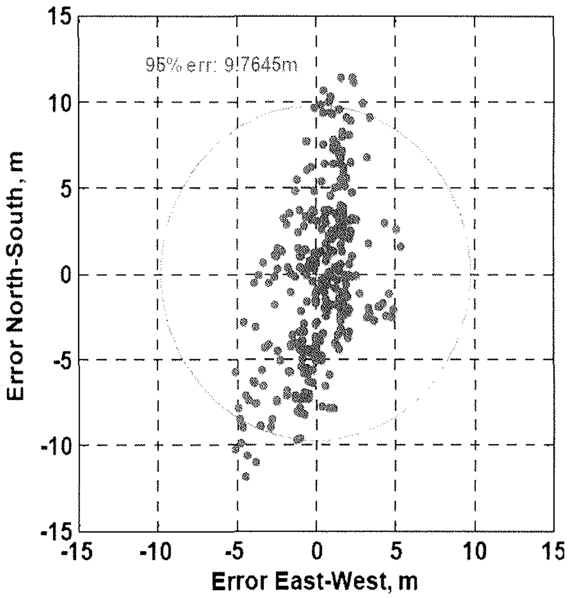
Remaining errors ε, such as noise and interference cause the calculated position to deviate from the real position

Differential eLoran Trials



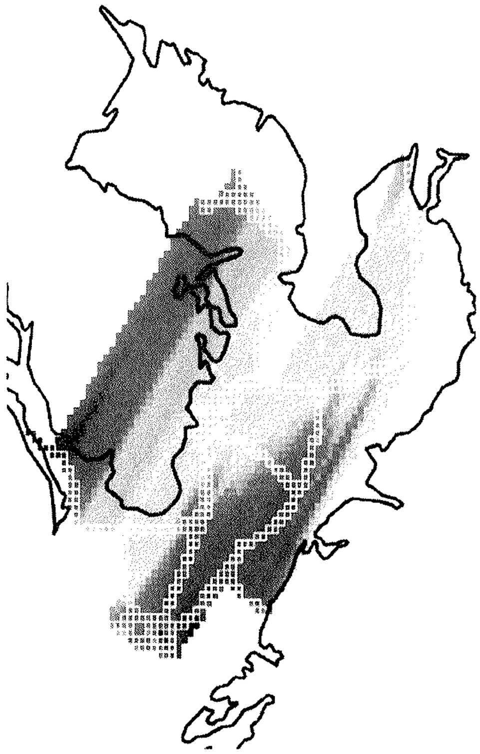
US Coast Guard Academy dLoran

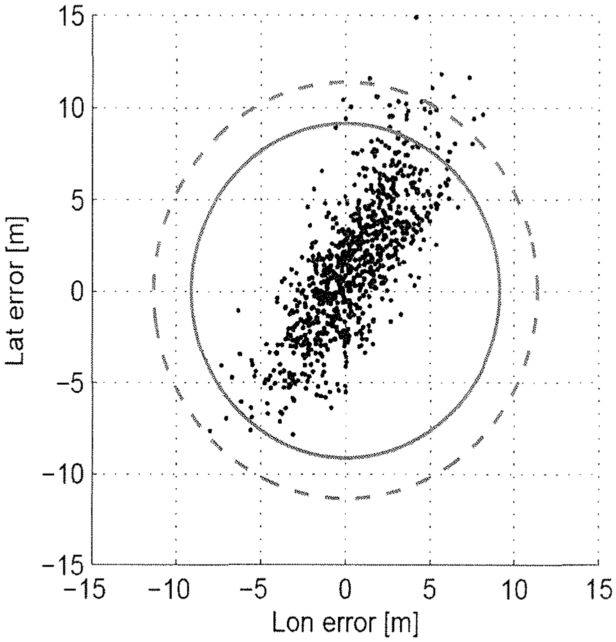




Pictures:Johnson, Dykstra, Oates, Swaszek & Hartnett, 'Navigating Harbors at High Accuracy Without GPS: eLoran Proof-of-Concept in the Thames River', ION National Technical Meeting 2007, Session E3, Paper 5, 2007

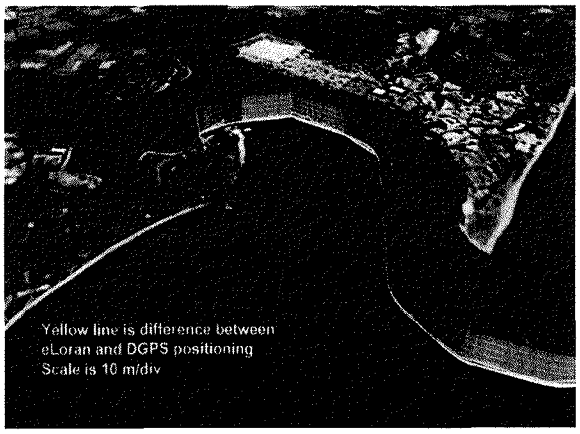
dLoran Trials in Tampa Bay, Florida

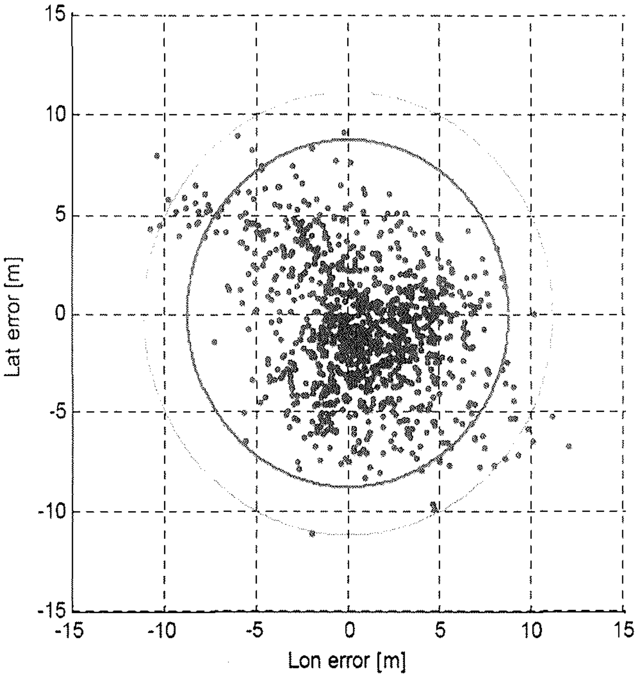




Pictures: Pelgrum, 'New Potential of Radionavigation in the 21st Century', Doctoral These, Delft University of Technology, Nov 2006

General Lighthouse Authorities (UK) Trials





Pictures: *Data Gathering in Support of the GLA's "European eLoran Performance Evaluation", Final report REEL-TH-R03, Prepared for Trinity House*

- Meets 10-20 m accuracy requirement for Harbor Entrance and Approach
- Meets availability, continuity and integrity requirements for Aviation Non-precision approach
- Meets Stratum-1 timing and frequency requirement, provides UTC within 50 ns
- Independent from GPS (or any other GNSS)

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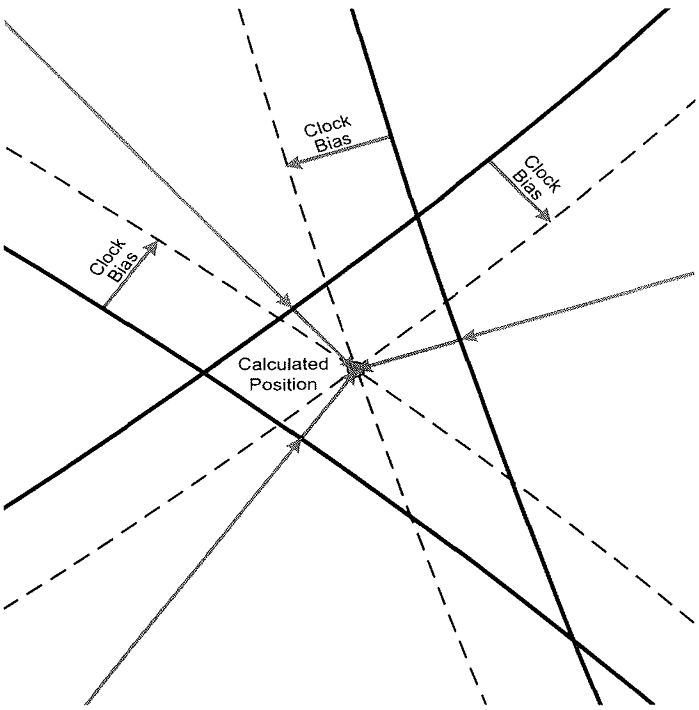
Back-up Slides

Washington DC Metropolitan Area
Leesburg, Virginia

Corporate Headquarters
Chesapeake, Virginia

EMEA Operations
Bertem, Belgium

Positioning and Clock Bias



- Clock bias is common on all measured TOAs
- Clock bias is solved in position iteration process
- Three TOA measurements to solve three unknows: Latitude, Longitude and Clock bias
- Additional TOAs enable (weighted) least squares positioning

Tutorial Session: Next Generation LF Transmitter Technology for eLORAN Systems

ILA-40, Busan, Korea
November 18, 2011
Tim Hardy

Tutorial Session:
Next Generation LF Transmitter Technology for eLORAN Systems

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Making Digital Radio Work.

Overview

- Nautel Introduction
- RF Class D Amplifier
- Antenna Behavior
- Alternate Signal Capability
- Proof of Concept Transmitter Test
- Overview of Operational Transmitter

Making Digital Radio Work.

Who is Nautel?

Nautel is: A designer and manufacturer of

Solid State NDB and DGPS Transmitters
+3,700 units since 1970
Solid State MF Telegraph Transmitters
+200 units since 1970
Solid State FM Broadcast Transmitters
+2500 units since 1992
Solid State MW/LW Broadcast Transmitters
+2,700 units since 1982

Customers include:
- FAA, USCG, CCG, ASA
- BBC, CBC, ABC, TRT
- many others …

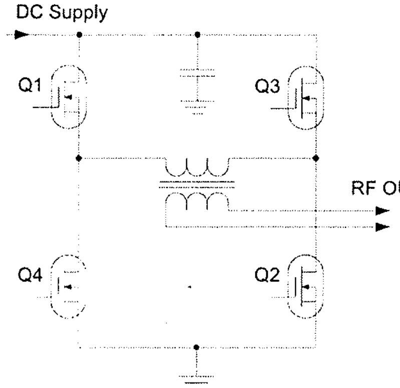
Global Installed Base

Making Digital Radio **Work.**

‘Class D’ Amplifier for eLORAN

Why Class D?

- Efficient: Can achieve 95% -100% DC to RF efficiency
- Flexible: Not limited to one waveform
- High Power: > 10kW per amplifier
- MOSFET Transistors: jitter < 1 nS (30 cm)
- Proven Technology at Nautel:
  > 5000 Class D transmitter shipped
  Manufactured since 1970



Making Digital Radio **Work.**

The Challenge:

- Can Class D work for eLORAN antennas?
  - RF frequency: 100 kHz
  - λ/4 antenna: 750 metres – not practical
  - Typical antennas are 100m to 200m (λ/32 to λ/16) – or less!
  - Electrically short - high Q and narrow bandwidth

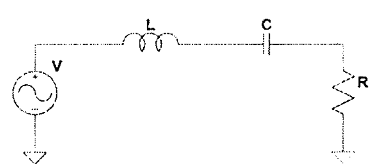
$$BW = \frac{f_c}{Q}$$

- To answer, we need a quantitative analysis of the antenna and signal interaction. (Transient analysis)

Making Digital Radio **Work.**

Antenna Equivalent Circuit

- Series RLC equivalent circuit
- Antenna may be directly measured:
  Impedance $(R + jX)$
  Reactance vs. frequency $(dX/d\omega)$



$$C = \frac{2}{\omega^2 \frac{dX}{d\omega} - \omega X} \qquad L = \frac{1}{2}\left(\frac{dX}{d\omega} + \frac{X}{\omega}\right)$$

- Equivalent circuit is useful from ~ 80 to 120 kHz

Making Digital Radio **Work.**

Antenna Example: 190 Metre Top Loaded Monopole

Antenna Base Measurements:

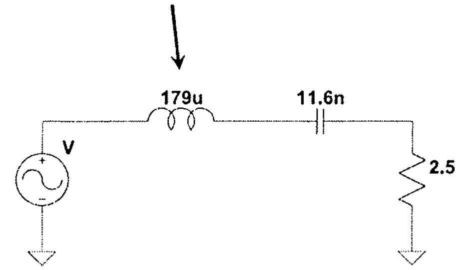
Base Impedance:	2.5 – j 25 ohms
Reactance Slope:	+ 2.5 ohms/kHz

Equivalent Circuit:

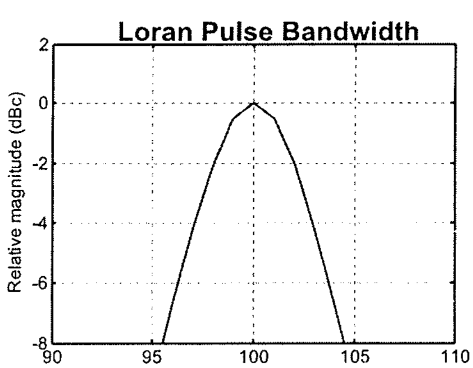
Resistance:	2.5 ohms
Capacitance:	11.6 nF
Inductance:	219 μH*
Q:	55
BW 3dB:	1818 Hz
Efficiency:	72%

* Additional 40 μH required for resonance at 100kHz

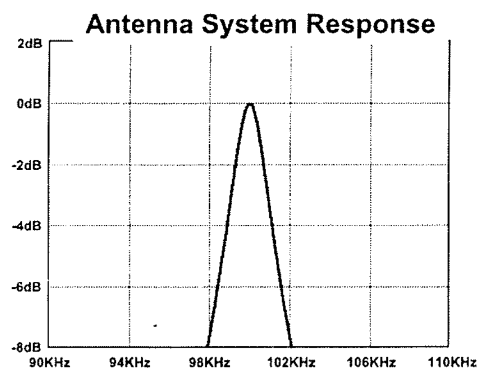
Increased to 219 μH to adjust resonance to 100kHz



Insufficient Antenna Bandwidth



3dB BW = 5 kHz



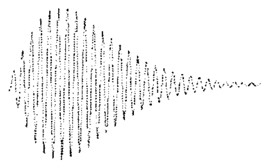
3dB BW = 1.8 kHz

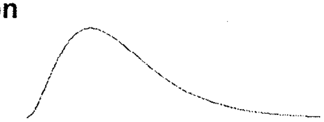
Pulse bandwidth is ~3 times greater than antenna bandwidth for Q = 55

Not Steady State!

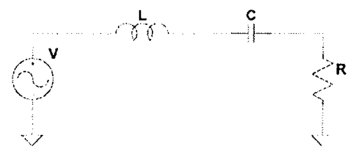
Simplified Transient Analysis

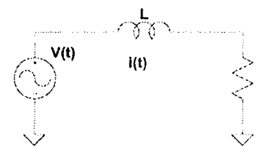
RF → Baseband Transformation





$$i(t) = t^2 e^{-at} \sin(0.2\pi t) \longrightarrow i(t) = t^2 e^{-at}$$





Network equation $V(t) = i(t)R + L\dfrac{di}{dt}$

What transmitter voltage is required? $V(t) = (2Lt - aLt^2 + Rt^2)e^{-at}$

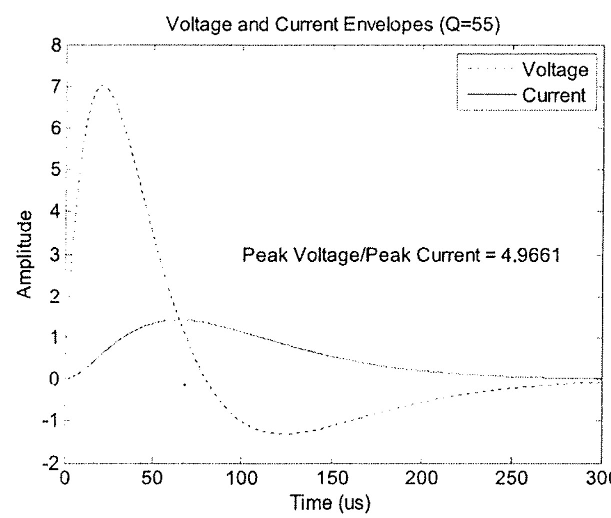
Antenna Q (L/R) determines transmitter voltage waveform

Making Digital Radio **Work.**

Transient Analysis – Key Results

- Voltage ≠ Current
- Impedance is variable
- **Peak voltage increased 5x**
- **Negative power flow** after the pulse peak

There is an opportunity to improve efficiency by recovering negative power flow.

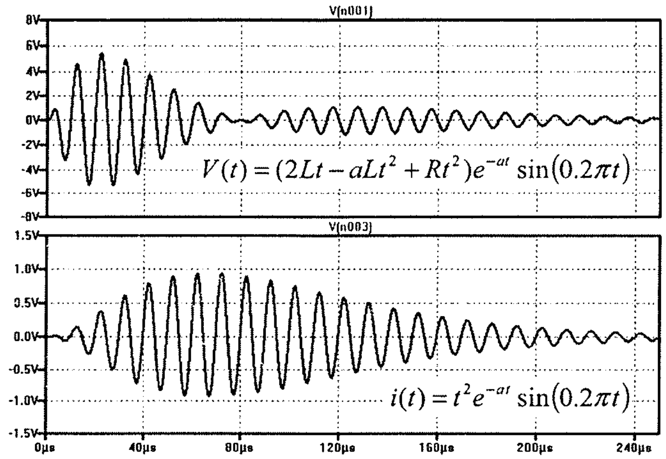


Making Digital Radio **Work.**

Standard Signal Spec. Pulse

Transmitter voltage fundamental component (blue)

Induced pulse current (red)

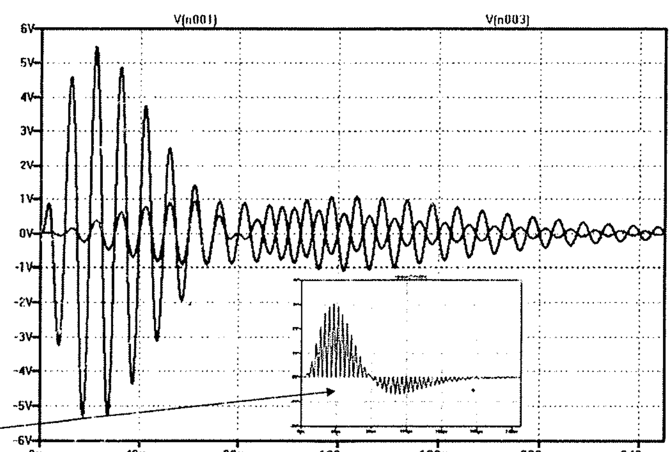


Making Digital Radio **Work.**

Standard Pulse

- 5x Voltage
- Voltage and current out of phase in tail
- Negative power flow in pulse tail

Power flow



Making Digital Radio **Work.**

Antenna Power Recovery

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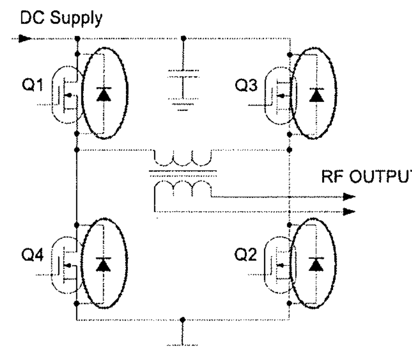
- "Recycles" power from the antenna after the pulse peak
- Must allow current to reverse
- Diodes are installed in reverse across the transistors
- Power is returned to the power supply
- Nautel patent pending technology



Making Digital Radio **Work.**

System Efficiency Overview

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- System efficiency determined by two key factors:

$$\eta_{System} = \eta_{Transmitter}\,\eta_{Antenna} \qquad \eta_{Antenna} = \frac{R_R}{R_R + R_L}$$

Radiation Resistance (R_R)

Antenna Loss Resistance (R_L)

- Transmitter efficiency:

$$\eta_{Transmitter} = \eta_{PS}\,\eta_{PA}\,\eta_{RCVRY}\left(1 - \frac{P_{SHUNT}}{P_{INPUT}}\right)$$

P_{SHUNT}: Loss from Fans, Control etc.

η_{PS}: Power Supply 90% Typical

η_{PA}: DC – RF 80-90% for Nautel Class D

η_{RCVRY}: Antenna Energy Recovery Factor 80 - 100% for Nautel Class D

Making Digital Radio **Work.**

Power Recovery Advantage

- Power recovery efficiency factor:

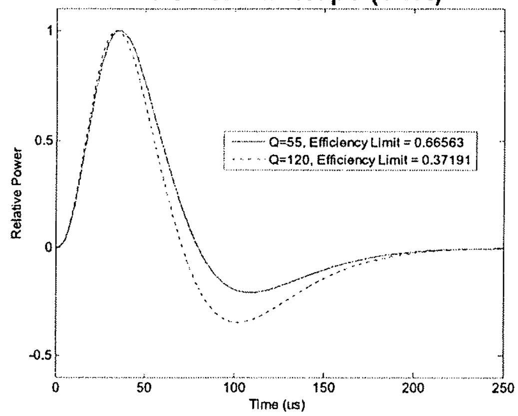
$$\eta_{Recovery} = \frac{E_S - E_R}{E_S}$$

E_S : energy delivered to antenna
E_R : energy returned from antenna

- For antenna Q = 55:
  $\eta_{Recovery} = 67\%$
- For antenna Q = 120:
  $\eta_{Recovery} = 37\%$

Up to **100%** for Nautel technology

Power Envelope (V x I)

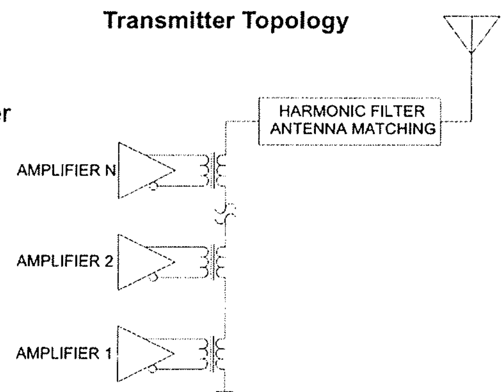


Making Digital Radio **Work.**

RF Transmitter Topology

- 10 or more amplifiers are required
- Voltage is controlled by varying the number of amplifiers on each RF cycle
- Transformers combine the amplifiers in series
- A harmonic filter is needed
- An antenna tuner is needed

Transmitter Topology



Making Digital Radio **Work.**

General Modulation Capability

Any waveform can be made, limited only by:

1. Transmitter peak voltage capability
2. Antenna response/bandwidth
3. System average power limit

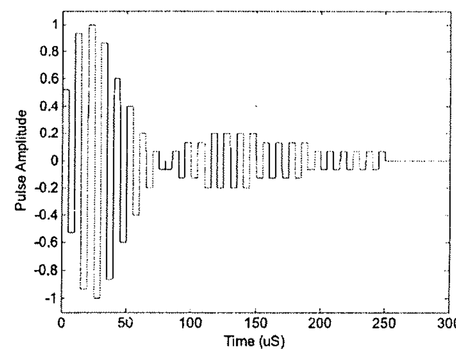
Amplitude is controlled by enabling amplifiers

Phase is controlled by moving the switching time

An example LORAN pulse for 15 amplifiers:
8, 14, 15, 13, 9, 6, 3, 1, -1, -2, -2, -3, -3, -3, -3, -2, -2, -2, -2, -1, -1, -1, -1, -1 and -1

Pulse shape may be exactly repeated

Combiner Output Voltage for LORAN Pulse



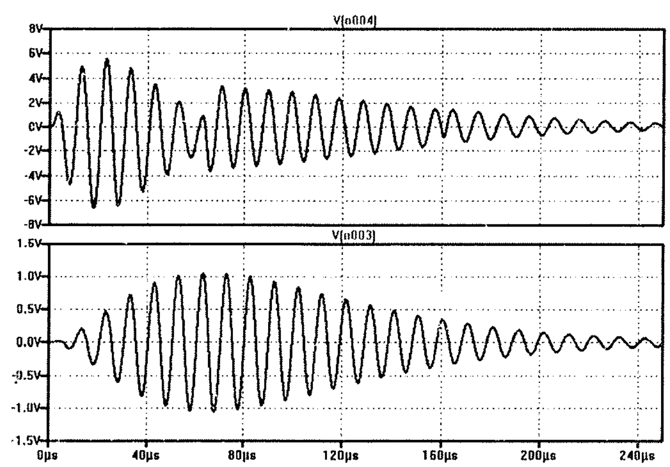
Making Digital Radio **Work.**

Alternate Pulse - Data Symbol

IFM employs discrete frequency changes in the pulse tail as a means to transmit data bearing symbols.

The intent is to minimally affect system PNT performance while offering increased data bearing capacity.

Required driving voltage may be predicted using analytical methods.



Standard pulse up to 60 µs

102.5 kHz from 60 to 160 µs

97.5 kHz after 160 µs

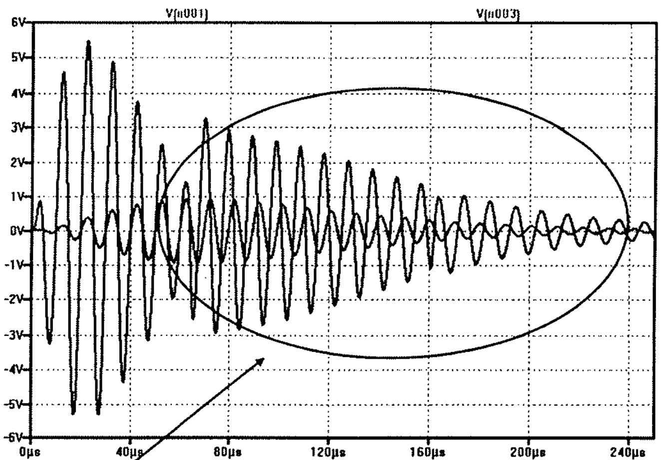
Making Digital Radio **Work.**

IFM Pulse

Peak voltage and RMS current are unaffected.

Transmitter power capability is unchanged.

IFM is an example of a phase modulated signal.



Voltage waveform in pulse tail is modified to pull resonant frequency off centre.

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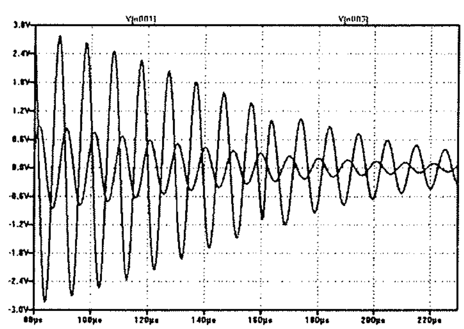
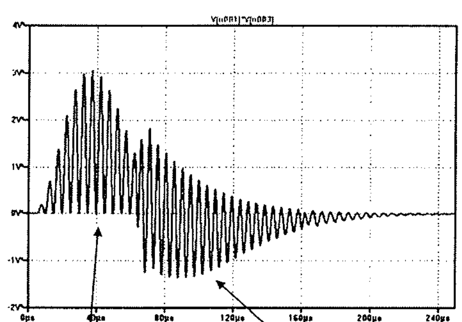
Phase Modulation – Reactive Power Required





Transmitter operates as a synthetic capacitor or inductor to control resonant frequency of the antenna.

Amplifier switching transitions at high current.

Real power flowing to antenna.

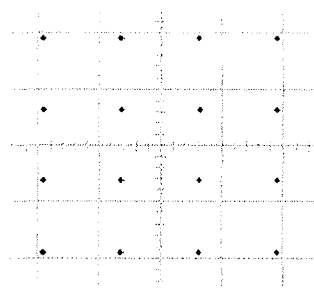
Complex power flow with negative real power flowing to transmitter.

Making Digital Radio **Work.**

Consider 16-QAM Waveform?

Use 4 IFM States to transmit information with the pulse phase.

Modify tail damping coefficient to allow for 4 amplitude states.



16 States per pulse yields 4 bits per pulse, un-coded.

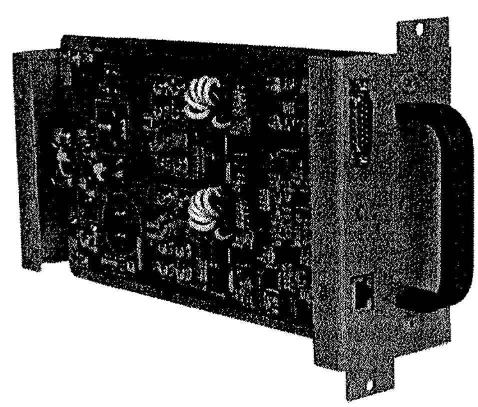
Using rate ½ coding and 100 pps, the data bearing capacity is 200 bps. 16 pulses per group would yield 400 bps.

Analysis of typical received Eb/No would help suggest appropriate waveform complexity ie. 4/8/16/32 states per pulse.

Making Digital Radio **Work.**

Proof of Concept - Amplifier

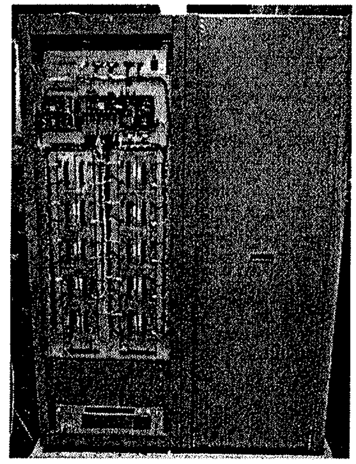
- Prototype amplifier developed September 2007
- Test system with high Q antenna simulator was constructed
- Design goals were achieved:
  Peak power > 30 kW
  Efficiency > 95%
  Power recovery



Making Digital Radio **Work.**

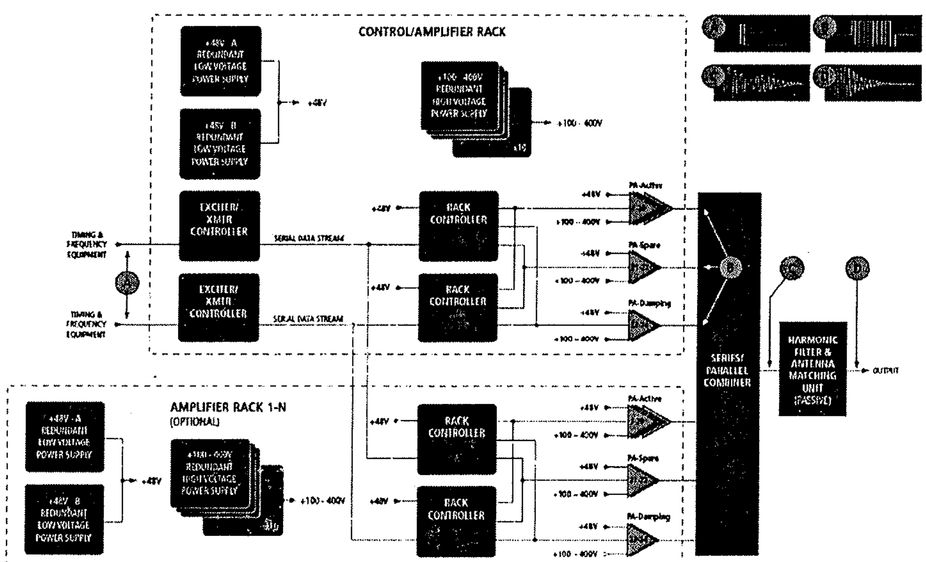
Proof of Concept Transmitter Test

- Proof of Concept Transmitter built 2008
- Transmitter Specifications:
    - 50 to 100kW Loran pulse capable
    - 600 pps
    - DSP based exciter
    - 15 Amplifiers + 1 standby
    - Hot Serviceable Amplifiers
    - Manual Antenna Tuning capability
- Trial conducted at USCG LSU (Wildwood) facility
- 1 day to install
- Independently tested (ILA 2009 proceedings)



Making Digital Radio **Work.**

NL Series Block Diagram



Making Digital Radio **Work.**

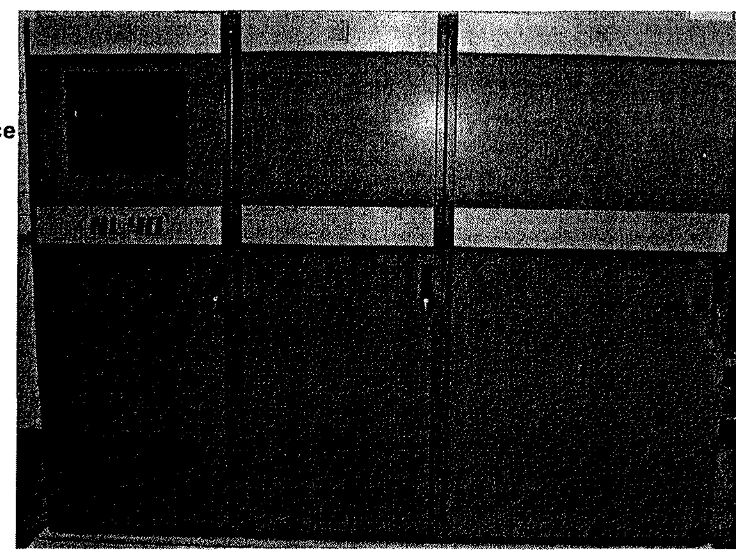
NL Series Fault Tolerance

- Full redundant backup:
  - Exciter/Control
  - Low Voltage Power Supply
- Parallel prime power supply modules:
  - Typically 50% failure tolerant without effect
  - Hot Serviceable
- Parallel RF Amplifiers:
  - 10 - 20% failure – no effect
  - Additional failures - graceful power reduction
  - Hot Serviceable

Making Digital Radio **Work.**

NL40 Operational LORAN Transmitter

Advanced User Interface (AUI)

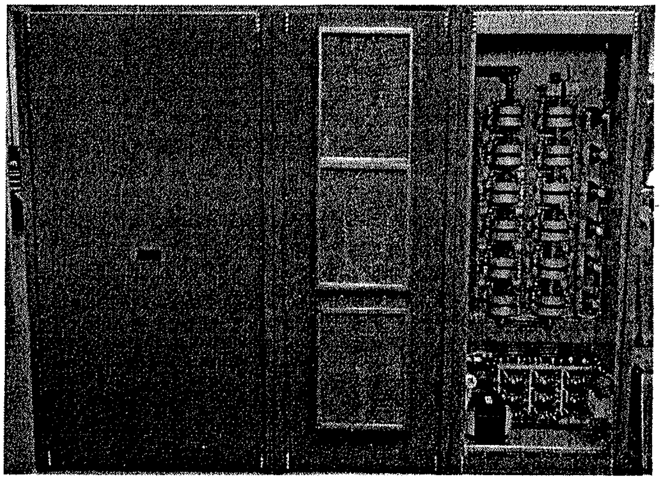


Harmonic Filter & Antenna Tuning/Matching Rack

Control/Amplifier Rack **Amplifier Rack**

Making Digital Radio **Work.**

NL40 Operational LORAN Transmitter



Series/Parallel Combiner

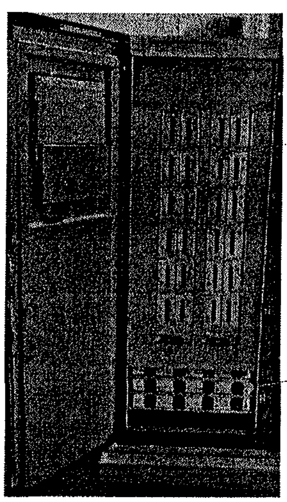
Harmonic Filter & Antenna Tuning/Matching Rack

Amplifier Rack

Control/Amplifier Rack

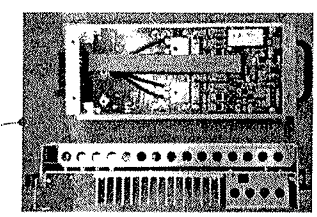
Making Digital Radio **Work.**

NL Next Generation LORAN Transmitter



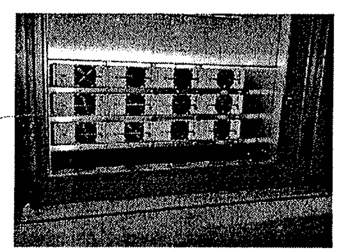
Control/Amplifier Rack

Amplifier Modules



Amplifier and P/S modules are "hot pluggable" to reduce MTTR..

Primary DC Power Supplies



Making Digital Radio **Work.**

Transient & Lightning Protection

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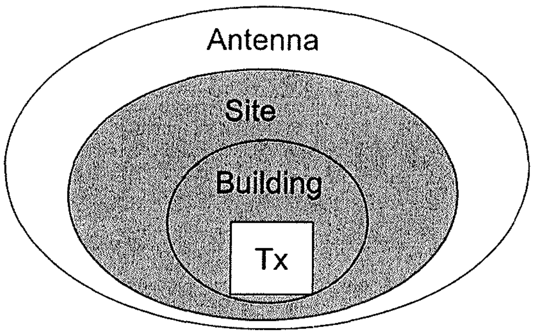
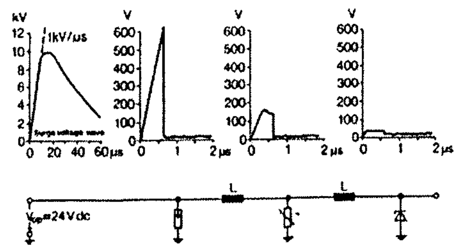
Primary threat is conducted energy

Staged protection system must be used



System level



Transmitter sub-assembly

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Site Layout to Improve Transient Immunity

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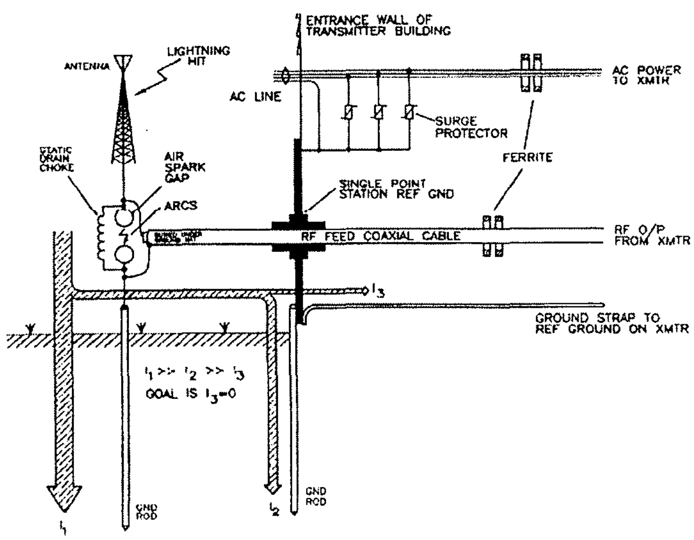

Making Digital Radio **Work.**

NL Series LORAN Transmitters

Overview

- High Efficiency Class D amplifiers
- Patent pending pulse power recovery technique
- Redundant architecture
- Software controlled pulse/signal shape
- Lowest jitter/noise
- Compact
- LRU diagnostics and fault monitoring

Making Digital Radio **Work.**

Thank you!

Questions?

Making Digital Radio **Work.**