GNSS based solutions for maritime “Safety of Life” Application with increased Accuracy Requirements

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Abstract

Future Global Navigation Satellite Systems (GNSS) like GALILEO or the modernised GPS will support “Safety of Life” (SoL) applications by the self-monitoring of the GNSS performance and by the provision of integrity information in dedicated services. The International Maritime Organisation (IMO A.915(22)) requires horizontal positioning accuracies better than 10 m in oceanic and coastal areas. If the positioning error induced by the used GNSS itself exceeds the tolerable positioning error of 25 m, the GNSS provider must detect this malfunction and inform the GNSS users within 10 s to fulfil the integrity requirement for “Safety of Life” applications. In critical traffic areas like sea channels and ports the desired position accuracy must be higher than 1 m. In case of GNSS based automatic docking manoeuvres the allowed positioning error must be lower than 0.1 m. Due to the fact that increased performance requirements are assigned to bounded areas the use of Ground Based Augmentation System (GBAS) is considered as a suitable technical solution to enable high-precision and reliable navigation in the port area. The project ALEGRO, funded by Mecklenburg-Vorpommern’s Ministry of Economics, Labour and Tourism and realised as one of the initial projects within the Research Port Rostock, is focussed on the development of a maritime GBAS. On the one hand corresponding research activities will be depicted by the description of the developed and deployed experimental GBAS in Rostock port and on the other hand preliminary results will be presented.

Introduction

A selection of IMO requirements regarding accuracy and integrity of GNSS based positioning in the maritime area is given in Table 1.

Considering the enhanced performance of renewed and future global satellite navigation systems (GNSS) it can be expected that accuracy and integrity requirements assigned to the ocean and coastal area are fulfilled using GNSS alone without additional assistance from augmentation systems or complementary used sensors. Though at this moment increased requirements in the oceanic and coastal area are actually unknown, a higher performance of GNSS based positioning could induce economies in the ship equipment sector e.g. by a reduction of the necessary number of board sensors as well as in the ship operation sector e.g. by an enhancement of the on-board navigation and manoeuvre functionalities based on improved positioning accuracies. Accuracies higher than 1 m or 1 dm are required in ports and as the fundament for the automation of special maritime operations like ship docking. Due to the spatial restriction of these increased requirements the use of Ground Based Augmentation Systems (GBAS) is considered as a suitable method of resolution. Therefore initial projects like SEA GATE (EADS RST) and ALEGRO (DLR) realised in the frame of the Research Port Rostock are focussed on the development of maritime GBAS considering complementary techniques.

Tab. 1: Required accuracy and integrity of GNSS based positioning (IMO A.915(22))

	System Level Parameters				**Service Level Parameters**		
	Accuracy	Integrity			Availability	Continuity	Coverage
	Horizontal (m)	Alarm Limit (m)	Time to Alarm (s)	Integrity Risk (per 3 hours)	% per 30 days	% over 3 hours	
Ocean / Coastal	10	25	10	10^{-5}	99.8	N/A	Global
Port	1	2.5	10	10^{-5}	99.8	99.97	Local
Automatic Docking	0.1	0.25	10	10^{-5}	99.8	99.97	Local

ALEGRO’s GBAS is designed to support the use of the Real Time Kinematic Technique (RTK) for precise positioning by the provision of augmentation data in the RTCM format. The additional use of future GALILEO signals, the exploitation of multi-carrier based navigation algorithms as well as the handling of integrity aspects are strategic development lines in the research area of GBAS to improve the accuracy and reliability of GNSS based and GBAS assisted positioning. Similar to the aviation sector, where the development progress is specified by the planned changeover from CAT I to CAT III landing systems in the next decades, a similar development process will take place in the maritime sector.

Within the project ALEGRO an experimental GBAS ground segment is developed and deployed, which enables the testing of innovative algorithms and techniques in the navigation area and supports the use and validation of GNSS techniques within maritime application systems. In the first chapter supported operation modes of the GBAS are described based on the shown architecture and its essentially components.

A core element of the GBAS ground segment is the GNSS Performance Assessment Facility (GPAF). This subsystem is responsible for the data based evaluation of the GNSS signal quality, for the detection of signal disturbances and for the determination of the current GNSS based positioning performance in the entrance and area of Rostock Port. For this purpose, the GPAF is composed of real time processor chains determining quantities, which describe the characteristics of single data types (e.g. phase and code noise, multipath errors) and satellite links (e.g. ionospheric propagation effects, residual user estimated range error, occurrence of scintillations) as well as the accuracy and reliability of the GNSS based positioning. At shown monitoring examples the processing strategy inside the GBAS ground segment will be explained in the following chapter.

From user's view GBAS is a service component, which can be used to improve the positioning accuracy and to support the integrity monitoring at user site. Besides used technical components, which are characterised by the GNSS itself, the GBAS ground segment, the used on-board equipment as well as the implemented algorithm, the complete communication chain and the expanded spectrum of application specific environmental conditions and disturbances should be additional included in the analysis of the GBAS performance. Though ALEGRO's development was primary aligned on the GBAS ground segment, measuring results gathered aboard a vessel and in the port area will be shown to illustrate the demand for continuative developments and to pre-characterise their content in the final chapter.

Architecture

In the GNSS market a lot of commercialised system solutions are available using differential navigation techniques to improve the accuracy of GPS and also GLONASS based positioning. Such standard solutions consist of a reference station at a known position, a rover receiver and radio connections (e.g. modems) at both sites to ensure the transmission of augmentation data from the reference station to the rover. At the rover site its position is derived from the determined distance vector between the reference and rover receiver using the navigation data of both receivers and additional information from the reference station.

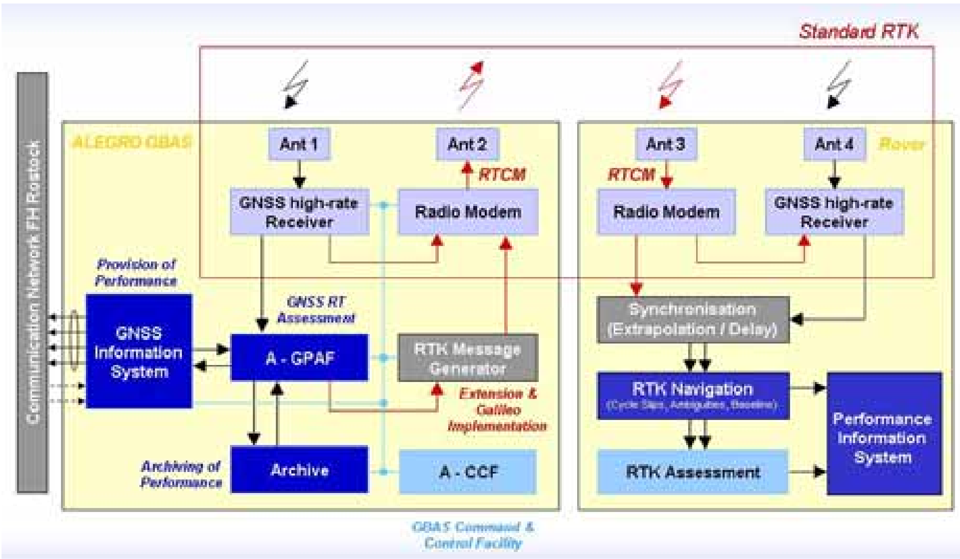


Fig. 1: Architecture of ALEGRO's GBAS

Basic module of ALEGRO's GBAS ground segment (figure 1) is a high-rate GNSS receiver operating with a raw data update rate of 20 Hz. An increased update rate of raw data is necessary to enable the short term modelling and monitoring of code and phase measurements. This is one method of resolution in the developed ground segment in order to differ between the nominal behaviour of GNSS data and anomalies induced by signal disturbances and will be explained more detailed in the following chapter. At this time the receiver provides code and carrier phase measurements with a high time resolution (20 Hz) as well as additional data like signal amplitudes and signal to noise ratios of each received GPS signal in the lower and upper L-band. After the conversion of all data into the GBAS internal data format, their ongoing processing is realised in the ALEGRO GNSS Performance Assessment Facility (A-GPAF).

In addition to the first receiver a second receiver is installed, which is equipped with an extended firmware version to generate standard RTCM3 messages especially for validation and comparison purposes. Though both tasks could be realised with a single receiver, the parallel use of two receivers at the same antenna is preferred to reduce the demand on receiver's processor capacity and to increase therefore the robustness (availability and continuity) of data provision. Furthermore both receivers are prepared to receive GALILEO signals in the future by a simple firmware update.

Inside the hierarchical deployed data assessment system, whose structure and functionalities are explained in the next chapter, the incoming high-rate data from the first receiver are checked on plausibility and completeness. Additionally link, satellite and station related performance quantities are determined based on implemented error detection and separation techniques. These quantities are derived always in real time. They are used on the one hand to describe the performance of the used satellite navigation systems (GNSS information system) and on the other hand to create the database, that enables a situation related and enhanced provision of correction and augmentation data (RTK message generator). On which way this can be realised, is an objective of current investigations and deals with such aspects like the selection of suitable data and their refinement and compression.

The technical implementation of the GBAS ground system is realised by reusing the EVnet technology (Experimentation and Verification network) developed in a previous project by DLR together with the German company Jena-Optronik GmbH. It offers the opportunity, that the handling of the complete HW and SW data management will be supported via TCP/IP based streaming technologies. Included functionalities are e.g.

- the data transmission from distributed sensors like GNSS receivers and weather stations to the central processing and control facility as well as their synchronisation
- the settings of the sensor stations and all sensors in remote control
- the combined processing of different data streams regarding project specific processing chains.

ALEGRO's GNSS Performance Assessment Facility (A-GPAF)

After the decoding of the incoming 20 Hz data stream into EVnet internal data formats of navigation and raw data, in the first processing sector the real time data are checked on completeness and partial on plausibility. If the receiver provides no data of a visible satellite, the GNSS signal is either shadowed or seriously disturbed. If the provided data of a visible satellite are fragmentary, the signal tracking is in the acquisition mode (satellite set) or in a reacquisition mode due to previous occurred signal disturbances. A temporally limited data base (e.g. no measurements at L2 of a single satellite) reduces the potential of applicable assessment algorithm to this satellite and commonly its usability (e.g. for dual pre-processing) during stand alone as well as GBAS supported positioning at the rover site. A plausibility check requires the knowledge of allowed value ranges of single data types, whereby their variation during a satellite pass must be taken into account or alternatively only a common valid a-priori value range can be applied. Therefore it was decided that the plausibility check of navigation data is realised on GNSS specific and station related a-priori value ranges. In the case of raw data the plausibility check will be considered as a standing task during the following pre-processing and data product generation.

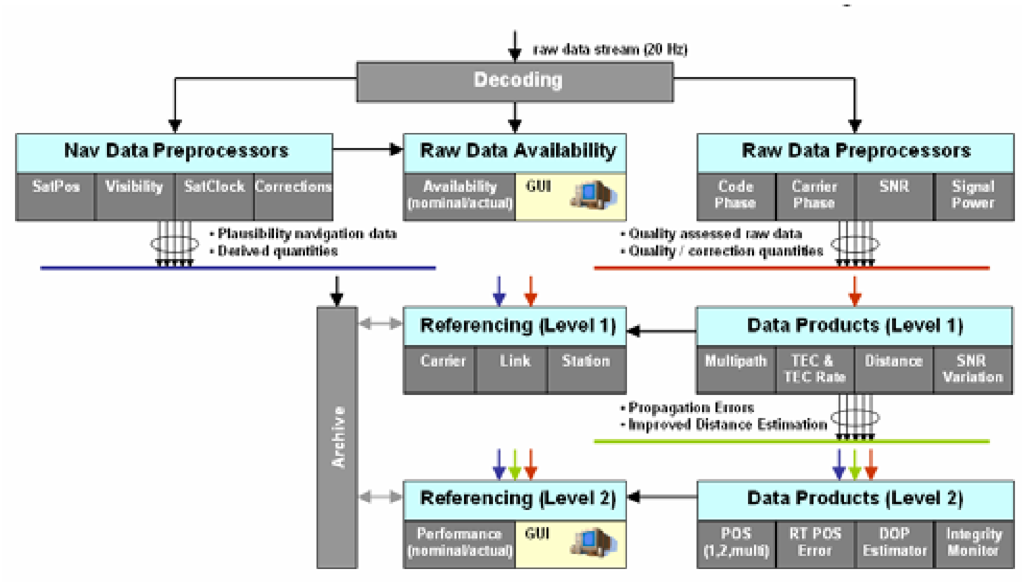


Fig. 2: Processing flow inside A-GPAF

Pre-processing of each measurement like code and carrier phases, signal amplitudes or signal to noise ratios is realised separately for each data type and therefore independently from other data types. Due to the high time resolution of the provided measurements (20 Hz) it is possible within a few seconds to model the dynamic of each measurement and to derive data specific quality parameters. Such parameters are the noise of code and carrier phases, the occurrence of cycle slips at carrier phases, and the variation of the signal power and the signal to noise ratio. An occurred temporal discontinuity of the quality parameters (except detected cycle slips) is an indicator for a disturbed signal. Additional value ranges (e.g. mean and standard deviation of code and carrier phase noise), which depend on elevation or alternatively on other data types, are used to differ between tolerable and critical signal disturbances. Such situation related value ranges are provided by the processing system itself from daily generated statistics of the pre-processing results. In figure 3 the standard deviation of the phase noise is shown dependent on the signal to noise ratio. Due to the fact, that the transmitting power of GPS satellites depends on the assigned satellite generation and can decrease during the life span of a satellite by up to 6 dB, it was decided to describe the value ranges of code and carrier phases in dependence on the signal to noise ratio. As shown in figure 3 this approach ensures an improved description of value ranges. But it should be mentioned that such edged performance quantities are only valid for a specific reference station (location, equipment, environment) and depend additionally on the used configuration of the assigned processor (sampling rate, validity area of short term models).

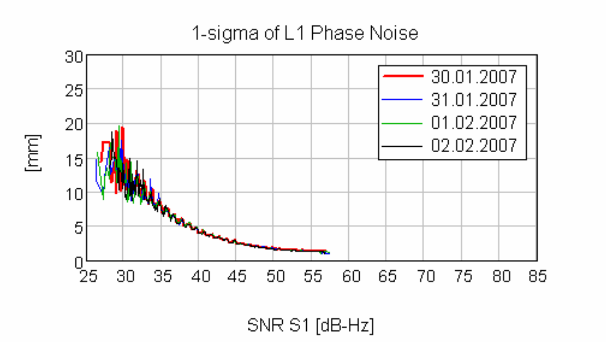


Fig. 3: Standard deviation of L1 phase noise in dependence on the signal to noise ratio

Level 1 data products (see figure 2) are generated by different linear combinations of pre-processed raw data types and are focussed on the provision of correction terms of satellite specific distance measurements. Inside this sector different methods of resolution are considered, which are determined mainly by the available number of signals per satellite at different carriers.

In case of single carrier processing only a multipath reduction can be applied using a Hatch filter. Ionospheric and tropospheric corrections are derived prevalently from standard correction models. Current activities in the aviation sector are focussed on the development of ionospheric correction models, which are conditioned by single frequency measurements at the reference site and which make it possible, that high spatial gradients decreasing the performance of differential positioning techniques can be identified. The easy implementation of such enhanced solutions into the GBAS is prepared by its modular architecture enabling processor extension and substitution.

Operating with dual frequency measurements a larger spectrum of algorithms can be used for example to mitigate multipath and ionospheric propagation errors (e.g. divergence and ionosphere free smoothing techniques) or to calibrate the low-noise phase measurements by ambiguity resolution (e.g. by filtering techniques or MLSE algorithm). Such techniques are mainly focussed on the provision of improved distance measurements to increase the accuracy of positioning. The monitored magnitude and short term variance of multipath, the variation of the signal to noise ratio as well as the link related ionospheric rate are additional indicators to support the estimation of the positioning performance (e.g. description of residual errors for measuring models) and to forecast their temporal development (e.g. risk of tracking loss). The combined consideration of different quality parameters furthermore enables the identification of signal disturbances' sources.

The example of figure 4 illustrates, that a moderate multipath propagation effect detected at the C/A range corresponds with a temporary decrease of the signal to noise ratio and increases slightly the phase noise estimations at L1 and L2.

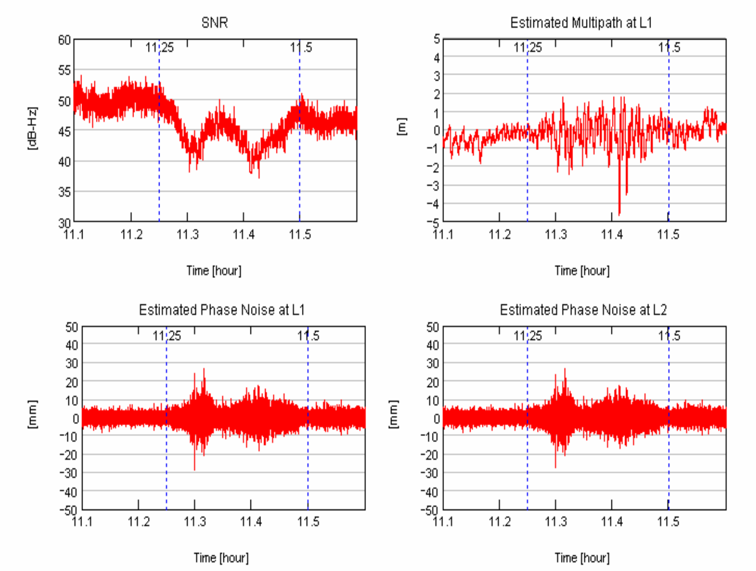


Fig. 4: Increased noise at both carrier phase measurements and at signal to noise ratio induced by multipath propagation

In figure 5 a further example is shown. Ab initio an increased multipath can be observed at the C/A range, whereby several minutes after 22:00 UT the multipath's magnitude reaches values above 90 metres before the data provision of the receiver will be broken. During this time the rate of the ionospheric path error is slightly increased, but this effect results from the increased phase noise itself.

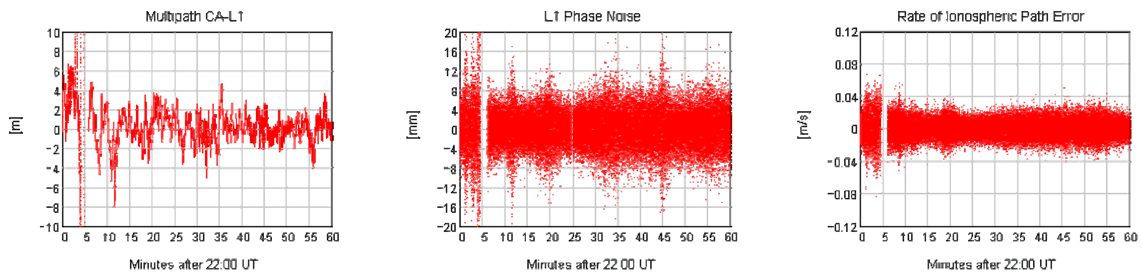


Fig. 5: Multipath, L1 phase noise and rate of ionospheric path error around a point, where the data provision of the receiver is broken

The data provision of the receiver can be also broken, if the rate of ionospheric path errors exceeds its specific sensitivity threshold regarding tolerable signal dynamics. The receiver type implemented in the GBAS ground segment was already used for measurements at the site of Tromsø. During the Halloween storm in 2003 it was verified by measurements, that the rate must be higher than 0.5 TECU/s before the receiver breaks the data provision.

In the last processing sector (data products level 2) the final assessment of the GNSS and GBAS performance is done based on the combined but controlled use of all satellite signals for positioning.

Algorithms dealing with stand alone positioning techniques (single and dual carrier processing, weighted least square algorithm) are applied on the one hand to validate the efficiency of done corrections, derived weighting factors or met decisions respectively the further use of specific satellite signals. On the other hand the results are used to describe the stand alone positioning performance around the reference station without any assistance but under consideration of the variety of techniques. Additional classical integrity algorithms based on the DIA-technique are applied (Detection, Identification, Adaptation – DIA) to approve the done corrections or to detect so far unidentified error sources. Additional error sources should mainly result from the navigation data (e.g. satellite clock correction, satellite orbit) or their erroneous decoding. Due to their identical mapping on all satellite related data they cannot be found during raw data pre-processing or satellite signal specific data assessment.

The effectivity of the applied DIA-algorithm can be seen comparing the positioning results shown in figure 6 and 7.

In figure 6 all satellites are used for MLSE based positioning, for which the receiver has provided code and carrier phase measurements. From 2:00 to 3:30 UT more than 7 GPS satellites can be used for positioning and the HDOP values vary around 1.0. The grey curve shows the horizontal position error gathered only with L1 measurements, which are corrected applying models (e.g. Klobuchar model for ionosphere) with respect to ionospheric and tropospheric propagation errors. Due to the additional multipath mitigation by Hatch filtering of the L1 code and carrier phases, the blue curve is more smoothed but in the same order of magnitude like the grey curve. The best positioning accuracy is reached, if the code and carrier phases at both carriers are used, which allows besides the mitigation of multipath effects a self-correction of the ionospheric path error. It should be mentioned that between 2.00 and 3:30 UT the geometric constellation as well as the quality of all usable satellites represent optimal conditions for GPS based stand alone positioning. After 3:30 UT the number of usable satellites varies between 6 and 8, whereby around 3:39 it reaches its minimum with 6 satellites. Assigned to this time point the HDOP is higher than 2.0 and the horizontal positioning error increases up to 10 m in cases of single carrier processing (with and without mitigation of multipath effects). The accuracy of dual carrier positioning is after 3:39 UT sometimes better and sometimes worse in comparison to the results of single carrier positioning. This effect results from the number of usable satellites, their influence on the HDOP and their specific error budget. In the case of dual carrier processing a satellite is usable, if raw data at both carriers are provided by the receiver. A worse signal quality induces the effect, that a civil dual receiver breaks at first the provision of L2 data. This can increase or decrease the accuracy of positioning. After 3:45 UT the accuracy of the dual processing lies between the results of single carrier processing with and without multipath mitigation though the number of used satellites and the HDOP is equivalent for all examples. This effect can be explained be the doubling of the noise and multipath budget, whose influence is increased, if satellites under low elevations are used and their influence due to the reduced number of usable satellites is increased.

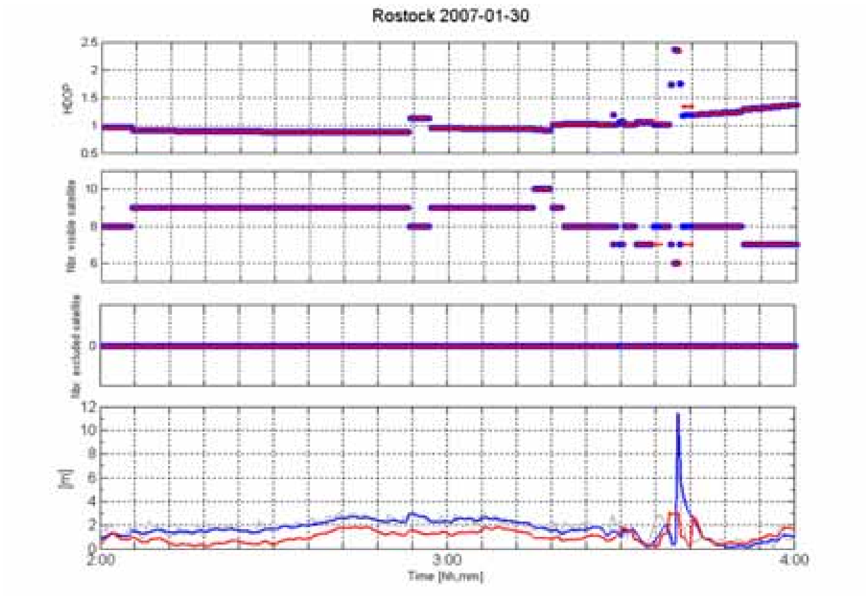


Fig. 6: Accuracy of GPS stand alone horizontal positioning using the MLSE technique (single carrier processing with (blue) and without (grey) multipath mitigation and dual processing (red) with multipath mitigation), assigned HDOP values and number of satellites

Figure 7 illustrates the results gathered with the same data base using the DIA technique.

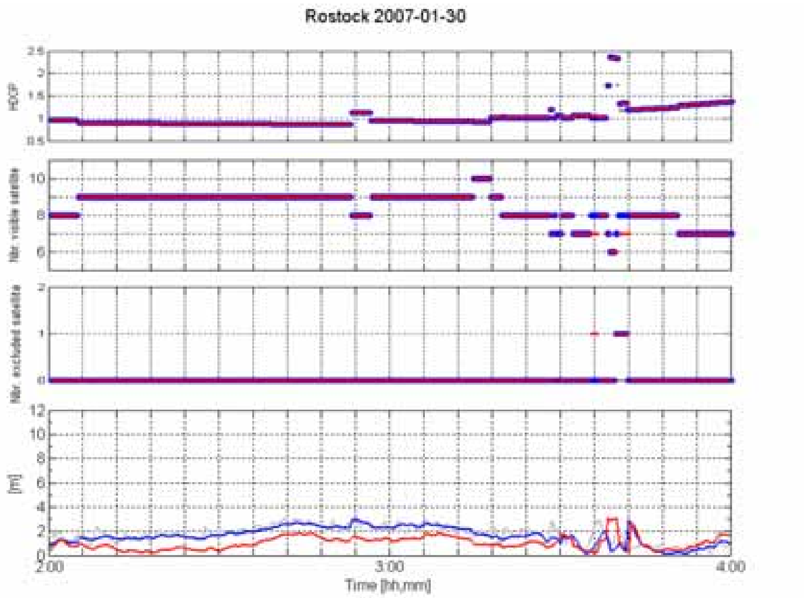


Fig. 7: Accuracy of GPS stand alone horizontal positioning using the DIA technique (single carrier processing with (blue) and without (grey) multipath mitigation and dual processing (red) with multipath mitigation), assigned HDOP values and number of satellites

Between 3:36 and 3:48 UT sometimes a satellite will be excluded from positioning by the DIA technique. This ensures that the horizontal positioning error is always below 3 meter. Though such results demonstrate the effectivity of the DIA technique continuing investigations and developments are necessary to increase the robustness of the algorithm. This can be realized for instance by improved measuring models and in respect of the complete GPAF processing system by an optimised assignment of task between the different processing sectors.

GBAS System Monitoring

In the frame of the ALEGRO project the monitoring of the GBAS ground segment is supported by different Graphical User (Operator) Interfaces, which visualise the main information about the operational status of the GBAS ground segment itself and illustrate the GNSS performance based on selected quality parameters. The upper window on the right site in figure 8 shows the status of a set of real time data streams, which are provided by the sensors of ALEGRO’s GBAS ground segment to the CPCF and can be distributed by the CPCF directly. In the lower window on the right site additional information are given for the high rate GNSS receiver, which can be used additionally to set up the receiver remotely. In the browser tree on the left site the station and the dedicated sensors are displayed below the path “sensor station msro01”.

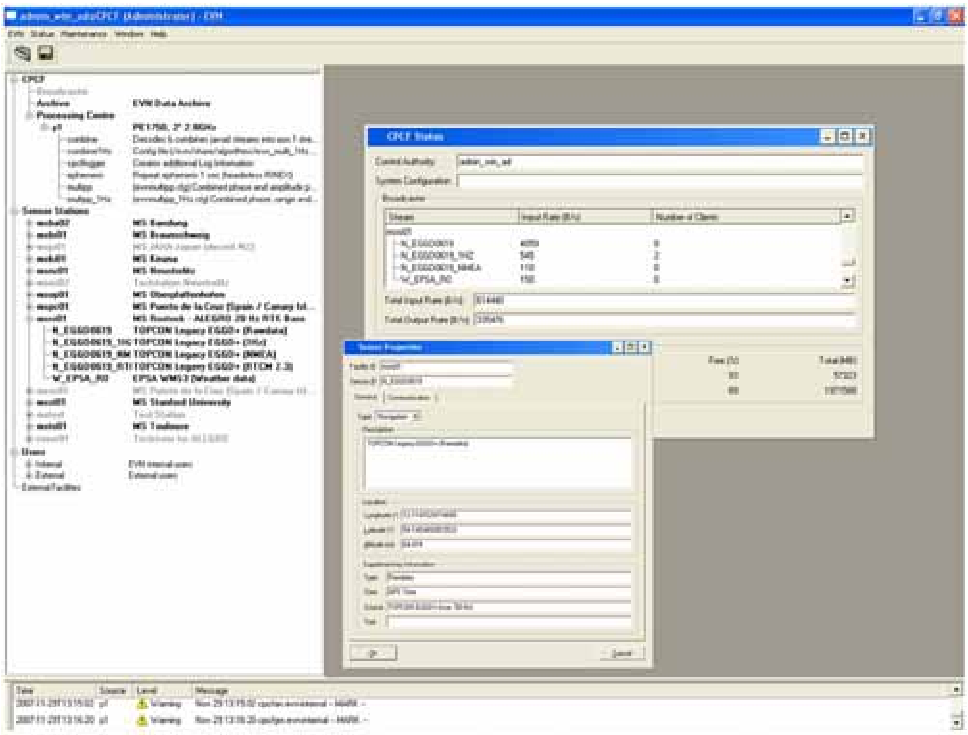


Fig. 8: Graphical operator interface to monitor and control the ALEGRO GBAS monitoring and processing system by EVnet

In another graphical window (figure 9) a polar plot is used to inform the operator about all satellites in view related to the location of the reference station. The assigned colour of a single satellite describes more sophisticated the available data types:

- the green colour signs a GPS satellite, whose data are complete provided by the receiver
- the yellow colour points on a uncompleted provision of the expected data
- the grey colour signs satellites, which are excluded from the assessment by the used elevation mask (< 5° in this case)

and

- the red colour is used, if no data are provided by the receiver though the satellite is signed as visible.

By clicking on a specific satellite (e.g. PRN 24) a new information window (figure 10), which shows the availability of single raw data types and corresponding quality parameters in a combined mode, will open.

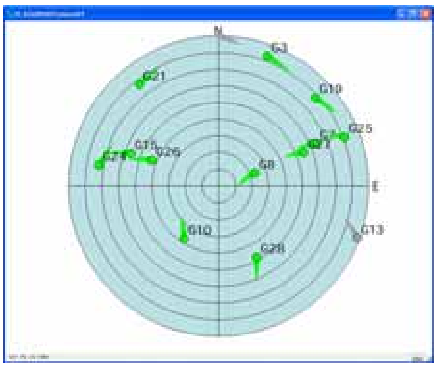


Fig. 9: Visible satellites and their utilisation potential derived from the availability of single raw data types

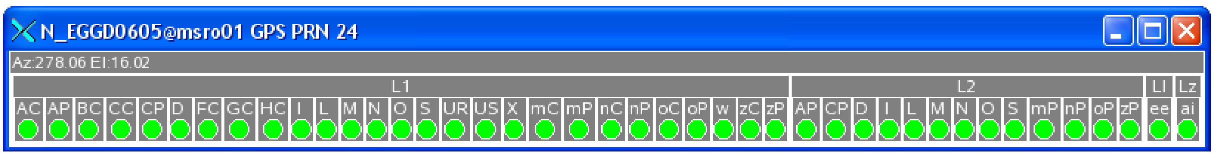


Fig. 10: Availability of received raw data and from these derived quality

Though the used code designation of each data type can be considered as cryptically, it corresponds with the EVnet internal nomenclature of all handled data types. For example, “AC” stands for the amplitude at the in-phase component of the L1 signal (carrier of C/A code) and corresponds therefore with a measurement provided by one of the used receivers. It can be seen, that this measurement type is only available in the case of GPS L1 signals. The identification code “mC” stands for a quality assessed L1 carrier phase measurement. That means that additional quality parameters like the estimated phase noise or a flag signing the occurrence of cycle slips are available.

In figure 11 and 12 two further examples are shown, which are representative for the visualisation of the performance of single data types. In figure 11 the phase noise estimated in real time (black line) is compared with the value range (blue bar), which is derived from the short term data history and is described by the 3.4 times of the expected standard deviation of phase noise. If the black line would leave the blue value range, it indicates either a disturbance at the L1 carrier phase measurement or a bad configuration of the used phase pre-processor.

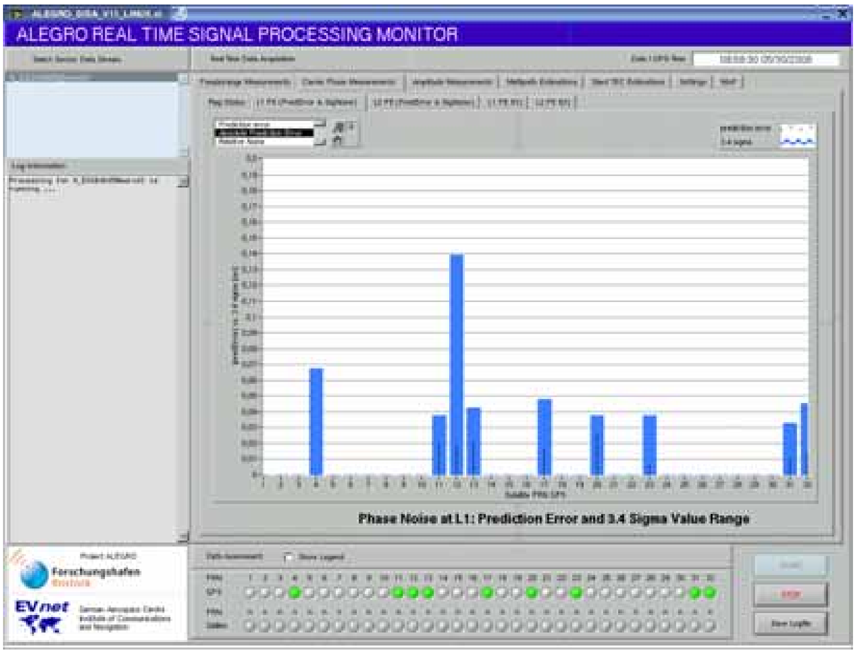


Fig. 11: Monitoring of the L1 phase noise

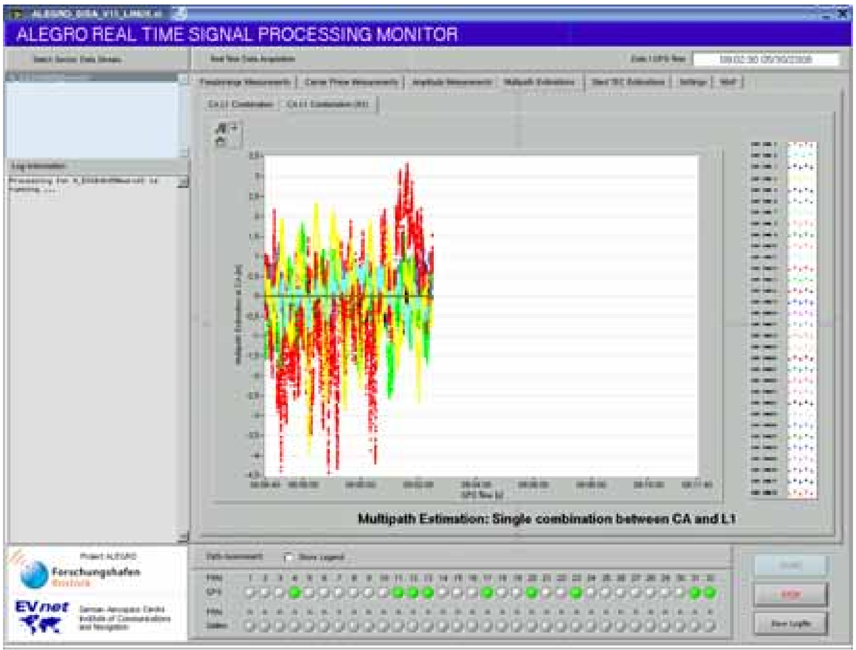


Fig. 12: Estimated multipath error at the C/A code based range measurements

In figure 12 the estimated magnitude of multipath induced propagation errors is given for C/A code based range measurements. Looking at the results of PRN 12 in both figures (see red colour plots in figure 12), the increase of phase noise and multipath error during a satellite fall can be seen.

As already explained in the previous chapter, the reached positioning accuracy depends on the number of usable satellites and their momentary signal quality. In this context it is important to consider additionally the geometry of the usable satellites and its influence on the positioning accuracy. In figure 13 the value ranges of HDOP are estimated in real time dependent on the number of usable satellites for positioning. Considering only the geometry, it could be expected, that an optimal selection of 4 satellites could result into the same performance using all visible satellites. In the worst case, where also only 4 satellites with a poor geometry can be used for positioning, a dramatic increase of the horizontal positioning error must be expected.

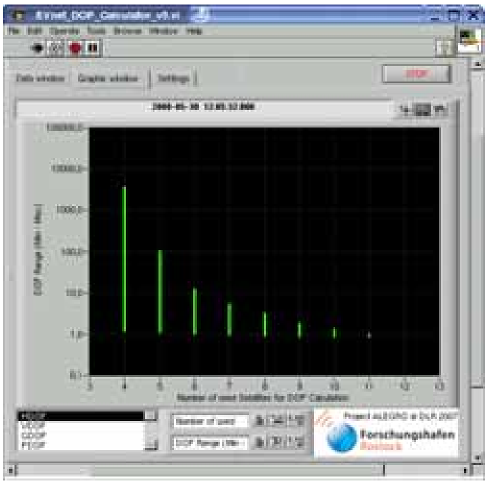


Fig. 13: Value ranges of HDOP dependent on the number of usable satellites

With ALEGRO's GPAF and the implemented monitoring functionalities the fundament for continuative investigations and developments is established. On the one hand an appropriate mapping of GNSS internal quality parameters onto the fulfilment of user requirements is desirable especially to prepare a stepwise automation of the monitoring service. On the other hand the gathered experiences must be expended on RTK techniques and their intrinsic algorithm variety.

Experimentation Results

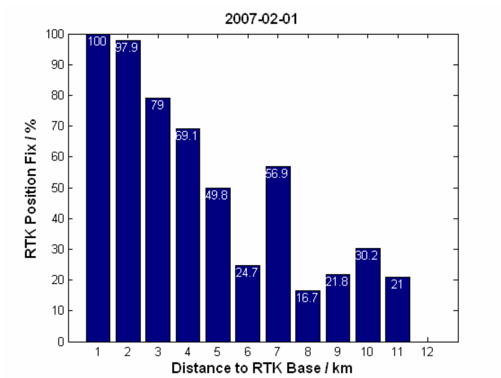
Positioning accuracies in the sub-meter level can be reached nowadays with operational GNSS systems and using RTK techniques. Important conditions to obtain such results are

- a short distance between reference station and rover
- an operation free of any malfunctions of all HW and SW components

- an undisturbed communication channel ensuring the complete and near real time reception of the augmentation data at the rover site

- and an environment free of shadowing and multipath at the rover's site.

With respect to maritime applications different measuring activities were realised to estimate the capability of RTK based positioning in the area of Rostock port. During a four day measuring campaign the rover was operated aboard the research vessel ship "Prof. A. Penck" crossing in the seaport and on the river Warnow as well as sometimes on the Baltic Sea near the port entrance. The proportion of RTK based positioning solutions in relation to the total number of measuring times is given in figure 14 for the 1st February 2007. It illustrates that only in the close-up range of the reference station an improved availability of RTK based positioning (>97%) was reached. This was induced on the one hand by the radio range of the used transmission system (Baltic Sea, Warnow) and on the other hand by shadowing of the augmentation signals induced by vessels and port buildings (oversea port and port entrance). To put this result into perspective it should be mentioned that during this measuring campaign the transmission antenna of the reference system was located at Pier 1 at the roof of a measuring vehicle. Therefore each ferry docking and vessel movement were realised in the



direct neighbourhood of the reference station.

Fig. 14: Availability (%) of RTK based positions solutions with fixed ambiguities

In the case of an RTK based solutions with fixed ambiguities the positioning accuracy was higher than several dm, if the allowed age of augmentation data was in the range of 1 up to 30 seconds. The use of near real time augmentation data (age <= 1s) resulted in accuracies higher than 1 dm. In the other cases the rover system has provided mainly stand-alone solutions with an accuracy of several meters.

After the deployment of the reference station at its final position the availability of RTK based positioning was again analysed in the area of the oversea port.

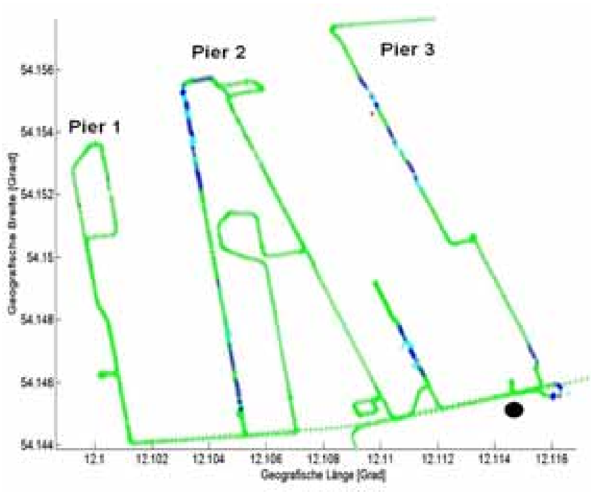


Fig. 15: Availability of RTK based positions solutions with fixed ambiguities in relation to the measuring point (red – no solution, green – RTK fixed, light blue – RTK float, dark blue – stand alone, black point – location of reference station)

For this purpose DLR's measuring vehicle equipped with the rover station was driven along the transport roadways of the port. From the displayed results in figure 15 it can be derived, that the availability of RTK based positioning solutions is increased but depends strongly from the specific operation area of the rover. Therefore the 3 cranes seen in figure 16 are responsible for the broken provision of RTK fixed positioning at the top of pier 2. Similar effects are observed at other locations induced by for instance buildings like production halls and silos.

Fig. 16: Cranes at the top of pier 2

Summary

With the project ALEGRO the German Aerospace Centre (DLR) has started its research activities in the development of GBAS for maritime applications. The deployed experimentation system is a suitable basis for ongoing research activities dealing with the enhancement of algorithms and techniques in the GBAS ground segment sector (e.g. by the use of GALILEO and Pseudolite signals). The provision of corresponding intelligent rover systems enabling a GNSS based and GBAS assisted positioning and fulfilling integrity requirements is seen as a complementary task in the GBAS sector.

Acknowledgements

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