Eurofix System and its Developments

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The existing Loran-C and Chayka infrastructure can, with some minor changes, become a very powerful augmentation system for GNSS (GPS, GLONASS and the future Galileo). Delft University initially proposed the Eurofix concept in 1989. Although the necessary modification to the LF navigation systems are minimal, the GNSS user may get significant benefits from the Eurofix signals in terms of accuracy, integrity and availability. The reason is the high signal structure, signal propagation, and the operations dissimilarity of both systems. The broadcast correction and integrity data improves GNSS accuracy down to the metre level. In this way, the measured Loran-C and Chayka ranges are continuously updated. Thus, in the case of GNSS signal interruptions, highly calibrated Loran-C/Chayka may take over the navigation function. Tests carried out in Europe at the Loran-C station at Sylt (Germany) drew large international attention, leading to further tests in the USA by the US Coast Guard in 1998. Recently, a Dutch–Russian consortium implemented Eurofix on the Chayka transmitter at Bryansk (Russia) which is now successfully broadcasting DGPS as well as DGLONASS correction data. This paper highlights some on-air Eurofix DGPS performance experiments carried out in Europe and the USA. With all the European Loran-C and Chayka transmitters modified, Eurofix can be used all over the European continent. As multiple stations can normally be received simultaneously, the user may locally apply networked DGNSS, which may reduce spatial decorrelation effects significantly. Post-processed results of this Regional Area Augmentation System are presented.

1. INTRODUCTION. A well-known problem of satellite positioning systems is the poor penetration of L-band radio signals in urban environments. The signals are often either blocked or reflected by man-made structures. Low-frequency Loran-C signals propagate quite differently from GNSS signals in built-up areas. As the wavelength (3000 metres) is long compared to the size of the structures, Loran-C signals are not easily blocked or reflected. However, due to large man-made constructions, phase alterations of the 100 kHz signals may be experienced. Interestingly, these effects are different for the Loran-C electric field and magnetic field.[2]

Low-frequency signals propagate along the Earth's surface slightly differently from free space. Due to the limited conductivity of water and soil, the signals experience an additional propagation delay. The delay due to seawater is known as the Secondary phase Factor (SF) and can easily be taken into account in Loran-C position calculations. The conductivity of ground or fresh water is less than for seawater and varies widely for different types of soil. This results in an extra delay, the so-called Additional Secondary phase Factor (ASF). If a receiver contains a database of ground conductivity figures or ASF corrections for the total Loran-C coverage area, the system's absolute accuracy can be improved. Research carried out by the USCG Academy,[2] by Megapulse, Inc.,[3] at the University of Wales, and at Delft University of Technology indicates that the H-field has better penetration of deep city canyons but also shows less deviations from the modelled ASF properties than the E-field.

By additional modulation of Loran-C pulses, a long-range data channel can be established which enables broadcasting of DGPS correction data and integrity information on one of its eight sub-channels. Other sub-channels may be allocated to DGLONASS/DGNSS messages. Delft University has been working on such a system, called Eurofix, since 1989.[1] The applied additional three-level modulation is fully balanced and has negligible influence on the basic Loran-C positioning accuracy. Figure 1 shows the predicted Eurofix coverage if the system were

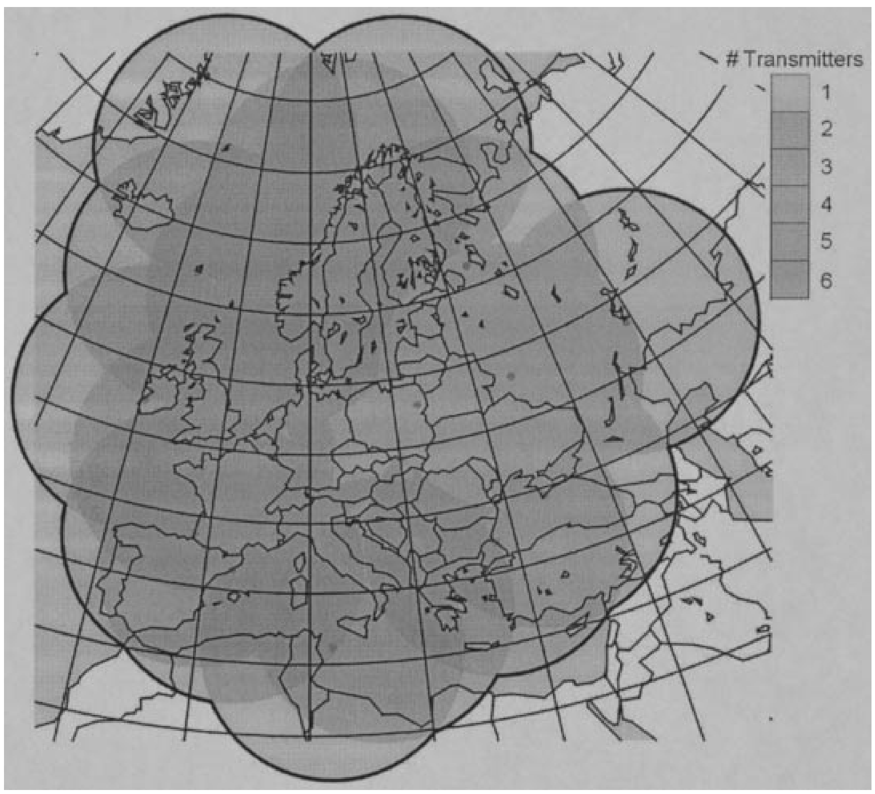

Figure 1. Eurofix coverage area with full NELS, SELS and European Chayka implementation.

implemented in all 17 European Loran-C and Chayka stations. The estimated 1000 km range has been verified during trials in France and Switzerland.

The Eurofix user can expect DGPS accuracies of better than three metres (95%). As long as DGPS performance is excellent, the Additional Secondary phase Factor (ASF) values of the Loran-C propagation can be updated continuously and accurately from the calculated DGPS positions and built into a correction database.[4] This calibration can be done much more accurately than with the best-known ASF tables. It offers the unique possibility of using calibrated Loran-C whenever GPS becomes unavailable.

The combination of GPS and Loran-C offers three important advantages:

(i) A differential GPS service through Loran-C over a larger coverage area.
(ii) Improved availability and continuity by using calibrated Loran-C when GPS is not available.
(iii) External integrity information.

This is in strong contrast to DGPS services currently operational. These services only supply DGPS correction data and, sometimes, external integrity. The continuity and availability of the total system depends on the continuity and availability of the basic GPS service as well as the DGPS correction data. In other words, whenever one of the two systems fails, precise position determination is no longer possible. Eurofix with its DGPS service can be seen as the ground-based version of GNSS-1, while the space-based versions are well known under the names EGNOS, WAAS or MSAS. The current infrastructure of Loran and Chayka in the US, Europe and Asia offers the possibility of covering the majority of the industrialised world with high-quality DGPS/DGLONASS services.

Section 2 outlines the Loran-C datalink. Choice of modulation, DGPS message format and Forward Error Correction will be briefly discussed. In Section 3, the Eurofix reference station implementation in the Sylt Loran-C transmitter is addressed. Some static measurements at Delft and dynamic test results of mobile test runs will be presented in Section 4 and 5. Finally, a new Regional Area Augmentation concept for Eurofix will be introduced in Section 6.

2. LORAN-C DATA TRANSMISSION. The basic Eurofix datalink is in essence a reliable long-range data broadcast system with eight sub-channels. The Loran-C pulses are additionally modulated to carry different types of information. One of the sub-channels is assigned to provide GPS differential correction data and integrity information, while other channels are reserved for DGLONASS, DLORAN-C and Short Message Services (SMS). As long as DGPS is available, the accurate position is continuously used to calibrate the Loran-C pseudoranges. If GPS fails, the user can continue navigation with accurate Loran-C positioning (10–20 metres), depending on the distance travelled and the validity of the rate-of-change of the on-board ASF tables.

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 of 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 blinking service must be preserved, which excludes the first two pulses of each Loran-C group from Eurofix modulation.
(ii) The modulation is not 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 6 out of 8 pulses per group will be modulated and the modulation is always balanced on a per Group Repetition Interval (GRI) basis. The application of 3-level modulation (a 1-μs advance, a prompt or a 1-μs delay) leaves a possible 7 bits of information per GRI.[5] With Loran-C GRIs varying between 40 ms and 100 ms, the raw bit rate available for data transmission ranges from 175 to 70 bps. Normal Loran-C users only experience a slight signal loss of 0·79 dB.[5] Future Loran-C receivers, which have knowledge of the Eurofix modulation, can easily compensate for the applied modulation, once the pulses 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 larger signal degradation. Earlier publications[5,6] describe the Eurofix datalink in more detail.

2.1. *DGPS Message Format*. The differential information is sent to the user in an asynchronous message format. To keep data latency within acceptable limits, an RTCM type-9 compatible message of 56 bits is applied; see Table 1. To enhance the

Table 1. Eurofix Message Format (based on RTCM Type-9 Correction)[7].

Function	Number of bits	Resolution	Range
Message type	3	—	8 types of messages
Modified Z-count	13	0·6 seconds	0–3599·4
Scale factor	1	——	
UDRE	2	—	4 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	—	
Total	56		

Eurofix datalink performance, the RTCM parity is replaced by a stronger combination of Reed–Solomon Forward Error Correction and a Cyclic Redundancy Check (CRC). However, as standard and commercially available DGPS receivers must be facilitated, the received Eurofix data is converted into a standard RTCM type-9 message. In September 1998, RTCM called a special Eurofix sub-committee to write specifications for Eurofix for the next version of the 'RTCM recommended standard for Differential Navstar GPS Service' (SC104).

2.2. *Forward Error Correction*. To ensure reliable broadcast data communication through Loran-C, Forward Error Correcting codes are applied. These codes provide an effective means to correct occasional errors (improving datalink availability) and validate the decoded data (integrity) at the cost of an increased message overhead. Figure 2 shows the modulation and encoding currently used to transmit data via Loran-C. Seven bits of information are translated into a balanced modulation pattern of six pulses per GRI. In Eurofix, the message integrity is ensured by a 14-bit Cyclic Redundancy Check (CRC), while the Reed–Solomon code ensures datalink availability for stations at ranges up to 1000 km. Each 56-bit message (8 GRIs of 7 bits) is protected by additional Reed–Solomon parity GRIs. In recent experiments, a message length of 30 GRIs was found to be sufficient. Depending on the GRI (40–100 ms) of the Loran-C station, the DGPS message update rate will be between once every 3 seconds and once every 1·2 seconds.

Depending on the user's datalink integrity needs, the Eurofix decoder can apply different demodulation/decoding strategies. The message integrity is protected in three steps:

(i) Before demodulation, a received pulse is first compared with a stored reference pulse, built up by integration of the first two unmodulated pulses (Receiver Autonomous Signal Integrity Monitoring, RASIM). This way, the quality of the demodulated pulses is preserved.[6]

(ii) The Reed–Solomon code inherently adds integrity to the messages. The Probability of Undetected Error, P_{UE}, for a 10-error correcting Reed–Solomon code (30-GRI Eurofix message) is $1/10! \approx 2{\cdot}7 \cdot 10^{-7}$.[8]

(iii) As a final safety net, a 14-bit Cyclic Redundancy Check (CRC) ensures a lower bound on the P_{UE} of better than $2^{-14} \approx 6{\cdot}1 \cdot 10^{-5}$.[9]

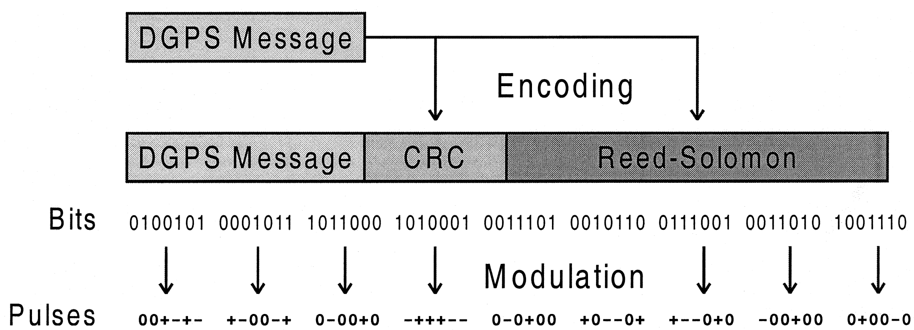

Figure 2. Encoding and Modulation for the Loran-C Data Communication.

3. IMPLEMENTATION OF DGPS SERVICE AT THE SYLT LORAN-C STATION. On 5 February 1997, Delft University installed a DGPS reference station at the Sylt Loran-C transmitter site (Germany) on an experimental basis. From that date on, RTCM-compatible differential corrections have been broadcast throughout Europe on the Sylt Secondary rate 6731. As mentioned before, the Eurofix datalink is not only suitable to broadcast differential GPS corrections but can also be used as a differential GLONASS, a GNSS integrity and a long-range Short Message Service (SMS). Furthermore, the Eurofix datalink is extremely suitable to correct Loran-C timing to UTC or GPS timing by broadcasting differences between the time-scales, thereby giving the possibility of using Loran-C in a rho–rho mode together with the GPS satellites.

Currently, corrections for all satellites in view are broadcast at an update rate of once every 2·01 seconds per satellite (30-GRI message at 67.31 ms). When the Master rate of Sylt (7499) is also used for data transmission, the correction update rate will be almost doubled. This extra data bandwidth can be used to enhance Eurofix performance.[10]

The reference station consists of an industrial PC with a 12-channel NovAtel GPS receiver. On average 8·7 satellites are in view at the reference station site; see Figure 3. The antenna is located on the roof of the office building located 100 metres from the transmitter. The antenna is placed in a choke ring to reduce low elevation multipath errors. The code multipath errors measured did not exceed 50 cm. Figure 4 shows the set-up at the Sylt station. The reference station can be remotely controlled by Delft University to allow maximum flexibility in testing the system. Tests with

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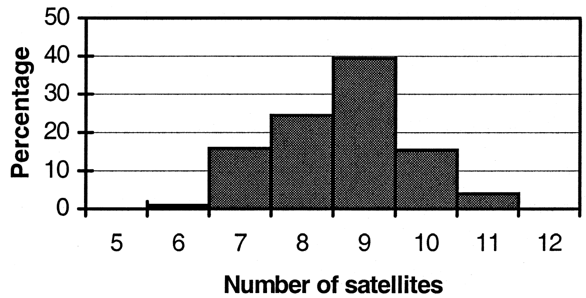

Figure 3. Number of GPS satellites visible at Sylt over 24 hours (average 8·7).

Figure 4. Reference station PC, GPS antenna and Sylt Loran-C transmitter.

different coding strengths (and thus different update rates) can be scheduled, and modulation on/off time can be controlled. To date the Loran-C monitor stations at Brest (France) and Bø (Norway) have not reported any degradation of the Loran-C signal quality due to the Eurofix modulation. Therefore, the test period, which initially was restricted to two months, has been continued indefinitely.

Triggered by the promising European test-results, the US Coast Guard approached Delft University in November 1997 to cooperate in a US-based Eurofix test. Delft scientists aided the US Coast Guard personnel at the Wildwood test-transmitter to install a Eurofix reference station. A station comparable with the one in Sylt was installed and went into operation in less than two days. The Eurofix transmissions were independently monitored for one week by the US Coast Guard Academy, Megapulse, Inc. and Delft University.[11–13] The results of these trials were very similar to the results of the European tests.

4. STATIC TEST RESULTS. Since the beginning of the experimental Eurofix transmissions from the Sylt Loran-C station, the quality of the transmitted data has been constantly monitored at Delft University. The Eurofix datalink was tested using different code rates for the Forward Error Correction (FEC), and the performance of the resulting DGPS position was measured. The overall quality of the DGPS service via the Eurofix datalink is a function of the following parameters:

(i) Integrity of the messages.
(ii) Availability of the datalink.
(iii) Accuracy of the DGPS positioning.

During the presented measurements, not a single DGPS message was lost (100%

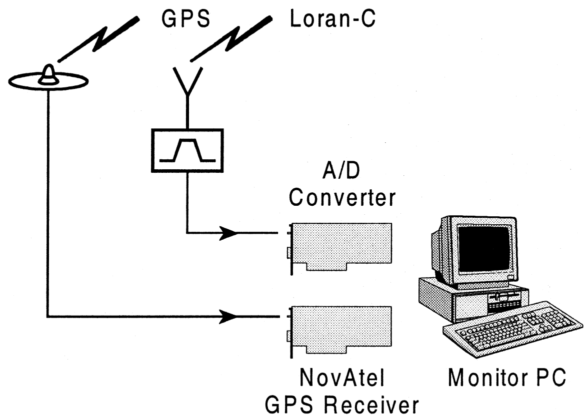

Figure 5. Eurofix Monitor at Delft University.

datalink availability). Furthermore, on all measured data, no CRC failures have occurred either. Due to the relatively long baseline between Delft and Sylt (400 km), some spatial decorrelation errors would be expected.

4.1. *Measurement Set-up*. The experimental measurement set-up built at Delft University consists of the following components; see Figure 5:

(i) A 486 DX 100 MHz PC.
(ii) A 12-channel NovAtel GPS PC board.
(iii) A 12-bit, 400 kHz A/D converter board.
(iv) A NovAtel GPS antenna with choke ring.
(v) A Loran-C E-field antenna with bandpass filter.

The Eurofix modulated signals are received by the E-field antenna, bandpass-filtered and amplified, and then sampled at 400 kHz (quadrature sampling) on the A/D converter board. The processing of the signals involves the demodulation of the pulses and the Reed–Solomon decoding of the DGPS messages. When the message is retrieved, it is converted into an RTCM type-9 message, which in turn is fed to the NovAtel GPS card. The GPS card outputs a position fix once every second. Further information about the Eurofix receiver design can be found in Helwig *et al*.[6]

4.2 *Test Results*. The accuracy of Eurofix DGPS is characterised by temporal and spatial decorrelation phenomena. Due to the limited datalink bandwidth, the received corrections need to be used for a relatively long period of time. If, for instance, every other second a correction is received, the cycle time for a complete set of nine satellites will be 18 seconds. The user has to extrapolate a satellite correction to cover this period until a new correction for the same satellite is received. The update rate of satellite correction data varies with the GRI of the broadcasting Loran-C station. If Eurofix stations are dual-rated, the effective update rate will be dramatically improved.[10]

Figure 6 shows the typical Eurofix DGPS performance at Delft over a 16-hour run. The 95% DGPS accuracy is 2·22 metres, with no errors above 5 metres. Due to the relatively long baseline between Delft and Sylt, the correction data experiences some spatial decorrelation. This results in a slight offset of the measured position compared to the surveyed position. If the DGPS performance is measured with respect to the mean position the 95% accuracy reduces to just 1·54 metres.

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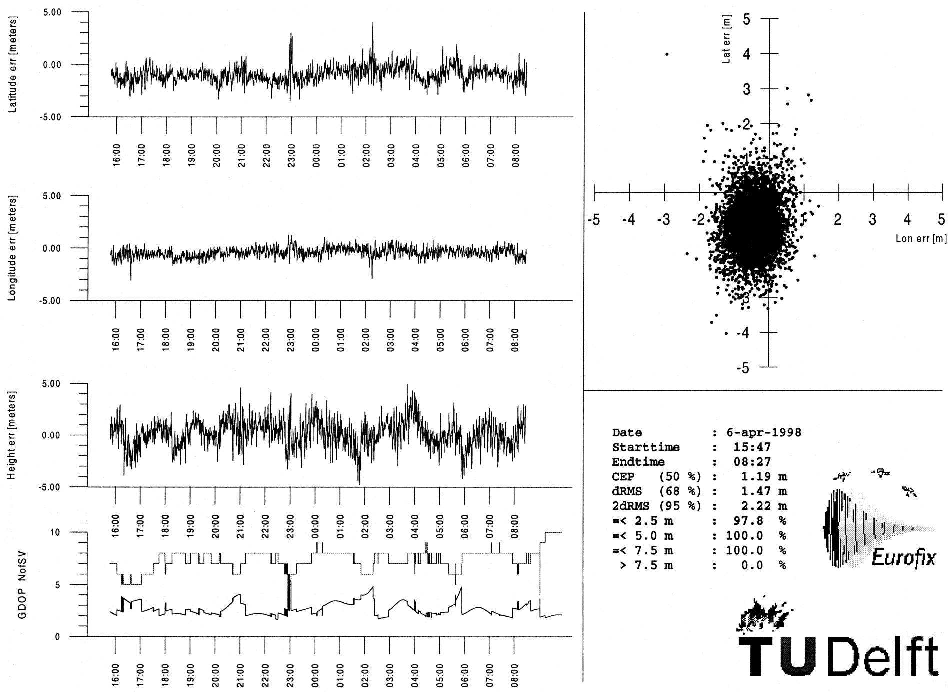

Figure 6. Static Test Results using a 30 GRI (28 bit per second) datalink, 6 April 1998.

It should be noted that the results presented here were generated with the single-station single-rate Eurofix experimental set-up at Sylt. During monitoring of the Eurofix transmissions, the experimental Loran-C/datalink receiver could easily receive and use five or six stations at two GRIs (dual rate). If all these stations were to broadcast DGPS corrections, the performance would be improved considerably by using the techniques described in Section 6. In any case, the results presented here correspond to earlier results of real-life simulations.[6,14]

An independent receiver test-site has been installed in Longborough, UK, at 740 km from Sylt. The initial results show a datalink performance comparable to the measurements in Delft. Within NELS, the coverage area of a single transmitter is estimated at about 1000 km. If corrections are used at these distances, the user might experience some spatial decorrelation of the transmitted corrections; the satellite signals penetrate a different section of the ionosphere and at different elevation angles for the user and reference station. In Section 6, a method to reduce the influence of spatial decorrelation will be outlined and test-results given.

5. DYNAMIC TEST RESULTS. The previous section illustrated the achieved DGPS performance of the Eurofix system in static conditions. Excellent static datalink availability at 400 km from Sylt was demonstrated. To evaluate the datalink performance dynamically, a number of mobile measurement-trials have been performed in various countries, including The Netherlands, France, Germany, the UK and the US. The purpose of the tests was to evaluate datalink behaviour in dynamic environments and at the extremes of estimated coverage ($\approx$ 1000 km). A prototype Eurofix receiver according to the concept shown in Figure 5 was mounted in a van of the Dutch Survey Department, Figure 7. Both an electric field and a

Figure 7. Measurement Van of the Dutch Survey Department.

Figure 8. Example of a Difficult Environment for Loran-C Reception.

magnetic field antenna were used during the trials. Tests were done on highways as well as on country roads. Some tests were also undertaken in an urban environment.

Generally speaking, the datalink behaviour in a dynamic environment is good. Messages were only occasionally lost while driving under highway crossings and power-lines, Figure 8, or in virtually radio-silent areas such as mountain canyons. The expected coverage range of 1000 km has been verified on two separate measurement trials. The actual Eurofix datalink coverage is a function of transmitter output power, ground conductivity, cross-rate conditions and atmospheric noise levels.

Initial tests with a magnetic field antenna performed in Germany verified the good reception of corrections and continuity of navigation using Loran-C when GPS fails in urban environments. More information on the mobile Eurofix tests and Loran-C performance in urban environments can be found in.[1,15,16]

6. MULTI-STATION DGPS RECEPTION. The static measurement results of Figure 6 showed a slight bias in position due to the phenomenon called Spatial Decorrelation. Figure 1 showed the European coverage (1000 km radius) if Eurofix is fully implemented. As can be seen, large parts of Europe are covered by two or

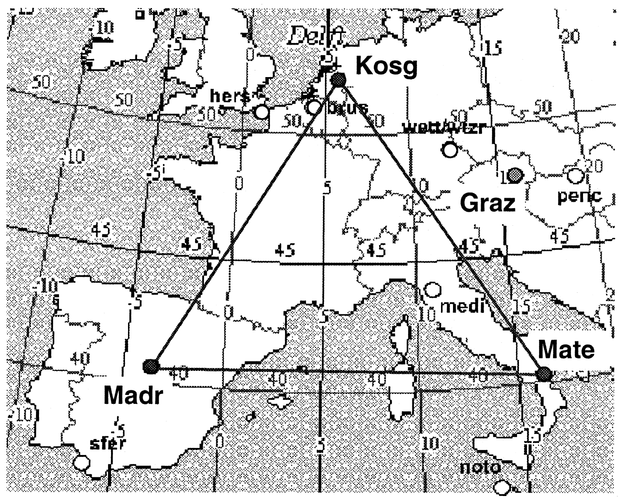

Figure 9. Location of IGS reference stations used in post-processing.

more stations. In these circumstances, the user can combine the corrections of multiple Loran-C stations to calculate a networked DGPS correction suitable for the user's current position. This Regional Area Augmentation System (RAAS) considerably improves both accuracy and integrity of the differential GPS position solution when compared to the single transmitter datalink. Temporal decorrelation effects will be reduced due to the increase in effective correction update rate, while spatial decorrelation errors can be reduced by applying a weighted average for each satellite correction.[17] Based on user-reference station separation and reference station geometry, a network correction can be calculated for all satellites common to the network and the user. Contrary to other networked DGPS services, the calculation of the combined correction is done by the Eurofix user. So, no additional communication infrastructure for centralised processing of the DGPS corrections is necessary. Theoretical research by Jin[18] has shown that regular RAAS-networks spanning a typical Eurofix region leave only very small spatial decorrelation errors (< 1 metre). The performance of the RAAS-network depends on the number of reference stations used in the network solution. With at least three stations, decorrelation in both latitude and longitude directions can be compensated. With two stations, the spatial error can be minimised on the baseline, with increasing degradation in the directions perpendicular to this baseline.

6.1. *Eurofix RAAS.* Assume that at n_r reference stations n_s satellites have been simultaneously observed and the pseudorange correction $\nabla^i_j (i = 1, \ldots, n_s; j = 1, \ldots, n_r)$ and its rate of change have been computed at each of these reference stations. Jin has shown that in an area occupied by the n_r reference stations, although a satellite correction will not be the same for all of the n_r reference stations, it can be approximated by a linear function of latitude ϕ and longitude λ. If one reference station is chosen arbitrarily as base station, the PRC for satellite i at reference station j can be related to the PRC of the base station b by:

$$\nabla^i_j = \nabla^i_b + a^i_\phi(\phi_j - \phi_b) + a^i_\lambda(\lambda_j - \lambda_b) \tag{1}$$

where a^i_ϕ and a^i_λ are gradients of satellite correction i in latitude and longitude direction, respectively. With corrections received from three stations, the two

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Table 2. Distances (km) between IGS Stations.

	Graz	Kosg	Madr	Mate
Graz	—	900	1746	720
Kosg	900	—	1515	1527
Madr	1746	1515	—	1502
Mate	720	1527	1502	—

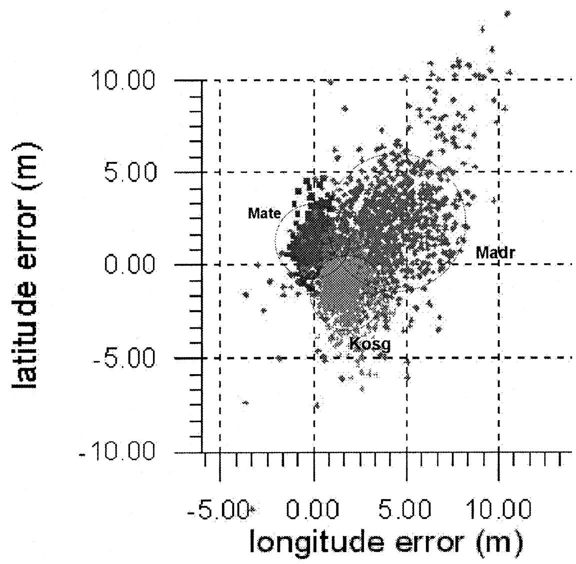

Figure 10. Local Area DGPS Performance.

unknown gradients can be calculated by the user. If even more than three reference stations can be received, the user can apply a least-squares algorithm to calculate the gradients. Having filled in an approximate position in Equation 1, the user calculates his accurate position based on the networked PRCs.

6.2. *Post-processing Results.* At Delft University, the RAAS concept was evaluated by post-processing using data from the International Geodetic System (IGS). Raw GPS measurements in RINEX format with a 30-second time interval from various stations throughout Europe were collected. Figure 9 shows the stations that were selected to reflect best the constellation of the NELS Loran-C stations; however, the distances between them were larger (1500 km). Stations *Kosg*, *Madr* and *Mate* were used as Eurofix reference stations, *Graz* as the Eurofix user. Table 2 lists the distances between them.

In post-processing, standard RTCM type-1 corrections were generated and applied to the user measurements. As data was only available with 30-second time intervals, the Eurofix RTCM type-9 transmission scheme could not be incorporated (no temporal decorrelation effects).

Figures 10 and 11 compare a single station differential service with the networked RAAS concept in a 24-hour run on 24 November 1996. The spatial decorrelation

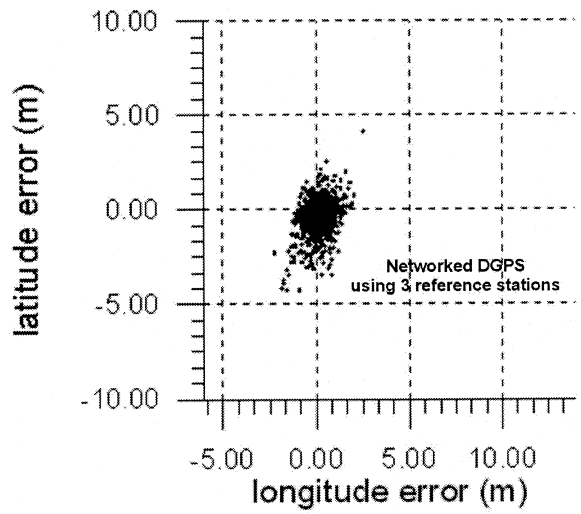

Figure 11. Eurofix Regional Area DGPS Performance.

effects can be clearly seen when a single station DGPS is applied. If networked DGPS is applied, these effects are minimised. Furthermore, the use of corrections from multiple reference stations reduces the measurement noise within the differential corrections.

7. CONCLUSIONS AND FURTHER WORK. This paper has outlined the possibility for Loran-C to augment GPS. By additional modulation of the Loran-C signals, differential corrections, and possibly other messages, can be broadcast to users at distances up to 1000 km. Using the Eurofix implementation at the Sylt Loran-C transmitter in Germany, test results from both static and dynamic operation were excellent and corresponded with earlier simulation results. Accuracies of better than 3 metres (95%) were easily obtained. The US-based trials showed the ease of installation and operation of Eurofix, and again verified its performance. Furthermore, if both rates in dual-rated stations are used for data transmission, the correction update rate will be increased, reducing temporal decorrelation effects. The static tests showed a slight bias in the measured position due to spatial decorrelation. These effects can be reduced by employing a Regional Area Augmentation concept to calculate networked differential corrections, which will better correspond to the range errors encountered at a user's location.

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KEY WORDS

1. Navaids. 2. Loran-C. 3. GNSS. 4. Datalink. 5. Augmentation.