Eurofix: Test Results of a Cost-Effective DGNSS Augmentation System

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Eurofix is an integrated navigation system, which combines Differential GNSS and Loran-C. The Loran-C system is used to provide differential corrections for the GNSS pseudo-range measurements and integrity information by additionally modulating the transmitted signals. This modulation, however, is not allowed to degrade normal Loran-C operations. As data transmission is hindered by the aggressive Loran-C signal environment, special modulation patterns and Forward Error Correcting codes are designed to fulfil the requirements. Compared to other DGNSS services, Eurofix has a number of advantages: It covers a large area, its implementation in an already existing infrastructure is basically low-cost, it offers enhanced datalink availability in urban and mountainous environment, it has wide-area capabilities and, finally, it provides a free backup navigation system in case either Loran-C or GPS fails.

The paper describes the Eurofix system, focusing on the Loran-C data channel. A modified RTCM type-9 message format is used with special Forward Error Correction. At Delft University a real-life test set-up has been built to evaluate the Eurofix performance for different scenarios. The results on datalink and DGNSS performance are presented. It is shown that metre-level DGNSS performance is achievable with low bit rate data channels, using Loran-C stations at up to 1000 km distance.

1. INTRODUCTION. In recent years, numerous differential GNSS services have been developed and implemented. Examples are the maritime radiobeacon and the FM/RDS system, while WAAS and EGNOS are proposed. It is widely accepted that for future satellite navigation groundbased augmentation is necessary. Also, the policy of the European Community states that, in addition to satellite navigation systems, terrestrial navigation systems should also exist.[1] For both the satellite augmentation and the second navigation system, Loran-C is a prime candidate.

Delft University has developed an integrated navigation system which combines the strong features of satellite navigation and Loran-C, to compensate for their weaknesses. In the Eurofix system,[2] the Loran-C signal is used as a carrier of differential and integrity information for the satellite system. In this way a reliable, cost-effective DGNSS service can be introduced with a continental-wide coverage area.

The Wide Area Augmentation System (WAAS) is a very costly solution adopted by the US government to augment GPS, primarily for aviation applications. Although in concept the system has a high potential, the numerous setbacks prove that its implementation is not at all trivial. One of the problems that remain is the limited coverage of the geostationary satellites for land-based use in urban and mountainous areas, and also in higher latitudes, for which WAAS was not designed.

For maritime users, an alternative is already available. The radiobeacon system provides vessels in Europe and the United States with differential information over a rather large coverage area (radius ⩽ 400 km). At night, however, the skywaves of the low-frequency (LF) transmitters can reduce the coverage area significantly. At distances as close as 75 km, the skywave may cause the signal to fade, and datalink availability will be reduced.[3] Also, other special purpose LF-transmitters broadcasting DGNSS data using a continuous wave modulation will experience skywave fading, which will reduce the effective coverage area significantly.

The commercial FM-broadcast DGNSS services also have problems with coverage. The DGNSS information is modulated on the Radio Data System of the FM transmitters. Unfortunately, the reception of these signals is frequently interrupted while driving through cities. Furthermore, coverage of FM transmitters is limited to the radio horizon. Therefore, it would require a large number of FM-stations to cover the European continent with DGNSS information.

This paper describes the Eurofix system and presents the results of the tests performed with the real-life test set-up at Delft. First, the system concept is outlined and the restrictions on the applied modulation are reviewed. Next, the Eurofix datalink and the test set-up at Delft University are described. Finally, the results of the tests are presented.

2. EUROFIX SYSTEM DESCRIPTION. Eurofix is an integrated navigation system which combines Differential GNSS with Loran-C. The Loran-C signals carry Differential GNSS information without interfering with normal Loran-C operation. The data is retrieved by demodulating the Loran-C signals. A minor modification to existing Loran-C receiver structures would make Eurofix data demodulation possible. Eurofix users have the following measurements available, Fig. 1:

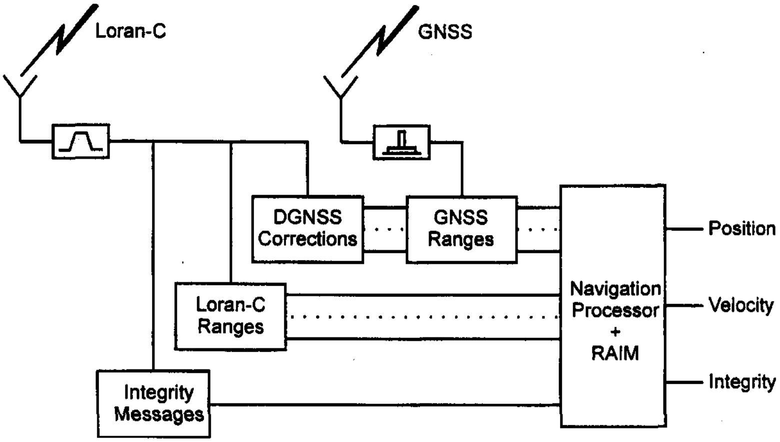

Fig. 1. Eurofix reviewed signals

1. GNSS pseudo-ranges generated by a standard GNSS receiver.
2. Differential GNSS corrections provided through the Loran-C datalink.
3. Loran-C pseudo-ranges or TD's.
4. Integrity information for GNSS and Loran-C.

Eurofix can be used in three different modes:

Mode 1. The Eurofix user is only interested in the differential corrections provided by the Loran-C signal. The Loran-C receiver outputs RTCM type-9 messages, which can be fed into a standard GNSS receiver.

Mode 2. The Eurofix user calculates his position with both Differential GNSS and Loran-C. The two position fixes can be compared to improve integrity. Also, if either system fails, the other remains operational, thus improving availability and continuity.

Mode 3. The Eurofix user combines GNSS corrected pseudo-ranges and Loran-C pseudo-ranges or TD's in an hybridized position solution. The number of observables for the hybridized position filter is increased compared to the single system use. If for instance only three satellites and two Loran-C pseudo-ranges are available, the user is still able to calculate his position, whereas the two single systems separately would fail to do so.

When operating in Mode 2 or 3, the highly accurate DGNSS position can be used to continuously calibrate the Loran-C pseudo-ranges (ASF calibration). If GNSS satellite signals are lost in an urban or mountainous environment, the user can continue positioning by using the calibrated Loran-C signal (soft degradation of positioning). Accuracies of 10–20 m using calibrated Loran-C, will still be achievable as the ASF corrections only slowly decorrelate with distance but hardly with time.

2.1. *Loran-C datalink parameters*. As Loran-C is a navigation system in itself, the transmission of information is restricted by Loran-C navigation requirements and parameters. The additional data modulation onto the Loran-C signal must not influence normal Loran-C operation. Therefore, the following requirements are imposed on the use of the Eurofix datalink:

(i) The Loran-C blinking service must be preserved, which excludes the first two pulses of each Loran-C group from Eurofix modulation.
(ii) The modulation cannot be allowed to induce tracking biases, which requires a balanced type of modulation.
(iii) The modulation index must be kept small in order to prevent an undesirable loss in tracking signal power.

Based on these requirements, a pulse position modulation with a 1 μs modulation index is chosen. Only six out of eight pulses per group will be modulated and the modulation is always balanced on a per GRI basis. The application of three-level modulation (1 μs advance, prompt or a 1 μs delay) leaves a possible seven bits of information per GRI (see Section 4.1). With Loran-C GRI's varying between 40 and 100 ms, the raw bit rate available for data transmission ranges from 175 to 70 b.p.s. Section 4 describes the modulation and coding strategies used for the Eurofix datalink.

2.2. *DGNSS message format*. The differential information is sent to the user in an asynchronous message format. The use of standard RTCM type-1 messages requires too much time to transmit a complete set of corrections. To keep data latency within acceptable limits, a bare minimum RTCM type-9 compatible message is applied. Unfortunately, the parity used in the RTCM messages does

TABLE 1. EUROFIX MESSAGE FORMAT (BASED ON RTCM TYPE-9 MESSAGES)

Function	Number of bits	Resolution	Range
Message type	3	—	Eight types of messages
Modified Z-count	13	0·6 s	0–3599·4
Scale factor	1	—	—
UDRE	2	—	Four states
Satellite ID	5	—	32 satellites
Pseudo-range correction	16	0·02 or 0·32 m	±655·34 or ±10485·44 m
Range rate correction	8	0·002 or 0·032 m/s	±0·254 or 4·064 m/s
Issue of data	8	—	—
CRC	7	—	Data integrity
Total	63	—	—

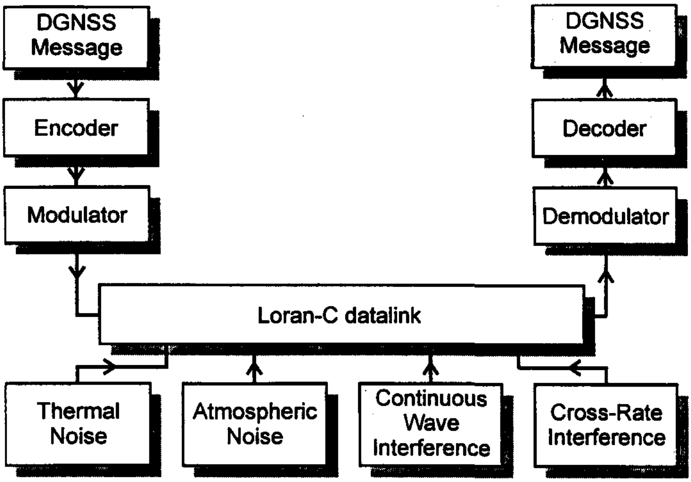

Fig. 2. The Eurofix datalink model

not suffice in the aggressive Loran-C environment of Cross-Rate interference and high ambient noise. Therefore, a different error correcting strategy is chosen. As standard and commercially available type-9 DGNSS receivers must be facilitated, the received Eurofix data is converted into a RTCM type-9 message.

Table 1 shows the message format currently used in the trials. This format is based on the RTCM message format, although Header, Station ID and Parity are removed. The reference station ID is resolved by the Loran-C station ID. The message is concluded with a seven-bit Cyclic Redundancy Check (CRC) to aid in the ensurance of the message integrity, see Section 3.

3. THE EUROFIX DATALINK. In this section, the Eurofix datalink is outlined in more detail focusing on the applied modulation and coding strategies. Figure 2 shows the Eurofix datalink model. At the Reference Station DGNSS corrections are generated. These messages are encoded and modulated onto the

Modulation Pattern	Bit Representation
- - 0 0 + +	1 0 0 0 0 0 0
- - 0 + 0 +	0 1 0 0 0 0 0
- - 0 + + 0	0 0 1 0 0 0 0
- - + 0 0 +	0 0 0 1 0 0 0
: :	: :

Fig. 3. Examples of translation from modulation pattern into 7-bit symbols.
'–' = 1 μs advance, '0' = prompt, '+' = 1 μs delay

Loran-C signal. The Eurofix receiver demodulates the Loran-C signals, which are disturbed by noise, continuous wave interference and cross-rate interference. After demodulation the message is decoded and the DGNSS message is retrieved. As described in the previous section, the use of the Loran-C signal for the Eurofix datalink is restricted. The purpose of the design of the Eurofix datalink is to get the best DGNSS performance under the imposed Loran-C restrictions. The following has to be taken into account:

(i) To get the best DGNSS performance, the differential corrections have to be transmitted with the highest possible update rate.
(ii) On the other hand, the hostile datalink environment necessitates the use of strong Forward Error Correction to ensure the datalink availability.
(iii) At all times, the data integrity must be ensured.

All three considerations play an important role in the total system performance of Eurofix. For signals originating from transmitters located nearby, the strong forward error correction imposes a large overhead, which reduces the effective update rate, and thus the achievable DGNSS accuracy. For more remote transmitters, the error correction is necessary to maintain the required availability. Clearly, the choice of error correction is a trade-off between the required message update rate and tolerable message error probability.

3.1. *Applied modulation scheme.* Based upon the restrictions set by the Loran-C user community and datalink bandwidth requirements, a three-level modulation scheme is chosen (1 μs advance, prompt, and 1 μs delay). With six pulses per Loran-C group modulated, a total number of $3^6 = 729$ modulation patterns are possible, of which 141 are balanced (equal number of advances and delays). 128 balanced modulation patterns are used to represent seven bits of data (Fig. 3). Each seven-bit symbol is spread over six transmitted pulses. This means that if one pulse is received incorrectly, more bits can be corrupted.

The influence of this type of modulation compared to earlier modulation schemes on normal Loran-C users is very small. Calculations show that this type of modulation introduces a signal loss of only 0·79 dB, which is 0·55 dB less than the loss of the earlier modulation schemes.[4,5] The additional modulation of the Loran-C signals thus hardly introduces any changes to the normal Loran-C performance. Future Loran-C receivers, which have knowledge of the Eurofix modulation, can easily compensate for the applied modulation, once the pulses

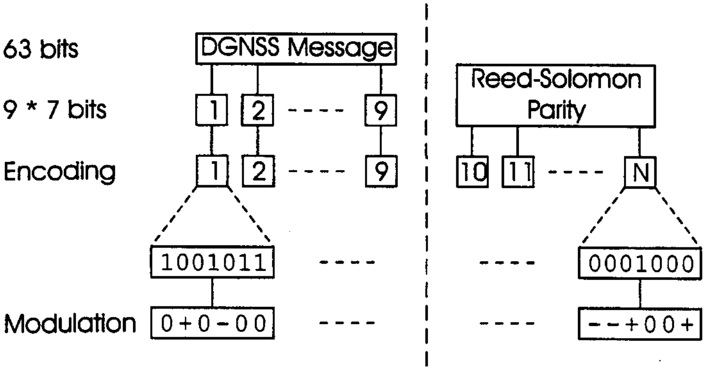

Fig. 4. Forward error correction for the Loran-C data channel

are demodulated. This will cancel the signal loss completely. Note that the influences of cross-rate interference and blanking, phenomena inherent to the choice of the Loran-C signal structure, cause greater signal degradation. Further tests should verify these theoretical assumptions.

3.2. *Forward Error Correction for the Eurofix data channel.* As stated previously, the Loran-C data channel is mainly disturbed by the following three error sources:

(i) Atmospheric noise.
(ii) Continuous Wave interference.
(iii) Cross-Rate interference.

In normal Loran-C receivers the effects of these error sources can be reduced to a certain extent through averaging. However, when data is transmitted using the Loran-C channel, every pulse carries information which has to be recovered. The use of averaging to improve the data signal quality before demodulation is therefore impossible.

Especially the signals from remote Loran-C stations are largely disturbed by cross-rate interference. When large cross-rate coincides with pulses carrying Eurofix information, the chances are very high that the data cannot be recovered. Also, if a group of pulses is hit by cross-rate it is very likely that more than one pulse is corrupted. Hence, cross-rate interference gives rise to so-called burst errors. In addition, the high ambient noise levels introduce additional random errors in the demodulation of the pulses. If no countermeasures are taken for these occurrences, the availability of the datalink will be reduced almost to zero.

The use of forward error correcting codes can compensate for a certain amount of errors at the cost of increased message overhead. The choice of the amount and the type of error correction has to be specially designed for the extraordinary Loran-C signal conditions. For Eurofix, it seems that a concatenation of a simple parity check (capable of detecting single errors) with a Reed-Solomon code (capable of correcting burst errors) is a good combination.

Figure 4 shows the encoding process of a DGNSS message as described in Table 1. The 63 information bits are divided into groups of seven bits each, so they can be represented by a single modulation pattern. Then, these nine groups are fed into a Reed–Solomon encoder. Based on the nine information symbols the encoder adds the parity symbols (each of seven bits length). The length of the total message depends on the strength of the applied Reed-Solomon code. Finally, each symbol is modulated onto the Loran-C signal using its unique balanced modulation pattern, and is transmitted to the user.

At the user site, the message is demodulated and decoded in the following way: In the receiver the incoming pulses are demodulated and translated into their corresponding seven-bit equivalent. Each received modulation scheme should be balanced though. Therefore, the demodulator can output a symbol-erasure (an indication that the demodulator is not able to output a correct symbol) every time the modulation pattern is not balanced. In addition, the demodulator can declare pulses invalid based on their signal quality (RASIM). After demodulation, the received symbols are fed into the Reed–Solomon decoder, which corrects possible symbol-errors and restores the declared erasures. For a more thorough explanation, the reader is referred to.[6,7] Currently, tests are being conducted with DGNSS messages encoded in 14, 20 or 30 GRI's to test different FEC strengths.

3.3. *Message integrity.* The third part in the datalink triangle is message integrity. When a message is received, demodulated and decoded, the user should be able to rely on its correctness. If the information contained in a message is wrong due to errors during transmission or reception, the use of it can have serious consequences for the safety of the total operation. Therefore, the probability of undetected error should be kept very low. The message integrity in the Eurofix system concept is protected using the following three mechanisms:

(i) The lowest level of integrity is provided by the signal demodulator using RASIM (Receiver Autonomous Signal Integrity Monitoring). Before a decision about the possible transmitted modulation pattern is made, the signal quality is checked. Strong cross-rate interference as well as large atmospheric noise peaks are easily detected.

(ii) The use of a Reed–Solomon code as the FEC code introduces an additional level of integrity. Depending on the dimensions of the code and the number of erasures contained in the demodulated message, the probability of undetected error is decreased.[8]

(iii) In the provisional data format, a seven-bit Cyclic Redundancy Check (CRC) is included, see Table 1. This CRC provides a final safety net for the message integrity.

All three integrity mechanisms act on different levels of the message. Therefore, it is valid to say that the three mechanisms are independent. Hence, the total message integrity will be the product of the contributions of the three mechanisms separately. Depending on the demands of the service provided through the datalink, the parameters of the three components can be adjusted to meet the required integrity level. As can easily be seen, a higher level of integrity will reduce availability. In any case, a measure for message integrity can be given for each received message. In none of the tests performed so far, has an integrity failure occurred.

4. TEST-BED DESCRIPTION. At Delft University a Eurofix test set-up is built, with which the system can be tested, Fig. 5. The set-up contains all elements of the DGNSS data transmission using Loran-C. The reference and user sites were provided with a 12-channel NovAtel GPS receiver. As a carrier for the messages real-life Loran-C signals as received in Delft were used. These signals are additionally modulated with the corrections generated by the reference station.

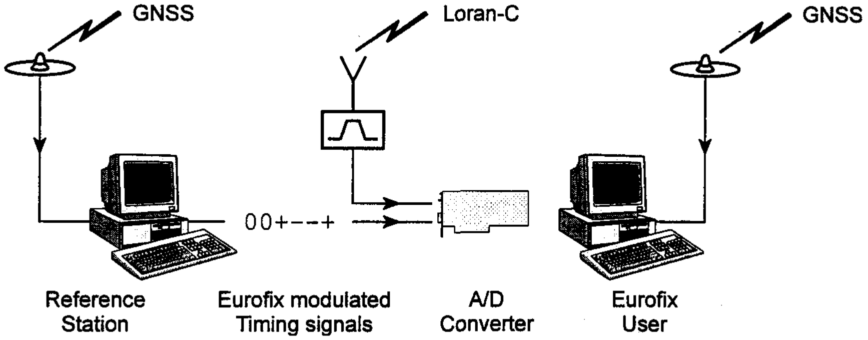

Fig. 5. Test set-up at Delft University

The purpose of the tests are two-fold:

(i) To test the performance of the datalink for different Loran-C stations and datalink parameters.
(ii) To test the DGNSS performance of Eurofix using a low bit rate datalink, for various message update rates.

The next sections describe the set-up in more detail.

4.1. *The DGPS reference station.* The DGPS Reference Station consists of a 12-channel NovAtel receiver in a PC. The GPS antenna is located on the roof of the building of the Department of Electrical Engineering in Delft. The use of a choke-ring with the antenna reduced the amount of multipath signals. The worst code multipath experienced in these trials was about 1 m.

The receiver autonomously calculates corrections for all satellites in view. These corrections are adjusted for the reference station clock error and frequent satellite jumps. Then, the corrections are packed in an asynchronous message format (a correction for one satellite per message, Table 1), encoded by the forward error correcting code and translated into modulation patterns.

Instead of time shifting the transmitted Loran-C signals, the received signals are modulated. Therefore, the reference station outputs timing signals with which the incoming Loran-C signals are artificially time-shifted. In this way, the Eurofix modulation is simulated using real-life signals. Now it is possible to evaluate the performance of the datalink for a number of different scenarios, defined by FEC parameters, the GRI, the selected Loran-C station, etc. The update rate of the transmitted messages depends on the GRI of the Loran-C station and the applied FEC parameters. In the trials, Loran-C transmitters located in Lessay and Soustons, France, and Sylt, Germany, were used. Update rates varied between once per 1·25 and 3 s.

4.2. *The Eurofix receiver.* At the receiving end, the Loran-C pulses are demodulated and the message is decoded. As described earlier, the Eurofix message can be transformed into a standard RTCM type-9 message. Then, the message is fed into a GPS receiver, capable of accepting RTCM type-9 messages (NovAtel). The receiver, hooked onto the same antenna on the roof, is able to correct its measurements and improve its positioning accuracy. The remaining positioning accuracy is limited only by the following three factors:

(i) Noise of the measurements in the Reference and the User receiver.
(ii) Temporal decorrelation of the DGPS corrections.
(iii) Fast fluctuating multipath errors.

Note that due to the zero base-line DGPS measurements, spatial decorrelation is not included.

The datalink receiver consists of the following functional blocks: a Loran-C bandpass filter, a signal demodulator, and a message decoder. After the Loran-C antenna the signals are first bandpass filtered. Note that for data demodulation, not the absolute time of arrival (TOA) is required but only the TOA relative to a certain time reference. Since there is no need to separate the groundwave from the skywave in the receiver, the bandpass filter may be somewhat steeper and narrower than a conventional Loran-C filter. In this way, the influence of continuous wave interference and atmospheric noise can be reduced considerably.

After filtering, the signals are A/D converted and processed in a computer. The demodulation is done by cross-correlating the received pulses with an image pulse stored in computer memory. Here, all the energy of the pulse can be used (including skywave). The image pulse is continuously updated by the first two pulses in each group, as they are not modulated. Furthermore, the image pulse is used to check the validity of the received pulses. If a pulse is hit by Cross-Rate or a large atmospheric disturbance, the chances are that the demodulation will not be correct. Hence, the demodulation must be stopped and an erasure has to be declared. This erasure is then compensated by the error correcting code.

Finally, the demodulated pulses (and erasures) are processed by the message decoder. First, the groups of 6 demodulated pulses are checked as to whether they are balanced or not. If a group is unbalanced (not an equal number of advances and delays) or not in the list of 128 valid patterns, the received symbol is erased. Otherwise, the modulation pattern is translated into its seven-bit symbol equivalent. The Reed–Solomon decoder accepts the valid and erased symbols and decodes the message.

5. TEST RESULTS. The purpose of the tests was to evaluate the datalink and DGPS performance. The presentation of the results can therefore be divided into two sections. The first section shows the datalink results, which are presented as

TABLE 2. LORAN-C STATIONS USED IN THE TESTS

Station name	Distance to Delft (km)	Power (kW)
Lessay, France	523	250
Soustons, France	1013	250
Sylt, Germany	407	250

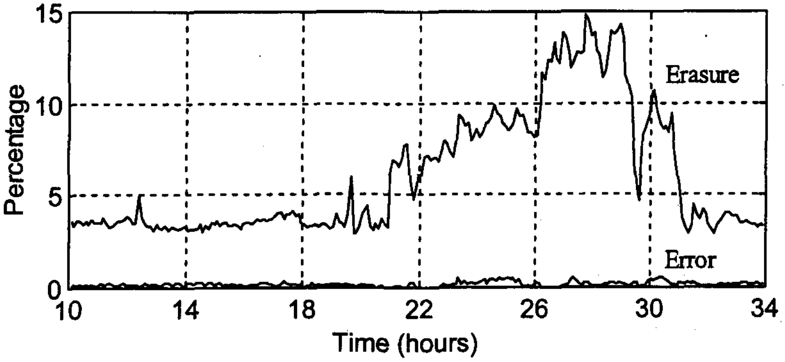

Fig. 6. GRI erasure and error rate as a function of time for the Lessay signals, 523 km. Run started dd. 22 September 1996, 10.00 hr.

GRI erasure and error rates as a function of the time of day. From these rates, the datalink availability can be calculated as a function of coding parameters.

The second section presents the zero base-line DGPS performance with type-9 messaging at different updates rates. The relation between datalink availability and update rate are the coding parameters. The raw data rate (without FEC) is fixed for every Loran-C Group Repetition Interval. The coding parameters should be chosen in such a way that the datalink availability approaches 100 per cent for all times in a specific coverage. As can be expected these analyses will not be trivial. Future measurements have to be conducted in order to evaluate different scenarios.

5.1. *Results of the datalink tests.* The following figures show the results of three 24-h runs with the test set-up described in Section 5. For the tests, three Loran-C stations were selected, all in the French Loran-C chain (GRI 8940). Table 2 lists the properties of the chosen Loran-C stations.

In Figs 6–8, the GRI erasure and error rates (in percentage) are shown as a function of the time of day. The time is accumulated after 00.00 hr. Erasures are mainly caused by cross-rate from stations in other chains. Lessay and Sylt are dual-rated Loran-C stations, which means they transmit signals at a different GRI too (7499). Since in one chain they act as cross-rating stations for the other, a certain number of erasures is inevitable.

As can be clearly seen in the figures, the Loran-C conditions at night are totally different from the conditions at day. At night, a higher skywave activity is observed due to changes in the ionosphere. This is especially important for

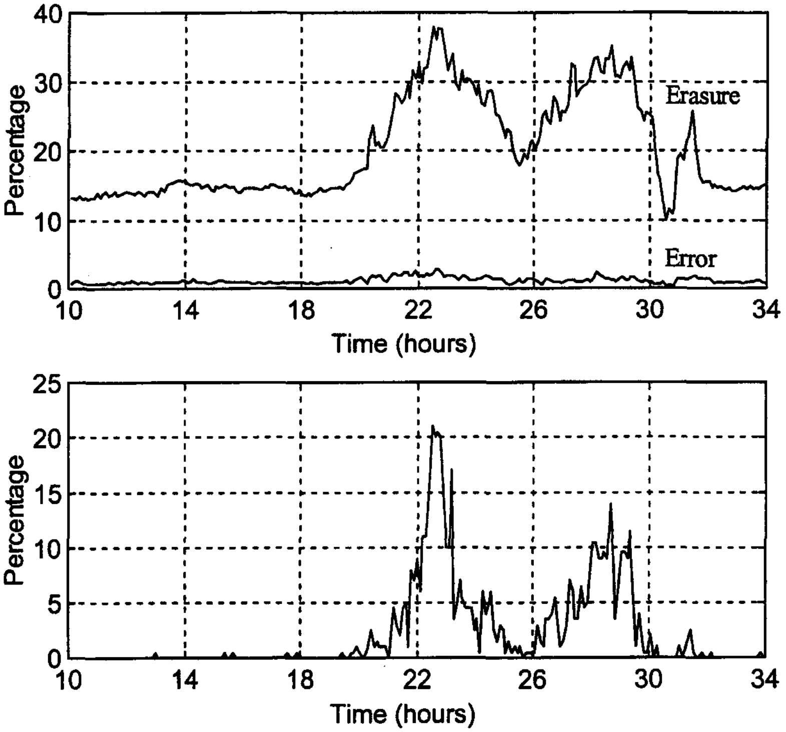

Fig. 7. (a) GRI erasure and error rate as a function of time for the Soustons signals 1013 km. (b) Percentage of decoder failures. Run started dd. 14 September 1996, 10.00 a.m.

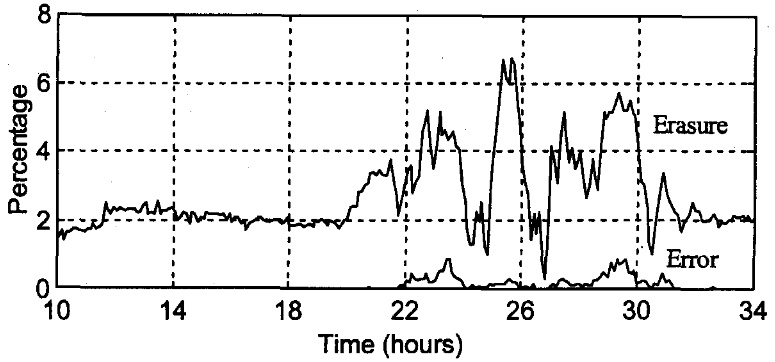

Fig. 8. GRI erasure and error rate as a function of time for the Sylt signals, 407 km. Run started dd. 19 September 1996, 10.00 hr.

datalink availability using very distant Loran-C stations. During the night, the Soustons Loran-C signals are largely disturbed by cross-rate, not only from nearby stations but also from skywaves of remotely located stations (> 1500 km). Although cross-rate can be detected, the signals corrupted by it cannot be reliably demodulated. This results in a higher GRI erasure rate.

TABLE 3. GRI ERASURE RATE VS. DATALINK AVAILABILITY FOR DIFFERENT REED–SOLOMON CODING PARAMETERS (A GRI ERROR RATE OF 2 PER CENT IS ASSUMED)

Reed–Solomon parameters (length, data)	Maximum number of erasures allowed per message	Maximum erasure rate for 95 per cent availability (%)	Maximum erasure rate for 99 per cent availability (%)
(14, 9)	4	8·9	2·2
(20, 9)	10	29·0	21·2
(30, 9)	20	48·1	40·9

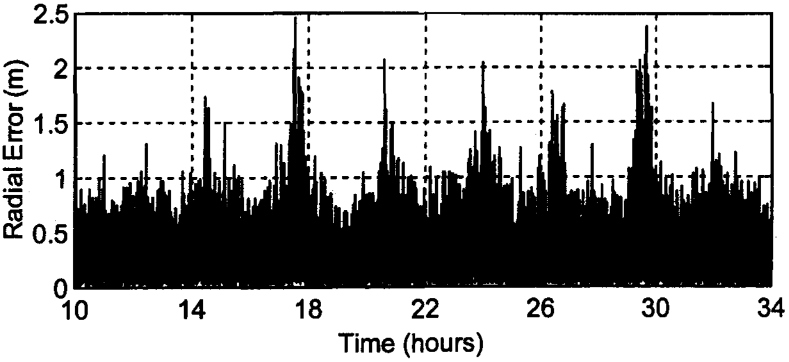

Fig. 9. DGPS performance with Eurofix type-9 messages at a once per 1·25 seconds update rate. Run started dd. 5 October 1996, 10.00 hr.

If a message contains too many erasures, the information cannot be recovered anymore. The maximum number of erasures which can be accepted depends on the selected Reed-Solomon coding parameters. Table 3 lists the maximum GRI erasure rate for different coding strategies. As an example, the decoder failure rate (note: not decoder error rate!) of the Soustons run is shown in Fig. 7b. Clearly, when the GRI erasure rate increases, the decoder failure rate increases too. In all runs 20 GRI's were used to transmit nine GRI's of data. In the runs of the stations closer to Delft (Lessay and Sylt), no decoder failures were experienced. Needless to say, it is better to declare a message undecodable than to decode it incorrectly. In none of the three runs did a decoder error occur.

5.2. *Results of DGPS performance.* Figures 9 and 10 show the results of the zero base-line DGPS performance over a 24-hour period using 14 GRI's and 30 GRI's, respectively, for the Eurofix messages. Messages for all satellites in view were transmitted over a simulated, error-free datalink. The Eurofix messages were presented to the NovAtel user receiver as standard RTCM type-9 messages. Using 14-GRI messages on a simulated Loran-C chain with Group Repetition Interval of 89·40 ms, every 1·25 s a correction for a single satellite is received. The maximum age of a correction used by the receiver in this scheme with nine satellites in view then becomes about 12·5 s. When 30 GRI's are used to transmit a single correction, the update rate is once per 2·7 s (27 s maximum age).

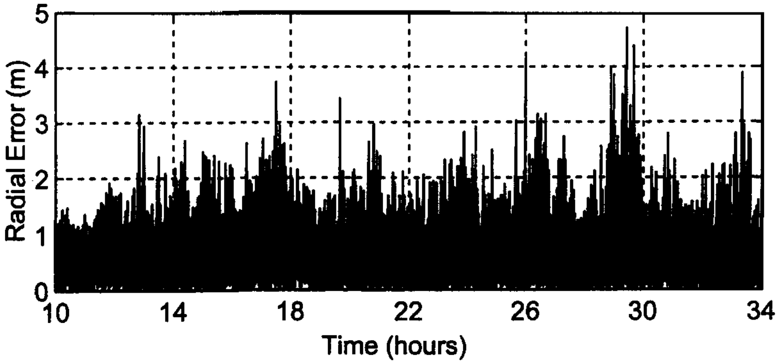

Fig. 10. DGPS performance using Eurofix type-9 messages at a once per 2·7 seconds update rate. Run started dd. 8 October 1996, 10.00 hr.

TABLE 4. ZERO BASE-LINE DGPS PERFORMANCE FOR DIFFERENT UPDATE RATES

	95 per cent error	Maximum error (m)
High speed type-1 messages	0·50 m	1·88
14 GRI's type-9	0·74 m	2·45
30 GRI's type-9	1·42 m	4·72

Table 4 summarizes the performance of the two schemes. For comparison, the results of a high speed type-1 DGPS test with the same receivers is included.

As can be seen from the figures and the table, the temporal decorrelation of the corrections grows as the update rate decreases, although its influence only reduces the 95 per cent accuracy from 0·50 m to 1·42 m. During the tests, no spatial decorrelation is included. Depending on the user-reference station separation the DGPS performance will deteriorate due to spatial decorrelation. The final DGPS accuracy depends on both the temporal and spatial decorrelation, and whether Eurofix is used in a LAAS or WAAS configuration.[9] Therefore, it is expected that DGPS accuracy using the Loran-C data channel over large distances will still be in the order of a few metres. Future tests with the Eurofix system concept should verify the correctness of this theory.

Figure 11 shows the basic capability of Eurofix over a 46-h time-span. Horizontal radial error DGPS performance is shown for DGPS data transmission over a simulated datalink using real Loran-C signals from the Soustons transmitter in France (1013 km from Delft). The 95 per cent horizontal accuracy as measured in this run is 1·57 m. The maximum error experienced is 11·50 m. During the run, corrections were lost due to severe cross-rate conditions. Obviously, to some degree the loss of messages does not severely degrade the achievable accuracy.

6. CONCLUSIONS AND FUTURE WORK. This paper has shown the system concept and test results of Eurofix. It can be concluded that reliable data transmission is feasible using the Loran-C data channel. Also, the DGPS test results with the Eurofix type-9 messages show the potential high accuracy achievable with a low data rate communications channel. In the near future we are planning

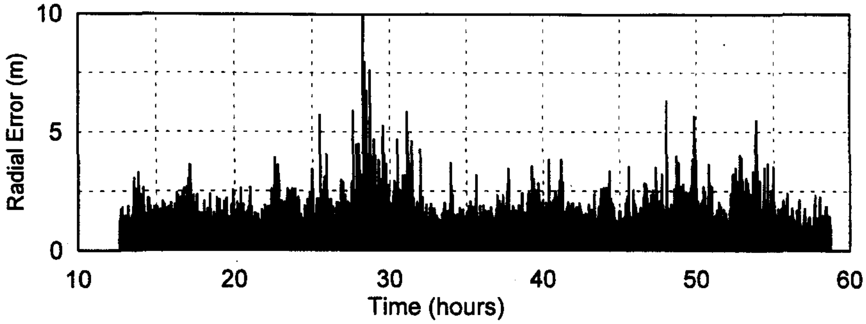

Fig. 11. Eurofix zero-baseline horizontal DGPS performance using a datalinked based on real-life Loran-C signals from Soustons (1013 km) at a once per 2·7 seconds update rate. Ninety-five per cent horizontal positioning accuracy is 1·57 km. Run started dd. 15 October 1996, 12.40 hr.

to do Eurofix tests using a real Loran-C transmitter. Then, all the theoretical calculations and test results can be verified.

Delft University continues research in the field of Eurofix on the following topics:

(i) Integration of DGNSS and Loran-C.
(ii) Development of improved Loran-C/Eurofix receiver concepts.
(iii) Improvement of the correction format especially for spatial decorrelation terms (Regional Area Augmentation System concept).
(iv) Further datalink improvement by implementing Soft Decision decoding techniques.

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KEY WORDS

1. Satellite navigation. 2. Differential systems. 3. Hyperbolic systems.