Statistical GNSS performance assessment as part of the ALEGRO Ground Based Augmentation System inside Research Harbour Rostock

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ABSTRACT: In the Research Port Rostock the Institute of Communication and Navigation of the German Aerospace Center deployed and operates an experimental Ground Based Augmentation System (GBAS). The first prototype of this GBAS system was developed under the project acronym ALEGRO to support positioning and navigation of marine users by the provision of phase based differential GNSS service. In time the implemented GBAS System is limited on a one receiver station system but will be extended by a second station up the end of 2009 for GBAS integrity monitoring.

For the development and operation of GBAS the assessment of Global Navigation Satellite System (GNSS) signal and positioning quality at reference station site has to be considered as one elementary task before augmentation and correction data are derived and provided to marine users. Based on the decomposition of GNSS related measurements like e.g. ranges, phases, amplitudes and Signal to Noise Ratios (SNR) different quality parameters are derived in real time. Related to the fact that GBAS are normally placed at reference locations with low multipath effects, the influence of the environment in form of shadowing and reflections should be strongly limited. Daily derived statistics of quality parameters like e.g. code and carrier phase noise, SNR and power noise are used to derive values ranges of their regular (undisturbed) behaviour and to describe dependencies between them.

For this purpose inside the ALEGRO processing system a statistical processor system operates to determine statistical parameters from 24 h measurements and derived real time quality parameters. They are used to model the regular value ranges and to identify thresholds for integrity monitoring in a next step. Such data are foreseen to support the monitoring of the GBAS operational system itself and to tune the measuring models used in the algorithms dealing with the provision of augmentation data and with the prediction and verification of the expected positioning accuracy and integrity in the GBAS environmental field.

The paper will discuss the results of a 1 month measurement campaign. Under regular GNSS operation and signal propagation conditions it will be demonstrated that the quality parameters are reproducible at successive days. On basis of selected measuring examples it will be shown that the exact quantitative knowledge and description of the reference behaviour enables the detection of signal disturbances during GBAS operation. Besides the investigation of single quality parameters a special attention has been given on the description of dependencies between various quality parameters and their relation to satellite elevation and signal strength.

1 INTRODUCTION

Ground Based Augmentation Systems are a suitable approach to increase the accuracy and integrity of GNSS based positioning and navigation in local areas. Already in the nineties the IALA Beacon Differential GNSS (DGNSS) [1] was developed and deployed to fulfil the GNSS performance requirements specified by the International Maritime Organisation (IMO) for coastal areas [2]. The provider of this service is the International Association of Marine Aids and Lighthouse Authorities (IALA) and cooperating national agencies. An IALA Beacon DGNSS is composed at minimum by a Reference Station (RS) and an Integrity Monitoring Station (IMS), whereby both are operated at known locations and support the application of code-based differential positioning. The RS is responsible to extract pseudorange and range rate correction terms for visible satellites and to provide these to the user. The IMS operates as an “artificial” user correcting its own GNSS observations with the correction terms provided by the RS. Different Performance Key Identifiers (PKI) will be applied inside the whole DGNSS to decide whether a single satellite or the complete augmentation system is “healthy” or not.

In expectation of the GNSS modernisation process the IMO has defined extended requirements for the maritime user community by using GNSS [2]. In detail in port areas an accuracy better than 1 m and for automatic docking better than 0.1 m is necessary for safe vessel operation. In addition to this the requirement to fulfil integrity are ten or hundred times tougher as well for coastal or port approach operations (see Table 1). To fulfil such requirements GBAS based on pseudolite

Table 1: Selected IMO requirements on future GNSS

	System Level Parameters				Service Level Parameters			
	Absolute Accuracy	Integrity			Availability (%) per 30 days	Continuity (%) over 3 hours	Coverage	Fix Interval² (s)
	Horizontal (m)	Alert Limit (m)	Time to Alarm² (s)	Integrity Risk (per 3 h)				
Ocean	10	25	10	10^{-5}	99,8	N/A¹	global	1
Coastal	10	25	10	10^{-5}	99,8	N/A¹	global	1
Port approach and restricted waters	10	25	10	10^{-5}	99,8	99,97	regional	1
Port	1	2,5	10	10^{-5}	99,8	99,97	local	1
Automatic Docking	0,1	0,25	10	10^{-5}	99,8	99,97	local	1

1 - Continuity is not relevant for ocean and coastal areas
2 - More stringent requirements may be necessary for ships operating above 30 knots

technology and/or supporting phase-based DGNSS techniques are considered as suitable approaches by the IALA [3]. Concerning the technical realization of prototypes the projects SEA GATE (EADS RST → pseudolite technology) and ALEGRO (DLR → phase-based DGNSS) were initiated in the Research Port Rostock.

Due to the fact that seafaring is considered as safety critical application the focus is set on integrity. The integrity term stands hereby for reliability of provided information or parameter on the one hand. On the other hand integrity can be understood as the crossover from one safe state into the next safe state. For this purpose all electronic means inside navigation systems and service shall be used to ensure the required monitoring and controlling processes. Consequently, innovative GBAS must be designed to fulfil the integrity requirement, whereby suitable PKI must be found, specified, and applied. This is the scope of the following paper.

2 ALEGRO MARITIME GBAS

With the project ALEGRO the first development and deployment stage of maritime GBAS was finished at the end of 2008 in the Research Port Rostock. The architecture of the prototype is shown in Figure 1. The gray highlighted modules are the planned extension of the GBAS in a further project.

The measuring unit is equipped with a geodetic high-rate GNSS receiver as well as weather sensors to measure temperature, humidity and air pressure. All data of the sensors are available at streams and serve as input values for the GNSS Performance Assessment Facility (GPAF) as the core processing element of the GBAS ground segment. The GPAF is composed by hierarchical designed chains of data processors enabling the determination of quality parameters for both the specific signals of the GNSS satellites and the GBAS as a whole in real time. During the pre-processing stage the GNSS observations are assessed per each data type and satellite. The dedicated processors are applied on the measurements of code and carrier phases as well as the signal strength of each received satellite signal. In more detail the processors are based on fast filtering techniques using the incoming data streams to estimate parameters like code and carrier phase noise and short term SNR variances. In addition to this discontinuities inside the data stream can be detected, induced by either receiver clock resets or the occurrence of cycle slips.

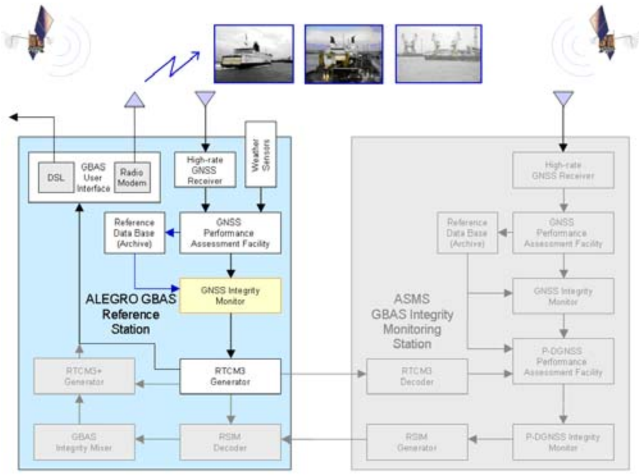

Figure 1: Architecture of ALEGRO experimental GBAS (left) and the planned extension (right)

The next higher processing stage deals then with the estimation of ionospheric path delays and multipath propagation errors. This is realized by the linear combination of the data and their filtering in relation to single and dual frequency processing techniques. The "highest" processing stage of the GFAP is based on the common use of available GNSS observations to estimate position relevant parameters. These are the position as code-based solution with carrier phase smoothing, the horizontal dilution of precision (HDOP), the receiver clock error, and the User Estimated Range Errors (UERE). For this purpose a DIA-GNSS positioning module is applied coupling a positioning algorithm based on weighted least square method with the DIA-technique (Detection, Identification, and Adaptation). DIA allows the detection of misspecifications in the GNSS observation model by means of statistical hypothesis testing. So GNSS observations of single links that are inconsistent with others are identified by the DIA-technique [4][5] and can be corrected or will be excluded in a second step. The success of the identification processes depends strongly on the GNSS observation model performance, the validity of the applied covariance matrix, and the applied thresholds during the detection and identification process. In the future this thresholds will be deduced with a statistical processor determining statistical parameters based on 24 hour loop in the GAPF. The analysis strategy and the applied algorithms will be described in more detail in chapter 4.

If a GBAS integrity monitor (yellow highlighted in Figure 1) will be implemented, the quality parameters provided by the GPAF can be used to validate the GNSS observations, to select the usable GNSS observations for P-DGNSS based positioning and to realise a self-monitoring of the reference station. The solution of this approach can be considered as a first step toward the fulfilment of integrity requirements in relation to the maritime application of Phase based GNSS (P-DGNSS) techniques and services.

3 GNSS DATA COLLECTION

The data collection was mainly focussed on the processing of measurements of the ALEGRO GBAS station installed in the Research Port of Rostock. Since investigations in site specific characteristics need the comparison of measurements at different locations, three comparable stations were included into the process of data collection. Although the principal installation and operation of all stations is following an identical scheme, each station comes with site specific characteristics. For this Table 2 gives an overview about the installed receivers, antennas as well as associated equipment.

At all locations high rate GNSS receivers were installed to measure GNSS raw observations with an update rate of 20 Hz. The operating mode of the receivers concerning the raw data management and signal processing parameters like e.g. loop parameters of Phase-locked Loop (PLL) and Delay-Locked Loop (DLL) was set up with the same configuration for all four receivers.

All stations were equipped with high precise Rubidium clocks to minimize the occurrence of cycle slips induced by clock jumps. Two stations (Rostock and Braunschweig) were equipped with Choke Ring antennas to eliminate or reduce the effects of multipath.

Concerning the output of observables all receivers were configured to deliver the following set of raw data per epoch:

- CA-Code pseudorange at L1
- P-Code pseudorange at L1 and L2
- Carrier phase measurement at L1
- Carrier phase measurement at L2
- Signal amplitude and SNR at CA/L1
- Signal amplitude and SNR at P/L1 and P/L2

For the statistical analysis and the derivation of statistical parameters the data of a nearly one month parallel measurement campaign (1th of April 2009 until 23th of April 2009) were selected. During this time at each station a set of 1350 histograms was generated per day. This means that for statistical analysis a set of more then 30000 histograms was available.

Table 2: Used GNSS equipment for measurement campaign

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

$h_{nx,ny} = h_{nx,ny} + 1$, $h_{ny} = h_{ny} + 1$.

Sample pairs (x_i,y_i), which are outside the value ranges of [x_u-dx/2,x_o+dx/2] and [y_u-dy/2,y_o+dy/2], will be not respected in the statistical analysis. In case of y-outliers, a further vector v_{ny} (dimension N_y, entries 0 after restart), is used for monitoring the applied technique:

$$v_{ny} = v_{ny} + 1.$$

In the case of x-outliers a single counter O_{nx} is adequate for monitoring.

At crossover from one day to the next, the frequency area will be used to extract the pdf $f_y(x)$ of x in dependency on y

$$f_{ny}(nx) = \frac{h_{nx,ny}}{h_{ny}}$$

before a restart is initiated and the procedure is working in the same manner again. A good statistical description of x can be expected, if the database h_{ny} contains a sufficient number of samples (and if the sum over all v_{ny} as well as O_{nx} is preferably 0). Than mean $\mu_{x,ny}$ and standard deviation $\sigma_{x,ny}$ of x in dependency on y can be determined by

$$\mu_{x,ny} = \sum_{nx=0}^{Nx} f_{ny}(nx) \cdot \left(x_u + nx \cdot \mathrm{d}x \right)$$

$$\sigma_{x,ny} = \sqrt{\sum_{nx=0}^{Nx} f_{ny}(nx) \cdot \left(x_u + nx \cdot \mathrm{d}x - \mu_{x,ny} \right)^2} .$$

The applicability of the applied method to achieve representative pattern for each parameter depends strongly on the availability of a database acquired under nominal conditions.

4 STATISTICAL ANALYSIS UNIT

The statistical analysis unit (Figure 2) is a specific software module of the GPAF to fill and upgrade the reference data base unit (see Figure 1). In detail serial arranged process chains are implemented to estimate derived parameters from the incoming observables. Dedicated quality parameters at signal specific level are code and phase noise, the ionospheric propagation error and the multipath error. Each quality parameter x can be characterised by a probability density function (pdf) $f(x)$ and by the statistical parameters mean μ_x and standard deviation σ_x.

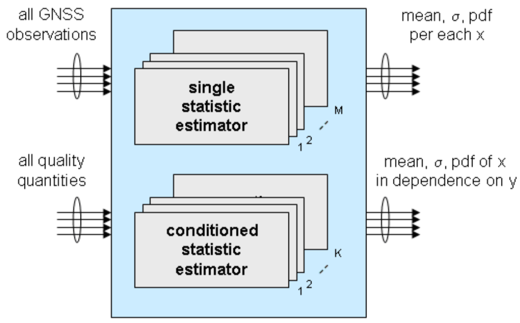

Figure 2: Statistical analysis unit

A parallel circuit of single statistic estimators is used now to derive the statistical characterisation ($f(x)$, μ_x, σ_x) for each parameter x. The necessary inputs are the GNSS observations coming directly from a receiver or derived quality parameters determined by the GPAF itself and used by a back coupling process. In addition to the single estimator a second parallel circuit is implemented to estimate interdependencies between pairs of parameters (x,y).

Because the long-term recording of the considered database was led to problems in memory allocation, the determination is based on a quantified processing technique. This technique will be short explained for the conditioned statistic estimator.

At begin or restart of processing the frequency area $h_{nx.ny}$ is created for each pair of parameters (x,y) with dimension N_x times N_y. The additional vector h_{ny} with dimension N_y is used to enable the counting of samples with respect to a quantified value range of x. The dimension of both is derived from a-priori value ranges [x_u,x_o] and [y_u,y_o] as well as specified quantification resolution dx=(x_o-x_u)/N_x and dy=(y_o-y_u)/N_y. During data processing each sample pair (x_i,y_i) will be fitted into the patterns based on the determination of related indices

$$nx = round\left(\frac{x_i - x_u}{\mathrm{d}x}\right), \quad ny = round\left(\frac{y_i - y_u}{\mathrm{d}y}\right)$$

and the updating of the frequency area $h_{nx.ny}$ and the counting vector h_{ny},

5 ANAYLSIS AND VALIDATION

The statistical analysis has been carried out on the data base explained in chapter 3. As a result the statistical processor has generated pdf's (histograms) per considered GNSS observable as well as derived quality parameters and 2D-plots (conditional pdf) to present the dependencies between two parameters or between one parameter and the elevation angle or the SNR.

With respect to chapter 4 it was outlined that the quantification resolution and the number of samples to generate a pdf has to be considered to obtain exploitable results. Therefore in a first step simulated data based on a vector of Gaussian noise were used to describe the influence of quantification resolution and number of samples on the validity of a pdf. The results are demonstrated in Figure 3. By using a normal distribution with theoretical values for mean and standard deviation of μ = 5 and σ = 3 different probability density functions can be achieved in dependence on the selected quantification resolution dx. The plot on the left hand

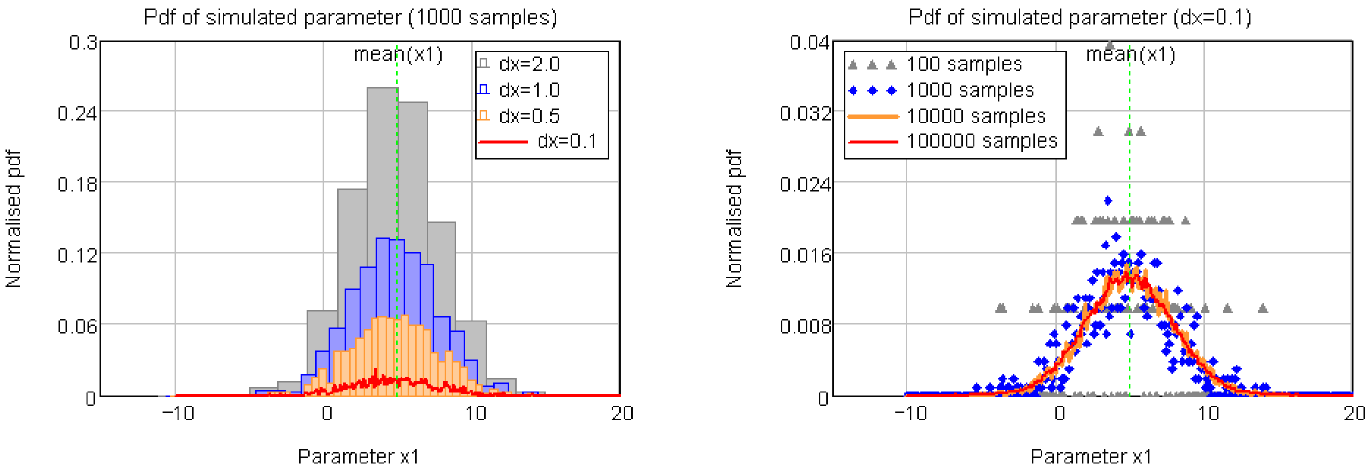

Figure 3: Influences of quantification resolution and number of samples on the curve behaviour of pdf

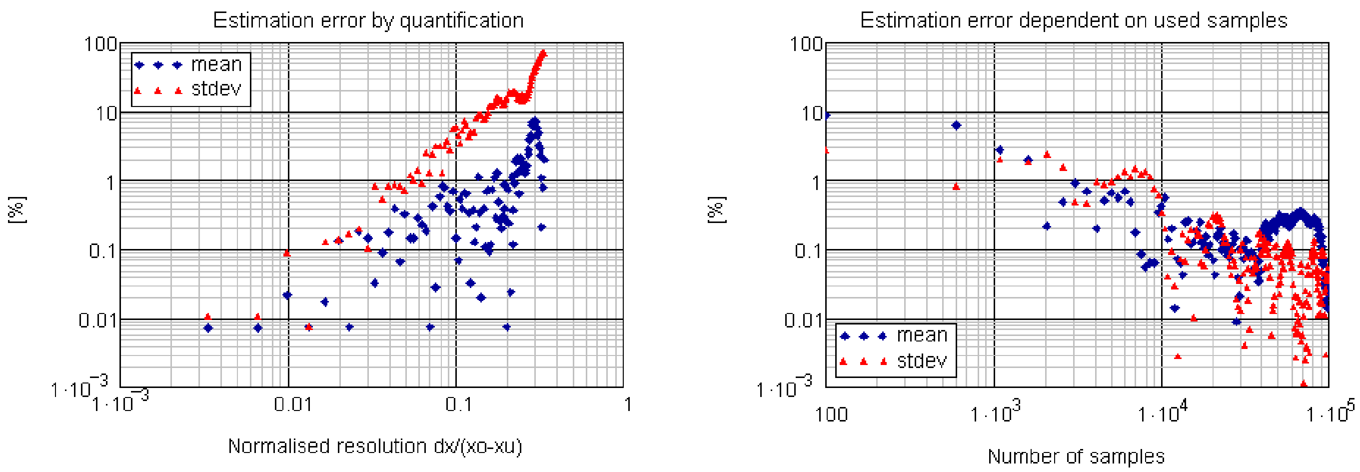

Figure 4: Estimation errors of mean and standard deviation in dependence on quantification and number of samples

side shows that the quantification resolution should be preferably ≤ 0,1 to achieve an applicable reproduction of the distribution function. Related to the number of necessary samples the plot on the right displays that around 10000 samples should be considered to obtain reasonable curve behaviours of a pdf.

Considering the accuracy of mean and standard deviation of the simulated example the estimation error is below one percent of the true value, if the a-priori value range should be modelled by more than 30 sub-segments and if more than 3000 samples are used for pdf determination (Figure 4).

Related to the measurement results which will be discussed in the following we can resume that based on the 20 Hz sample rate of the measurement systems (receivers) as well as the applied method of one day data collection the sample rate to generate a pdf was more than 100 times higher as required. For the quantification resolution, values within the range of 0.05 and 0.1 were used based on suitable configuration settings of the statistical processor.

For the validation daily histograms of quality parameters such as code noise at C/A, carrier phase noise at L1, and multipath errors (CA/L1 combination) have been derived and analysed over a period of 23 days. Comparable quality parameters are also derived for P1 and P2 code and L2 carrier measurements. However, in the case of civil receivers their results are correlated with C/A and L1 results due to the internal processing approach of those receivers.

Figure 5 shows the derived probability density functions of Code Noise at CA/L1 (blue curve on the left) and Phase Noise at L1 (blue curve on the right) for the receiver at the ALEGRO GBAS station in Rostock. These curves incorporate the daily histogram values of all GPS satellites acquired over a period of 23 successive days except the GPS satellite with Pseudo Random Noise (PRN) number 1. This satellite was excluded due to its unhealthy status broadcasted by ephemeris and almanac data. Mean and standard deviation has been estimated for these curves. Using these values the pdf of the normal distribution has been plotted (green curves). That means, if the pdf of the measurements (blue curves) would be normally distributed, they would follow the green curves. However, the blue curves appear less stretched along the x-axis than the green ones. This deviation from the normal distribution is also confirmed by the statistical

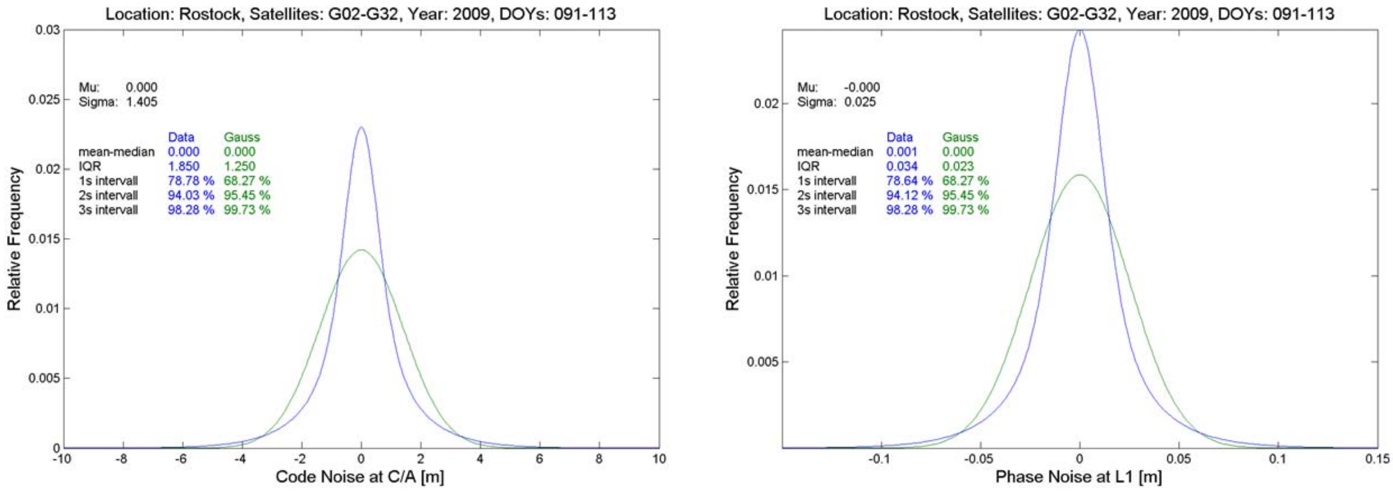

Figure 5: pdf of the code noise at C/A-L1 code (left) and the carrier phase noise at L1 (right) added up for 23 successive days and the GPS Satellites PRN2 - PRN32 for ALEGRO GBAS system (blue) in comparison to standard normal distribution (green)

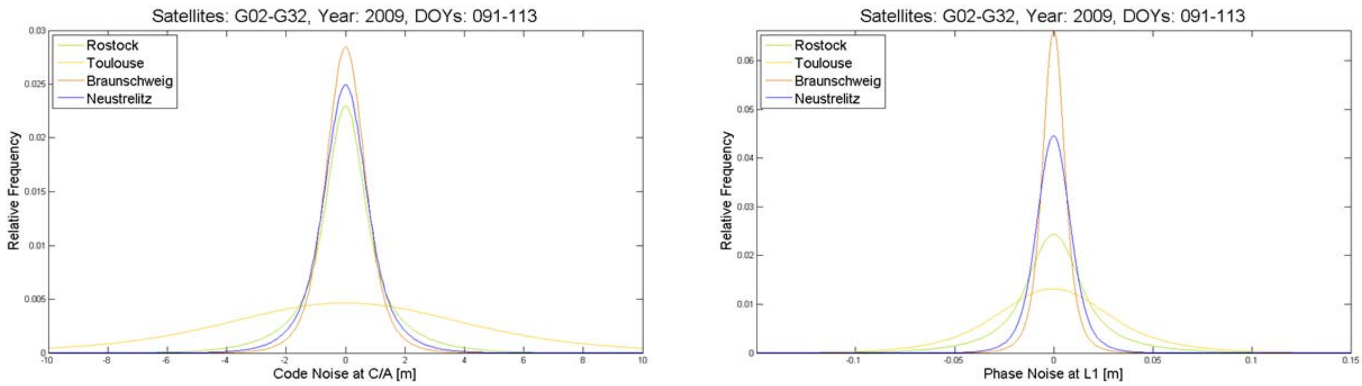

Figure 6: Comparison of pdf of the code noise at C/A-L1 (left) and the carrier phase noise at L1 (right) added up for 23 successive days and the GPS Satellites PRN2 - PRN32 for four stations

indicators displayed for both pdfs in the figures (e.g. mean-median, interquartile distance, measurements falling into 1σ, 2σ, 3σ intervals).

Looking at the results of all four stations (see Figure 6) it is clearly visible that each station has its own distinct distribution.

Considering the code noise (see left hand side), the 3 stations Rostock, Braunschweig and Neustrelitz exhibit a comparable behaviour with marginal differences in compression of the curves. One reason could be the employment of these three stations with choke ring antennas. In contrary to this the station in Toulouse is equipped with a normal micro strip antenna and generates much higher code noise than the other ones. Furthermore it can be seen that the ranking of the stations is the same for the code and carrier phase noise. Although the code and phase noise is estimated by a similar approach, there is no strong correlation in the behaviour of their pdf's apparent. This is due to different configuration and controlling**.**

Similar effects can be observed for the pdf of multipath errors (Figure 7). The greater variation and a changed ranking of stations can be explained by the influence of environmental conditions in combination with equipment-specific signal reception.

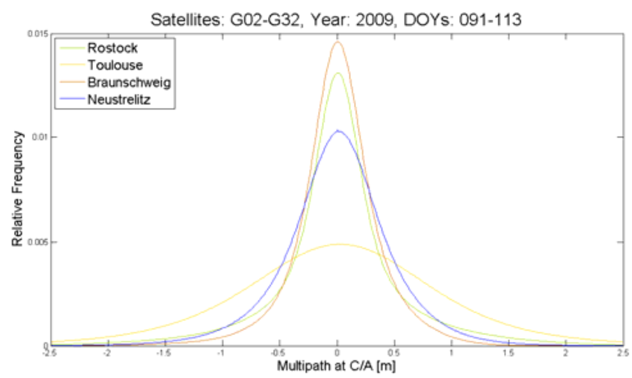

Figure 7: pdf of the multipath error at CA/L1 combination added up for 23 successive days and the GPS Satellites PRN2 - PRN32 for all stations

Table 3: Estimated threshold values of code noise at C/A-L1 and phase noise at L1 for different standard deviations

	ALEGRO GBAS Rostock		Station Braunschweig		Station Neustrelitz		Station Toulouse	
% stdev	Code Noise CA/L1 [m]	Phase Noise L1 [m]	Code Noise CA/L1 [m]	Phase Noise L1 [m]	Code Noise CA/L1 [m]	Phase Noise L1 [m]	Code Noise CA/L1 [m]	Phase Noise L1 [m]
68.27 1σ	± 1.02	± 0.018	± 0.75	± 0.006	± 0.85	± 0.009	± 4.45	± 0.032
95.45 2σ	± 3.12	± 0.055	± 1.75	± 0.016	± 2.15	± 0.022	± 10.05	± 0.074
99.75 3σ	± 6.35	± 0.114	± 3.35	± 0.035	± 4.45	± 0.045	± 14.4	± 0.132
99.99 4σ	± 11.12	± 0.181	± 5.65	± 0.066	± 7.85	± 0.080	± 15.0	± 0.187

Multipath differences are derived by filtering the difference of code and carrier phase measurements. In yaddition to multipath influences, thus the estimated value includes averaged code phase noise and residual errors coming from the drift behaviour e.g. of ionospheric propagation errors.

The estimation of generic pdf's as shown in Figure 6 and Figure 7 was focussed on the definition of initial threshold values for outlier detection within the scope of the automatically refinement of the reference data base. Related to the confidence intervals of 68.27%, 95.45% 99.75% and 99.99% (correlated with 1σ until 4σ of the normal distribution) the corresponding threshold values for code noise at C/A-L1 and phase noise at L1 were estimated (see Table 4).

The estimated values of standard deviation (σ) for code and phase noise can be used as configuration values to update the dedicated reference data base. But to detect outliers within the GPAF assessment facility in real time specific dependencies of code noise and phase noise in relation to the SNR and the elevation have to be taken into account.

To investigate in this topic 2D-plots were generated to describe functional dependencies on SNR and elevation per station and day. First results are exemplarily displayed for the standard deviation of the phase noise at L1 in dependence on elevation and SNR for all available GPS satellites (see Figure 8 and Figure 9).

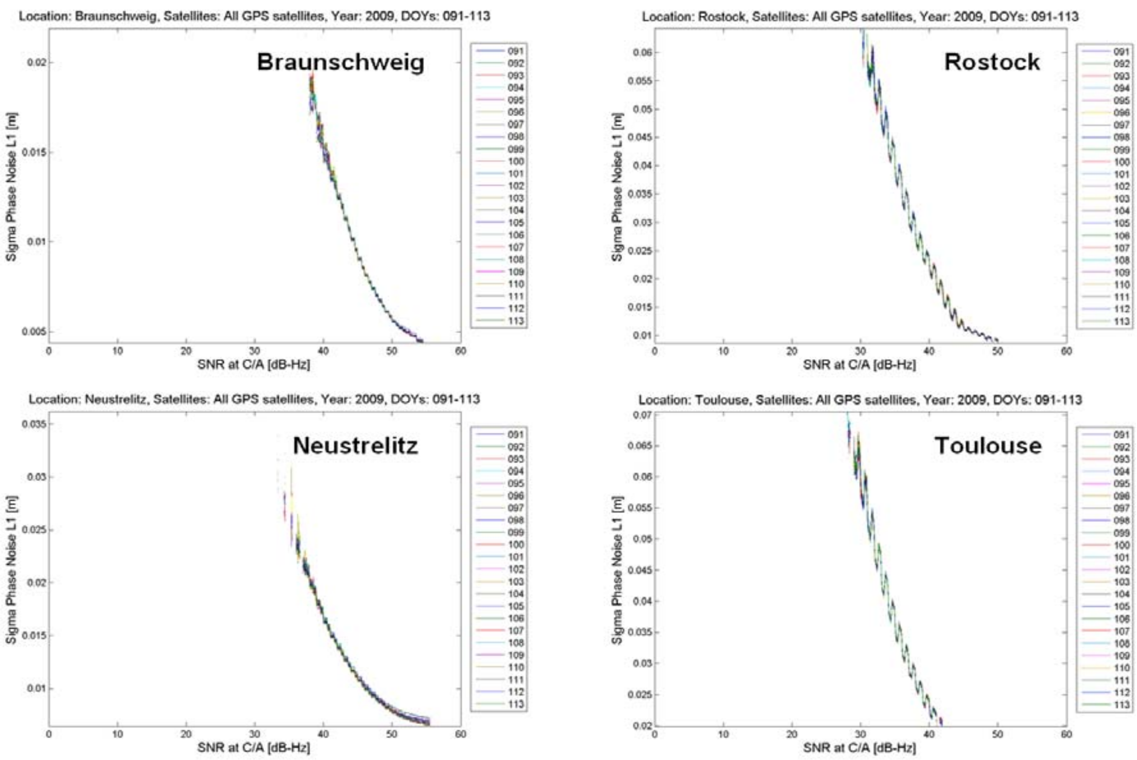

Figure 8: Standard deviation of the phase noise at L1 plotted against SNR for each GBAS station at 23 successive days in 2009 (DOY 91 – 113, different colours)

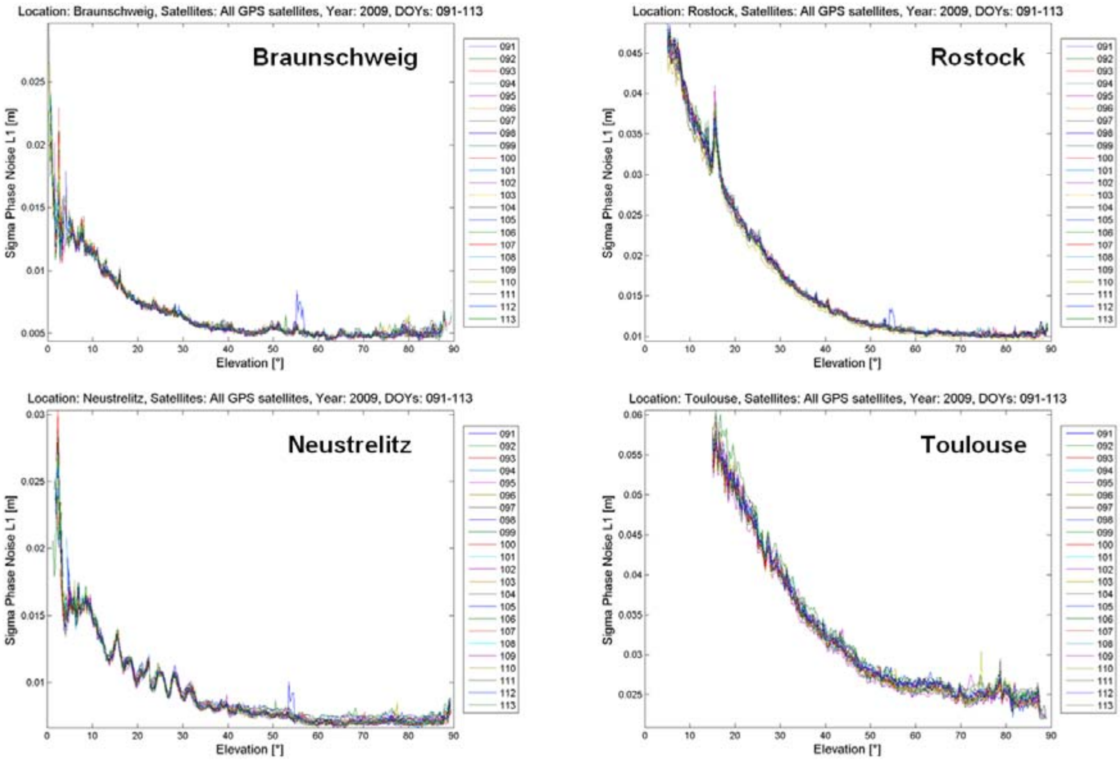

Figure 9: Standard deviation of the phase noise at L1 plotted against elevation for each GBAS station at 23 successive days in 2009 (DOY 91 – 113, different colours)

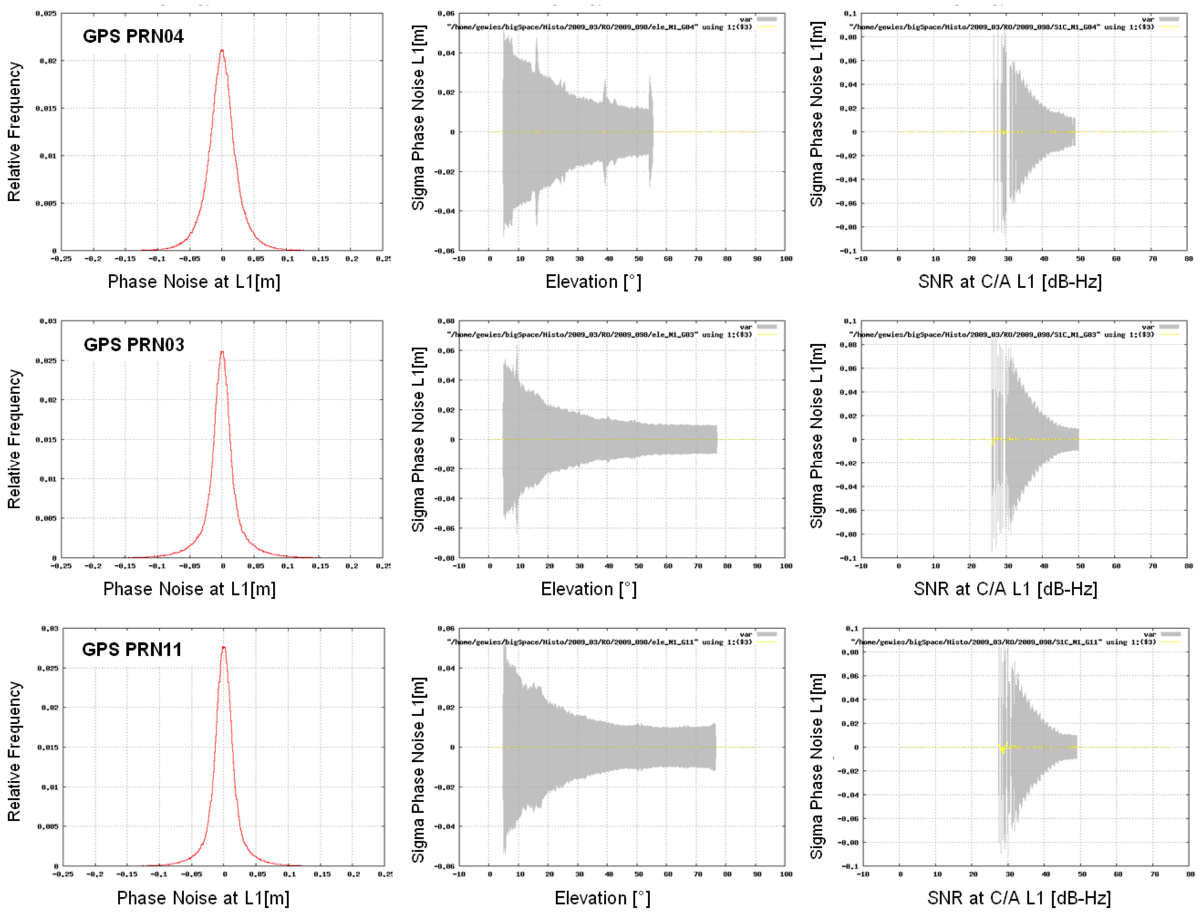

Figure 10: pdf of Phase Noise and 2D plots of Sigma Phase Noise al L1 against elevation and SNR at CA/L1 for GPS Satellites PRN04, PRN03 and PRN11 at 8th of April (DOY 98) for ALEGRO GBAS station Rostock

The SNR related plots given in Figure 8 demonstrate that the standard deviation of phase noise follows nearly the same behaviour at each successive day. When comparing the station's plots, a site-specific behaviour concerning the value range can be observed. At Toulouse site this effect is visible by the compression of the curve to a

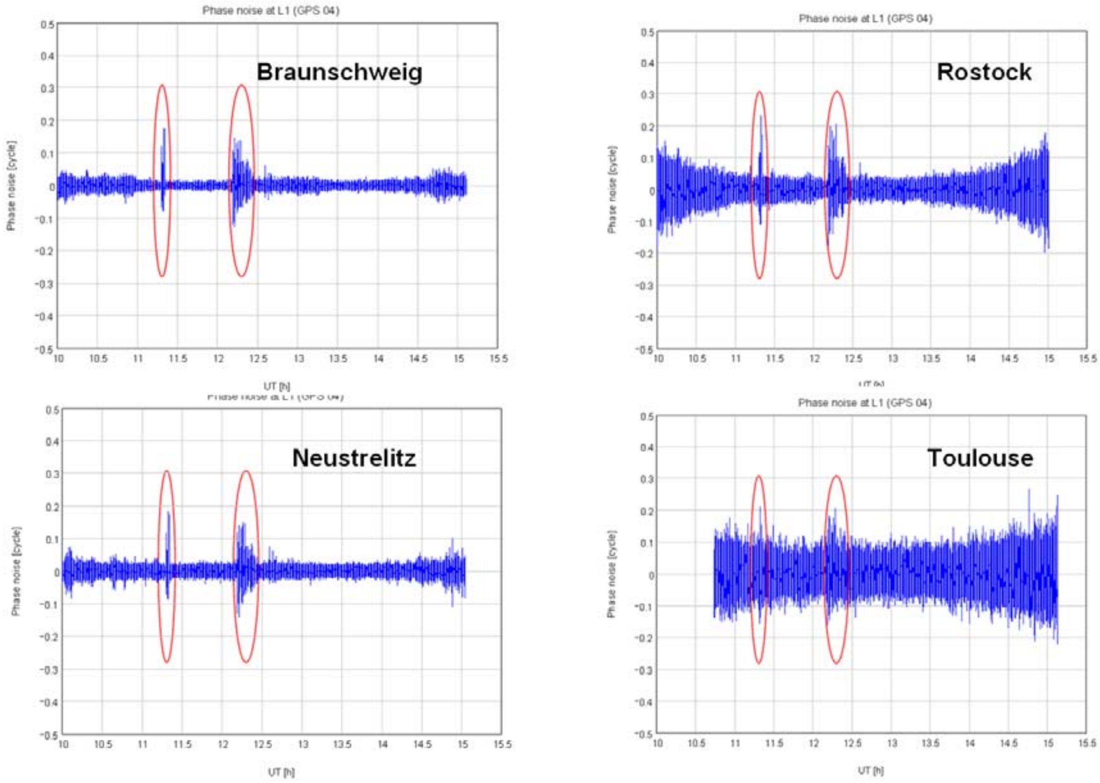

Figure 11: Time series of Phase Noise at L1 for GPS Satellite PRN4 at the four different stations (red ellipses show the occurrence of anomalies)

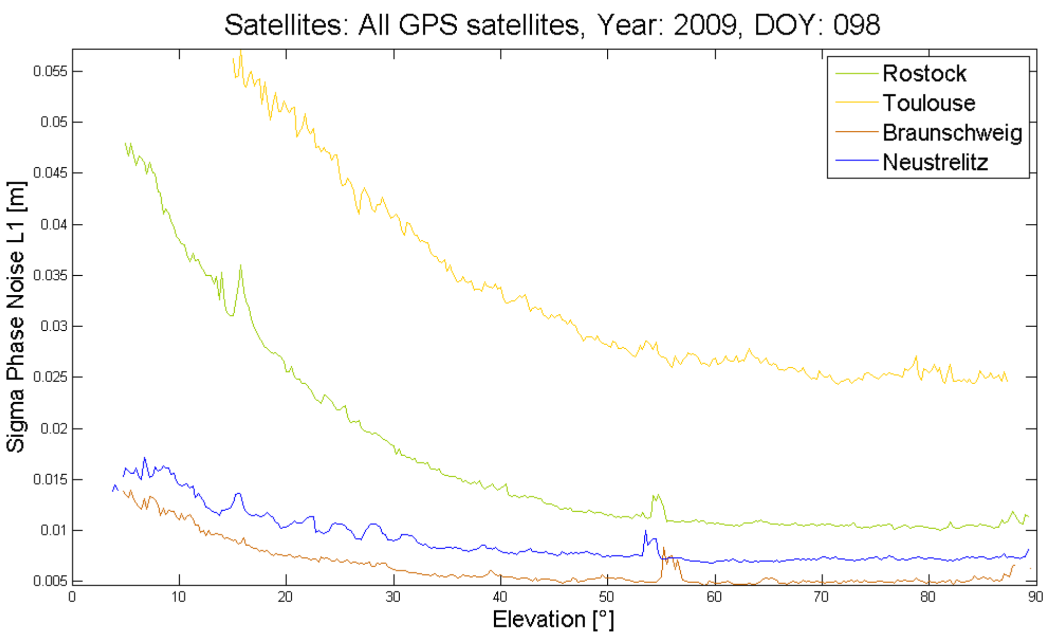

Figure 12: Standard deviation of the phase noise at L1 plotted against elevation for all four stations at DOY98

smaller value range. The smaller SNR values are a possible explanation for the higher values range of the code and phase noise represented in Figure 6 and Table 4. The increase of the value range of the estimated multipath errors (Figure 7) can be explained by the overlaid residual bias term of code noise resulting from the applied filtering technique.

In the plots of Figure 8 and Figure 9 the data of all days are included. Especially in Figure 9 the blue curve of the day 98 (DOY98 or 8th of April) shows a significant deviation between 50° and 60° in comparison to all others DOY's. A detailed analysis of this effect has led to the conclusion that GPS satellite PRN04 was affected by anomalies.

In Figure 10 these effect becomes visible by a wider spreading of the phase noise pdf and the outliers in the 2D plot of dependencies between elevation and sigma phase noise for higher elevations. The same behaviour could be verified for all other stations, too.

Looking at the specific time series of phase noise of GPS satellite PRN04 at DOY98 two anomalies between 11:00 and 12:30 UTC can be monitored (see red ellipses in Figure 11). 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 pdf and 2D plots (for the 2D plot see Figure 12). Due to the fact that the anomaly can be observed at all stations, it can be assumed that this effect is induced by a problem of the GPS satellite PRN04 itself. Hence the applied method of a-priori defined value ranges can be used to detect disturbances.

6 SUMMARY AND CONCLUSIONS

In the first part of the paper an approach for a statistical processor as part of the GNSS performance assessment facility (GPAF) was outlined. In detail the statistical processor supports the derivation of reference values (threshold levels) for each quantity parameter and can also be used to detect disturbed satellites at pre-processing level in real time.

The analysis of statistical data for the ALEGRO GBAS station of Rostock has delivered a first set of threshold levels in dependency of typical confidence intervals.

The comparative analysis between the ALEGRO GBAS station and three other stations deployed with different equipment but operated with the same configuration concerning internal signal processing has shown that each station has to be considered separately. This means that general approaches related to the use of standard reference values can lead to misinterpretations of the observed data and should be avoided. This clearly shows that a proper station calibration using a long term statistical analysis is essential.

A critical point of the applied method is the occurrence of samples outside the a-priori defined value range. This can be an identifier for a worse specification of the a-priori value range with respect to the nominal behaviour of the parameter. Otherwise the occurrence of irregular propagation effects and signal interferences could result into quality parameters, which are outside the regular value range and interpreted as outlier.

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 ALEGRO GBAS system.

7 ACKNOWLEDGMENTS

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