eDLoran – next generation of differential Loran

Durk van Willigen[1], René Kellenbach[2], Cees Dekker[3] and Wim van Buuren[4]

[1] Reelektronika, Netherlands, d.vanwilligen@reelektronika.nl

[2] Reelektronika, Netherlands, r.kellenbach@reelektronika.nl

[3] Reelektronika, Netherlands, c.dekker@reelektronika.nl

[4] Dutch Pilots' Corporation, Netherlands, w.vanbuuren@loodswezen.nl

Abstract: To counteract vulnerability of GNSS, dissimilar backup systems are needed for harbour approaches. Rotterdam pilots want accuracies of 5 metres for such systems. Loran is likely the best basic candidate for this.

Reelektronika has, on request of, and in close cooperation with the Rotterdam Pilots, developed and tested a new differential Loran system called eDLoran, enhanced Differential Loran. Extensive research made clear that 5-metre accuracy cannot be met by the currently tested DLoran system. The main reason for that is twofold: latency of the broadcast (Eurofix) DLoran data is far too large causing loss of temporal correlation, and, accurately measuring correction data (ASF) is in a technical sense problematic. Therefore, a much simpler and more accurate method of measuring ASF data has been applied. Finally, the construction of enhanced differential Loran reference stations showed to be much less complex and expensive. For pilots' use it is also needed that the equipment is wireless, portable, small, and battery-powered.

A full prototype eDLoran system has been implemented and extensively tested in the Europort area. Instead of applying the usual pseudorange correction technique, well known in the GNSS world, position corrections are used instead. To reduce correction data latency by at least one to two orders of magnitude, standard mobile telecom networks and the Internet are used. The tests showed achieved accuracies of 5 metres. Further, pilots' receivers are, in addition of the GPS-RTK data, storing the received Loran data which are after return sent to the central eDLoran server for nearly continuously updating the Loran ASF correction data base. The eDLoran system is very cost effective and standard hardware can be used. There is no need to upgrade legacy Loran or Chayka transmitters with a Eurofix channel.

BIOGRAPHIES

Durk van Willigen is retired professor on Electronic Systems for Navigation at the Delft University of Technology. He is founder and president of Reelektronika B.V., a small company active in the field of radio navigation systems. He started the development of Eurofix in 1985 and received various awards for his research. In 1999 the Thurlow Navigation Award of the Institute of Navigation (US) and the Gold Medal of the Royal Institute of Navigation (UK) in 2002. Dr. van Willigen is Fellow of the Royal Institute of Navigation and member of the advisory board of the Netherlands Institute of Navigation. He is also chairman of the board of the Gauss Research Foundation.

René Kellenbach graduated from Delft University of Technology in Electrical Engineering. After joining Reelektronika as a Systems Engineer, he has been involved in designing hard- and software for radionavigation and radar systems. Specialized in analogue and digital hardware design, he designed and implemented all hardware of the LORADD series integrated GPS/eLoran equipment, the Tele-Disco, VTS-Master and TeleMaster radar sub-systems. He is also involved in hard- and software development for the eDLoran system.

Cees Dekker graduated at the Delft University of Technology in the field of telecommunications. He worked ten years at Philips Research Labs and product development in the Netherlands, and in the United States in the field of GPS developments. He started in 1985 an information technology company InfoControl B.V. to develop intelligent electronic manual systems for use in technical industrial companies in the aircraft manufacturing industry, and in the process and energy industry. He assists since 1995 the Dutch company Reelektronika B.V. with the development of Loran systems and GPS related projects and information systems.

Wim van Buuren graduated from nautical college and followed a nautical career at the merchant navy both as deck officer and ships' engineer. Since 1996 he has been a licensed maritime pilot in Rotterdam. As a pilot Mr. van Buuren became lecturer and researcher on behalf of Dutch Pilotage at the Dutch Military Defence Academy. From 2009 until 2014 he was the manager of ICT & Innovation for the Rotterdam Pilot Corporation. Portfolio: development of Portable Pilot Units (PPU), development of European PPU standards, Dynamic Under Keel Clearance measurement and application, development of AIS standards, wind and current load calculations for ships, squat calculations, Port Risk Assessment tooling and, eDLoran.

1 INTRODUCTION

For maritime applications, eLoran is considered as the most promising backup for GNSS in case the use of navigation satellite signals is denied. This was the reason for the Dutch Pilots' Corporation to request Reelektronika to investigate whether differential Loran could meet the Dutch Pilots' accuracy requirement for a harbour navigation system which is 5 metres. This proved to be an enormous challenge as preliminary tests showed that even 10 metres was difficult to achieve with differential Loran (DLoran) as promoted by Trinity House. This challenge had led to a thorough renewed investigation of all possible error sources of a complete differential Loran system. The outcome of this research is very promising as a couple of major error sources could be isolated. This made the complete system better understandable, so adequate countermeasures could be taken.

2 LORAN

The development of Loran-C started in the United States about fifty years ago. It is a terrestrial low-frequency (100 kHz) system organised as chains each consisting of a master station with two or more secondary stations. Each station broadcasts in a strict time format series of 8 or 9 pulses of approximately 250 µs. The effective radiated power is in the range of 100 to 1,000 kW, depending on the required working range. These high powers are mandated by the high levels of atmospheric noise in the 100 kHz frequency band.

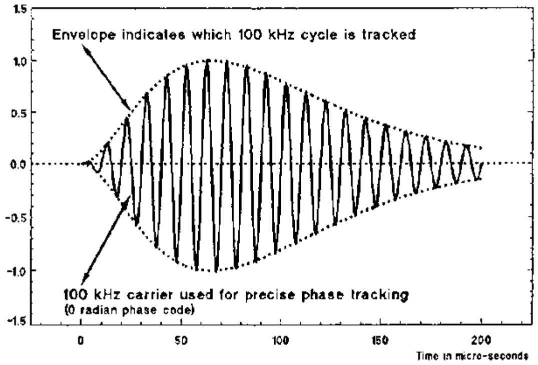
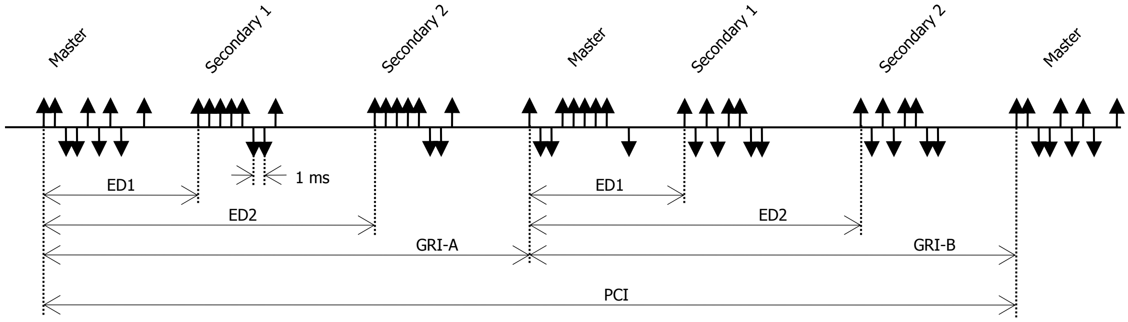


Figure 1. Basic Loran pulse.



↑ = 0º carrier phase
↓ = 180º carrier phase

ED = Emission Delay = coding delay + propagation time from Master to Secondary
GRI = Group Repetition Interval (40-100 ms)
PCI = Phase Code Interval (80-200 ms)

Code and time multiplex give unique chain and station ID
Chain is identified by GRI, Master by Code, Secondaries by Code and Emission Delays
Start of 1st pulse of PCI for all Loran chains coincided with the PPS (TAI) tick on January 1st, 1958, at 00:00:00 hr

Figure 2. Pulse frame structure of Loran signals based on TDMA (time division multiple access) and CDMA (code division multiple access).

Figure 1 and 2 depict the signal structure of a Loran pulse and the pulse frame structure of a Loran chain. Typical accuracies of 100-200 metres are achieved in areas with good signal-to-noise ratios and Loran station geometry configurations.

Figure 3. The Loran configuration in the test area of Europort.

Figure 3 shows the test area of enhanced Differential Loran (eDLoran). The Loran stations of Lessay (France), Sylt (Germany) and of Anthorn in the UK were throughout used.

To radiate such high power pulses large vertical transmitting antennae of about 200 metres tall are required. See Figure 4. Due to the limited radiation efficiency of the antennae, the electric power generated by the transmitter is even higher. For long, these high power levels have been seen as a nuisance of Loran-C. However, the upcoming GNSS interference risks changed this apparent nuisance into a blessing as jamming such high field strengths is hardly achievable unnoticed. GNSS satellites, for comparison, radiate approximately 100 Watts. Loran-C is, unfortunately, less accurate than GNSS but it is nearly impossible to jam over large areas. This is one of the major reasons that

Loran gets so much renewed interest by all who face risks in life- and environmental critical applications of radio navigation.

Figure 4. The left picture shows the antenna park of 13 masts of ≈200 metres at Anthorn in the UK. The picture on the right depicts the ≈200 metres vertical Loran mast at Sylt in Germany.

3 DIFFERENTIAL LORAN

Standard Loran does not meet accuracy requirements for harbour entrance and approaches. IMO requires 10 metres (95%) which is at least 5 times more demanding than standard Loran can offer. So, differential techniques have been developed and implemented which are comparable with differential GPS. Although the error sources of GPS and Loran are quite different, the major common error source in both systems is the lack of accurate propagation models.

Several years ago, the General Lighthouse Authorities (GLA's) of the UK and Ireland implemented Differential Loran (DLoran) in the test area around Harwich. DLoran is based on a Loran reference station in the area of interest which measures temporal deviations of the measured pseudoranges. These "errors" are then sent to the user receiver through the so-called Eurofix Loran Data Channel. This technique strongly resembles the technique of Differential GPS where the correction data are sent through LF-radio beacon stations to the user receiver. Unfortunately, for a number of reasons it proved to be impossible to achieve absolute accuracies of better than 10 metres with DLoran while better accuracies are wished.

This has led to a new research project to find a more accurate differential Loran technique. All possible error sources have been investigated again where possible, which resulted in some unexpected results regarding accuracies and costs.

3.1 Error sources

The total position error of Loran depends on the accuracy in time of the high-power generated Loran pulses feeding the antenna, the stability of the physical phase centre of the Loran transmitter antenna, the stability of the tuning of the antenna circuit, the accuracy of the measured additional secondary phase factor stored in the so-called ASF-database and, finally, the quality of the Loran receiver. ASF is the additional delay when Loran signals propagate over land with a varying conductivity. As the ASF data are not fixed but slightly varies with time, the so-called temporal de-correlation, differential techniques have been developed to counteract that effect. In standard DLoran systems, the differential corrections are sent to the user through the Eurofix data link. In the following paragraphs some very specific system errors are discussed in more detail. Atmospheric and man-made noise is not discussed as they do not result in static errors.

3.1.1 Transmitter timing accuracy

As shown in Figure 2, Loran pulses are broadcast in series of 8 pulses (Master stations 9 pulses) in one Group Repetition Interval (GRI) which is in the range of 40 to 100 ms. So in average, a transmitter sends about 100 pulses per second. Each Loran transmitter has three Caesium (Cs) clocks. The trigger pulses of the transmitters are tied to UTC via a rather complex and not extremely accurate time transfer network. It is expected that in the future the station clocks will be controlled via a satellite two way time transfer system. In case this link fails, the stability of the three Cs clocks may bridge the time windows that the time-control network fails. Although no detailed and specific timing errors have been measured during this project, the specifications of timing accuracies of transmitters as having been published (Specification of the transmitted Loran-C signal, 1994) are not tight enough to achieve high position accuracies of 5 metres.

3.1.2 Physical antenna phase centre stability

Loran transmitter antennas are vertical towers of approximately 200 metres high to provide vertical polarisation. With a number of guywires the mast is stabilised to keep the position of the antenna, and its phase centre, at the published position. Although during heavy storms this is quite demanding, the tower does not move more than about 1 metre according to the station crew at Sylt.
This situation is very different for a wire antenna as is installed at the station at Anthorn in Northern England. Figure 4 shows the antenna park at Anthorn where 13 masts of about 200 metres tall are used for military communications, timing broadcasting and Loran.

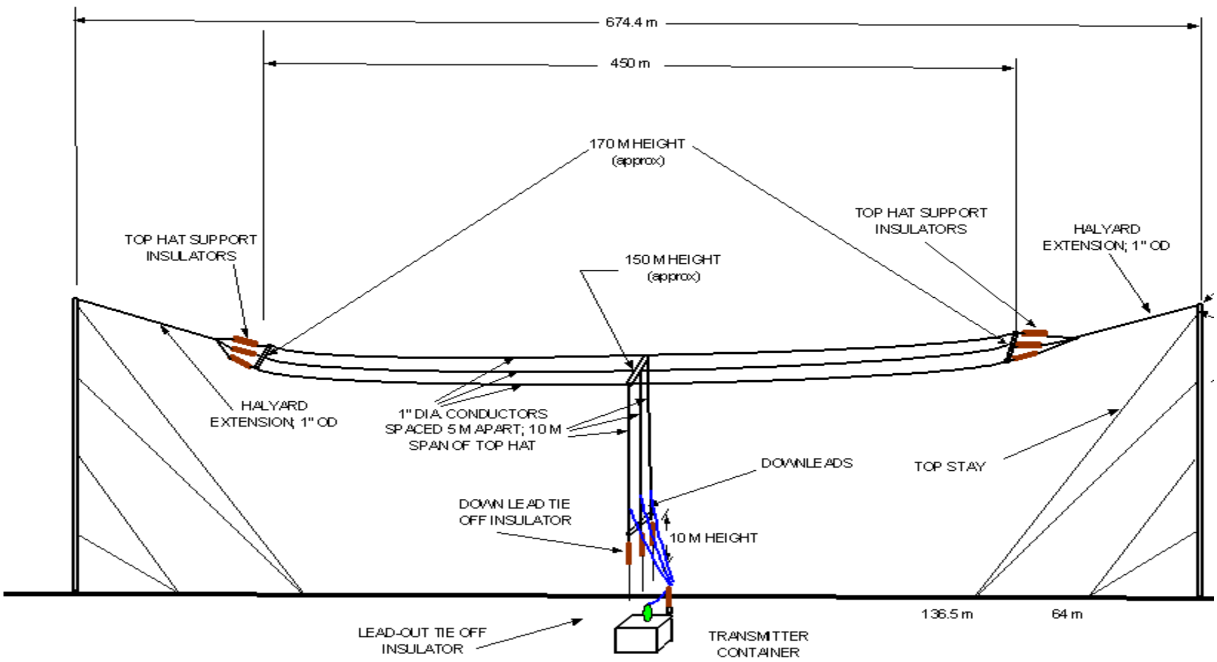


Figure 5. The enormous top-loaded Loran wire antenna at Anthorn. This type of antenna is not rigidly stable during storm. By courtesy of Babcock International Group.

The antenna in Figure 5 shows the wire antenna installed between two towers of approximately 200 metres tall. With stormy weather the antenna position is not stable and does not continuously coincide with the published position of the antenna. This instability has been measured in the Netherlands.

As the Anthorn Loran antenna is part of a complex antenna park, maintenance work on the non-Loran antennae is quite noticeable. Grounding one of the other antennas causes a significant position jump due to detuning of the Loran antenna as is shown in Fig. 6.

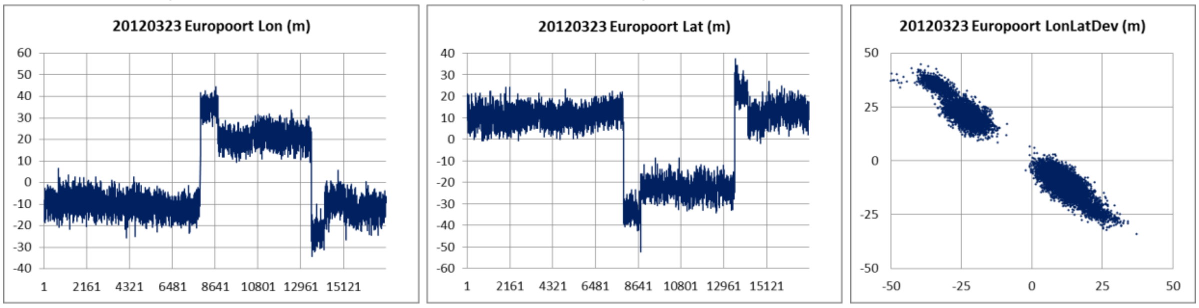


Figure 6. Longitude and latitude jumps due to maintenance on the non-Loran antennae at Anthorn.

3.1.3 ASF data

As mentioned before, ASF data are needed to strongly improve the position accuracy. These data are measured by determining the travelling time of the Loran signal from the transmitter to the receiver. Thereto, the time of transmission is measured relative to UTC as is the time of arrival at the receiver. The difference of these two times is the net travel time. During the measurements the exact location of the receiver antenna must be known and is mostly derived from a DGPS or GPS-RTK receiver. As the transmitter antenna position is published, the distance between the two antennas can be computed. Then the signal travel time through the atmosphere is derived from the known propagation velocity. Next, the additional propagation time due to the extra delay (known as Secondary Factor - SF) when the signal travels over seawater is calculated. Now the ASF value can be found by subtracting the SF delay from the measured propagation time. This sounds as an easy technology but is rather tricky as neither the departure time of the broadcast Loran pulse nor the arrival time of the pulse can be measured with nanosecond accuracies relative to UTC.

3.1.4 Differential Loran

As mentioned above, the groundwave of a Loran signal travels slightly slower over land than over sea because the conductivity of land is lower than that of seawater. The additional delay over seawater relative to the delay in the atmosphere is called the secondary factor SF. Standard formulae are used to compute these delays. If the signal also travels partly over land, the situation becomes more complex as the conductivity varies strongly with the type of terrain. For example, cultivated land causes less delay than ice, sand or snow. This extra delay is called the additional secondary factor, or ASF. Although attempts have been made to model ASF values on a large set of measured ground conductivities, the practical technique is to measure these ASF delays. Generally speaking, this is a quite costly operation.

Having measured ASF data over a limited area, for example a harbour entrance, the absolute value may change when the weather conditions change. Rain will cause increased conductivity while snow will show the opposite effect. The carefully measured ASF map may then show slowly changing lateral movement. This is the reason that in such areas a so-called reference receiver is installed to continuously measure the shift in ASF. These variations are sent to the user via a data link. In the UK, many tests have been conducted in the areas around Harwich and Dover in order to measure these ASF shifts and use the Eurofix data link for sending correction data to the user receiver. As it is generally assumed that variations in ASF are very slow, no attempts have been made to use faster data links than the 30 bps of Eurofix. The Loran stations at Sylt (Germany) and Anthorn (UK) broadcast Eurofix data for DGPS, UTC and DLoran (Anthorn only). DLoran data are sent as pseudorange corrections per station in pairs of two. A complete set of DLoran correction data takes about 90 seconds. The corrections are the outcome of a moving median of the measured ASF data per station and per DLoran location. So, only slowly varying data are effectively sent. As the UK authority plans to use data from up to seven reference stations on the same Loran Eurofix data link, the latency of the data will increase accordingly.

For simulation and analysis purpose we have installed two identical fully autonomous Loran receivers with respective antennae separated by approximately 2 metres. Both receivers are battery powered and linked to PC's via a bluetooth link. So, no cables were connected to avoid any possible spurious coupling. The so-called reference receiver output data have been sent through a 600 seconds moving median filter with the same length as has been published by the GLA's (Williams, 2009). This output is used as the differential correction data as would be received from a DLoran reference station. In fact, this means that the two data sets are subtracted to get the corrected position. See the plots in Figure 7.

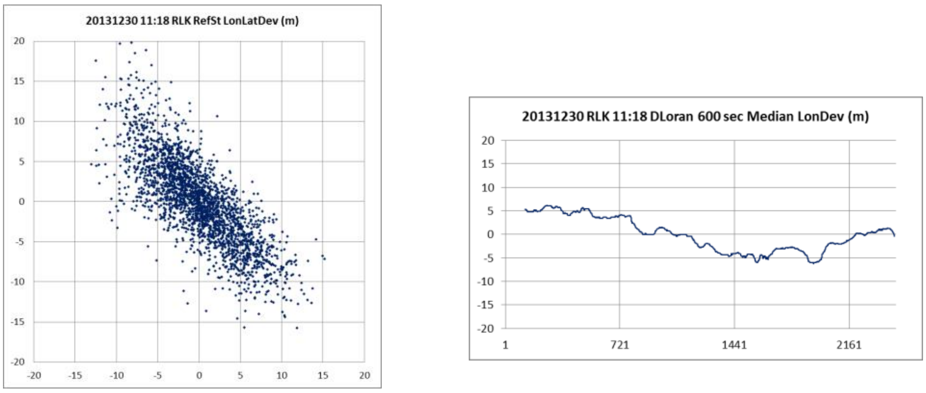


Figure 7. The position deviation scatter plot on the left is generated by the reference station's receiver. The right-hand plot shows the moving 600 seconds median value of the longitude correction data. This data will be sent through the Eurofix data channel to the user's receiver.

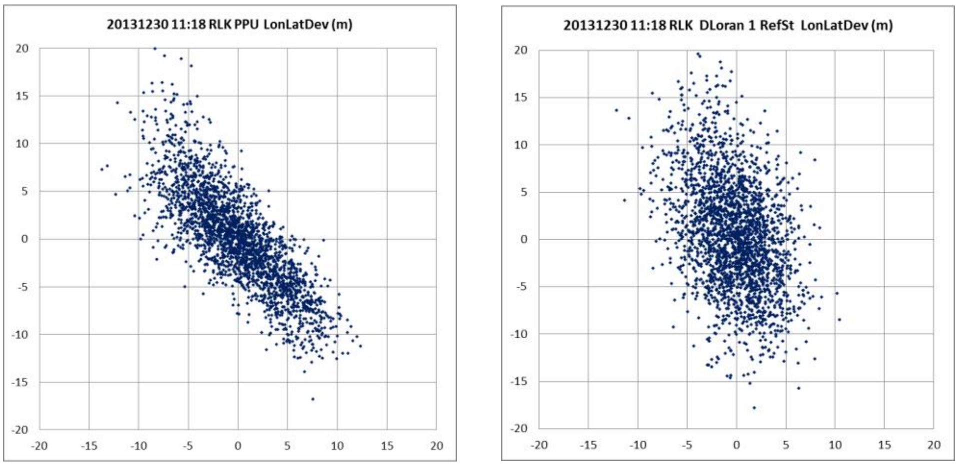


Figure 8. On the left plot the uncorrected data of the user receiver is shown. The plot on the right depicts the resulting position deviation according to the DLoran correction technique. The scatter form changes slightly due to the compensation of drift due to changing temporal propagation velocities.

Figure 8 depicts a simulated DLoran result based on real data. The accuracy is less than was expected. The preliminary conclusion was that the scattering stems from interference and atmospheric noise. To check this assumption an alpha-type low-pass filter has been used on the measured longitude and latitude values. If noise would be the cause of the scattering, low-pass filtering might reduce the problem. Figure 9 shows the effect of low-pass filtering the plot of Figure 8. The position dots do now form lines and the dots are not any longer spread as random positions due to noise. The deviations have not strongly reduced as would be expected by applying an alpha value of 0.95. As the antenna at Anthorn sways during strong wind gusts to avoid mechanical damage, and the large data latency, it may take many minutes before any corrections can be offered to the user's receiver.

This unexpected result forced us to drastically change the concept of differential Loran to get much better accuracy results as required by the Rotterdam pilots. The source of the problem showed to be the slow data rate through the Eurofix channel. So, the solution had to be found in a much faster data link which could neither be offered by Eurofix nor by the US-proposed OFDM technique with a data rate of approximately 1 kb/s. An additional hurdle is that multiple DLoran reference stations have to be served by a single 'Eurofixed' Loran transmitter station. The UK plans to install seven DLoran reference stations along the east coast of the UK, all to be served by the Anthorn station. This would mean that the DLoran data latency may increase to 630 seconds, or more than 10 minutes.

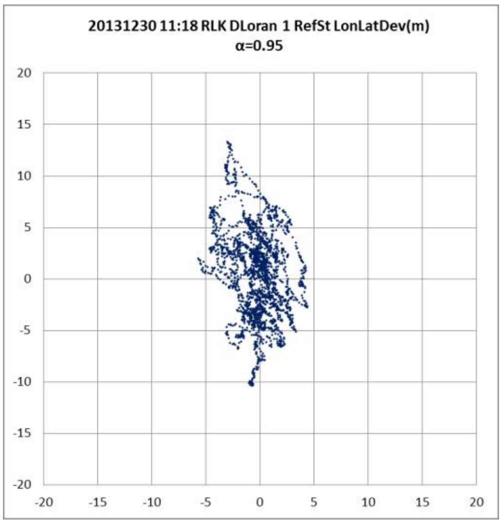


Figure 9. The Low-pass filter result of the right-hand plot in Figure 8. The position dots are apparently not quite random and likely the result of movements of the transmitter antenna at Anthorn and internal time-control loops, and not of atmospheric noise.

4 ENHANCED DIFFERENTIAL LORAN - eDLoran

The above mentioned difficulties with DLoran have led to a new concept of differential Loran which had to fulfil two important primary improvements. The first is a significant reduction in the latency of the data in the data channel; the second is that a large number of reference stations should be capable of receiving the data channel, without saturating the data channel. The simple conclusion was that Eurofix couldn't meet these two improvements. As Eurofix is an invention of Delft University, it was somewhat painful for the Dutch to admit that a much faster data link is absolutely needed to achieve a two-fold better differential Loran position accuracy. However, Eurofix is still the prime GNSS backup candidate for distributing accurate UTC over very large parts of Europe. Further, Eurofix has the capability to send short messages which might be encrypted for secure communication purposes which might then form a terrestrial backup for e.g. Galileo PRS.

Instead of using the Eurofix channel, eDLoran uses the public mobile GSM (Global System for Mobile) network to send the differential corrections to users. eDLoran receivers therefore contain a simple modem for connection to the GSM network. The eDLoran reference stations are also connected to the Internet which may be implemented via a cabled access or also via a GSM modem.

Fortunately, today many GSM networks are robust in respect of GPS outages. The concept is quite simple and is shown in Figure 10.

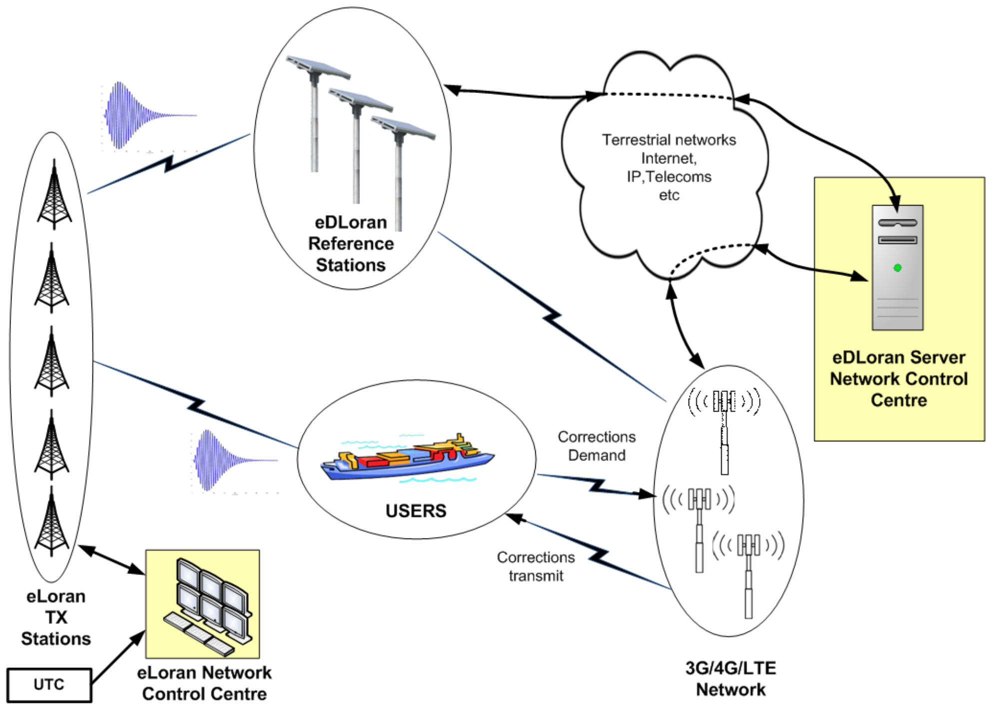


Figure 10. Concept of eDLoran. By courtesy of Babcock International Group.

The eDLoran infrastructure is not connected with any eLoran transmitter station and operates completely autonomously. An eDLoran reference station is connected to a central eDLoran server by its connection to the network.

The measured positions of these reference receivers are processed in the eDLoran server, which in turn sends the results to the user, also via the Internet. Data latency will be not more than 2 seconds. The user starts the entire process by sending as a client the raw position to the server which will then find the optimal corrections for that particular position. Corrections can be calculated by using data from multiple reference stations. Reference stations for eDLoran are small and consume not more than 10 Watts. Two types of reference stations are under development. A portable simple battery-powered version, not larger than 2 metres, can operate for 8 hours. This version is meant to do interference analysis on selected candidate locations. For a permanent installation, a solar-powered unit which can operate continuously is also under development. See Fig. 11.

It has been mentioned that measuring accurately the departure and arrival times of Loran pulses is difficult. It is however needed in order to work out the ASF data on the pseudorange measurement for each Loran station in view. Therefore, a DLoran ASF measurement receiver concept uses Rubidium (Rb) clocks and is relatively large and power hungry. With eDLoran, position offsets due to ASF effects are measured and an eDLoran reference server outputs position- instead of pseudorange-corrections. Measuring positions is much simpler and more accurate and can be done with standard miniature low-power eLoran receivers. The associated costs are also significantly lower. The gain in accuracy of this simpler ASF measurement receiver together with the very low data latency is one of the reasons that the resulting eDLoran position accuracy is now approximately 5 metres instead of 10 metres with DLoran.

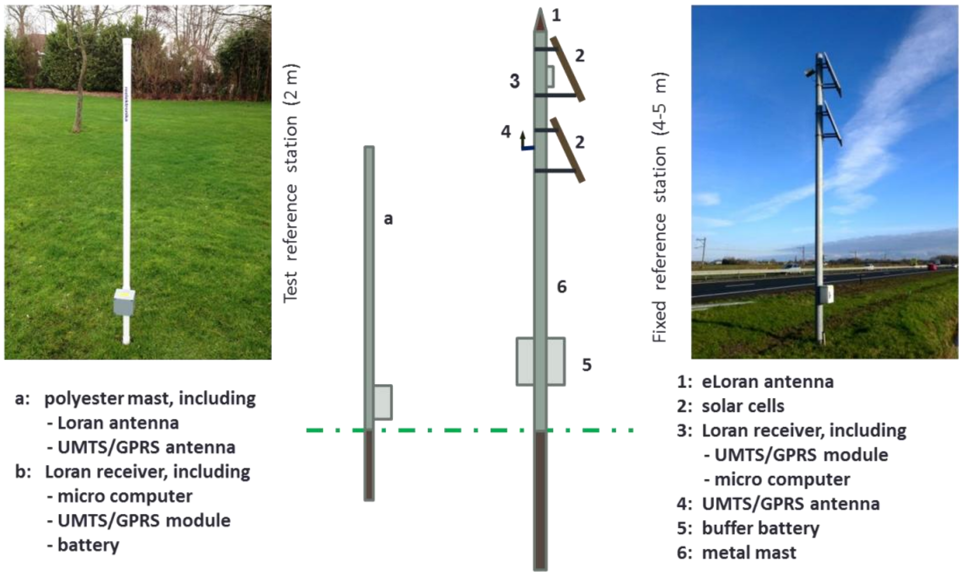


Figure 11. Concepts of a mini reference station (left) and a permanent eDLoran reference station.

5 eDLoran RESULTS

Real-life static and dynamic tests have been executed to demonstrate the capabilities of this new concept. The static tests have been done in post-processing using logged data from Hook of Holland and at Reelektronika at about 40 km's east of Hook of Holland. Only standard eLoran receivers, predominantly equipped with E-field antennae, have been used and no atomic clocks were applied. At Reelektronika we used two 2 metre tall mini-reference stations while in Hook of Holland the antenna was mounted on the 30 metre tall lighthouse. The dynamic tests have been done on board of the MS Polaris, the new Pilot Station vessel of the Dutch Pilots' Corporation. See Fig. 15.

5.1 Static tests

To give a realistic image of the resulting errors of eDLoran, the scatter plot is used in the position domain, while the radial error is given in the time domain. The horizontal divisions are given in hours.
The eDLoran plots on the right depict interesting results as those variations in ASF are largely cancelled but the scattering is also smaller than that of the measurements at Reelektronika and Hook of Holland. The scattering at the two locations was apparently partly due to low-frequency disturbances, e.g. because of the moving phase centre of the antenna at Anthorn or instabilities in the time-control loops in the transmitters. This effect is further demonstrated by applying an alpha-tracker (α=0.9) on the position data of both receivers which have an update rate of 5 seconds.

The disturbances in Fig. 13 contain due to the low-pass filtering less high-frequency terms. The differential radial errors are at some places higher than expected. These errors are dependent on the distance between the user and the reference receiver which is known as spatial decorrelation. Using two receivers separated by just 20 metres offers less differential errors as is shown in Fig. 14.

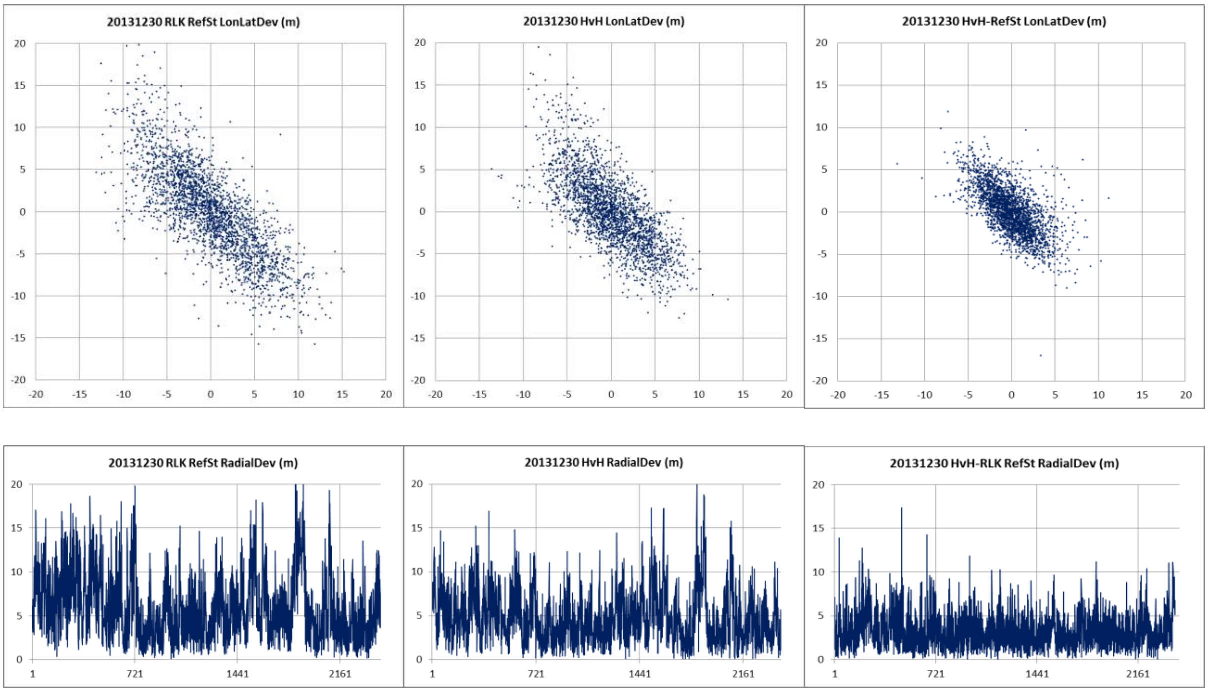


Figure 12. Position scatter plots in the upper row and radial error plots in the lower row of the receivers at Reelektronika and Hook of Holland. The right-hand column depicts the results for eDLoran. The two sites are about 40 km separated which may introduce some accuracy degradation due to spatial decorrelation.

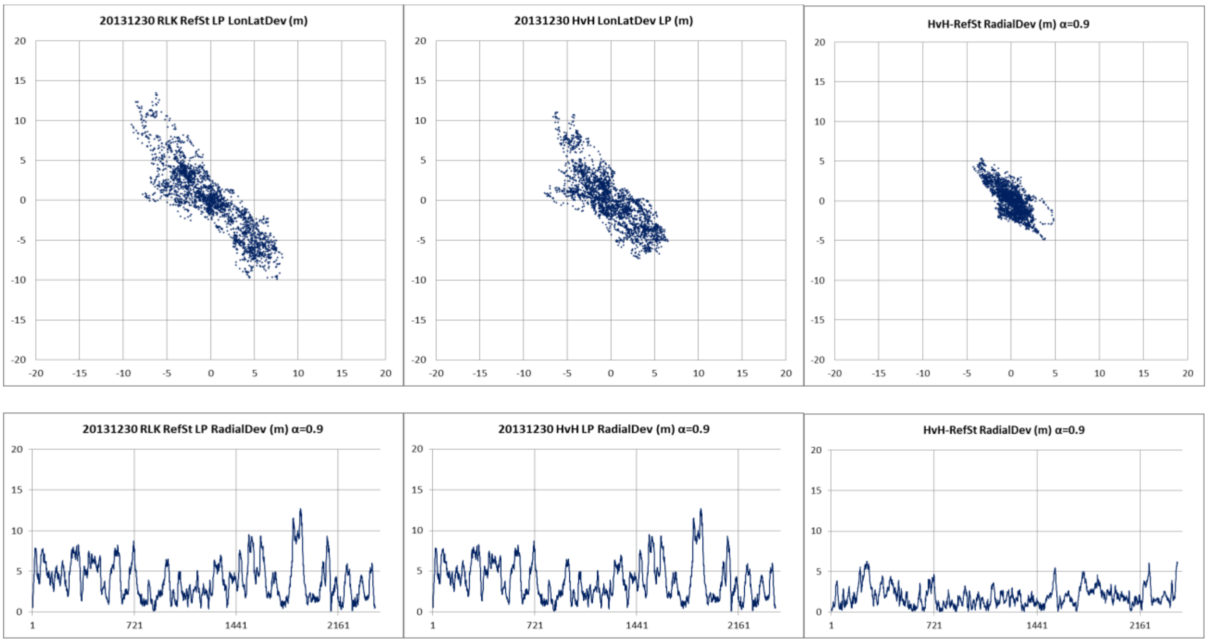


Figure 13. Above plots are based on the same data as in Fig. 12 but now after passing through an alpha tracker with $\alpha = 0.9$

Investigating the radial error plots of Fig. 12, it is remarkable that the large excursions at event 1880 largely cancel while this is not happening at event 250. The disturbance at event 250 might be caused by strong wind loading on the antenna at Anthorn which, due to non-identical directions from Anthorn to the antennae of the two receivers, may result in slightly different time shifts. The disturbance at event 1180 might be caused by an internal transmitter time error which is nearly perfectly cancelled by eDLoran as the difference in headings is then not noticeable.

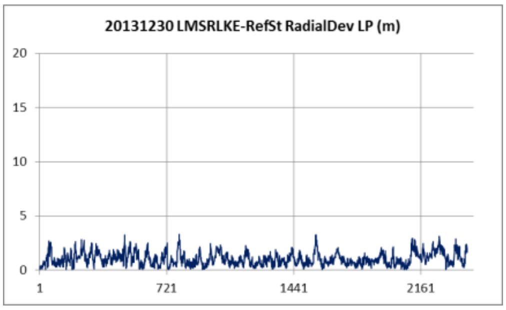


Figure 14. Remaining radial error when both receivers are separated by just 20 metres. The applied alpha-filter constant was 0.9.

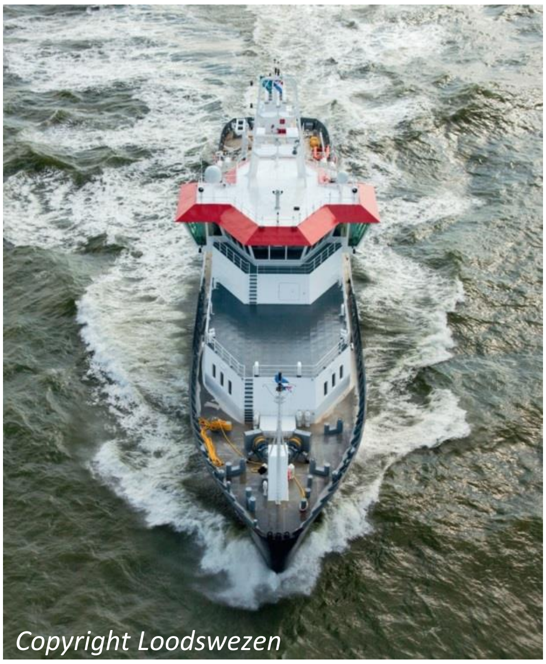


Figure 15. The Pilot Station Vessel MS Polaris (80 metres) used to test eDLoran. On the right is a complete eDLoran receiver with a life-line connected to avoid losing the receiver by accident.

5.2 Dynamic tests

Dynamic testing on board of the Polaris at sea is somewhat more complex to do it correctly. The eDLoran receiver was installed about 1 metre above the GPS-RTK reference receiver. In this way the lever-arm problem of not installing the antennae of the two receivers at the same location was avoided. The next issue was measuring ASF position data which should happen synchronously with the GPS measurements. Time synchronisation can be achieved by using simple GPS receivers at both Loran receivers. Some months later, the eDLoran concept was tested by using the stored AFS data and using an eDLoran receiver as a portable pilot unit (PPU) which looks identical to the GPS-based units the Rotterdam pilots use, manufactured by AD Navigation in Norway.

Figure 16. Five test antennae on the MS Polaris. From left to right the ADNav Master Processing Unit, the ADNav Heading Unit, the ADNav Position Unit with the Reelektronika eDLoran receiver 1 metre above it and, finally, a second Reelektronika eDLoran receiver.

The results have been demonstrated to the harbour authorities in real-time on the laptop of the pilots on which the GPS-RTK and the eDLoran position were simultaneously shown. See Fig. 17 where the grey large ship model represents the position and heading derived from GPS-RTK. The width of the ship model is 10 metres. The red triangle gives the eDLoran position it shows that it remains within the borders of the ship symbol. For further demonstration purposes, the logged GPS-RTK data could also be plotted on a Google Earth map (Fig. 18). The track was widened to 10 metres as the accuracy requirements are 5 metres on either side of the track. The raw eLoran track is also shown, as well as the final white eDLoran track.

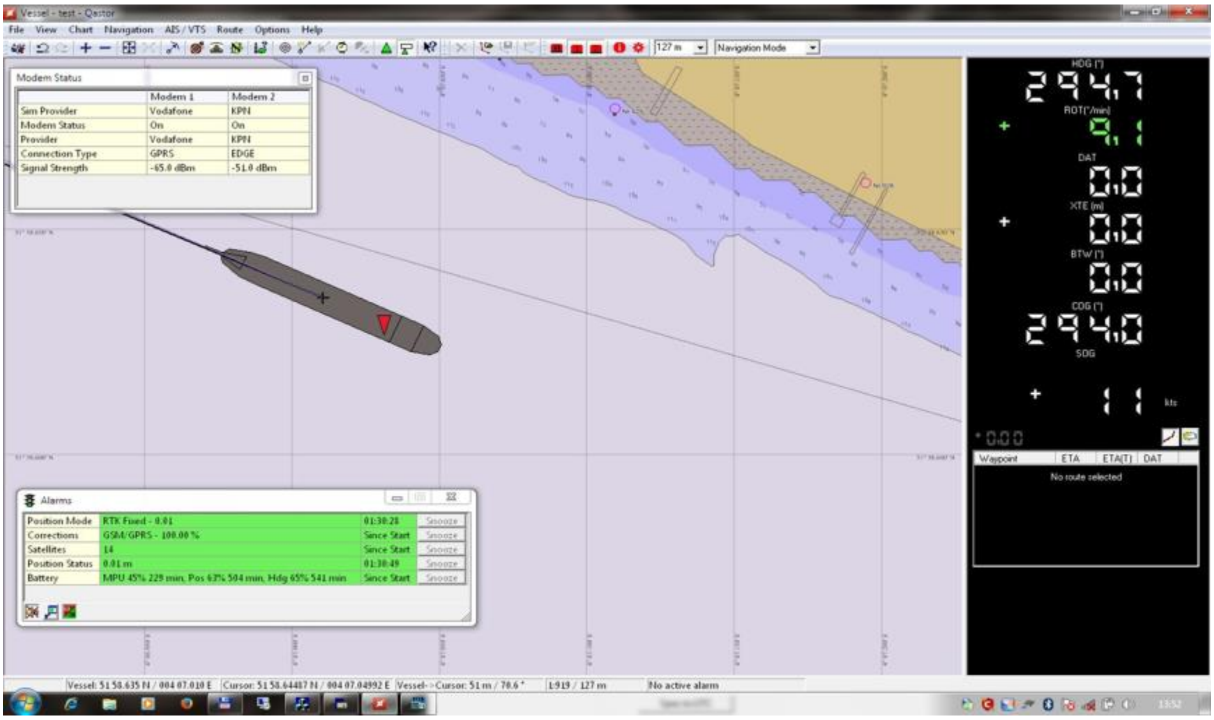


Figure 17. The large ship symbol (grey) is derived from the GPS-RTK receiver of the Rotterdam pilots. The width of the ship symbol is 10 metres and the speed-over-ground was 11 kts. The red triangle is generated by the eDLoran receiver and should remain between the required ± 5 metre limits for eDLoran.

Figure 18. The red track is based on raw eLoran data without any corrections. The transparent blue line is made by GPS-RTK and is widened to 10 metres giving the required ± 5 metre limits of eDLoran. The white line is output from the eDLoran receiver which stays within the borders of the 10 metre wide transparent blue line.

During the sea trials, the eDLoran receiver was connected to the server on land via a miniature GSM modem to the Internet. All differential data were read via this mobile link. The required data bandwidth is very low, approximately 150 bps per ship (client).

6 CONCLUSIONS

The outcome of the described research opens new quite surprising possibilities for multiple applications:

1. eDLoran offers the best possible eLoran accuracy as it does not suffer from swaying wire antennas, sub-optimal timing control of the transmitter station and differential data latency.
2. There is no need to replace older Loran-C stations with eLoran transmitters saving large amounts of money. The existing Loran stations have a proven reliability track record. Further savings may be obtained by containerising the transmitter and operating the stations unmanned.
3. Installing eDLoran reference stations is fast, simple and very cost effective.

4. The Eurofix Loran Data Channel can be freed from a relatively large stream of DLoran data which leaves the full data bandwidth available for UTC and Short Message Services over very large areas.
5. As there is no data channel bandwidth limitation, multiple reference stations can be installed which offers increased reliability and makes the system more robust against terrorism and lightning damage.
6. A single or multiple eDLoran servers can be installed in a protected area. There is hardly a practical limit in the number of differential reference stations to serve.
7. The server selects the most optimal differential data based on the raw position of the user (client) and the available reference stations.
8. As there is no need for any Loran data channel, eDLoran can be installed in all locations where Loran or Chayka coverage and access to the Internet are available. Required data bandwidth is approximately 150 bps per user.
9. Standard eLoran receivers used on controlled trajectories (e.g. pilots and ferries) collect position data when accurate DGNSS is available. The collected GNSS and eLoran data can be uploaded to the server to further refine the ASF data base. It is basically a self-learning system.
10. Existing Loran receivers without Eurofix capability can be used as just the found position data of the receiver should be corrected by the received correction data via the GSM modem. Most receivers are connected to a navigation computer on board, in which a very small programme can be installed.
11. All eDLoran reference stations monitor the eLoran and GNSS positions to offer alarm services in case of jamming or spoofing GNSS.

ACKNOWLEDGEMENTS

We are very grateful for the near endless hospitality of the Rotterdam Pilots and especially the crew of the MS Polaris and the MS Markab. Without their help we wouldn't have reached the eDLoran results as are presented in this document.
During the days at sea we learned how much experience and professionalism is needed to bring those extremely large vessels safely in the harbour of Rotterdam.
We thank Mr. Martin Rumens and Mr. Dave Kelleher of Babcock International Group for their valued comments and offering us some drawings for this paper.

REREFERENCES

COMDTINST M16562.4A (1994). Specification of the transmitted Loran-C signal.
Willams, P. and C. Hargreaves (2009). eLoran Performance in the Orkney Archipelago, Proceedings of the 38th International Loran Association Convention.
Buuren, W. van (2014). The need for reliable, robust electronic positioning systems in the approaches to Rotterdam, ENC-GNSS 2014, Rotterdam.