Integrity concepts for future maritime Ground Based Augmentation Systems

Thoralf Noack, Evelin Engler, Anja Klisch, Stefan Gewies, David Minkwitz

Deutsches Zentrum für Luft- und Raumfahrt e.V., Institut für Kommunikation und Navigation
German Aerospace Centre, Institute of Communications and Navigation
Email: Thoralf.Noack@dlr.de

ABSTRACT

Global Navigation Satellite Systems (GNSS) require augmentation to achieve integrity and accuracy performance for high-precise safety of life applications. The current standard maritime GNSS augmentation system is a differential GPS (DGPS) beacon system, which provides correction data and integrity information according to the IALA-standard [IALA-R-121]. They are broadcasted in the 300 kHz radio-navigation band in accordance with ITU-R Recommendations [DIN EN 61108-4]. Even if such systems, also called Ground Based Augmentation Systems (GBAS), increase the accuracy and integrity of GNSS substantially, the performance reached by these systems is not sufficient to meet all International Maritime Organization (IMO) requirements, especially those for critical traffic areas like ports and for e.g. automatic docking manoeuvres [IMO A.915(22)].

In order to support the applicability of satellite navigation in such areas, the German Aerospace Centre (DLR) has started to develop a maritime GBAS that meets all IMO requirements. While the current IALA (International Association of Marine Aids to Navigation and Lighthouse Authorities) GBAS is a Code-based Differential GNSS (C-DGNSS), what means it broadcasts information concerning code corrections, our developments aim for multi-frequency Phase-based Differential GNSS (P-DGNSS). For this purpose DLR has installed an experimental maritime GBAS in the port of Rostock (Germany) enabling algorithm development in the ground and user subsystem as well as their validation.

The ground subsystem consists of two independent stations. The first station is operating as reference station and the second one as integrity monitoring station. This is similar to the hardware architectural design of the current IALA Beacon DGNSS architecture [IALA-R-121], whereby the GBAS uses high-rate receivers to enable a fast signal assessment in real time. Moreover, the proposed software architecture consists of real time processor chains that enable a hierarchical assessment from single data types via satellite signals up to the used GNSS with respect to the supported P-DGNSS service. Each of the implemented processors provides quality parameters like code and phase noise, Signal to Noise Ratio (SNR), Horizontal Positioning Error (HPE). These are considered as suitable input data for the GBAS integrity monitoring and the conditional provision of augmentation data and integrity flags.

Thus Performance Key Identifiers (PKI) must be specified for each quality parameter which allows distinguishing between the nominal and the disturbed behaviour of GNSS and GBAS according to different positioning performances. The GBAS is complemented by a statistical analysis, which is deriving statistical performance parameters with respect to real time quality parameter collected during the previous 24 hours. The statistical performance parameters are used in the first instance to gradually improve the measuring models by an auto-adaptive system and to specify PKIs described by valid value ranges and thresholds. Then they are employed to detect outliers in real time and to estimate protection levels.

The proposed quality parameters and related PKIs have been derived from 20 Hz GPS raw data of four GBAS stations in Germany (Research Port Rostock, DLR in Neustrelitz, Braunschweig) and France (Toulouse). Based on examples it will be shown that the nominal signal behaviour at the reference station can be employed to detect signal disturbances during GBAS operation in real time. In addition to the investigation of the single performance key identifiers, special attention is paid to the description of dependencies between the various performance key identifiers.

KEY WORDS

1. GNSS 2. Maritime GBAS 3. Integrity 4. Differential GNSS 5. Port Navigation

1. INTRODUCTION

The development of differential positioning methods was accelerated by the civilian community of Global Positioning System (GPS) users at the beginning of the 1990s in order to effectively reduce accuracy problems with single-frequency GPS positioning. At established measuring stations, errors with high spatial correlations such as ionospheric and tropospheric propagation delays, orbit inaccuracies, artificial quality reduction of the orbit and system-time information by the system operator, are identified and passed on to the users in the vicinity of the reference station as correction values. At the same time, IALA DGNSS networks were set up for maritime applications in order to reliably ensure accuracy to within 10 m in coastal areas, in compliance with the IMO [IMO MSC.114(73)] requirements for GPS-based positioning systems.

Meanwhile, the performance requirements set by the IMO for GNSS-based localisation are risen [IMO A.915(22)]. To ensure accuracy in the decimetre range while simultaneously monitoring integrity in port areas, augmentation systems are still required, though with modernised techniques. According to initial studies by IALA, augmentation systems that meet the IMO requirements have to use pseudolites or phase-based differential methods [IALA-R-135].

Localization and navigation in the shipping industry and other transport sectors are safety-critical applications of satellite-based navigation systems. It is therefore necessary to provide a reliable self-assessment of the positioning accuracy that can currently be achieved, taking into account all the technical and environmental factors. GALILEO is the first GNSS that systematically implements this integrity function, and consequently it also must be systematically developed and implemented for GBAS. To fulfil the safety requirements, users of GNSS/GBAS-based localisation systems must be informed within a few seconds in the event of system errors and signal interference that result in the loss of accuracy greater than the permitted positioning error. The challenge is to develop integrated system solutions that allow high-precision localisation coupled with integrity monitoring under all conditions.

2. BACKGROUND

The scope of this paper is the development of a preliminary integrity concept for a high-precision maritime phase-based GBAS and its validation in the test area. In the frame of the national funded project ALEGRO ([ALEGRO], [ALEGRO-FR]), hardware and software for a phase-based GBAS experimental system have been developed and deployed in the Research Port Rostock. The experimental system was realized on the basis of EVnet technology, a universal platform for data acquisition, processing, and data product distribution [EVnet]. A key element in the GBAS processing system is the "GNSS Performance Assessment Facility" that derives signal-specific quality parameters from the incoming data streams of a receiver to provide a first real-time performance monitoring of the used GNSS. Provision of augmentation data from the reference station to the users is decided on the basis of the usability of satellite specific measurements for DGNSS, which is inferred from the relationship between quality parameters values measured in real time, station-specific PKI, and positioning with the DIA (Detection, Identification and Adaptation) process at the established location. The GBAS will be completed in the project ASMS by an integrity monitoring station (IMS) validating in real time the provided augmentation [ASMS]. For this purpose the integrity monitoring station operates as an artificial user. The IMS determines its position using the data provided by the reference station and applying differential positioning techniques. This widely follows the integrity concept applied in IALA DGNSS Beacon Systems ([IALA-R-121], [Hoppe-2006]). But due to the open maritime standardization process of phase-based GBAS, the selection of suitable performance key identifier for reference station and integrity monitoring station is still an open topic of research. It will be discussed and investigated in this paper.

3. FUTURE CONCEPTS OF MARITIME GBAS

The term integrity stands for reliability of provided information or parameter on the one hand. On the other hand integrity can be understood as the transition from one safe state into the next safe state. For this purpose all electronic means inside navigation systems and services shall be used to ensure the required monitoring and controlling processes.

Basic Concept

P-DGNSS techniques are based on the common use of GNSS observations on reference station and user side. Thus the GBAS provides its own measurements in the RTCM3 format via a communication channel to the user [RTCM3]. Therefore a minimum of integrity self-monitoring on Reference Station (RS) side must exist, which validates the measured GNSS observations and assesses their usability for P-DGNSS positioning in real time. An assessment of P-DGNSS positioning performance can be only achieved, if the GBAS is extended by an IMS. Hence the provided GNSS observations of RS are combined with the observations gathered by the IMS to enable a P-DGNSS based positioning on IMS side. This concept results in the generic system architecture shown in Figure 1.

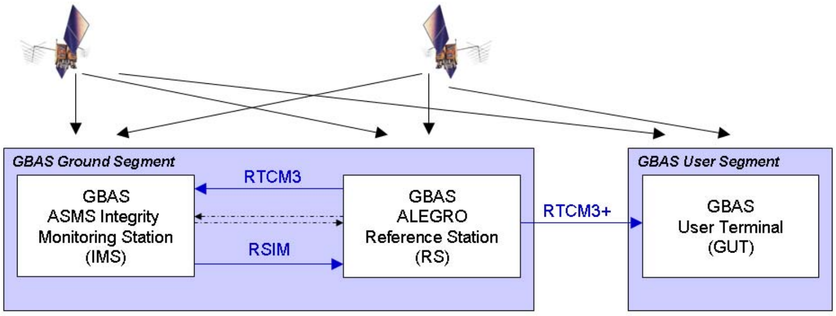

Figure 1 Generic system architecture of phase-based GBAS (dotted line: GBAS internal control and command channel)

With the RTCM3 data stream the GNSS observations collected at RS are provided to the IMS. In this data stream only observations of the RS are included, for which the Performance Key Identifiers (PKI) are fulfilled. The PKIs are derived during the self-monitoring process on RS side. The IMS itself analyses both, its own measurements and the ones of the RS, which enables the P-DGNSS positioning. The achieved validation results are used to generate the IMS feedback in form of a reference station integrity monitoring (RSIM) message to the RS. The combination of the validation results at the RS (self-monitoring) and IMS (local or far field integrity monitoring) controls then the generation of the final RTCM3+ message. The main difference between the Local Integrity Monitoring (LIM) and the Far Field Integrity Monitoring (FFIM) is the distance between the RS and IMS. The application of FFIM is preferred due to its capability to consider decorrelation effects of GNSS error sources in the coverage area. Though this generic architecture is similar to IALA Beacon DGNSS ([IALA-R-121], [Hoppe-2006]), the transition from C-DGNSS to P-DGNSS requires the specification of extended GBAS operation states and new PKIs under consideration of the hierarchical GBAS data processing supporting P-DGNSS.

The standard data format used for the provision of P-DGNSS related augmentation data is RTCM3. The term RTMC3+ indicates that only those GNSS observations are transmitted to the user, which passed the integrity monitoring process at the GBAS successfully. If additional data describing the GBAS integrity state shall be provided to the user, new or special message types must be specified. If the GBAS User terminal (GUT) will apply all augmentation data of the GBAS, a special firmware is necessary.

Assuming that GBAS supports the application of single and dual frequency P-DGNSS techniques, the GNSS observations of a single satellite can be characterised by five states given in Table 1. A Satellite Vehicle (SV) is “usable”, if all PKI applied to the GNSS observations at RS and IMS are in the valid range. If GNSS observations of a specific satellite are missed on IMS side (*) and the assessment is only based on the validation results of the RS side, the satellite is assigned to “unmonitored”. Only in such cases, where all processing mode related PKI are fulfilled, the satellite is set to “usable”. Assuming an independency between single and dual frequency mode, these summarised states can be described by “usable”, “single do not use”, “dual do not use”, or “do not use”. Considering GPS as used GNSS, the single frequency mode will be based on C/A code phase and L1 carrier phase measurements in the secured upper L-band. Momentary, the application of the dual frequency mode using GPS can be only realised with P1 and P2 code phase measurements combined with L1 and L2 carrier phase measurements. Therefore an unfulfilled PKI at the L1 carrier phase results directly in the satellite state “do not use”.

	Single Frequency Mode	Dual Frequency Mode	Satellite state
1	usable	usable	usable
2	do not use	usable	Single do not use
3	usable	do not use	dual do not use
4	do not use	do not use	Do not use
5	(*)	(*)	unmonitored

Table 1 State classification of GNSS satellites

With respect to supported single and dual frequency mode the GBAS can operate in 9 different states like seen in Table 2. Each of the states is assigned to specific combinations of GBAS related PKIs derived at RS and IMS by complementary data processing techniques.

State	Single Frequency Mode	Dual Frequency Mode
1	unhealthy	unhealthy
2	unmonitored	unhealthy
3	healthy	unhealthy
4	unhealthy	unmonitored
5	unmonitored	unmonitored
6	healthy	unmonitored
7	unhealthy	healthy
8	unmonitored	healthy
9	healthy	healthy

Table 2 State classification of GBAS

If the self-monitoring at the RS comes to the conclusion that the provided data base of GNSS observations is insufficient for a P-DGNSS based positioning, the GBAS will be set to "unhealthy". If by self-monitoring the IMS detects that their data base is insufficient to operate as integrity monitoring station, the GBAS state will be set to "unmonitored". That is the synonym for the utilisation of the GBAS on the own risk and without validation of the instantaneous performance of P-DGNSS based positioning.

A validation of the P-DGNSS performance at IMS is only possible, (a) if self-monitoring tests at both stations are successful finished, (b) if the RS observations are transmitted with an acceptable time delay, and (c) if the intersection of usable RS and IMS observation is great enough for P-DGNSS based positioning. An unacceptable time delay of augmentation data provided by the RS indicates that the GBAS is "unhealthy". If the intersection of usable RS and IMS observations is insufficient for P-DGNSS positioning, it is impossible to identify whether it is caused by the RS or IMS. Therefore the GBAS is set to "unmonitored".

A higher-order PKI is the achieved P-DGNSS performance at the IMS. But for port areas two different requirements of the IMO on GNSS accuracy and integrity exist: one for vessel port operation and one for automatic docking [IMO A.915(22)]. The GBAS will be set to "healthy", if the Horizontal Positioning Error (HPE) is smaller than the required HPE for vessel port operation (<1 m). Additionally, a flag will be provided to the user that indicates, whether the GBAS fulfils also the docking requirements (HPE < 0.1 m). Thus the GBAS is enabled to assess its state for both requirements.

Architecture Design

The proposed integrity concept for GBAS (supporting P-DGNSS based positioning) relies on the hierarchical application of PKIs on the results derived from self-monitoring of each station (RS and IMS) and the P-DGNSS based monitoring at the IMS. This results into the proposed architecture of integrity monitoring at RS (Figure 2) and IMS (Figure 3).

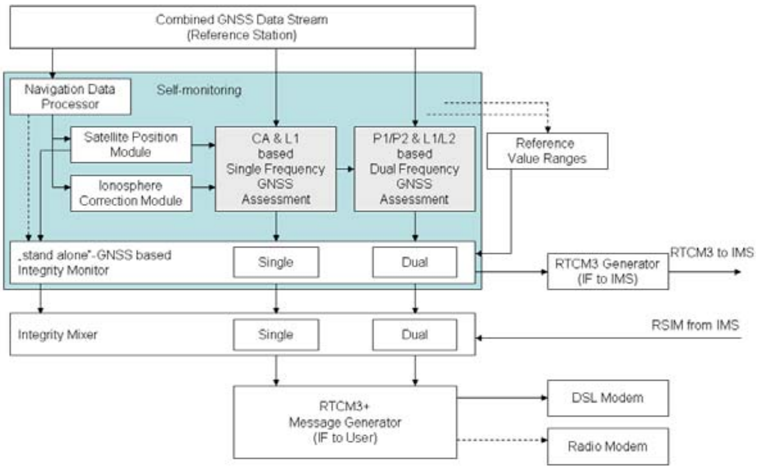

Figure 2 Architecture of integrity monitoring at RS of GBAS

The self-monitoring of each GBAS station (blue highlighted in both figures) employs an identical data processing approach covering (a) the pre-processing of each single GNSS observation type to extract quality parameters, (b) the estimation of propagation errors by data combination and filtering, and (c) the "stand alone"-positioning. The "stand-alone"-GNSS based integrity monitor decides on the basis of derived performance indicators in comparison to applied PKI, whether the RS and IMS are usable with respect to their specific GBAS functionality or not. A critical point in this context is the specification of PKI thresholds describing tolerable value ranges. A site-related determination and application of reference ranges should be preferred to enable an adaptation on environmental conditions of the RS and IMS site. This is indicated by the box "Reference Value Ranges" and will be specified in chapters 4 and 5. The generation of the RTCM3 stream accounts for the self-monitoring results of the RS in dependence of the internal RS state ("healthy") and the GNSS observations signed as usable for P-DGNSS based positioning. The generation of the RTCM3+ stream for P-DGNSS users in the coverage area takes into account the integrity mixer overlaying the assessment results at the RS and the IMS transmitted via the RSIM message to the RS.

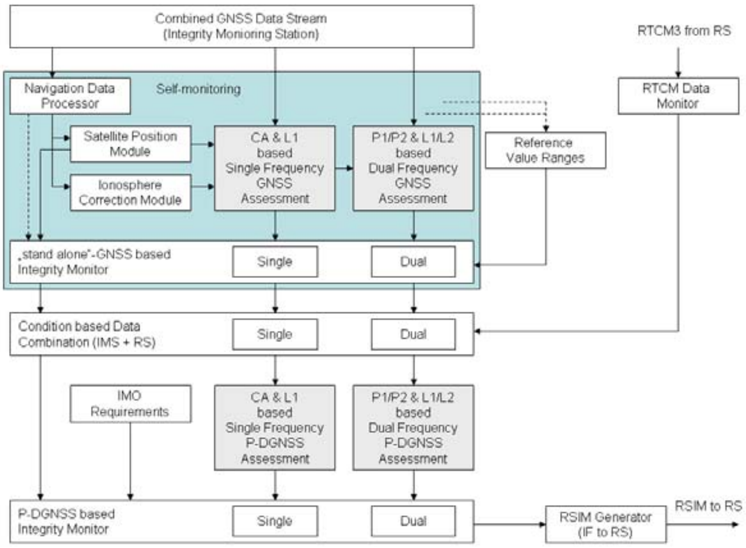

Figure 3 Architecture of integrity monitoring at IMS of GBAS

At IMS based on the combination of RS and IMS GNSS observations, which is conditioned by the result of self-monitoring and the successful transmission of the RS observations to the IMS, the module "Condition Based Data Combination" proves the age of RS augmentation data and the common intersection of observations for P-DGNSS positioning. Only if the data base is sufficient, the position of the IMS is determined by P-DGNSS based positioning. The module "P-DGNSS based Integrity Monitors" overlays all assessment results to create the IMS feedback to the GBAS RS.

4. PERFORMANCE KEY IDENTIFIERS AND PROCESSING ALGORITHMS

Self monitoring and PKI at RS and IMS

The self-monitoring at both stations is realised by a chain of processors (Figure 4) providing performance parameters in real time

- on data specific level: C/A-, P1- und P2-Code Phase Pre-processor as well as L1- and L2-Carrier Phase Pre-processor
- on satellite signal specific level: CA & L1 Carrier Smoother as well as P1/P2 & L1/L2 Carrier Smoother
- on system level: CA & L1 GNSS DIA-Positioning (RAIM) as well as P1/P2 & L1/L2 GNSS DIA Positioning.

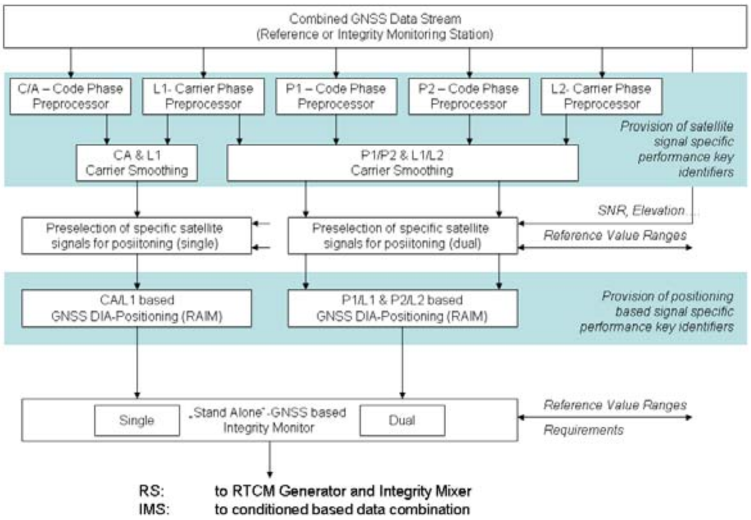

Figure 4 Self-monitoring at IMS and RS of GBAS

The main task of the code and carrier phase processors is the estimation of code and phase noise and the detection of discontinuities in the specific data stream caused by receiver clock reset operations or by occurrence of cycle slips. For this purpose a short term history of the incoming data stream is used to model its dynamic behaviour and to predict the next measurement. The difference between predicted and measured value can be considered as noise, if the filtering process takes only few seconds. This can be ensured, if the filtering process will be applied on high-rate data streams ($\geq$ 20 Hz). Furthermore a filtering of high-rate data streams enables short acquisition and reacquisition delays, before assessed code and carrier phase observations can be provided again. Quality parameters are the code and carrier phase noise, and flags describing the processing progress and the validation result (in acquisition, usable, corrected, and unusable) of the observations ([Engler-04][Engler-06][Hirrle-08]).

Carrier smoothing is the preferred filtering technique to reduce the influence of multipath propagation on code phase measurements ([Kim-07], [Hwang-90]). Therefore time constants of more than 1 minute are necessary to achieve a suitable separation between geometric conditioned code phase dynamic and multipath effects. A side effect of this filtering technique is the possibility to estimate the amount of multipath influences as a further quality parameter. In the case of single frequency processing the input data of the filter are the assessed C/A-code and the L1-carrier phase. Due to the opposite sign of Ionospheric Propagation Errors (IPE) at code and carrier phases, the filtering results are affected by the IPE. Assuming a linear drift of the IPE, the multipath estimation will be overlaid with an additional bias term. A self-correction of the IPE can be achieved operating with GNSS observation at two carriers. For this purpose the difference of code phases and carrier phase are used as input data streams for the filtering process. But the linear combination of observations increases the influence of noise and multipath. Therefore it must be expected, that the multipath estimations for single and dual frequency processing are different.

After this processing stage only such GNSS signals are selected for "stand alone" positioning whose multipath error, code and phase noise lie inside the reference value ranges, derived from statistical analysis of quality parameters for the specific station site (see Table 3). Bias errors which could be induced by satellites itself are undetected up to this moment. The next processing stage can only be started, if the availability of GNSS observations is sufficient.

Inside the DIA-GNSS positioning module the position algorithm (Weighted Least Square Method) [Misra-06] is coupled with the DIA-technique, which allows to detect misspecifications in the GNSS observation model by means of statistical hypothesis testing (e.g. [de Jong-01], [Teunissen-98]). In the first processing stage (detection) the overall model test statistic is applied to decide whether an unspecified model error exists or not. An unspecified model error induced by the GNSS observations must be assumed, if the posterior variance factor exceeds the critical threshold. Only in cases, where a model error is detected, the identification process will be initiated. Adjusted GNSS observation models are created per each GNSS observation by extension of the nominal GNSS model with additional but unknown bias terms. These models are used to estimate the amount and variance of each possible outlier. The largest estimation is than considered as the most likely outlier. Removing the most likely disturbed GNSS observations and repeating the test procedure shows than, if additional or other outliers must be identified. The success of the complete identification processes depends strongly on the model performance and the validity of the applied covariance matrix. During the adaptation process all GNSS observations with identified outliers are excluded from the final position determination. Due to the increasing availability of GNSS observations in the future (combined use of GPS and GALILEO) and under consideration of reliability aspects the existing alternative – to correct disturbed GNSS observations with the estimated bias term – is not preferred. The DIA-based assessment is considered as successful, if the achieved horizontal positioning error at RS and IMS site is smaller the IMO requirements for coastal areas.

Inside the “stand alone”-GNSS Integrity Monitor the processing results are summarised to derive the first specification of satellite states. A single satellite is usable for the ongoing GBAS processing, if all PKI listed in Table 3 are fulfilled.

	Single Frequency Processing (SFP)	AND	
Availability	C/A code phase	ok	SV usable for SFP
	L1 carrier phase	ok	
	C/A code noise	ok	
	L1 phase noise	ok	
	CA/L1 multipath estimation	ok	
Performance	C/A code noise inside value range	ok	
	L1 phase noise inside value range	ok	
	CA/L1 multipath inside value range	ok	
	CA/L1 used in DIA-GNSS Positioning	ok	

	Dual Frequency Processing (DFP)	AND	
Availability	P1 code phase	ok	SV usable for DFP
	P2 code phase	ok	
	L1 carrier phase	ok	
	L2 carrier phase	ok	
	P1 code noise	ok	
	P2 code noise	ok	
	L1 phase noise	ok	
	L2 phase noise	ok	
	P1/P2 & L1/L2 multipath estimation	ok	
Performance	P1 code noise inside value range	ok	
	P2 code noise inside value range	ok	
	L1 phase noise inside value range	ok	
	L2 phase noise inside value range	ok	
	P1/P2 & L1/L2 multipath inside value range	ok	
	P1/P2 & L1/L2 used in DIA-GNSS Positioning	ok	

Table 3 Sum of PKI applied to pre-specify the satellite state by self-monitoring

Table 4 summarises the PKIs which independently are applied on single and dual frequency processing to gain the status of RS and IMS. Only if all four conditions are fulfilled (signed by “1”: the number of satellites (NSAT) is greater than 3, the Horizontal Dilution Of Position (HDOP) is smaller than 7.5 and HPE is available with a value lesser than 10 m) for reference as well as monitor station, both stations can be used for P-DGNSS Positioning. Than the final GBAS state will be derived from P-DGNSS validation. But if RS is set “unhealthy” (0) during self-monitoring, then the complete GBAS will be evaluated on “unhealthy” independent from the IMS result. If only the IMS is “unhealthy” (0), the GBAS is “unmonitored”.

		HPE available / HPE < 10 m			
		0 / 0	0 / 1	1 / 1	1 / 0
NSAT >3 / HDOP < 7.5	0 / 0	0			
	0 / 1				
	1 / 1	0	0	1	0
	1 / 0	0			

RS=0	GBAS=unhealthy
IMS=0	GBAS=unmonitored
RS = 1 and IMS = 1	GBAS state depends on P-DGNSS validation result

Table 4 Sum of PKI applied to pre-specify or specify the GBAS state by self-monitoring at RS and IMS

P-DGNSS Monitoring and PKI at IMS

The P-DGNSS based assessment at the IMS starts with the combination of RS and IMS GNSS observations to determine the joint intersection of usable GNSS data (see Figure), which must be assigned to the same measuring time. If the processing and transmission of RS GNSS observations result into unreasonable delays (several seconds), the augmentation data of the RS are out of use. The GBAS will be set to “unhealthy”. If the number of satellites included in the common data base of RS and IMS is insufficient (NSAT<4) or if the assigned HDOP (>7.5) is too large, the GBAS is set to “unmonitored”.

Therefore the DIA-DGNSS positioning module can be only started, if a sufficient data base is found. Inside this module the differential positioning module (Weighted Least Square Method) is coupled with the DIA-technique, which allows the detection of misspecifications in the DGNSS observation model. The applied DIA-procedure is similar to the DIA-GNSS positioning module described above. Thus the change from the GNSS to the DGNSS observation model is the main difference between both modules.

If outliers are detected at further satellites during the single and dual frequency positioning processing, their state will be changed to "unhealthy" with respect to the specific processing type. All PKIs, applied on the P-DGNSS monitoring results for the final characterisation of the GBAS state, are shown in Table 5. Only if the GBAS is signed "healthy", its capability to support P-DGNSS based positioning under consideration of IMO requirements is fulfilled. In the case of evaluation the HPE, furthermore a Boolean additional performance flag is provided to the user. If this flag is set 0, it indicates that only the port accuracy (0.1m <= HPE < 1m) requirements of the IMO are fulfilled. Otherwise, if the flag has the value 1, also the docking requirements (accuracy < 0.1m) are satisfied.)

			HPE available / HPE < 1 m			
			0 / 0	0 / 1	1 / 1	1 / 0
Acceptable delay of RS data	NSAT >3 / HDOP < 7.5	0 / 0	unmonitored			
		0 / 1				
		1 / 1	unmonitored		healthy	unhealthy
		1 / 0	unmonitored			
Unacceptable delay of RS data		1 / 0	unhealthy			
		1 / 1				
		0 / 1				
		0 / 0				

Additional Performance Flag	
0	0.1m <= HPE < 1m
1	HPE < 0.1 m

Table 5 Sum of PKI applied to specify the GBAS state by P-DGNSS based monitoring at IMS

5. STATISTICAL ANAYLSIS

Location Site Information

Four GBAS stations operated by DLR were chosen to analyse and validate the quality parameters and statistical performance parameters of GNSS signals. Three of them are situated in Germany (Research Port Rostock, DLR in Neustrelitz, Research Airport Braunschweig) and one station in France (Toulouse). All stations are equipped with scientific high rate GNSS receivers. In detail it comprises the following receiver, antennas as well additional GNSS related components:

Location	Receiver Type	Antenna Type	Cable length between receiver & antenna	Antenna altitude about ground	Additional elements
Braunschweig	Topcon NetG3	LEICA AR25 (Choke Ring)	~ 15 m	~ 10 m	Rb clock
Rostock	Topcon EGGD+	Topcon GR-3 (Choke Ring)	~ 15 m	~ 20 m	Rb clock and passive antenna splitter
Neustrelitz	Topcon NetG3	Topcon G3-A1 (+ ground plane)	~ 10 m	~ 6 m	Rb clock and passive antenna splitter
Toulouse	Javad Legacy	Javad Legant	~ 30 m	~ 20 m	Rb clock

Table 6 Used hardware equipment at four GBAS stations

Data Processing

The statistical analysis has been carried out on 20 Hz GPS raw data at all four stations. A specific statistical processor is implemented in the real time processing facility of each GBAS station to determine the statistical parameters. Like already described, chains of processing modules are implemented to provide quality parameters like code noise, phase noise, multipath and UERE (User equivalent range error) per each sampling time point in real time. At the end of each day, the statistical processor generates a set of about 1350 histograms per station. The large number of histograms comes a) from the number of considered GNSS observations, b) from the number of derived parameters, c) from the applied analysis mode supporting the determination of satellite and station related statistical parameters, and d) from histograms of a performance parameter in dependence on another performance parameter. The first histogram type is referred as 1D-histogram and the second type as 2D-histogram.

For this paper daily histograms of quality parameters such as code noise at C/A, carrier phase noise at L1, and multipath errors at C/A code have been derived and analysed over a period of 23 days (1st of April until 23rd of April 2009). Additionally, daily histograms are generated describing their dependency on elevation and on SNR. Although comparable quality parameters are derived for P1 and P2 code and L2 carrier measurements, in the case of civil receivers their results are correlated due to influences by receiver internal correlation based processing techniques. So the analysis was limited to C/A and L1. However, all processors are designed to run under multi-frequency constellations (e.g. for using GALILEO signals).

Distribution Functions of Code and Carrier Phase Noise as well as Multipath Effects

In the first instance 1D-histograms are shown in Figure 5 and Figure 6 presenting the “nominal” behaviour of code and carrier phase noise as well as multipath effects. For this purpose the daily histograms have been aggregated over all satellites and days for each GBAS station.

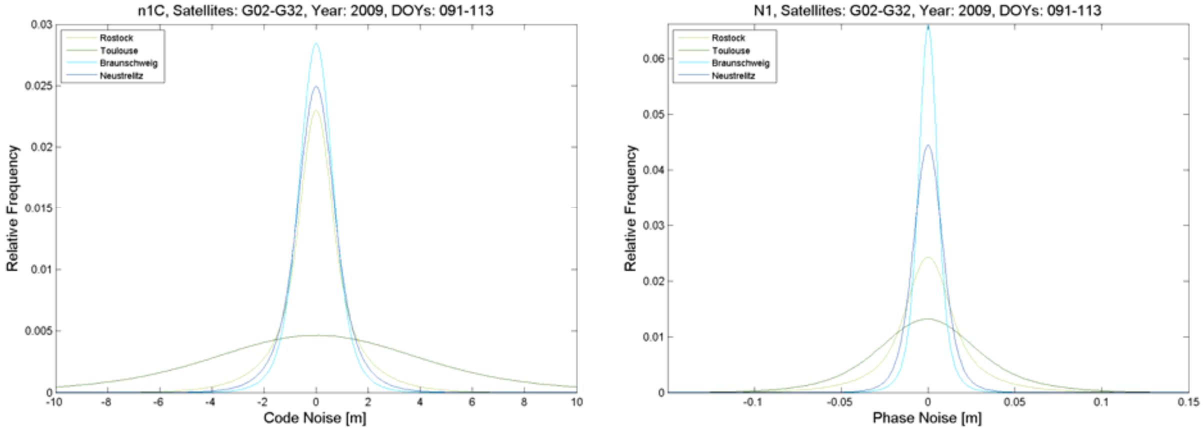

Figure 5 1D-Histogram of the code noise at C/A (left) and the carrier phase noise at L1 (right) added up for 23 successive days and the GPS Satellites PRN2 – PRN32 for four GBAS stations (different colours)

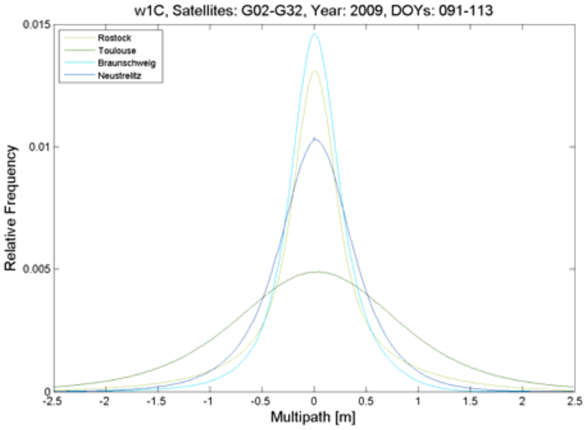

Figure 6 1D-Histogram of the multipath effects at C/A added up for 23 successive days and the GPS Satellites PRN2 – PRN32 for 4 GBAS stations (different colours)

It is clearly visible in both figures that each GBAS site has its own distinct distribution function. Considering the code noise (Figure 5), the 3 stations in Germany exhibit a nearly comparable behaviour with marginal differences in compression of the curves, since they are employing choke ring antennas. In contrary, the Toulouse station is equipped with a normal micro strip antenna. Thus the histograms are wider spread than the other ones. It can be seen that the ranking of stations is similar for the code and carrier phase noise. The lowest noise is achieved at the Braunschweig site and the worst at the Toulouse site indicated by a larger value range. Code and phase noise are estimated by a similar approach but with different configuration and controlling. It uses the short term data history to model the temporary behaviour. The noise of the next incoming observation is determined by subtracting the predicted and the measured value.

Similar effects can be observed considering the histograms of multipath effects (Figure 6). However, these histograms display a greater variation and a changed ranking of the 3 stations in Germany. It can be explained by the influence of environmental conditions in combination with equipment-specific signal reception. Multipath differences are derived by filtering the difference of code and carrier phase measurements. In addition to multipath influences, thus the estimated value includes averaged code phase noise and residual errors coming from the drift behaviour e.g. of ionospheric path errors.

The presented results already demonstrate that site-specific and equipment-specific characteristics are importance for the specification of PKI's. Furthermore it clearly shows that calibration of GBAS station equipment will be crucial for safety-sensitive applications.

<u>Dependencies on Elevation and SNR</u>

Next, 2D-histograms are generated to describe the functional dependency between a single performance parameter and elevation or SNR per station and day. For each performance parameter, the mean and the standard deviation have been calculated. The considered performance parameters are code noise at C/A, phase noise at L1 and multipath effects at C/A. The results are exemplarily displayed for standard deviation of the phase noise at L1 in dependence on elevation and SNR for all available GPS satellites (see Figure 7 and Figure 8).

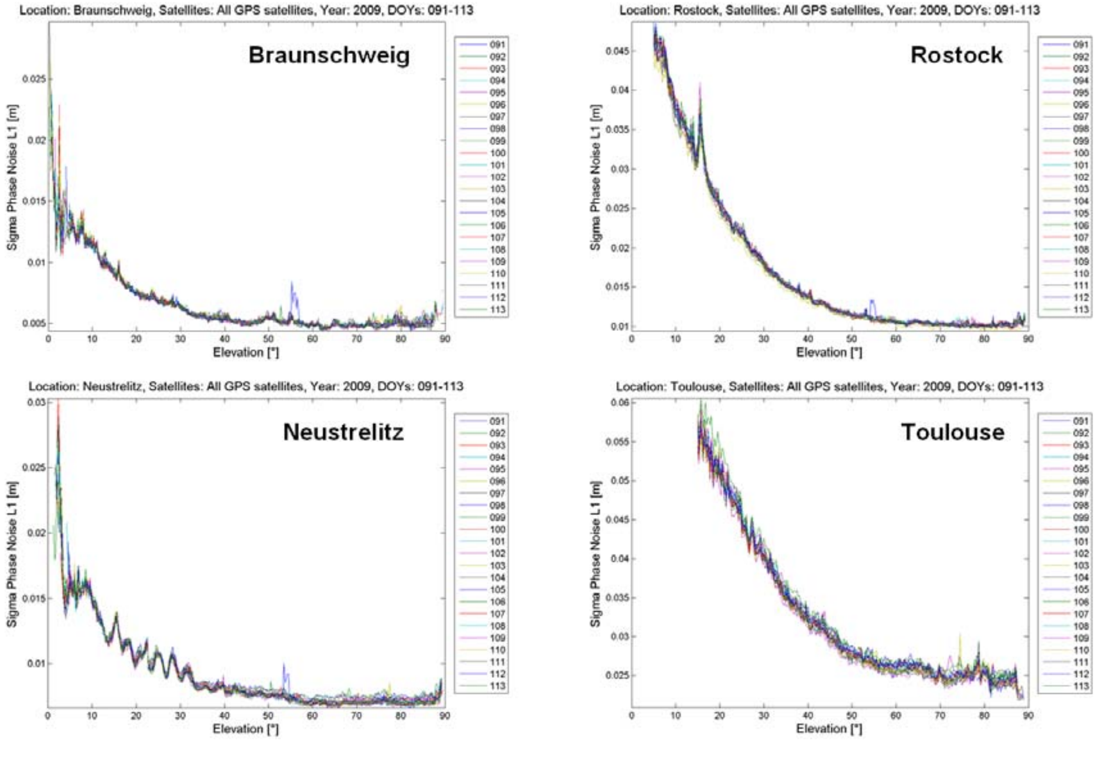

Figure 7 Standard deviation of the phase noise at L1 plotted against elevation for each GBAS station at 23 successive days in 2009 (DOY 91 – 113, different colours)

The four plots given in Figure 7 demonstrate that in the most cases the standard deviation of phase noise follows a very similar behaviour for each day. When comparing the station's plots, again a site-specific behaviour can be observed.

The same conclusions can be drawn from Figure 8, where the standard deviation of phase noise is plotted against the SNR. But these plots show that the value range of the observed SNR is shifted to smaller values at the Toulouse site in comparison to the German stations. The smaller SNR values are a possible explanation for the higher values range of the code and phase noise (see Figures 5 and 6). The increase of the value range of the estimated multipath effects can be explained by the overlaid residual bias term of code noise resulting from the applied filtering technique.

The plots of the German stations in Figure 7 and Figure 9 exhibit a significant anomaly for DOY 98 (blue line) between elevation angles of 50 and 60 degrees. A detailed analysis of the histograms of the single satellites did show that this anomaly is explicitly caused by PRN 4 for the same elevation range.

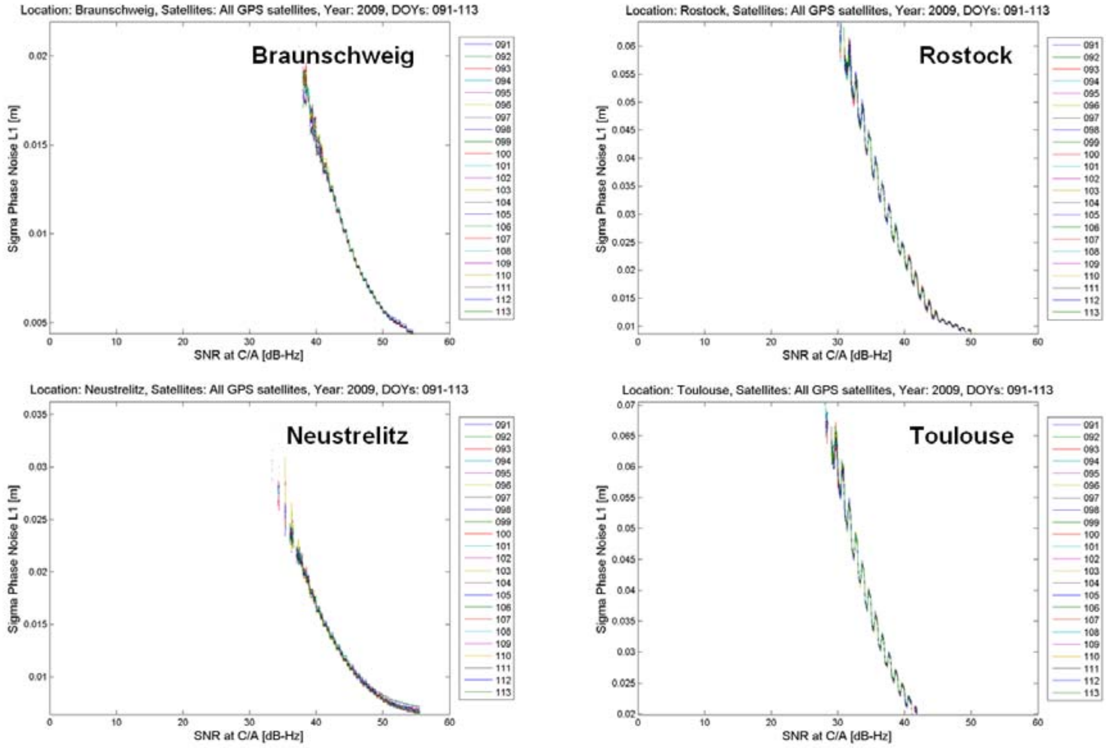

Figure 8 Standard deviation of the phase noise at L1 plotted against SNR for each GBAS station at 23 successive days in 2009 (DOY 91 – 113, different colours)

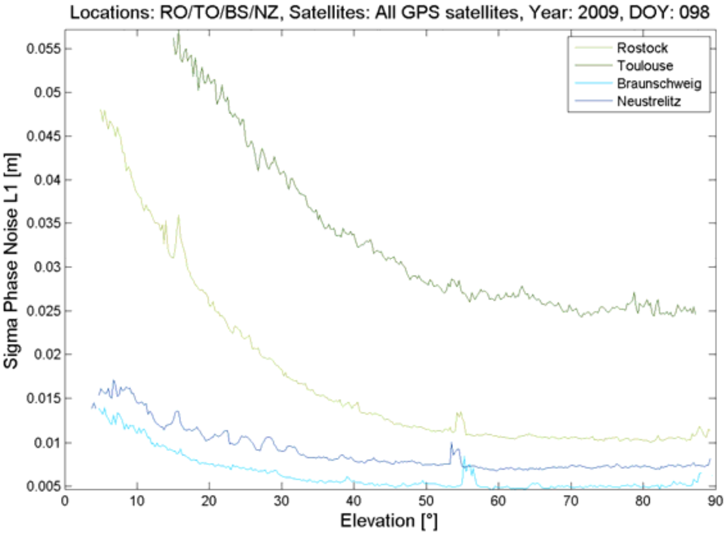

Figure 9 Standard deviation of phase noise at L1 of PRN 4 plotted against elevation for four GBAS stations (different colours) on DOY 98 in 2009

To further clarify the cause of the anomaly, a time series of the estimated phase noise is presented in Figure 10 covering about 5 hours of DOY 98. It can be seen that at each GBAS station two time periods occur with increased phase noise (see red ellipses). Although a slightly increased noise is also visible in Toulouse, the "normal" scatter inherent to the noise makes it difficult to detect this effect in the time series as well as in the daily histograms. Due to the fact that the anomaly can be observed at all GBAS stations, it can be assumed that this effect is induced by the GPS satellite itself. With respect to the strength of the effect (mostly below 0.2) an influence on P-DGNSS based positioning can be excluded.

Using the daily 2D-histograms for outlier detection would result in allowed value ranges up to about 1 cm for the German GBAS stations and up to 8 cm for the French station. According to these site-specific value ranges, the effect would be detected only at the German stations.

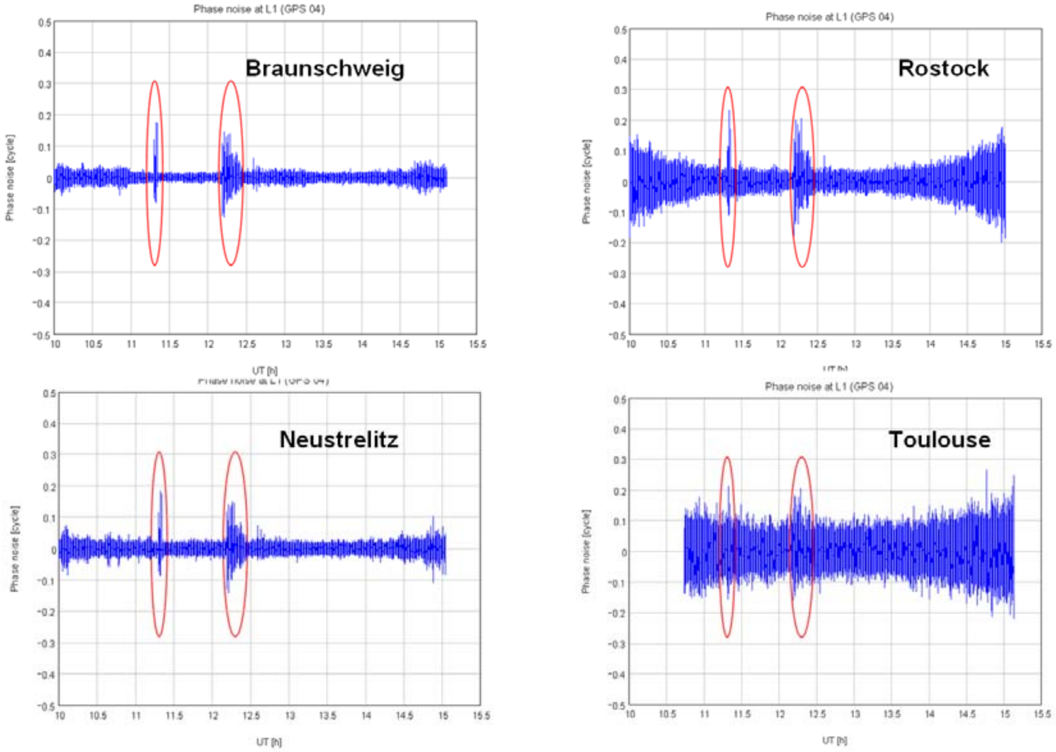

Figure 10 Time series of Phase Noise at L1 for GPS Satellite PRN4 at 4 different located GBAS stations (red ellipses show the occurrence of anomalies)

In summary, all presented examples point out that a site-specific as well as an equipment-specific management of permitted value ranges should be preferred to attain the goal of a reliable and precise integrity monitoring. A first step towards this goal has been realised by setting up the currently deployed GBAS. But further investigations are necessary to improve the models and techniques used for quality controlled processing and provision of data for maritime GBAS.

6. SUMMARY AND CONCLUSIONS

In the first part of the paper our approach for a P-DGNSS based GBAS was outlined. To detect anomalies concerning the acquired signals, specific approaches at different processing levels are implemented. One approach to support the selection of satellites at pre-processing level is based on a statistical processor to derive reference values (threshold levels) for each parameter.

The analysis of statistical data of four GBAS stations at different locations has shown that each station has to be considered separately due to its characteristic behaviour. This means that general approaches related to the use of standard reference values can lead to misinterpretations of data.

It clearly shows that a proper station calibration using statistical analysis is necessary. However to model the nominal behaviour of a single GBAS station appropriately, it would be useful to analyse data at different time periods of a year. In this way, variations throughout the year have to be investigated, which will be subject to future work. Based on the continuation of the statistical validation of the experimental GBAS the improvement of the used PKIs and their reference ranges (thresholds) shall be achieved in the near future. The use of additional PKIs during the self-monitoring (e.g. applied to ionospheric path errors and their rates, signal to noise ratios) and the implementation of gain monitors (e.g. real time assessment of filtering progress) are seen as further opportunities to increase the robustness of the GBAS-based positioning. With respect to the applied DIA-GNSS and DIA-P-DGNSS algorithm we are convinced that ongoing investigations are necessary to optimise GNSS observations models as well as their measuring error models. In this frame it is also important to consider alternative positioning algorithms (e.g. Kalman Filter, different methods of ambiguity resolution).

The future applicability of phase-based DGNSS for vessel port operation requires its standardisation and its approval by the IMO on the one hand. On the other hand the RTCM3 format must be extended and suitable user terminals must be available to enable the transmission of integrity relevant augmentation data and their utilisation during positioning at user site.

The integrity monitoring and management can be enhanced, if similar to the aviation sector protection level are estimated and used in real time. That requires a complete description of the measuring errors under consideration of the applied algorithms and the interaction between GBAS service element and GBAS user terminal. The implementation of this approach is a seen way to reduce the occurrence probability of hazardous misleading events. The specification and conditioning of protection level related algorithms for the maritime sector is a further open but necessary research and development task.

ACKNOWLEDGEMENTS

We thank the Ministry of Economics of the Federal State Mecklenburg-Vorpommern and the DLR Space Agency for the strong and continuous interest in the maritime GBAS topic and the promotion of the related projects ALEGRO and ASMS.

Also we thank the Port Development Company Rostock, in particular Mr. Vatterott, for the cooperative and uncomplicated support during the deployment and operation phases of the experimental GBAS.

We are deeply grateful to our colleagues Stefan Schlüter, Carsten Becker, Jamila Beckheinrich, and Roland Reimer for their research activities and kind support in the frame of both projects.

REFERENCES

[IALA-R-135]	IALA: Recommendation R-135 on The Future of DGNSS. Edition 1., Dec. 2006.
[IMO A.915(22)]	IMO: Revised maritime Policy and Requirements for a future Global Navigation satellite System (GNSS), 22.01.2001, A22/Res.915, (http://www.imo.org, Download 01.10.2008)
[IMO MSC.114(73)]	IMO: Adoption of the Revised Performance Standards for Shipborne DGPS and DGLONASS maritime Radio Beacon Receiver Equipment. 01. Dez. 2000, MSC 73/21/add.3, (http://www.imo.org, Download 01.10.2008)
[IALA-R-121]	IALA: Recommendation R-121 on the Performance and Monitoring of DGNSS services in the Frequency Band 283.5 – 325 kHz; Edition 1.1, Dez. 2004 (http://www.tidelandsignal.com/web/information/IALA/Recommendations/R-121-DGNSS-2004.pdf, Download 15.10.2008)
[Hoppe-2006]	M. Hoppe: Technische Daten, Systemparameter, und Aufbau der DGPS-Station nach IALA-Standard. DGPS-Dienst der WSV. 28.12.2006. (http://www.fvt.wsv.de/dgps/informationen/dgps_empfaenger.pdf, Download 15.10.2008)
[de Jong-01]	K. de Jong, H. van der Marel, N. Jonkmann: Real-Time GPS and GLONASS Integrity Monitroring and Reference Station Software, Delft University of Technology, Department Geodesy (http://igscb.jpl.nasa.gov/projects/meetings/nw2k/abstracts/ext/vandermarel2.pdf, Download 12.10.2008)
[Teunissen-98]	P.J.G. Teunissen: Quality Control and GPS. Inside P.J.G. Teunissen and A. Kleusberg (Eds.): GPS for Geodesy. Springer Verlag, 2nd Edition, 271-318.
[ALEGRO]	Projektinformation unter: http://www.dlr.de/kn/desktopdefault.aspx/tabid-4309/3222_read-9153/ (Download, 25.07.2009)
[ALEGRO-FR]	ALEGRO - AUFBAU EINES LOKALEN MARITIMEN ERGÄNZUNGSSYSTEMS ZUR UNTERSTÜTZUNG HOCHPRÄZISER GALILEO-ANWENDUNGEN UND –DIENSTE IM FORSCHUNGSHAFEN ROSTOCK. Final Report of the Project ALEGREO. FKZ V230-360-08.TIFA-560, Version 1.0, 04.12.2008
[EVnet]	B. Bellabas, S. Graf, T. Noack: EGNOS Performance Monitoring using the DLR's Experimental Verification Network. IEEE ION PLANS 2006, 2006-04-25-2006-04-27, San Diego.
[ASMS]	Projektinformation Advanced Sailing Management System (GALILEO basierte Dienste zur landunterstützenden Betriebsführung von Schiffen) unter: http://www.dlr.de/kn/desktopdefault.aspx/tabid-4305/6933_read-9207/ (Download, 25.07.2009)
[RTCM3]	Amendment 2 to RTCM Standard 10403.1: Differential GNSS (Global Navigation Satellite Systems) Services – Version 3. Developed by RTCM Special Committee SC 104, Amended 31. August 2007

[Engler-06]	E. Engler, A. Hirrle, S. Schlüter, T. Noack, D. Klähn (2006) Carrier autonomous Cycle Slip Detection and Correction based on High-rate Processing. In: 3rd ESA workshop on Satellite Navigation User Equipment Technology, 11.-13. Dezember 2006, Noordwijk
[Engler-04]	E. Engler, S. Schlüter(2004): Characteristics of high rate GNSS navigation data and their utilisation for different monitoring purposes. In: 2nd ESA Workshop on Satellite Navigation User Equipment Technologies NAVITEC '2004, 8-10 December 2004, Nordwiijk, The Nederlands, Nordwiijk, Holland.
[Hirrle-08]	A. Hirrle (2008): ALEGRO-Range-Preprocessor, Technical report of the project ALEGRO.
[Kim-07]	E. Kim, T. Walther, J.D. Powell: Adaptive Carrier Smoothing Using Code and Carrier Divergence. ION nTM 2007, 22-24 Jan. 2007, San Diego, CA
[Hwang-90]	P.Y.C. Hwang, R.G. Brown: Combining Pseudorange with Continuous Phase using Kalman Filter", NAVIGATION, Journal of the Institute Navigation, Vol. 37, No. 2, Summer 1990
[Misra-06]	P. Misra, P. Enge: Global Positioning System: Signals, Measurements, and Performance. Ganga-Jumuna-Press, 2006, ISBN 0-9709544-1-7, Chapter 6.
[DIN EN 61108-4]	Navigations- und Funkkommunikationsgeräte und –systeme für die Seeschifffahrt – Weltweite Navigations-Satellitensysteme (GNSS) – Teil 4: DGPS- und DGLONASS-Seefunkbaken-Empfangsanlagen – Leistungsanforderungen, Prüfverfahren und geforderte Prüfergebnisse (IEC 61108-4, 2004)