

# Algorithms and Performance of the EGNOS CPF Independent Check Set

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## BIOGRAPHIES

Dr. Wolfgang Werner received in 1994 a diploma in Computer Science from the University of Technology in Munich. He worked as a Research Associate at IfEN in the field of high precision DGPS, ambiguity resolution and APL (airport pseudolite) research. In 2000 he received his PhD from the University FAF Munich. Since 1999 he is Technical Director of IfEN GmbH.

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Robert Wolf studied Aerospace Engineering at the Technical University of Munich. In 1995 he received his diploma degree and entered the Institute of Geodesy and Navigation, University FAF Munich, as a research associate. He worked in the field of hybrid GPS / INS navigation and later on precise orbit simulation and orbit estimation. He contributed to German and European studies concerned with onboard satellite state estimation and inter satellite ranging. Since 1999 he is working for IfEN GmbH. He is currently involved in the development of the EGNOS CPF Check Set algorithms and integration into the EGNOS end-to-end simulator.

## ABSTRACT

One of the main objectives of the European Geostationary Navigation Overlay System (EGNOS) is the protection of the user by offering not only position accuracy but also service integrity. For this reason the Central Processing Facility (CPF) is divided into two sets: the Processing Set (PS) and the Independent Check Set (CS). While the task of the PS is to generate ionosphere as well as ephemeris and clock corrections with corresponding error bounds, the CS

is in charge of verifying the correctness of this information by checking the whole set of NOF (Navigation Overlay Frame) messages independently.

Two main issues have to be addressed by the CS to ensure the user's integrity: the integrity of satellite corrections on the one hand and of the ionospheric corrections on the other hand. For each of these two types of corrections error bounds are transmitted to the user. These are the User Differential Range Error (UDRE) for satellite corrections and the Grid Ionospheric Vertical Error (GIVE) for ionospheric corrections.

Two key requirements are conflicting with each other: integrity and continuity of service. Concerning the Check Set, the continuity of service corresponds to the false alarm rate and implicitly determines decision thresholds, while the integrity requirement corresponds to misdetection probabilities in given error situations. When the PS-provided error bounds are close to the true minimum error bounds, the CS false-alarm probability will increase, thus leading to a probable "don't use" for a satellite or ionospheric correction and hence to a continuity of service problem. However, when the error bounds are conservative (thus raising integrity), the continuity of service at user level might be endangered through his protection level equations for a given phase of flight.

The achievable overall performance depends on a wide variety of key parameters, like measurement accuracy, number of monitoring stations and observability of the ionosphere. This paper describes the CS algorithms that have been developed within the EGNOS project and presents some results concerning their performance figures in terms of integrity and continuity of service.

## INTRODUCTION

In literature many papers can be found on WAAS (Wide Area Augmentation System) or EGNOS discussing integrity and continuity from a system point of view (e.g. [1], [2]). The requirements for WAAS are derived from

RTCA standards (WAAS MOPS [3], [4]). For reasons of interoperability they are also applicable to EGNOS.

In this paper a view on performance issues is presented from set level view of the EGNOS CPF Independent Check Set. The paper details for the first time individual performances of the algorithms (algorithmic limitations) rather than the risk allocation coming down from system level.

One of the main algorithmic limitations is that, due to the demanding time-to-alarm requirement, long-term filters are allowed only to remove noise on measurements, but not for monitoring some system properties like satellite orbital errors, as these could change suddenly. To ensure the users' integrity even in these cases, instantaneous algorithms have been developed for checking the EGNOS signal-in-space (SIS).

### CPF CS PHILOSOPHY

The primary task of the CPF Independent Check Set (CPF CS) is to protect the user from invalid EGNOS system data ("misleading information", MI). This type of information could result in a position computation that is outside the accuracy specifications and must therefore be avoided. If there is no timely warning to the user, then the misleading information becomes "hazardous misleading information" (HMI) and will have severe consequences. Any occurrence of such situations has to be avoided in any case.

Due to this reason, the EGNOS system has to be quite conservative in order to be able to detect such situations and raise an alarm in very short time. The time span allowed for the system to raise an alarm is dependent on the users' requirements, with CAT-I precision approach requirements being the most demanding. The time to alarm there must not exceed 6 seconds.

The EGNOS system does not provide position information to the user, but only ranging information (corrections for the users' satellite pseudorange measurements) and integrity information. This leaves open the actual satellite geometry the user is using, and simultaneously imposes demanding requirements on the CS.

In principle, there are two possibilities to verify the user's integrity in EGNOS:

- Check the user's integrity in position domain, and
- Check the user's integrity in pseudorange domain.

There are several advantages and disadvantages involved in the one or other check:

Position Domain
+ Verify the user computations' end product
- Enormous computation power needed
- User-satellite geometry not known at ground segment
- Very limited statistical fault detection and isolation capability
- Two integrity tests (at user and ground segment levels) working similarly

Pseudorange Domain
- Verify pseudorange corrections only
+ Moderate computation power needed
+ User-satellite geometry information not needed
- Transformation from PR domain to position domain not known
+ Good statistical fault detection and isolation capability
+ Ground segment integrity is complemented by user's RAIM

Due to the advantages and disadvantages given above, the philosophy of the CS is to check the user's integrity mainly in pseudorange domain. This pseudorange domain check, however, will be complemented by a rough position domain check.

Due to the demanding time-to-alarm requirement, only about 50 ms are available for the CS to check the EGNOS integrity of a new message that is to be sent to the user. For this reason, it is not possible to guarantee the full integrity of the EGNOS information including the new message by detecting and isolating any potential correction fault. Therefore, the CS contains two main checking subsets. These are the Check After Down-link subset, and the Check Before Up-Link subset. While the Check Before Up-link is limited to the above mentioned 50 ms of time between receiving the new message from the PS and sending it to the up-link station (NLES), the Check After Down-Link is allowed about 500 ms of time.

Due to the limited time allowed for the Check Before, the tests performed here are only rough statistical tests with no isolation capability. However, these rough tests include a position domain test (user like) as well as a simple combined (satellite and ionospheric) correction pseudorange test. So, the CS is designed in such a way, that misleading information may be sent to the user (at low probability), but has to be detected at least when this information has been received from the RIMS and sent again to the CPF.

The integrity of the current active set of EGNOS information will then be verified by the more thorough Check After subset. The Check After subset will perform statistical tests to verify the correct transmitted bounding levels for satellite corrections (UDRE) and for ionospheric corrections (GIVE). For the Check After subset not only fault detection, but also fault isolation is possible, because of the less limited allocated time interval. The high performance required necessitates statistical tests that are not only user-like. For the UDRE check, all measurements to one single satellite are combined to obtain maximum statistical information of this satellite and the quality of the correction to its pseudorange. The UDRE check therefore is partially user-like, in that the EGNOS corrections are applied to the pseudoranges, but then deviates from the user concept by making use of the whole RIMS network.

The GIVE check is even less user-like than the UDRE check. It combines all ionospheric information (from dual-frequency GPS measurements) in a single estimation for the ionospheric delay at the EGNOS ionospheric grid points (IGPs). This estimation is then compared against the value given by the PS and its error bound. If the CS GIVD (grid ionospheric vertical delay) estimation deviates significantly from the PS GIVD estimation and its error bound limit, a “don’t use” will be raised. The GIVE check is thus not at all user-like, but more PS-like. The reason for this approach is, that not only failure detection but also isolation is required, so the best way is to re-compute the value that should be checked (with independent RIMS data).

Note that a single EGNOS message can not be tested per se, because its content is only valid and useful in the context of the set of already transmitted EGNOS messages. Therefore, no EGNOS message can be checked for integrity at a stand-alone basis, but can only be checked when the EGNOS message context (history of previous messages) is available.

### CHECK SET ARCHITECTURE

A top-level view of the CS architecture and its main internal interfaces between CS subsets as well as external interfaces to RIMS, NLES and PS is presented in Fig.1. In principle the CS also has interfaces to CCF for commanding the operational CS, archiving data etc, but focus is given to performance relevant parts concerning the core algorithms rather than operational issues.

The CS is designed to check up to three different GEO NOF lanes. Therefore, for each of the operational NOF lanes there is an instance of one Check After and one Check Before subset (named CKAOpX and CKBOpX in the figure). Additionally, there are three unique subsets:

Pre-processing & Validation (Pre&Val), Check After of the internal lane (CKAInt) and the Quality of Service (QoS) subset.

In the following the four different types of CS subsets

- Pre-processing & Validation
- Check After
- Check Before
- Quality of Service

are briefly explained.

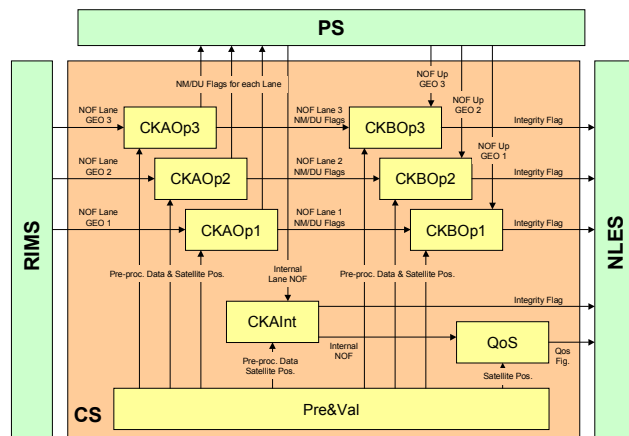


Figure 1: CS top-level architecture

### Pre-Processing & Validation

The main task of the Pre-processing & Validation subset is to provide pre-processed measurements to the Check After and Check Before subsets. These measurements have to be as “clean” as possible to enable the checking subsets to decide whether NOF integrity is ensured or not.

Therefore, many plausibility checks on the raw measurements have to be performed. These include validation of pseudorange and carrier-phase measurements (range variation checks as well as range cross-checks), multipath detection and exclusion, cycle-slip detection and repair.

Moreover, all input data received from RIMS have to be validated. This includes validation of navigation data (ephemeris data as well as almanac data), validation of time, validation of ionospheric parameters (for the GPS Klobuchar model), UTC and GLONASS time offsets etc.

Measurement data have to be pre-processed and prepared for input to the check subsets. This includes correction of tropospheric and other effects. To reduce receiver noise to a minimum, a carrier-smoothed pseudorange is computed. Finally, the ionospheric-free combination as well as the ionospheric observable (delay) are computed

and provided to the Check After. Non-ionospheric-free pseudoranges are provided to the Check Before, because in its user-like design this subset applies ionospheric corrections from the NOF to be checked.

### Check After

As already mentioned, the Check After is the heart of the CS. Its task is to verify the integrity of the broadcast corrections. Therefore, two main statistical tests are implemented. One test is designed to check the correctness of the satellite corrections (called UDRE check), while the other one is designed to check the ionospheric corrections (called GIVE check).

These two tests are the core of the CS and their algorithms as well as their performance will be detailed in the next sections. For both (satellite as well as ionospheric) types of corrections fault detection and isolation is requested. Therefore the algorithms have to be designed appropriately.

### Check Before

Due to the limited allocated computation time for the Check Before, only rough checks on the integrity of the NOF (including the next NOF message to be up-linked) can be made. Currently, there are two main tests foreseen for the Check Before: a position domain VPL (vertical protection level) test as well as a rough UDRE/GIVE combined pseudorange residual test is performed. Due to the limited time, fault detection, but no fault isolation is performed here.

Due to the severe consequences of a failed Check Before test (CPF non-integrity flag is raised), it can only serve as a rough check that detects big errors.

In the present paper the focus is laid upon the core algorithms of the CS, which are implemented in the Check After. Therefore, no details will be given on the Check Before algorithms.

### Quality of Service

The Quality of Service module is responsible for generating a Quality of Service figure. This figure gives a first glance of the CPF integrity and quality to NLES, easing the select CPF function of the NLES. The Quality of Service figure is computed based on a weighted mean of typical vertical protection levels, as seen from arbitrary users at several pre-defined locations (main airports within the service area).

As this module is not of importance for performance of the overall CS, it is not discussed further in this paper.

## UDRE CHECK ALGORITHM

The task of the UDRE check is to verify, whether the broadcast UDRE is bounding the residual orbit and satellite clock errors sufficiently. As, however, the true worst-user residual orbit and satellite clock error is not known, an estimation has to be used.

Figure 2 illustrates the UDRE validation problem of the CPF CS.

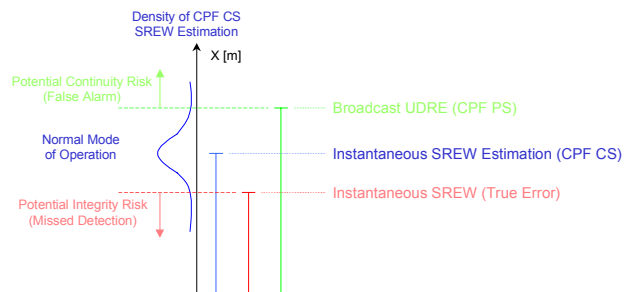


Figure 2: Illustration of the UDRE validation task of the CPF CS

It must be guaranteed that the true SREW is sufficiently bounded by the broadcast UDRE of the CPS PS. Fig. 2 shows the normal operation case, where the broadcast UDRE is above the true instantaneous SREW, and also above the CPF CS estimated SREW. In this case, no alarm will be raised and integrity is ensured. The broadcast UDRE is considered as fix at any instant in time and is therefore seen from an objective point of view. The CS SREW estimation is a random variable, as it depends on CS estimation errors, introduced by measurement noise.

In case that the SREW estimation is above the broadcast UDRE, an alarm will be raised, as it cannot be ensured that the true SREW is bounded sufficiently. Whether this is a false-alarm is dependent on the relation of both values to the true SREW.

On the other hand, if the CS SREW estimation is below the broadcast UDRE, no alarm will be raised, assuming that the own SREW estimation is bounding the true SREW with sufficient confidence. This, of course, leads to a potential integrity risk, when the CS SREW estimation is below the true SREW.

For these reasons, it can be seen that there are two critical parameters for the CS UDRE check: the shape of the SREW estimation distribution and the conservativity of the broadcast UDRE with respect to the true SREW.

To obtain maximum information from a statistical UDRE test, all available data for a considered satellite has to be gathered from the RIMS network.

After the satellite corrections have been applied to the ionospheric-free pseudoranges provided by the Pre&Val subset, the basic observation equation can be written in the following form:

$$R_{sm,r}^i = \rho_r^i + \delta_r - \delta_{res}^i + \delta_{Orb,r,res}^i + v_{r,Rsm}^i \quad (1)$$

with

- $R_{sm,r}^i$  smoothed pseudorange from RIMS r to satellite i,
- $\rho_r^i$  true geometric range between RIMS r and satellite i,
- $\delta_r$  clock error of RIMS r,
- $\delta_{res}^i$  residual clock error of satellite i,
- $\delta_{Orb,r,res}^i$  residual orbit error of satellite i,
- $v_{r,Rsm}^i$  noise and other unmodelled effects.

To obtain the true correction residuals, the RIMS-specific clock bias has to be eliminated from the measurements. The RIMS clock bias can be easily computed as the mean of all pseudorange residuals of the RIMS. However, this implies that all (or at least most) of the corrections are correct and necessitates a certain isolation logic (see below).

The result then is:

$$\mathcal{E}_r^i = \mathcal{E}_{r,clk}^i - \frac{1}{n} \sum_{k=1}^n \mathcal{E}_{r,clk}^k = -\mathcal{E}_{res}^i + \mathcal{E}_{Orb,r,res}^i + \mathcal{E}_{r,v}^i \quad (2)$$

with the definitions

$$\mathcal{E}_{res}^i = \left( \delta_{res}^i - \frac{1}{n} \sum_{k=1}^n \delta_{res}^k \right) \quad (3a)$$

$$\mathcal{E}_{Orb,r,res}^i = \left( \delta_{Orb,r,res}^i - \frac{1}{n} \sum_{k=1}^n \delta_{Orb,r,res}^k \right) \quad (3b)$$

$$\mathcal{E}_{r,v}^i = \left( v_{r,Rsm}^i - \frac{1}{n} \sum_{k=1}^n v_{r,Rsm}^k \right) \quad (3c)$$

and n being the number of satellites tracked at the considered RIMS.

As can be seen from equations (2) and (3a-c), residual satellite orbital errors and satellite clock errors can be monitored nearly directly in these correction residuals.

If only satellite residual clock errors were to be considered, a (weighted) mean of all residuals of the considered satellite would give a good monitor with quite simple probability density function dependent on measurement noise and residual tropospheric effects.

However, as in the UDRE bound orbital errors should also be covered, some more sophisticated approach is necessary.

Analysing the effects of some arbitrary (residual) satellite orbit error on a user at some location within the service area, it turns out that the orbit error translates to a residual surface that can be approximated by a simple plane.

Figures 3a and 3b show two examples of the effects of an orbit error on the pseudoranges of a monitor within ECAC.

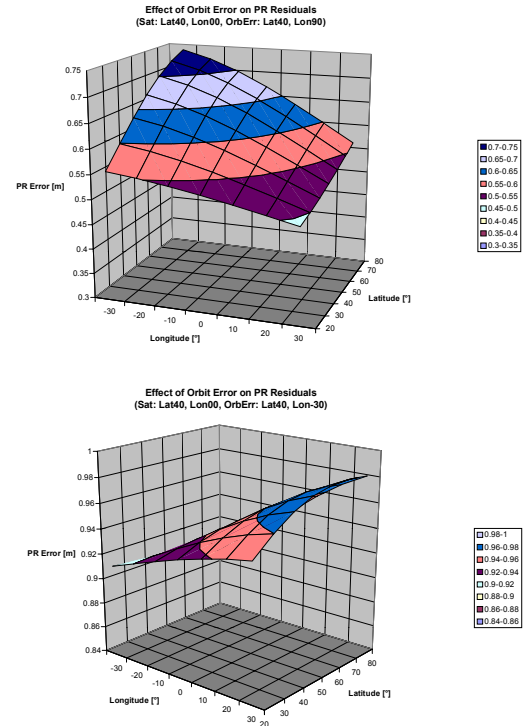


Figure 3a,b: Effects of example orbit errors on pseudorange measurements of a monitor within ECAC

This plane has to be estimated and extrapolated to the worst user location. This worst user location must be within the EGNOS service area and simultaneously in the considered satellite footprint. The value of the plane at the worst user location is called satellite residual error at worst user location (SREW).

From all the pseudorange measurements (at different RIMS locations) to one single satellite the corresponding bias plane can be estimated. The plane will be determined

by estimating three parameters: the value of the plane at some arbitrary reference point ( $f_{Bias}(\lambda_0, \phi_0)$ ) and two gradients in latitudinal and longitudinal direction ( $\alpha$  and  $\beta$ ). Therefore, the plane can be represented by the following formula (4):

$$f_{Bias}(\lambda, \phi) = f_{Bias}(\lambda_0, \phi_0) + \alpha \cdot (\lambda - \lambda_0) + \beta \cdot (\phi - \phi_0) \quad (4)$$

After having solved the appropriate linear equation system, the estimation of the SREW value can then be written in the following form:

$$SREW_{CS,estimated} = \max_{\lambda, \phi} \left( |f_{Bias}(\lambda, \phi)| + k \cdot \sqrt{Var(f_{Bias}(\lambda, \phi))} \right) \quad (5)$$

Linked to the estimation of this bias plane is some uncertainty in the plane due to measurement noise. Note that the term  $Var(f_{Bias}(\lambda, \phi))$  is geometry dependent and some a priori measurement noise has to be assumed. Note further, that the empirical noise of the measurement cannot be taken as a priori noise, because smoothed pseudoranges are processed and over-optimistic precision values would be obtained. It must be ensured that (residual) tropospheric and other unmodelled effects have to be bounded by this a priori noise.

This uncertainty (scaled to a sigma value) can then be multiplied by some constant k for tuning the conservativity of the CS UDRE estimation. This parameter will have severe consequences with respect to false-alarm rates and missed-detection probabilities and, thus, the risk apportionment between Integrity and Continuity.

An alarm (“don’t use” flag) for the satellite is raised, if the estimated SREW exceeds the broadcast UDRE. This flag is then transmitted to the PS and has to be incorporated in the broadcast information immediately, to ensure the users’ integrity.

Special attention must be paid to the case, when the UDRE check algorithm has indeed detected a correction error. In this case, some special isolation logic has to be applied. Note that a faulty satellite correction has effects on many satellite correction checks, not only on the single check for this satellite. This is due to the fact that the RIMS clock errors can only be computed reliably using more than a single measurement from a single satellite, i.e. several corrected satellite pseudorange measurements are used in the clock error computation. A faulty satellite correction thus could affect all satellite correction checks,

which are connected to the faulty satellite correction via a common RIMS clock error.

The isolation logic used in the UDRE check algorithm is based on the fact that the statistical check of the true error will provide a much worse test statistic than any other influenced check. Due to the accumulation of statistical information in these checks, such a fault isolation is more reliable than a single RAIM algorithm would be, when it were applied on a per RIMS basis.

After this worst test has been isolated through a dependency analysis, an iteration in clock error computations and a partial repetition of the remaining statistical tests is necessary.

Note that the UDRE and the GIVE check can be considered as independent with respect to detected failures, because the input to the UDRE check are clean ionosphere-free pseudoranges, while the GIVE check bases on the ionospheric observables from dual-frequency measurements. In these potential clock errors cancel, and thus GIVE checks are independent from UDRE check results.

## UDRE CHECK PERFORMANCE

Due to the non-linear and geometry-dependent operations involved in the SREW determination, a statistical analysis is very difficult.

For this reason, intensive simulations have been carried out. The following steps and parameters have been used for the simulations:

- Number of simulation runs: 50000
- Simulated satellite position in latitude and longitude has been randomised
- Visibility has been computed and if the visibility was between DOC (depth of coverage, i.e. number of RIMS monitoring the satellite) 3 and 10 the simulation run has been continued. Otherwise, a new satellite position has been determined. (The reason for this decision is, that these cases of low DOC are the critical cases, where low performances must be anticipated.)
- True SREW was computed in each constellation
- For each of these constellations, 1000 runs have been carried out with varied simulated measurements
- CS SREW estimation performed for each case

The effects of the following key parameters have been analysed:

- Size of residual orbit error
- Noise of pre-processed measurements (including any residual tropospheric effects)
- Conservativity factor k

Figures 4 to 7 present some of the results.

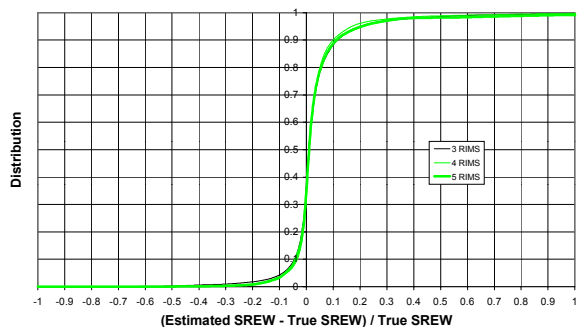


Figure 4: Distribution of estimated SREW (residual orbit error 5.0 m (one sigma), pre-processing noise 0.05 m (one sigma), conservativity  $k = 0$ )

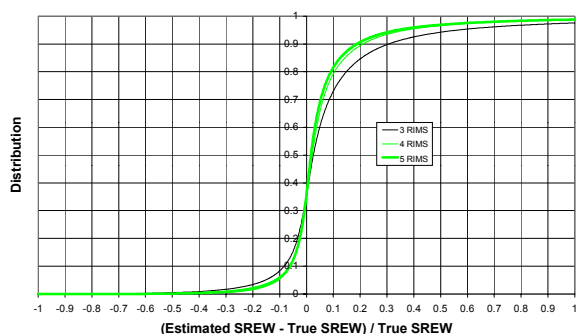


Figure 5: Distribution of estimated SREW (residual orbit error 5.0 m (one sigma), pre-processing noise 0.20 m (one sigma), conservativity  $k = 0$ )

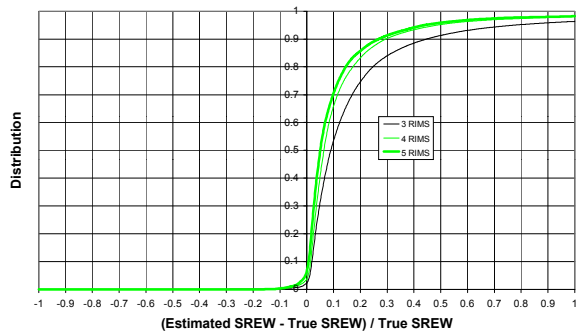


Figure 6: Distribution of estimated SREW (residual orbit error 5.0 m (one sigma), pre-processing noise 0.05 m (one sigma), conservativity  $k = 3.29$ )

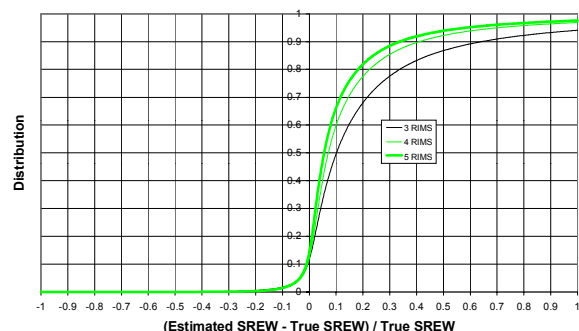


Figure 7: Distribution of estimated SREW (residual orbit error 5.0 m (one sigma), pre-processing noise 0.20 m (one sigma), conservativity  $k = 3.29$ )

As the critical results can be found in those cases, where only a few measurements to a satellite are available, the cases of having 3, 4 or 5 RIMS are considered especially.

All figures give distribution curves of the CS SREW estimation. The x-axis of the figures depicts the relative level of over-/under-bounding the true SREW (in percentage), whereas the y-axis gives the accumulated probability for a result beyond the given x-axis value.

So, from the figures the conditional probabilities for missed detection and false alarm can easily be derived.

E.g. in fig. 4 the curve values at -0.2 and -0.1 are about 0.03 and 0.05 for all curves. This translates into a conditional probability for missed detection of 0.02 (or 2 %) at relative level of under-bounding between 10 to 20 %. I.e., if the PS relative level of under-bounding is about 10 to 20 % of the true SREW, the conditional probability for missed detection will be about 2 %.

Furthermore, e.g. in the same figure, the curve values at 0.3 and 0.4 are about 0.98 and 0.99 for all curves. This translates to a conditional false alarm probability of 0.01 (or 1 %) at relative level of over-bounding of 30 to 40 %. I.e., if the PS relative level of over-bounding is about 30 to 40 % of the true SREW, the conditional probability for false alarm will be about 1 %.

As can be seen from figures 6 and 7 (conservativity factor set to 3.29), an under-estimation of the true SREW is very unlikely. However, the false-alarm risk is much higher than in the case of conservativity 0. In fact the false-alarm probability will become much too high considering the number of checks that have to be performed each epoch.

The fine-tuning and harmonisation of the UDRE check behaviour has to be performed thoroughly and in consideration of the PS side of the CPF algorithms. The probabilities that can be obtained from the figures as presented here are conditional probability figures. To

achieve the necessary overall performance at CPF level, the probability density function of the broadcast UDRE with respect to the SREW (over- or under-bounding probabilities) must be known in addition to the probabilities given here.

### GIVE CHECK ALGORITHM

An estimate of the vertical delay at the grid point is derived from one single measurement at the pierce point by assuming

$$\tilde{d}_{IGP,r}^i = \alpha_{IPP,r}^i \cdot (d_{IGP})_{Model} \quad (6)$$

with

$$\alpha_{IPP,r}^i = \frac{d_{IPP,r}^i}{(d_{IPP,r}^i)_{Model}} \quad (7)$$

being the ratio between the measured delay at the pierce point and the model delay at the pierce point. The estimated vertical ionospheric delay is then derived from a weighted mean of the single measurement estimates

$$\hat{d}_{IGP} = \frac{1}{\sum_{N_{IPP,IGP}} w_{IPP,IGP,r}^i} \cdot \sum_{N_{IPP,IGP}} (w_{IPP,IGP,r}^i \cdot \tilde{d}_{IGP,r}^i) \quad (8)$$

With  $N_{IPP,IGP}$  being the number of pierce points lying "in the vicinity" of the grid point and the weights of the single measurement  $w^i$ . The weighting factors  $w^i$  are derived from an a-priori function for the spatial ionospheric correlation divided by the standard deviation of the vertical delay at the pierce point.

$$w_{IPP,IGP,r}^i = \frac{e^{-\left(\frac{\Psi_{IPP,IGP,r}^i}{\Psi_0}\right)^2}}{\sigma_{d_{IPP,r}^i}} \quad (9)$$

$\Psi_{IPP,IGP,r}^i$  is the spherical distance between one pierce point and one grid point.

$$\Psi_{IPP,IGP,r}^i = \cos^{-1} \left( \begin{array}{l} \sin \phi_{IPP,r}^i \cdot \cos \phi_{IGP} \\ + \cos \phi_{IPP,r}^i \cdot \cos \phi_{IGP} \cdot \cos(\lambda_{IPP,r}^i - \lambda_{IGP}) \end{array} \right) \quad (10)$$

It is scaled by the spatial ionospheric correlation parameter  $\Psi_0$ . In the current design this parameter is set to 2.9°. The actual check is performed by comparing the difference between estimated vertical delay at the grid point and GIVD with the error bound (GIVE).

$$\left| \hat{d}_{IGP} - GIVD_{IGP} \right| \leq GIVE_{IGP} \quad (11)$$

If the above condition is violated, the GIVE check sets the corresponding flag for this IGP to "Don't Use", otherwise it is set to "Monitored".

For  $N_{IPP,IGP} = 0$ , i.e. no pierce point fulfils the minimum weight condition, the GIVE check can not be performed at all for this IGP, and the corresponding flag for this grid point is set to "Not Monitored".

The following table summarises the GIVE check results with corresponding conditions:

Result	Condition
$f_{IGP} =$ "Monitored"	$\left  \hat{d}_{IGP} - GIVD_{IGP} \right  \leq GIVE_{IGP} \quad \wedge \quad N_{IPP,IGP} > 0$
$f_{IGP} =$ "Not Monitored"	$N_{IPP,IGP} = 0$
$f_{IGP} =$ "Don't Use"	$\left  \hat{d}_{IGP} - GIVD_{IGP} \right  > GIVE_{IGP} \quad \wedge \quad N_{IPP,IGP} > 0$

Figures 8 and 9 depict the principle of the GIVE check. In figure 8 the GIVE contains misleading information because it does not bound the GIVD error. The red marked (hatched) area indicates the misdetection probability of the GIVE check. In figure 9 the GIVD error is also not zero, but bounded by the broadcast GIVE. In this case the red marked (hatched) area on the left hand side indicates the false alarm probability.

Assuming a Gaussian distribution, the probability to have no alarm can be derived from

$$P_{Non Alarm} = \Phi(\varepsilon_{GIVD} + GIVE) - \Phi(\varepsilon_{GIVD} - GIVE) \quad (12)$$

with the integrated probability density function of the normal distribution

$$\Phi(x) = \frac{1}{\sqrt{2\pi} \cdot \sigma_{CS}} \cdot \int_{-\infty}^x e^{-\frac{t^2}{2\sigma_{CS}^2}} dt \quad (13)$$

The probability of alarm is simply the alternate event.

$$P_{Alarm} = 1 - (\Phi(\varepsilon_{GIVD} + GIVE) - \Phi(\varepsilon_{GIVD} - GIVE)) \quad (14)$$

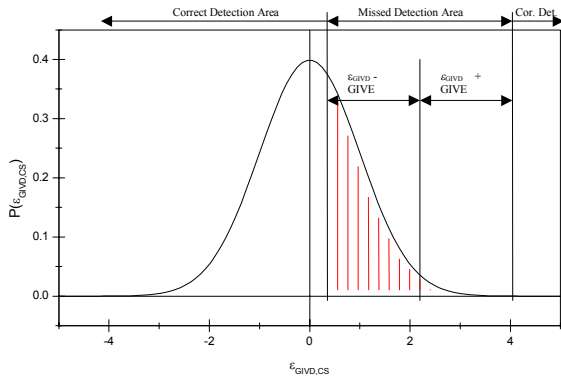


Figure 8: GIVE check misdetection probability

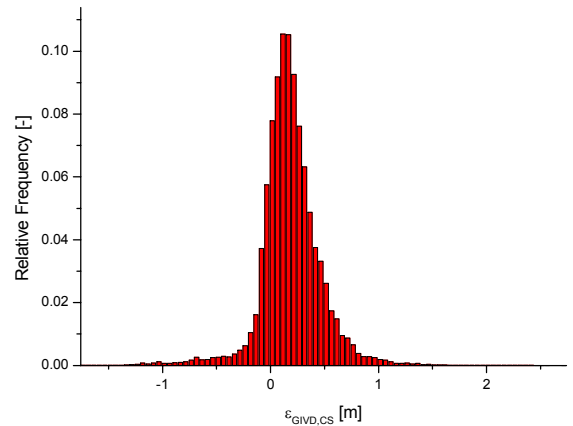


Figure 10: Sample distribution of GIVD estimation error

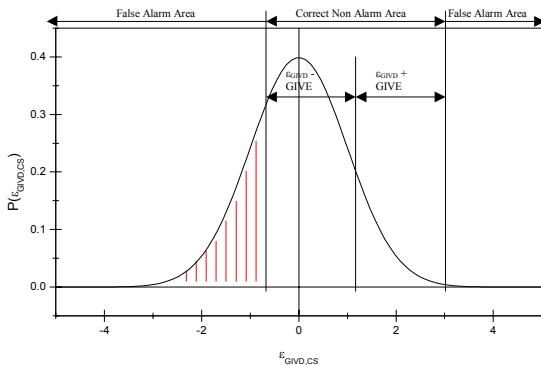


Figure 9: GIVE check false alarm probability

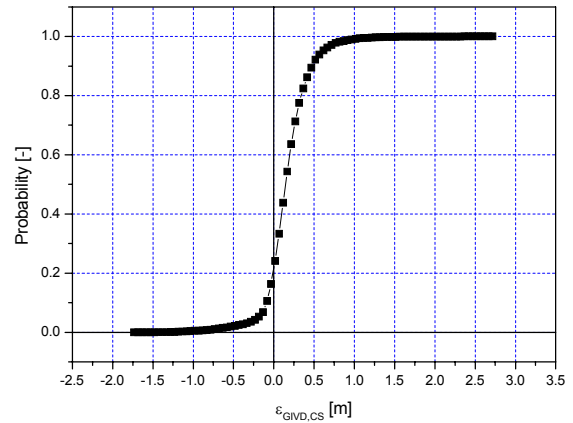


Figure 11: Cumulated probability distribution of GIVE check

An alarm, as well as a non alarm can either be correct or not, according to the following table.

	$\varepsilon_{\text{GIVD}} \leq \text{GIVE}$	$\varepsilon_{\text{GIVD}} > \text{GIVE}$
$P_{\text{Alarm}}$	$P_{\text{False Alarm}}$	correct detection
$P_{\text{Non Alarm}}$	correct non alarm	$P_{\text{Missed Detection}}$

## GIVE CHECK PERFORMANCE

Figure 10 has been derived from simulations in the EGNOS end-to-end simulator using the BENT model as true ionosphere. It shows the histogram of the GIVE check error, i.e. the relative frequency versus Check Set estimation error. Computing statistics of this (significant non-Gaussian) distribution yields:

mean	0.18 m
standard deviation	0.28 m

Due to the long-tailedness of the distribution, the Processing Set will have to add some margin on the GIVE to avoid too many false alarms. The non-zero mean is mostly due to an imperfect estimation of the interfrequency biases.

Figure 11 shows the cumulated probability distribution.

Figure 12 has been derived analytically under the assumption of Gaussian distribution. It shows the alarm probability of the GIVE check, with respect to the ratio of true error ( $\varepsilon_{\text{GIVD}}$ ) to error bound (GIVE). The curves are given for various ratios of Check Set accuracy to Processing Set conservativity.

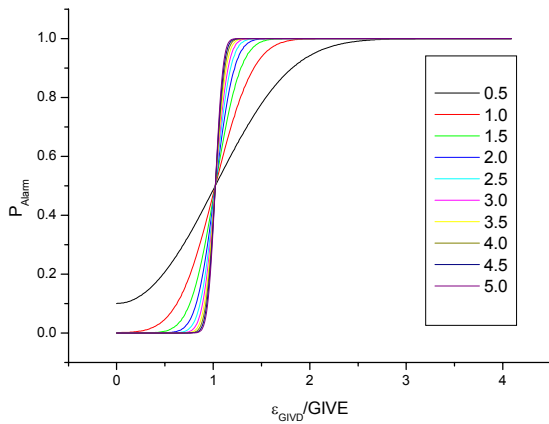


Figure 12: Alarm probabilities vs. relative GIVD error

To achieve a reasonable false alarm rate ( $10^{-7}$  for a GIVD error of 30 % of the broadcast GIVE) the  $\sigma_{\text{GIVE}}$  has to be at least twice as high as the standard deviation of the GIVE Check. Current simulations show that the broadcast GIVE (index) has to be around 4, corresponding to 1.2 m error bound.

## CONCLUSIONS

The core algorithms that have been developed for the EGNOS CPF Independent Check Set have been presented. These are the UDRE check algorithm and the GIVE check algorithm.

Statistical properties and performance results obtained from intensive simulations have been presented. Note that the performance figures with respect to integrity and continuity presented here are only conditional figures at set level. To obtain overall figures at system level (or even at CPF sub-system level), similar results from the second set in the CPF, the PS, must be available.

The following conclusions may be drawn from the results of the simulations:

- There are two critical parameters concerning the UDRE bound check feasibility: the shape of the CS SREW instantaneous estimation distribution and the a priori conservativity of the CPF PS broadcast with respect to the true SREW.
- Similarly, for the GIVE check also two critical parameters are involved: the shape of the GIVD estimation distribution and the CPF PS broadcast GIVE conservativity.
- Difficult tuning of the conservativity parameters between PS and CS is necessary at CPF level to optimise CPF, and hence, EGNOS overall performance. Of course, the number of tests that have

to be performed in a single epoch as well as the correlation times have to be considered.

- The tuning will affect three of the performance parameters: integrity, continuity and availability. If the UDRE/GIVE values are too conservative, there will be no service availability for the user. On the other hand, if the UDRE/GIVE values are too low, either no integrity can be guaranteed, or the continuity risk due to CS false-alarms rises.
- Due to the demanding TTA requirement the exclusion of long-term filters has to be compensated. Therefore, it is important for the CS to have good quality input measurement data from RIMS and as many measurements for each satellite to be monitored as possible to obtain maximum statistical significance.

Note that the demanding CAT I integrity requirement cannot be fulfilled by each statistical test per se, but that a risk allocation has to be made to different components.

First, there has to be a situation, where the user's integrity is not ensured, e.g. due to the CPF PS broadcast UDRE not bounding the true SREW, with some small probability  $p_1$ . Second, this problem is not detected with some conditional missed-detection probability  $p_2$  at CPF CS. Therefore, by assuming statistical independence between PS and CS computations due to independent measurement data, the overall integrity risk for this situation will be only  $p_1 \cdot p_2$ .

Integrating all possible cases then leads to an overall integrity figure for the signal-in-space.

Note further that there is no possibility for the EGNOS ground segment to monitor pure user-local effects. An appropriate risk budget has to be allocated to these cases at user-level (and system-level) therefore.

## ACKNOWLEDGMENTS

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