Group Repetition Interval Selection for eLoran

Jan Šafář[1], Paul Williams[2], Seung Gi Gug[3]

[1] Czech Technical University, Prague

[2] The General Lighthouse Authorities of the UK and Ireland

[3] Korea Maritime University

Biographies

Mr. Jan Šafář was awarded the degree of Ing. (MEng) by the Czech Technical University in Prague, Czech Republic in 2007. Currently, he is a PhD student in the Department of Radio Engineering at the same university. His studies have focused on radio navigation systems; most recently concentrating on eLoran during a three month study period undertaken at the General Lighthouse Authorities of the United Kingdom and Ireland.

Dr. Paul Williams is a Principal 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 from real-time differential-Loran system development to the quality assurance of Loran ASF data. He holds BSc and PhD degrees in Electronic Engineering from the University of Wales, is a Chartered Engineer, an Associate Fellow of the Royal Institute of Navigation and is a board member of the International Loran Association.

Prof. Dr. Seung Gi GUG is an Associate Professor of the Department of Maritime Police Science at the Korea Maritime University where his main areas of research are Maritime Safety relating to Aids to Navigation/Waterway Design, and the Marine Environment related to the work of the Korean Government. In March 2008 he began work at the General Lighthouse Authorities' Research & Radionavigation Directorate on a year-long professional sabbatical where he has been investigating the benefits that enhanced Loran (eLoran) can bring to the Far East Radionavigation Service. He received the degrees of BSc and MA from the Korean Maritime University, and the degree of PhD from the Kyushu University in Japan. He is a board member of the Korean Institute of Navigation and Port Research, the Korean Aids to Navigation Association and is the Technical Chairman of FERNS.

Abstract

For a long time now, the General Lighthouse Authorities (GLAs) of the UK and Ireland have been interested in eLoran. In their Radio Navigation Plan the GLAs set out their proposal to develop current Loran infrastructure to an enhanced-Loran (eLoran) as primary complement and backup to GNSS. On the road to eLoran the system providers will face several challenges. Meeting the accuracy target of 8 to 20 m for harbour entrance and approach will likely involve expanding the current Loran transmission network. When introducing a new station the factors that will determine its effectiveness have to be understood, namely: the station(s) location(s), signal field strength, the effect on the horizontal dilution of precision (HDOP) with other stations and Group Repetition Interval (GRI) within which the new station(s) will transmit. This paper is focused on optimal GRI selection taking into account some aspects of contemporary eLoran technology through the development of new software tools written in Matlab™.

Introduction

In the early 1990s, when the European Loran-C chains (NELS) were planned a lot of attention was paid to the optimal GRI selection. Major work was carried out at Technical University Delft. Report [1] was published in 1992 and provides a starting point for the research presented in this paper. Based on previous work of Remmerswaal, Arriens, Van Willigen, and Beckmann [2] [3] [4] [5], the TU Delft report explains how judicious choice of GRI can minimize the interference caused by other (non-Loran) low frequency transmitters. The following year an addendum [6] to this report was submitted introducing some important updates. Report [7] produced by DCN Brest contains experimental data supporting the method proposed in [1] and presents some other issues regarding Loran transmitters and signal timing.

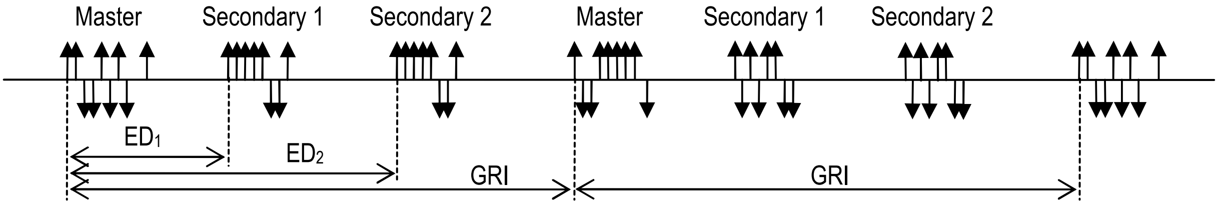

Figure 1: Loran signal structure; ED – Emission Delay, GRI – Group Repetition Interval

The greatest interferer to Loran is Loran itself in the form of Cross Rate Interference (CRI). Further work at TU Delft explored this interference between Loran stations, which is due to stations transmitting signals with different GRIs. Thorough time-domain analysis of this problem was performed in [8]. This report was later extended in [9] including evaluation of data loss in the Loran Data Channel (LDC). Some useful thoughts on GRI selection can also be found in report [10] by NODECA[1] and manual [11] describing the procedure used by United States Coast Guard (USCG). The main premises of the techniques employed were subsequently adopted by IALA [12].

This paper starts with a brief description of the Loran system, then summarizes the main factors affecting the selection of GRI and presents a procedure for optimal GRI selection. Some aspects of contemporary eLoran technology are taken into account and further updates are suggested. The procedures were implemented in a set of three Matlab™ tools, and these tools were used during a case study involving the addition of eLoran stations to the Far East Radionavigation Service (FERNS).

Loran Operation and Signal Structure

The basic operating principles of Loran and its signal structure have remained largely the same over the many years of its existence. Loran is a terrestrial system with geographically widely spaced transmitters broadcasting low frequency high-power pulses. Loran transmissions are precisely timed and a position solution can be determined from the time of arrival of the signals of at least three stations.

Figure 1 shows typical Loran pulse transmissions within chain, for the case of a chain containing three stations. Each station emits groups of pulses. In this example, the master station is followed by two secondary stations separated by their respective emission delays (ED), and then the transmissions repeat. The time interval between master transmissions within the same chain is the Group Repetition Interval (GRI) and this is how the receiver distinguishes a particular chain. The pulses are phase-coded according to the arrows shown in the figure, and this phase coding repeats every two GRIs. Therefore, for spectral analysis, it is appropriate to use 2xGRI as the period of the signal.

Factors Affecting GRI Selection

There are two key factors that affect GRI selection. Firstly, Continuous Wave Interference (CWI) is caused by transmitters broadcasting close to the Loran frequency. The significance of this problem, in particular for European chains, has been underlined many times before [6, 13, 14]. Secondly, Cross-Rate Interference occurs due to overlapping Loran signals. This is of great importance as all the Loran transmitters operate on the same frequency. Besides these two factors, there are also some other constraints, which will be mentioned later in the text.

Continuous Wave Interference

The shape of the Loran pulses is such that 99% of the signal's energy is concentrated between 90 and 110 kHz (Figure 2). This frequency band is reserved for Loran [15] and it should be free from any intentional and unintentional interference. In Europe, however, there are hundreds of non-Loran transmitters that operate near this band and these interfere to a greater or lesser extent depending on the GRI.

The receiver's susceptibility to continuous wave interference depends on the particular GRI of interest. This can be illustrated easily in the frequency domain. A closer look at the Loran spectrum reveals distinct spectral lines every 1/(2xGRI) as a result of the signal being periodic in 2xGRI (Figure 3). Interference from continuous waves appears as single lines depicted as arrows. If these fall between the

[1] Norwegian Defense Communications and Data Services Administration

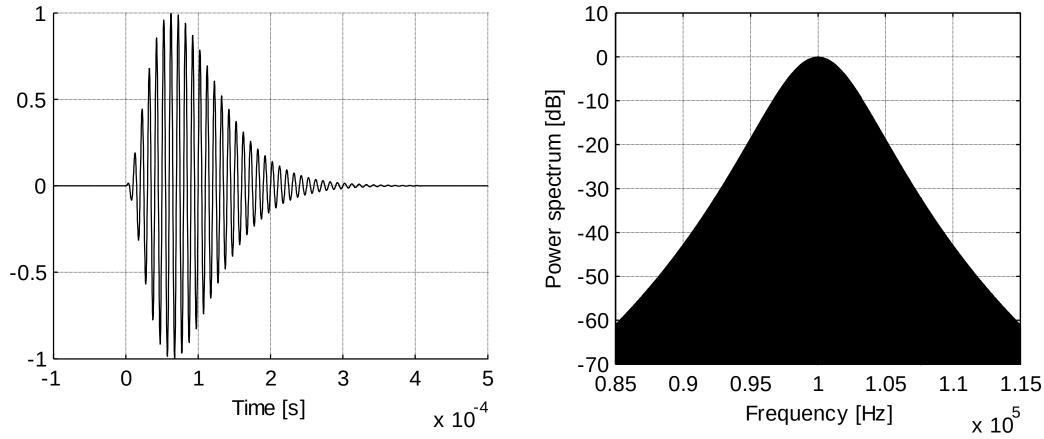

Figure 2: Loran pulse and power spectrum

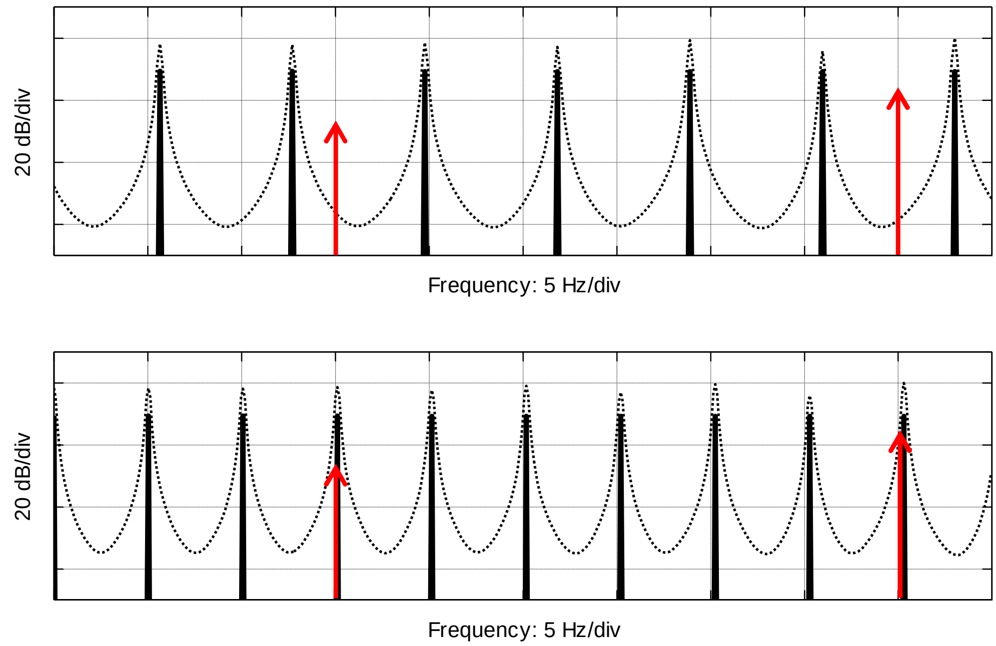

Figure 3: Detail of Loran spectrum for two different GRI values; continuous-wave interference is depicted as red arrows

Loran spectral lines then they are less harmful than if they coincide. Further, as a consequence of the receiver signal processing, an area of sensitivity to near-synchronous interference is introduced as shown by a dashed line. It can be clearly seen from Figure 3 that with a given set of interferers some GRIs are more susceptible to continuous wave interference than others.

Cross-Rate Interference

Figure 4 shows the effect of Cross Rate Interference. This interference cannot be prevented, but rules can be applied to the GRI selection, which minimize its effect. Unlike in the case of continuous wave interference, a frequency domain analysis is not a convenient approach as it cannot reveal all of the harmful relations between interfering GRIs. However, several time domain characteristics can be identified, which may serve as a set of “rules” for GRI selection.

- Crossover Time - This corresponds to the number of successive groups of pulses affected by the overlap between two GRIs. The cross-over time should be negligible compared with the receiver’s time constant, otherwise noticeable signal distortion after averaging will be encountered [9].

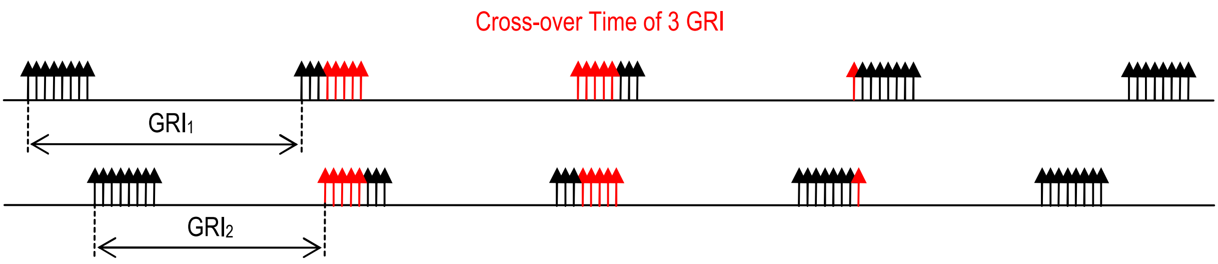

Figure 4: Cross-rate interference

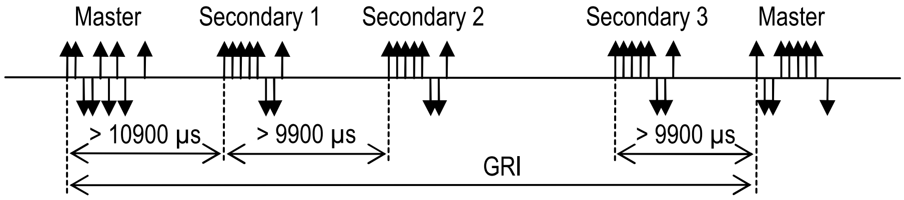

Figure 5: Constraints for spacing of transmissions in one chain

- The proposed GRI should be relatively prime with respect to all interfering station GRIs. In Europe the greatest common divisor between GRIs is 10 µs. This ensures a long period of the interference patterns with these GRIs. Nevertheless, special attention has to be paid to possible sub-periodicity in these patterns caused by near-integer relations between GRIs. Further explanation of this phenomenon can be found in [8, 9].
- The cross-rate interference should be assessed to ensure a high number of effective radiated pulses. This is of interest mainly for dual-rated stations broadcasting on two GRIs, where overlapping pulses have to be blanked. Further, considering the Loran Data Channel, the shorter the GRI then the greater the data bandwidth of the transmission.

Other GRI Constraints

Besides continuous wave interference and cross-rate interference some other constraints on GRI selection have to be taken into account. The USCG signal specification requires the GRIs to be in the range of 4000 to 9999 (tens of µs). Further, the specification sets out restrictions on the spacing between consecutive transmissions in one chain as shown in Figure 5. In order to meet these requirements anywhere within the coverage area, the GRI has to be selected greater than some minimal permissible value determined by the configuration of the transmitters.

With dual-rated transmitters improper choice of GRI can lead to a higher pulse rate than the maximum rate specified by the manufacturer. For Loran-C transmitters this limit was 300 pulses-per-second. For eLoran, with modern solid-state transmitters, this number may be higher; recent new transmitter technology promises pulse rates of 500 pulses-per-second.

Also, the UTC Time of Coincidence repetition period depends on the GRI and could be of interest to Loran time and frequency users.

Finally, there needs to be space built-in to the GRI for the presence of signals from Loran simulators that are used at Loran transmitters to measure and maintain Loran transmission timing.

Building a List of Candidate GRIs-Implementation

The selection of the best GRI is accomplished by comparing each GRI’s performance against the radio environment within which any new Loran stations are being installed. This takes place in a series of processing stages until we end up with a list of the best GRIs ordered in preference. Each stage of the selection process discounts particular GRI values from our candidate list, and we are left with the best GRIs to go through to the next round – a kind of “X-Factor” competition for GRIs!

Minimum and Maximum Values

The first stage is to determine the minimum and maximum GRI allowed for the given geographical location of the transmitters,

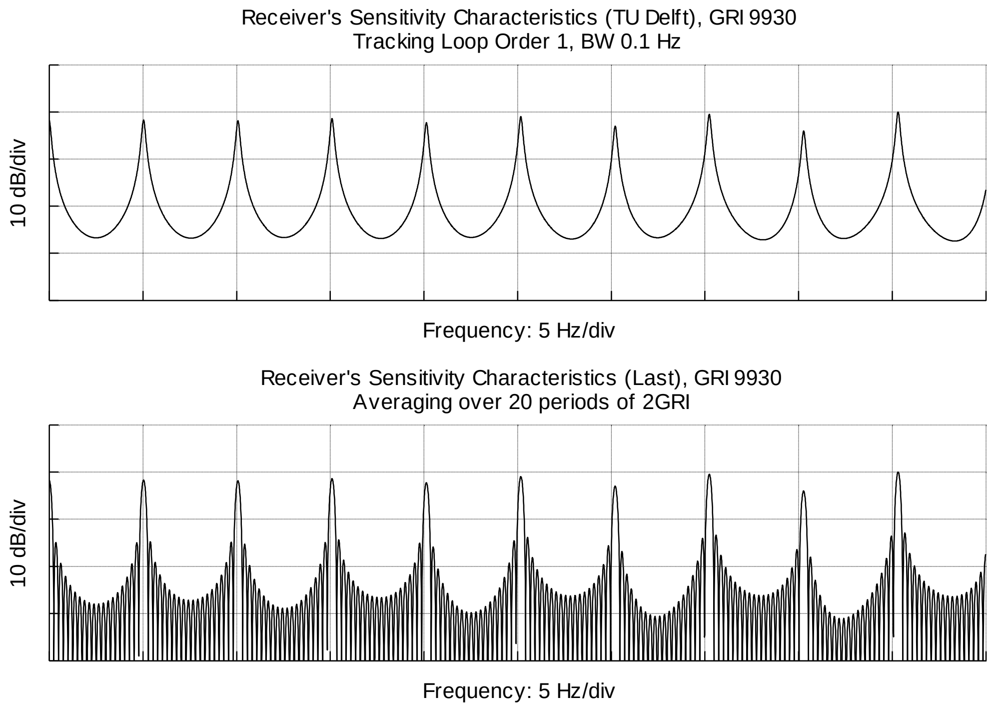

Figure 6: Receiver's sensitivity characteristics according to [1] and [20] respectively

taking into account the USCG signal specification and signal propagation times using a conservative estimate for signal propagation velocity. Free slots for transmitter simulators have to be provided and also the resolution used for emission delay assignment should be considered. The computations required are described in [1] [6].

The remaining candidate GRIs are then tested for continuous wave interference (CWI) and cross-rate interference. For Europe, it was decided to prioritise the CWI analysis before the CRI analysis for the reasons mentioned earlier. For other regions with the low-frequency radio environment not so hostile as in Europe it may turn out beneficial to put greater emphasis on achieving the lowest possible CRI.

Continuous Wave Interference Analysis

As was explained above, it is mainly the frequency of the interfering signal, which determines how harmful it is. Nevertheless, the amplitude of the signal plays its role too and therefore field strengths for all potential interferers in the area of interest have to be evaluated. The best available source of transmitter power, frequency and location data, to the authors' knowledge, is the ITU International Frequency List [16]. Although there are concerns about the reliability of the data contained within it. For example, the latest edition of the list (July 2008) still contains decommissioned Decca stations, and these stations were therefore ignored in our considerations. Even so, a list of nearly 400 interferers was generated. In accordance with [1], only interferers within the area of 30°N to 90°N and 60°W to 60°E and inside the band of 50 kHz to 150 kHz were included in the analysis presented here.

Concerning interferers' field strength, two methods of calculation were examined. Firstly, the classical Millington's method as described in [17] supplemented by the ITU method of calculating sky-wave field strength [18]. A database of electrical ground conductivity data obtained from the ITU's World Atlas of Ground Conductivities [19] was used. Groundwave and skywave attenuation arrays were generated in software written by Williams [18].

Secondly, in an attempt to reproduce results of previous studies on GRI selection, the method adopted by TU Delft in [1] was implemented also. This method provides more conservative estimates of interference based on a composite field strength curve combining data for ground-wave propagation over seawater with sky-wave measurements. The field strengths were computed over the area of 40°N to 80°N and 30°W to 30°E with a resolution of 0.5° latitude and 1° longitude.

In order to reflect the already mentioned fact that for a fixed GRI some interferers pose greater threat than others, a receiver's sensitivity characteristic needs to be taken into account. In [1] such a characteristic was derived by investigating how the sampling and tracking mechanisms influence the signal in the frequency domain. A different approach to the problem of modelling receiver's sensitivity to continuous wave interference was presented in [20]. Here the authors start with a description of the effect of phase decoding and averaging on the interfering signal. Both of these methods were implemented and the resulting characteristics are shown in Figure 6. It should be noted that the characteristics differ between master phase code pattern and secondary pattern.

The receiver sensitivity acts as a transfer function on interference and produces effective field strengths as seen by the receiver, which show predicted levels of interference experienced by a receiver tracking that particular GRI. The total interference levels for each investigated GRI are estimated by taking the root of sum of squares of the individual effective field strengths.

To accomplish the CWI analysis, the interference levels need to be related to the Loran field strengths. A Loran coverage area is defined and, within this coverage area, signal-to-interference ratio and tracking error estimates are calculated. The mean value of this tracking error estimate is then used as a measure to rank the GRIs.

The previous paragraph provokes several questions, however. The first one concerns the coverage area estimation. TU Delft in assessing CWI [1] [6] used coverage plots based on hyperbolic Loran-C [12]. However, modern eLoran receivers no longer operate in hyperbolic mode. In eLoran all-in-view receivers are being developed that use Loran transmission in the same way that GPS receivers use GPS satellites – they measure pseudoranges directly from the eLoran transmissions. Therefore some changes compared to the TU Delft technique have to be introduced. The authors decided to use what they have called 'Estimated Regions of Use'. These are the bounds on the geographical areas within which an all-in-view receiver is expected to use a particular eLoran station in its position solution. In a least-squares all-in-view position solution each station's contribution to the position solution is weighted according to the variance of the pseudorange measurements. A low pseudorange variance is weighted high, while a high variance is weighted low – in this way very noisy measurements are eliminated from the position solution. Measurements were made at Harwich and a mathematical relationship was derived relating a station's weights to its measured pseudorange variation. A further step then also related pseudorange variation to modelled field-strength for the various stations received. This then allowed us to compute a relationship between weight and modelled field-strength, which was then projected to a wider geographical area. Thus the geographical bounds are based on the weights computed from modelled field-strength computations.

Another question is: Which Loran station(s) are to be used to calculate signal-to-interference ratio? TU Delft assumed that the receiver always uses the signal of the master station and two strongest secondary stations in the chain to produce its navigation solution (hyperbolic mode). Based on this assumption they performed two analyses – one using the master signal only and one using the second strongest secondary signal in each grid point of the coverage area.

For the first analysis, the effective field strengths produced by the sensitivity characteristic calculated with the master phase code pattern were used, for the latter the secondary phase code was used. The GRIs were then ranked by the sum of the mean tracking errors obtained from these two separate analyses.

But for eLoran again there are the all-in-view receivers, which can operate with signals from many more than three stations. Thus, for all-in-view receivers the authors have proposed running as many separate analyses as there are stations in the particular GRI. Instead of one common coverage area for the whole chain, the 'Estimated Regions of Use' for each individual station are now used. The GRIs are again ranked by the sum of the errors from individual analyses.

A third question is that of the final measure used for the ranking - the tracking error. Exact evaluation of tracking error caused by multiple interferers with arbitrary frequencies is not a trivial task. In general a statistical approach to the problem is required as described in [13]. Nevertheless, making use of the receiver's sensitivity characteristic, a simple deterministic method providing satisfactory results [7] can be applied. As mentioned earlier the sensitivity characteristic of the receiver is used to weight the field strengths of individual interferers (according to their frequency), and based on this the interfering signals can be classified into three categories.

Interferers coinciding in frequency with the positions of Loran spectral lines are considered most harmful. This synchronous interference results in a time-invariant tracking error. The maximum value of the error caused by a single interferer can be calculated according to the following formula [5]:

$$E_{track} = \frac{T_L}{2\pi} \arcsin\left(\frac{I}{S}\right), \qquad (1)$$

where $T_L = 10$ µs is the period of the Loran carrier, I is the amplitude of the interfering signal and S represents the measured signal composed of the Loran signal and interference:

$$S = \sqrt{L^2 + I^2}\,. \qquad (2)$$

Here L is the amplitude of the Loran signal at the sampling point, which is about 4dB down from the peak of the pulse.

Near-synchronous signals with a frequency close to one of the Loran spectral line frequencies cause an oscillating tracking error. These signals are weighted less than the synchronous ones and formula (1) can be used again to estimate the amplitude of the oscillating error.

Asynchronous CWI signals, which fall between Loran spectral lines are suppressed by the receiver's sensitivity characteristic and their impact on the overall tracking error is negligible. In a real receiver these signals would be attenuated by the low-pass nature of the receiver's tracking loop [21].

Cross Rate Interference Analysis

Once the process of CWI analysis is finished, a list of promising GRIs can be compiled. The next step in the procedure is to compare these against the GRIs of existing chains and to identify combinations resulting in unacceptable cross-rate interference.

The method of CRI analysis implemented follows-up on algorithms derived in [8]. A set of parameters defined therein is calculated for each combination of promising GRIs with GRIs of interfering stations. The evaluation is done manually according to the set of rules described earlier. Eliminating those GRIs, which show unacceptable CRI results in a final list of surviving GRIs.

Summary of the Method

The overall procedure of GRI selection is summarized in Figure 7.

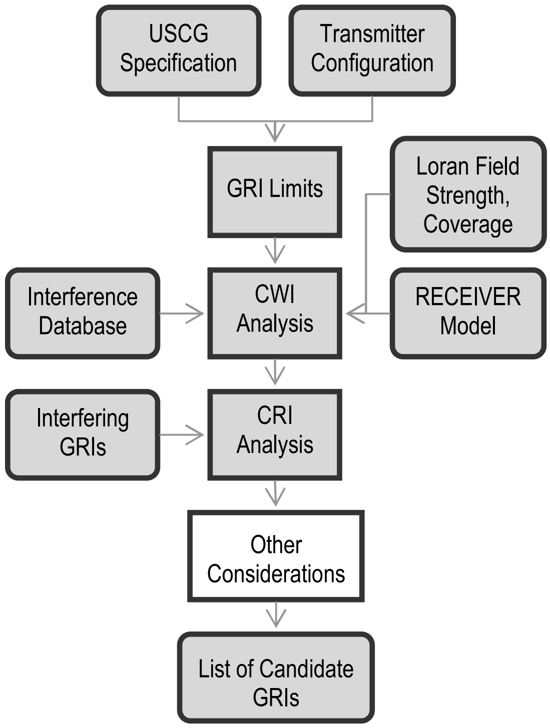

Figure 7: The overall procedure of GRI selection

Results and Validation

In order to perform all the necessary operations, three Matlab™ tools were implemented covering the issues of minimum GRI calculation, CWI analysis and CRI analysis. Validation was carried out by comparison of the results given by these tools with the results of TU Delft from 1993 when the chains of the North-west European Loran-C System (NELS) were planned [1] [6] [8].

Results Summary

Each of the separate phases of GRI selection was validated against previous computations performed by TU Delft using an example existing GRI.

The values obtained by the tool for minimal GRI calculation are slightly higher than those in the TU Delft reports probably because of differences in assumed signal propagation speed and the geodetic computations used.

For the purpose of CWI analysis validation a database of interferers published in [6] was used and methods of interferers field strength calculation and tracking error evaluation according to [1] and [6] respectively were employed. The analysis was run for GRI 6731, the Lessay chain, and the results are encouraging – 22 of the top 30 GRIs recommended by the implemented procedure agree with the Delft results, while all of the 30

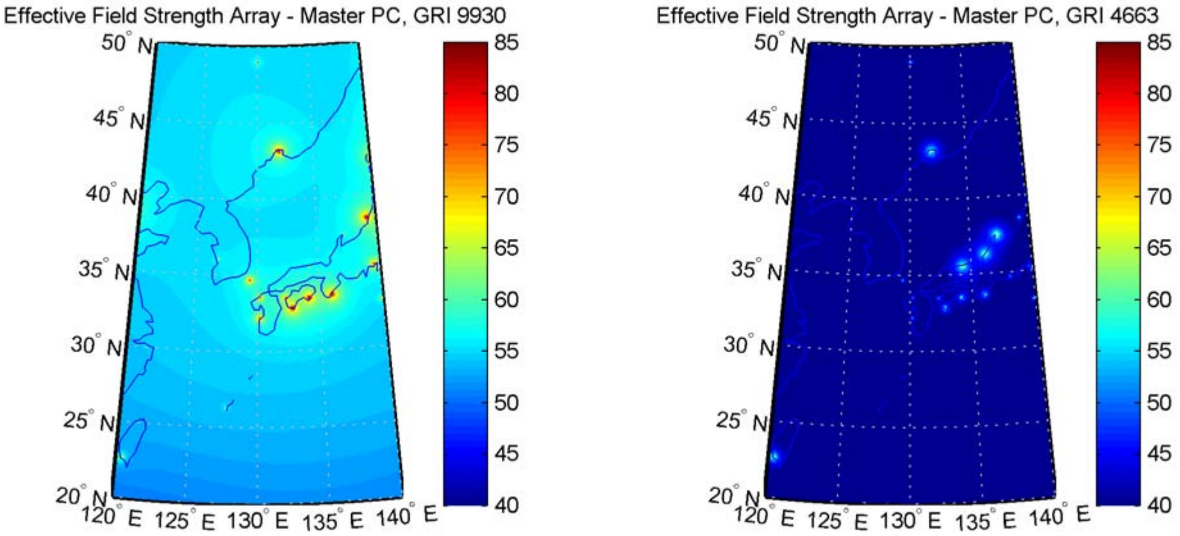

Figure 8: Effective field strength arrays for GRI 9930 (East Asia chain) and 4663 in the FERNS coverage area

values recommended by Delft can be found within the first 48 positions of the generated list. The differences are most likely due to the replacement of the Loop Head transmitter with the one at Anthorn and slight changes in the coverage area.

The results of the CRI analysis agree wholly with those of TU Delft.

Case Study

It is not only the GLAs who are currently interested in Loran, there has been growing concern regarding the vulnerabilities of satellite navigation systems worldwide and eLoran is believed by many to be the best candidate to serve as a complement and backup of GNSS. The US Congress continues to fund Loran research, continues to operate Loran stations and is preparing for the implementation of eLoran [22]. Former NELS stations continue to operate, there are stations in Saudi Arabia and the Far East Radio Navigation Service (FERNS) is being upgraded by collaboration between China, Japan, Korea and Russia. The modernization of FERNS provides an excellent opportunity to demonstrate the presented GRI selection procedure by solving a real-life problem as a case study.

Through their links with FERNS the GLAs' Research and Radio Navigation team was asked to assist in finding an optimal GRI for a new chain in South Korea.

There is a possible need for two additional stations on the Korean Peninsula [23]. Kwangwhado and Goseong were suggested as locations and a power of 50 kW was assumed for each. This case study shows what considerations need to be made if the two stations are to be assigned a new GRI.

We proceed in our analysis as follows:

1. Minimum GRI

The minimum GRI for the given configuration of stations was calculated and was found to be 4220, which includes two 9.9 ms slots for Loran simulators used for time of emission control of the station [7]. Emission delays are assumed to be assigned with a resolution of 0.1 ms.

2. Continuous Wave Analysis

Using the current version of the ITU International Frequency List database, a list of interferers was generated. Only interferers within the area of 10°S to 80°N and 70°W to 190°W and inside the frequency band of 50 kHz to 150 kHz were included (transmitters in the Loran band of 90 kHz and 110 kHz were deleted).

For calculating interferers' field strengths the simpler and more conservative method [1] described earlier was used. The field strengths were computed over the area of 20°N to 50°N and 120°W to 140°W with a resolution of 0.1° latitude and 0.1° longitude.

The use of all-in-view receivers was assumed and the sensitivity characteristics according to [1] was used with tracking loop effects modelled by a 1st order Butterworth filter with a -3 dB bandwidth of 0.1 Hz. An 8th order Butterworth front-end filter with a bandwidth of 28 kHz was also used. This takes into account

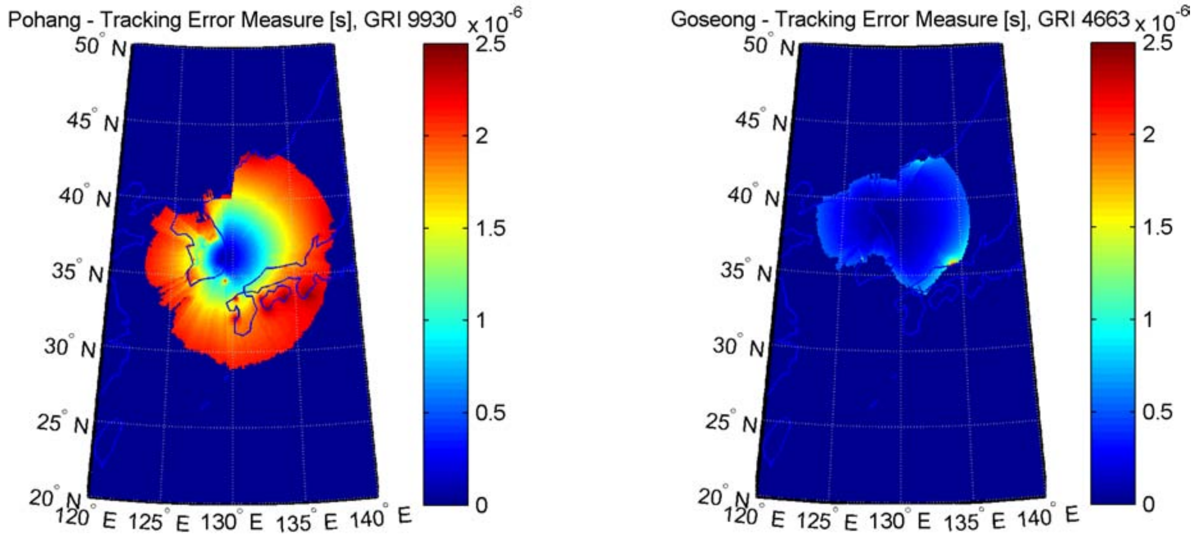

Figure 9: Tracking error estimates computed within the Estimated Region of Use (ERU) of Pohang transmitter using the GRI of 9930 (East Asia chain) and within ERU of a planned transmitter in Goseong using the GRI of 4663, which minimizes CWI in the FERNS coverage area

the capabilities of typical modern eLoran receivers.

3. Crossrate Interference

The top 60 GRI values resulting from the CWI analysis were used as the input to the CRI analysis and compared with the GRIs of existing FERNS chains. Those showing high cross-over time or hazardous sub-periodic overlap patterns [8] [9] were rejected producing a shorter list of 8 preferred GRIs. This shorter list was compared with other GRIs from all existing chains worldwide (to take into account nighttime skywave borne interference for example) applying less strict criteria than for the neighboring FERNS chains, following which only 2 GRI values remained: **4663** and **5281**.

The final decision on what GRI value to use is a compromise. 4663 is a GRI that demonstrates the lowest CWI. This is illustrated in Figure 8 and Figure 9 where the comparison with the existing 9930 East Asia chain is given showing dramatic differences in effective CWI levels. As far as CRI is concerned, however, 4663 cannot be considered ideal – there is a cross-over time of 4 and 3 intervals with FERNS 8930 and 9930 chains respectively and 3 intervals with the 9990 North Pacific chain. Furthermore every 7th interval of 9990 there is a near-integer overlap with every 15th interval of 4663. These issues might outweigh the benefit of GRI 4663 showing the lowest CWI, therefore alternatives were sought.

GRI 5281 seems to demonstrate generally better CRI relative to both the strong FERNS chains and the more distant chains. There is a cross-over time of 6 intervals with the 5543 Calcutta chain but due to relatively low power of the transmitters of both chains (50 kW maximum) no complications are expected. Also there is a cross-over time of 5 intervals with the 4970 North Western Chayka chain combined with near-integer overlaps. In this case the spatial separation of the two chains is believed to be sufficient to minimise any potential interference.

The other benefit of 4663 compared to 5281 is that, being the shorter GRI of the two, Loran Data Channel bandwidth will be higher.

The GRIs of existing FERNS chains (6780, 7430, 7950, 8390, 8930, 9930) span nearly the whole range of permissible GRIs and when the other potentially interfering chains are taken into account, introducing a new GRI in FERNS appears to be rather difficult. The authors would suggest further research into the possible benefits of reorganizing the current FERNS chains assignments.

Summary and Future Work

Within this paper a procedure for GRI ranking was reviewed and some updates were introduced to it that take into account eLoran, including:

- The use of all-in-view (pseudoranging) position mode.

- Some modern receiver filtering and processing capabilities.

A number of questions still remain to be answered as outlined below.

Database Reliability

There are concerns about the reliability of the database of interferers. The ITU's International Frequency List includes some inactive stations (for example decommissioned Decca stations). Furthermore there is no information about antenna efficiency and radiation patterns for the low-frequency interferers, which would allow more accurate estimates of received field strength. For the field strength computations non-directional antennas with 100% efficiency were assumed.

Modulation Versus Carrier Only

Also, modulation of the interfering signals was not taken into account, although this can be easily accomplished using the interferer's emission class information from the ITU database together with the estimated distribution of normalised power between the carrier and sidebands published in [18]. And besides, ignoring modulation only overestimates the effect of modulated interferers [20], so by considering carrier waves alone we are being more conservative in our GRI selection.

Modern Receivers

Notch filters should probably be included in the model as modern receivers can handle up to 60 automatic notches but signal distortion will be introduced and this may need to be considered in future analyses.

The implemented method of CRI analysis assumes total blanking of interfering Loran signals whenever they overlap. This is suitable for dual-rated stations but it overestimates the interference from distant stations. Also the influence of CRI on the Loran Data Channel rate should be investigated, since the data channel is vital for eLoran.

Other Considerations

Other considerations include emission delay assignment and its influence on minimal GRI, time of coincidence repetition period, maximum pulse rates for dual-rated transmitters and possible eLoran derived changes to phase codes. It might also be useful to re-examine current chain assignments and investigate possible improvements to be gained by single-rating all stations. This should result in lower CRI levels. Furthermore, single-rated transmitters show lower jitter compared to dual-rated [24] thus improved signal-to-noise ratio can be expected. However, there is an obvious trade-off between maintaining sufficient pulse rate and CRI reduction. Similar attempts were made in the United States and increased system performance was demonstrated in [24].

Table 1 summarises the major eLoran updates to the TU Delft GRI selection method and suggests some topics for further investigation.

TU Delft Method	eLoran Update	Changes Required	Further Investigation
CWI Analysis			
Data on interferers			
ITU International Frequency List (IFL)	Updated version of ITU IFL	Use current version of ITU IFL, delete Decca stations, identify other decommissioned stations, check for other transmitters (not listed in IFL)	Antenna efficiency values and Radiation patterns missing. Frequency stability of the transmitters.
Receiver Model			
Receiver's sensitivity characteristic	Modern receiver signal processing	The idea of sensitivity characteristic emphasising the influence of synchronous and near-sync. interferers and suppressing asynchronous is applicable even for eLoran	Two methods: TU Delft [1] vs. Prof. Last and Yi Bian [20], both implemented, which one to use?
Front-end filter: Butterworth, 5th order, 20 kHz bandwidth (-3dB)	Modern receiver architectures	Alter parameters of the model: Butterworth, 8th order, 28 kHz bandwidth (-3dB)	eLoran signal distortion caused by the front-end filter - is it of any importance?
Notch filters were not taken into account (different implementation by different manufacturers)	Modern receiver signal processing (e.g. up to 30 notch filters in both channels)	Changes in effective field strength computation and perhaps even the receiver sensitivity characteristics	eLoran signal distortion caused by the notch filters
Interferers Effective Field Strength			
Interferers' field strength weighted according to receiver's sensitivity char.	Automatic notch filters	(as described above)	
Signal-to-Interference Ratio			
Hyperbolic mode: 2 separate analyses using Master signal field strength and second strongest Secondary signal field strength	All-in-view receivers	As many analyses as there are transmitters transmitting on the GRI of interest and introduction of Estimated Regions of Use	
Tracking Error Estimation			
TE is evaluated only within the "hyperbolic" coverage area and the sum of mean values resulting from Master and Secondary analyses is then used to rank candidate GRIs	All-in-view receivers	Substitution of chain coverage area by Estimated Regions of Use, separate analyses for each transmitter, sum of the resulting mean TEs is used to rank the GRIs	The critical value might be maximal TE value rather than mean value. The effect of asynchronous interference.
CRI Analysis			
Time domain analysis [8], suitable mainly for dual-rated transmitters (blanking of interfering signals is assumed whenever they overlap)	Modern receivers signal processing Higher sensitivity of contemporary receivers	Receivers can track, estimate and subtract the signal of interfering GRIs [14] Even more distant transmitters can now become potential interferers	The method [8] is useful for dual-rated transmitters, but overestimates CRI from distant transmitters
No data channel considerations	The introduction of the Loran Data Channel	Analysis on data loss due to CRI has to be done. A simple method of data loss evaluation is derived in [9]	(as above)
Other Considerations			
Dual-rated transmitters Pulse Rate			
Maximal pulse rate for dual-rated transmitters: 300 p-per-sec	Modern solid-state transmitters: Pulse rate 500 p-per-sec; single-rating all transmitters	No need to consider dual-rated transmitters for eLoran	

Table 1: eLoran considerations (blue - already implemented).

Conclusions

When considering new stations factors like the minimum GRI for the given transmitter configuration, continuous wave interference and cross-rate interference need to be taken into account. To tackle these problems three Matlab™ tools were implemented at the General Lighthouse Authorities and validated. These tools follow up procedures for GRI selection derived for Loran-C and introduce some eLoran updates to them.

Using the updated procedure candidate GRIs for a new chain in FERNS have been proposed with 4663 and 5281 being the most promising.

Acknowledgements

The authors would like to thank Dr. Sally Basker and Chris Hargreaves of the General Lighthouse Authorities, and Prof. František Vejražka of the Czech Technical University for their support and assistance during the performance of this work.

References

[1] H. J. L. Arriens and M. Beckmann, "Selecting Group Repetition Intervals for North-West European Loran-C Chains," tech. rep., Delft University of Technology, 1992.

[2] L. P. Remmerswaal and D. V. Willigen, "Interference and Loran-C: A European Problem," in *Proceedings of the 17th Annual Technical Symposium*, 1988.

[3] H. J. L. Arriens and M. Beckmann, "Selecting Group Repetition Intervals for European Chains," in *Proceedings of the 18th Annual Technical Symposium, Wild Goose Association*, 1989.

[4] L. Remmerswaal and D. van Willigen, "Some aspects of interference on Loran-C," *IEE Proceedings F Radar and Signal Processing*, vol. 136, no. 3, pp. 109–117, 1989.

[5] M. Beckmann, "Synchronous Interference to Loran-C and its Influence on Cycle Identification," in *Proceedings of the 19th Annual Technical Symposium*, 1990.

[6] H. J. L. Arriens and A. K. Nieuwland, "Selecting Group Repetition Intervals for North-West European Loran-C Chains Addendum," tech. rep., Delft University of Technology, 1993.

[7] F. Hubert, "GRIs Selection in the NELS," tech. rep., DGA DCN Brest, 1993.

[8] A. K. Nieuwland and H. J. L. Arriens, "Determining Cross-Rate Interference for the North-West European Loran-C Chains," tech. rep., TU Delft, 1993.

[9] A. K. Nieuwland, "GRI Ranking Based on Cross-Rate Interference in Loran-C," *The Journal of Navigation*, vol. 48, pp. 136 – 152, 1995.

[10] P. E. Kvam, "GRI Selection - Minimum GRIs and Coverage Diagrams for Comparison of GRIs," tech. rep., NODECA, 1993.

[11] R. W. Nutting, *Loran-C Rate Selection Process*. United States Coast Guard, 1988.

[12] *IALA List of Radionavigation Services - Loran-C/Chayka*, first ed., July 1996. Collated and published by the International Association of Lighthouse Authorities.

[13] D. Last and B. Yi, "Carrier-wave interference to Loran-C: a statistical evaluation," vol. 29, pp. 1260–1274, Oct. 1993.

[14] W. Pelgrum, "Noise - From a Receiver Perspective," in *Proceedings of the 34th Annual Convention and Technical Symposium of the International Loran Association*, 2005.

[15] International Telecommunication Union, *ITU-R M.589-3, Technical characteristics of methods of data transmission and interference protection for radionavigation services in the frequency bands between 70 and 130 kHz*, August 2001.

[16] "ITU BR International Frequency Information Circular (Terrestrial Services)." DVD, July 2008.

[17] M. Searle, D. Last, and R. Farnworth, "Loran-C Low-Frequency Ground-Wave Modelling," in *Proceedings of Bangor Symposium on Communications*, 1991.

[18] A. I. Williams, *Prediction of the Coverage and Performance of the Datatrak Low-Frequency Tracking System*. PhD thesis, University of Wales Bangor, 2004.

[19] International Telecommunication Union, *ITU-R P.832-2 World Atlas of Ground Conductivities*, January 1999.

[20] D. Last and Y. Bian, “Carrier wave interference and Loran-C receiver performance,” *IEE Proceedings F Radar and Signal Processing*, vol. 140, no. 5, pp. 273–283, 1993.

[21] M. Beckmann, *Carrier Wave Signals Interfering with Loran-C*. PhD thesis, TU Delft, 1992.

[22] “Adoption of a National Backup Service to GPS.” United States Department of Homeland Security Press Release, February 2008.

[23] S. G. Gug, T. Ikeda, P. Williams, and T. G. Jeong, “Far East Radio-navigation Service (FERNS) Update,” in *Proceedings of NAV08/ILA37*, 2008.

[24] G. Johnson, M. Wiggins, P. F. Swaszek, L. Hartshorn, and R. Hartnett, “Possible Optimizations for the US Loran System,” in *Proc. IEEE/ION Position, Location, And Navigation Symposium*, pp. 695–704, April 25–27, 2006.