



**HAL**  
open science

## Integrity Based on MT28 for EGNOS: New Algorithm Formulation & Results

Thierry Authié, Sébastien Trilles, Jean-Claude Fort, Jean-Marc Azaïs

► **To cite this version:**

Thierry Authié, Sébastien Trilles, Jean-Claude Fort, Jean-Marc Azaïs. Integrity Based on MT28 for EGNOS: New Algorithm Formulation & Results. International Technical Meeting of The Satellite Division of the Institute of Navigation (ION GNSS+ 2017), Sep 2017, Portland, United States. pp. 1077-1088. hal-01646740

**HAL Id: hal-01646740**

**<https://hal.science/hal-01646740>**

Submitted on 23 Nov 2017

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



## Open Archive Toulouse Archive Ouverte (OATAO)

OATAO is an open access repository that collects the work of some Toulouse researchers and makes it freely available over the web where possible.

This is an author's version published in: <https://oatao.univ-toulouse.fr/18572>

### To cite this version :

Authié, Thierry and Trilles, Sébastien and Fort, Jean-Claude and Azaïs, Jean-Marc Integrity Based on MT28 for EGNOS: New Algorithm Formulation & Results. (2017) In: International Technical Meeting of The Satellite Division of the Institute of Navigation (ION GNSS+ 2017), 25 September 2017 - 29 September 2017 (Portland, United States).

Any correspondence concerning this service should be sent to the repository administrator:

[tech-oatao@listes-diff.inp-toulouse.fr](mailto:tech-oatao@listes-diff.inp-toulouse.fr)

# Integrity Based on MT28 for EGNOS: New Algorithm Formulation & Results

T. Authié, S. Trilles, *Thales Alenia Space, France*;  
J-C Fort, *MAPSS laboratory, Descartes University, France*;  
J-M Azaïs, *ESP laboratory, Paul Sabatier University, France*

## BIOGRAPHIES

**Thierry Authié** is a specialized engineer in the field space flight dynamics, precise orbit determination and navigation. He received his M.S. degree in Applied Mathematics from the INSA, Toulouse (France) in 2004.

**Sébastien Trilles** is a specialist in Navigation Algorithm and Performance with Thales Alenia Space. He received his Ph.D. degree in Pure Mathematics from the Paul Sabatier University, Toulouse (France) in 2000 and an Advanced M.S. in Space Technology from the ISAE, Toulouse, France in 2003.

**Jean-Claude Fort** is emeritus Professor of probability and statistics at University Paris Descartes. His main topics of research are the stochastic algorithms and more recently the sensitivity analysis of large systems.

**Jean-Marc Azaïs** is a Professor of Statistics and Probability at University of Toulouse. He graduated from Ecole Normale Supérieure (Paris) and is a specialists of Gaussian processes and of Extremes.

## ABSTRACT

The purpose of a Satellite Based Augmentation System, such as EGNOS or WAAS, is to decompose all range error sources and to distribute them to the civil aviation user community with reliable navigation services for different flight phases. Integrity refers to the notion of trust that the user may have in the positioning. Integrity includes the ability of the system to provide confidence thresholds as well as Alarms in case of anomalies.

Considering satellite integrity, two ways are possible for an SBAS. The first is to broadcast per satellite the same UDRE value applicable for every user located inside the service area defined by the message type 27 content. As these UDREs are dimensioned to protect the worst user location – generally at the border zone – it penalizes automatically the users having lower residual errors. The second is to broadcast per satellite a covariance matrix of residual errors through the message type 28. This matrix contains all the structure of the orbitography and synchronization residual errors. It can be seen as a protective ellipsoid around the computed satellite position and clock containing the true – but unknown – satellite position and clock at a certain level of confidence. Using the MT28 message each user is able to reconstruct the integrity value by projecting this protective ellipsoid along its line of sight. EGNOS operational system is implementing the MT27 solution whilst the WAAS is based on the MT28 one. The MT28 approach is the current baseline for EGNOS V3.

Starting from recent R&D activities, Thales Alenia Space together with CNES (French Space Agency) has developed a dedicated module providing the message type 28 based on orbitography and fast synchronization variance-covariance matrices combined with satellites residual measurement errors. The MT28 formulation has been designed in collaboration with Statistics and Probabilities laboratories (Paris Descartes and Toulouse Paul Sabatier) in France. The algorithm contains also a mechanism that reacts immediately to orbit or clock satellite feared events such as a clock jump. This new concept for EGNOS provides a drastic improvement with respect to the first studies provided during EGNOS V3 phase A & B and HISTB V2 by the Thales consortium.

The new MT28 module is integrated into a SPEED platform, the SBAS Operational Test-bed that fully represents EGNOS performances in terms of accuracy, continuity, availability and integrity for Safety Of Life services. The performance evaluation shows a very good level of EGNOS LPV200 availability with respect to the MT27 current approach. The integrity is constantly maintained on the Geostationary Broadcast Area with a good level of integrity margin.

This paper provides a high level architecture description of this new EGNOS algorithm as well as a set of performance figures showing the achieved improvements.

## INTRODUCTION

An SBAS transmits to the users corrections on the position and the clock of the GNSS satellites used for positioning. Next to that the SBAS also provides to the users the means to calculate a confidence interval on the projection over the line of sight of a satellite of the error between the true position and clock of the satellite and the positions and clock calculated by the SBAS. This confidence interval is called the User Differential Range Error (UDRE) in standard L1 MOPS [1], the Dual Frequency Residual Error (DFRE) in standard L5 DFMC. It allows to define the concept of integrity, the notion of trust that the user may have in the positioning and the ability of a system to provide confidence thresholds as well as alarms within the time to alarm in case of anomalies.

These corrections and integrity data put the user in an new navigation context where the accuracy level of the user positioning is monitored and controlled by the SBAS.

According to MOPS and DFMC standards, the residual error associated with the correction applied for a satellite is assumed to follow a normal distribution centred around zero. The variance of this normal distribution is formed by the updated integrity data broadcast by the SBAS plus a sum of degradation factors. According to the two standards, two types of satellite information must be transmitted to the users so that they can calculate their UDRE / DFRE for each satellite. The calculation formula of the UDRE / DFRE user for a satellite is given by:

$$UDRE = 3.29 \cdot \sigma_{UDRE} \cdot \delta UDRE \quad (\text{standard L1 MOPS})$$

$$DFRE = 3.29 \cdot \sigma_{DFRE} \cdot \delta DFRE \quad (\text{standard L5 DFMC})$$

The  $\sigma_{UDRE, DFRE}$  is a scalar value broadcast from Message Type 2-6, 24 in the MOPS standard and Message Type C in standard DFMC.

Following the L1 MOPS standard, the term  $\delta UDRE$  can be formulated in several ways according to the transmission of two radically different Message Type 27 or 28.

The Message Type 27 allows to define a specific set of geographic areas (five at most), either triangular or rectangular shape, with the possibility to broadcast a dedicated  $\delta UDRE$  factor when the user is inside or outside of each area. Currently EGNOS broadcasts a Message Type 27 which sets its value to 1 for a user in the service area and 100 (maximal value) for a user outside the service area. The rationale of this design is to cut the EGNOS monitoring outside the ECAC service area and to guarantee integrity only inside ECAC.

The Message Type 28 broadcasts a  $4 \times 4$  covariance matrix of residual position / clock errors for the satellite in question. An SBAS is not allowed to broadcast both Message Type 27 and 28 in the same NOF.

In standard DFMC, the equivalent of Message Type 27 no longer exists, only the use of the covariance matrix with the Type D message is possible.

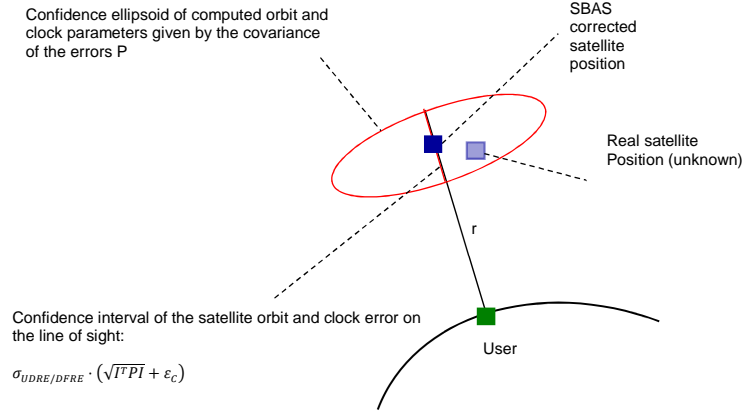
In both situations, Message type 28 or D, the user will compute the terms  $\delta UDRE$  or  $\delta DFRE$  by the following formula described by the standards:

$$\delta UDRE ; \delta DFRE = \sqrt{I^T P I} + \epsilon_c$$

Where:

- $P$  is the  $4 \times 4$  covariance matrix of residual position and clock errors,
- $I$  is a 4 dimensional vector whose the first three component are the unit vector of the line of sight oriented in the direction from the user to the satellite, and the last component is a 1 for the clock,
- $\epsilon_c$  is a term to compensate for the error introduced by the quantization process and obtained from Message Type 10 in standard L1, and from Message Type F in standard L5.

Mathematically, the term  $\sqrt{I^T P I}$  represents the confidence interval at 1 sigma of the error on the line of sight. This is summarized in the following figure:



**Figure 1: UDRE/DFRE computation representation on a line of sight**

Where the quadrivector  $I$  is defined by:

$$I = \left( \frac{x_{sat} - x_{user}}{r}, \frac{y_{sat} - y_{user}}{r}, \frac{z_{sat} - z_{user}}{r}, 1 \right)^T$$

The covariance matrix  $P$  contains the structure of the non-modeled orbit and clock residual error distribution. It depends mainly on the satellite movement, the geometry of the Station-Satellite network and the quality of the measurements. In nominal condition, the dynamics of this matrix is correlated with the propagation of the orbit error that evolves slowly. Consequently the time update of the covariance matrix is consistent to the time update of the slow orbit and clock corrections. Typically the messages 27, 28 or D will be refreshed every 120 seconds or less.

This paper focuses on the development of MT28 according the standard L1 MOPS. Thus the emission of MT28 shall deal with the emission of fast correction MT2-6, 24 and then to define and manage the role of  $\sigma_{UDRE}$  with respect to  $\delta UDRE$  value.

In the following the  $\sigma_{UDRE}$  value is considered without dimension, simply as a factor scalar while the  $\delta UDRE$  bring the unit that is the meter.

## MT28 COMPUTATION

The MT28 contains the satellite residual orbit and clock error covariance. This covariance contains in particular all the information regarding the structure of orbital error in particular in the tangent and normal direction. This covariance is necessary the result of a satellite positioning process using known reference stations coordinates. The structure of the satellite positioning errors depends on different contributions. The geometric distribution of the reference station has a direct impact on the observability direction of the satellite location. The measurement quality i.e. level of code noise, code carrier inconsistency, carrier quality (cycle slip amplitude and detectability) ... has an impact on the satellite positioning confidence level.

The precision of the dynamics applied on the satellite can propagate different errors according to the lack of modelling as for instance unknown bias and pressure solar radiation not correctly calibrated. The precision of measurement model (troposphere, clock model, ...) impacts the residual with respect to real measurement to minimize and then the final orbit positioning.

The determination of the satellite position using a snapshot inverse point computation, as described in [2], will provide a strong correlation between the clock and radial error and then a very large covariance errors leading the exploitation of the covariance ineffective to reach SBAS availability performance. The structural correlation in the measurements between orbit and clock is the key issue to solve in order to provide usable MT28. So the production of the desired covariance matrix shall come from a process that separates the orbit part of the clock effect in the structure of the covariance matrix.

The computation of the covariance matrix proposed in this paper is based on a satellite restitution position process combining :

- The real pre-processed measurements delivered each second,
- The information of the a-priori  $3 \times 3$  orbit covariance coming from a precise orbit determination process (OEP module, Orbit Estimation & Prediction) [3],

- The information of the clock covariance coming from fast clock synchronization process (CEP module, Clock Estimation & Prediction) [3].

The covariance information from the real time orbitography modules (OEP) is launched every 120 seconds and computes the orbits and snapshot clocks of the satellites, as well as their covariance. The synchronization module (CEP) computes satellite clocks and stations every 10 seconds with their associated variances. Theoretically these information provide all the necessary material to build the MT28. Nevertheless the information provided by the orbitography and synchronization modules is not refreshed every second, so it is necessary to use in the calculations information per second given by the measurements for an immediate reaction in case of Feared Events.

The information of orbit and clock covariance are used as a priori constraints inside a global least square process. Let  $(X, h)^t$  be the state vector of the position and clock problem where  $X$  is the satellite position vector and  $h$  is the satellite clock. The equations to deal with are the following

$$\begin{cases} W \cdot (A, \mathbb{I}) \cdot (X, h)^t = W \cdot B \\ [Var(X_{OEP})]^{-1} \cdot X = [Var(X_{OEP})]^{-1} \cdot X_{OEP} \\ \frac{h}{Var(h_{CEP})} = \frac{h_{CEP}}{Var(h_{CEP})} \end{cases}$$

Where

- $A = (I_1, \dots, I_{Nsta})^t$  is the geometric design matrix
- $\mathbb{I} = (1, \dots, 1)^t$  is a colon vector
- $W$  is a weighted measurement matrix
- $B$  is the colon vector of residual measurements
- $X_{OEP}$  and  $Var(X_{OEP})$  are the satellite positioning computed by the orbitography module (OEP) and its  $3 \times 3$  associated covariance matrix
- $h_{CEP}$  and  $Var(h_{CEP})$  are the satellite clock computed by the fast clock synchronisation module (CEP) and its associated covariance

The process of resolution of this problem has been made to ensure a separation between the orbit estimator  $\hat{X}$  and the clock estimator  $\hat{h}$  as well as the covariance between them. The full covariance matrix to consider for MT28 is the  $4 \times 4$  covariance matrix of the estimator  $(\hat{X}, \hat{h})$  build as

$$P = \begin{pmatrix} Var(\hat{X}) & Cov(\hat{X}, \hat{h}) \\ Cov(\hat{X}, \hat{h})^T & Var(\hat{h}) \end{pmatrix}$$

## UDRE MIN INTRODUCTION IN MT28

Currently in EGNOS, the UDRE transmitted to users has a minimum value, which is transmitted even if the internally calculated UDRE could be lower. This lower limit is today fixed at 3 meters at 3.29 sigma, which corresponds to the UDREi index of 5 in the MOPS standard.

If such an operation is to be implemented with the MT28 a dedicated process shall be designed inside the structure of the covariance matrix. It is the scope of the following.

Let  $P_t$  be the covariance matrix  $4 \times 4$  computed at the second. Since the matrix is symmetric and definite positive, it is diagonalizable in a basis of orthogonal vectors, so there exists an orthogonal matrix  $M$  and a diagonal matrix  $D$  containing the eigenvalues such that

$$P_t = M^T D M$$

With

$$D = \begin{pmatrix} \lambda_1 & 0 & 0 & 0 \\ 0 & \lambda_2 & 0 & 0 \\ 0 & 0 & \lambda_3 & 0 \\ 0 & 0 & 0 & \lambda_4 \end{pmatrix}$$

The UDRE value of a 1 sigma is given by the formula

$$\sigma_{UDRE}^2 = I^T P_t I = I^T M^T D M I = (M I)^T D (M I)$$

Assuming that the eigenvalues of  $P_t$  are ranked in descending order  $\lambda_1 \geq \lambda_2 \geq \lambda_3 \geq \lambda_4$  we get:

$$\sigma_{UDRE}^2 \geq \lambda_4 \|M I\|^2 = \lambda_4 \|I\|^2 = 2\lambda_4$$

If the 1-sigma UDRE must not be less than a certain value, it suffices that:

$$\lambda_4 = \frac{\sigma_{UDRE \min}^2}{2}$$

The principle is therefore to fix all eigenvalues of  $P_t$  inferior to  $\sigma_{UDRE \min}^2/2$  to the value  $\sigma_{UDRE \min}^2/2$ . Applying this procedure, one can define a new diagonal matrix  $D'$  whose elements are given by  $\max\left(\lambda_i, \frac{\sigma_{UDRE \min}^2}{2}\right)$ ,  $1 \leq i \leq 4$  which re-inflates the covariance matrix along its too small principal directions.

The covariance matrix ensuring the minimum UDRE is reconstructed with:

$$P'_t = M^T D' M$$

By doing so, the orbit and clock error covariance structure is left intact. Only the size of the eigen directions of the covariance is increased if necessary.

### $\sigma_{UDRE}$ COMPUTATION

The transmission of the MT28 is performed every 120 seconds. During these 120 seconds, the user knows only the last matrix sent, so it is possible that this matrix "ages" and is less and less representative over the seconds of the true covariance matrix at the current date. Moreover, at the time of the encoding in the message, the matrix undergoes a discretization, which will distort it and make it imperfectly representative of the user's errors, even at the refresh date of the matrix.

The scalar parameter transmitted in the fast corrections MT2-5 in standard L1 is used to solve this problem. This scalar is transmitted every 6 seconds and allows the user to calculate its UDRE

This term allows to re-inflate or possibly to decrease the covariance matrix by a scaling applied to all the components. If the user had every second of the covariance matrix computed at time, the term  $\sigma_{UDRE}$  would be equal to 1, since by construction the covariance matrix gives the confidence interval for any line of sight at one sigma. However, since the last transmitted covariance matrix can no longer be modified before the corresponding message is refreshed, a value of  $\sigma_{UDRE}$  to be sent every 6 seconds is calculated in order to protect the user.

It is necessary to define how this value will be calculated. Each second an internal covariance matrix is computed and is representative of the errors that the user will make at the current date. From the last transmitted matrix, it is necessary to calculate how much to inflate this matrix by scaling in such a way that the confidence interval on any line of sight is greater than the interval that would be obtained if the covariance matrix calculated per second was used. If the covariance matrices are represented as a 1 sigma ellipsoids, the principle of computation is summarized by the following scheme (Figure 2):

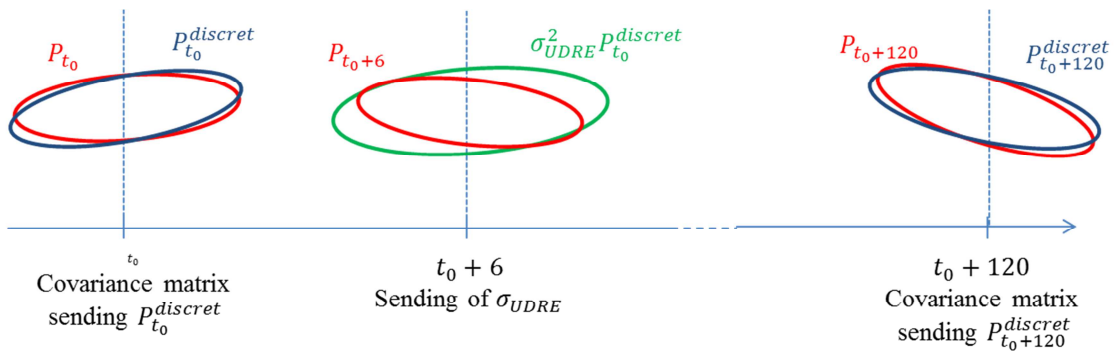


Figure 2: Refresh and discretization of 1 sigma ellipsoid

The ellipsoids shown in red are those calculated internally every second. Every 120 seconds, the covariance matrix is discretized and sent, which is represented here by the blue ellipsoids. The ellipsoid in green represents the matrix sent to  $t_0$  multiplied by a factor  $\sigma_{UDRE}^2$  such that it encompasses the matrix computed internally at  $t_0 + 6$ .

Mathematically, the problem to be solved is to determine the smallest value  $\sigma_{UDRE}^2$  such that:

$$u^T (\sigma_{UDRE}^2 P_{t_0}^{discret}) u \geq u^T P_t u$$

Where the inequality holds for all quadrivectors  $u$  defined in section 3.

This inequality can be rewritten as:

$$\frac{u^T (\sigma_{UDRE}^2 P_{t_0}^{discret}) u}{u^T P_t u} \geq 1$$

The discrete matrix  $P_{t_0}^{discret}$  has been transmitted in the MT28 in form of its Cholesky factorization

$$P_{t_0}^{discret} = B^T B$$

where matrix  $B$  is obtain by  $B = 2^{e-5} E_{discret}$ . The previous inequality become:

$$\sigma_{UDRE}^2 \cdot \frac{(Bu)^T (Bu)}{u^T P_t u} \geq 1$$

Writing vector  $u$  as  $u = B^{-1}Bu$  we get:

$$\sigma_{UDRE}^2 \cdot \frac{(Bu)^T (Bu)}{(Bu)^T B^{-T} P_t B^{-1} (Bu)} \geq 1$$

The vector  $u$  being arbitrary, we can simplify the formulation by defining a new vector  $v = Bu$ , the vector  $v$  being arbitrary as well.

$$\sigma_{UDRE}^2 \cdot \frac{v^T v}{v^T B^{-T} P_t B^{-1} v} \geq 1$$

The matrix  $B^{-T} P_t B^{-1}$  is symmetric positive defined thus it is diagonalizable in a base of orthogonal vectors. So it exists an orthogonal matrix  $M$  and a diagonal matrix  $D$  such that  $B^{-T} P_t B^{-1} = M^T D M$ . As an orthogonal matrix conserve the scalar product,  $v^T v = (Mv)^T (Mv)$  the formulation becomes:

$$\sigma_{UDRE}^2 \cdot \frac{(Mv)^T (Mv)}{(Mv)^T D (Mv)} \geq 1$$

Finally the inequality to solve can be written as

$$\sigma_{UDRE}^2 \cdot \frac{w^T w}{w^T D w} \geq 1$$

where  $w$  is a new vector defined as  $w = Mv$ . Let  $\lambda_1$  be the largest eigenvalue of matrix  $B^{-T} P_t B^{-1}$ .

As  $w^T D w \leq \lambda_1 w^T w$  the left member can be minored by

$$\sigma_{UDRE}^2 \cdot \frac{w^T w}{w^T D w} \geq \frac{\sigma_{UDRE}^2}{\lambda_1}$$

So a sufficient condition for  $\sigma_{UDRE}^2 \cdot \frac{w^T w}{w^T D w} \geq 1$  is that

$$\frac{\sigma_{UDRE}^2}{\lambda_1} \geq 1$$



This gives us a minimal value of  $\sigma_{UDRE}^2$  which ensures that the last matrix sent multiplied by this factor includes the matrix calculated each second:

$$\sigma_{UDRE}^2 = \lambda_1$$

With  $\lambda_1$  be the biggest eigenvalue of  $B^{-T}P_tB$  and  $B$  is the Cholesky factorization of  $P_{t_0}^{discret}$ .

## FEARED EVENT DETECTION

The estimators  $(\hat{X}, \hat{h})$  described in §5 allow to implement a method of detecting the Feared Event, that is to say an event transcribed in the measurements that makes inconsistent the measurements and the information coming from orbitography and synchronization process.

Regarding positioning detection the variable  $\hat{X}$  represents an estimator of the real satellite position  $X_{real}$ . If the measurement noise is Gaussian then  $\hat{X}$  follows a normal law centered on the true satellite position:

$$\hat{X} \sim N(X_{real}, \sigma^2(AWA)^{-1})$$

Where  $\sigma^2$  is the unknown variance of the residual after estimation, the residuals being defined as  $\varepsilon = B - A\hat{X}$ . As the real position  $X_{real}$  is unknown the better candidate to replace it is the computed position  $X_{OEP}$  given by OEP module.

Let  $Y$  be a new random variable defined as

$$Y = (\hat{X} - X_{OEP})^T \frac{(AW^{-1}A)}{\sigma^2} (\hat{X} - X_{OEP})$$

It follows that  $Y \sim \chi_3^2$  has a chi-square distribution with three degrees of freedom.

Let  $Z$  be the random variable defined as

$$Z = \frac{ns_n^2}{\sigma^2}$$

where  $s_n^2$  is the estimator of the variance  $\sigma^2$  defined usually by:

$$s_n^2 = \frac{1}{n} \sum \varepsilon_i^2$$

It follows that  $Z \sim \chi_{n-4}^2$  has a chi-square distribution with  $n - 4$  degrees of freedom.

Then the random variable defined by

$$T = \frac{\frac{Y}{n}}{\frac{Z}{n-4}} = \frac{n-3}{n} \cdot \frac{(\hat{X} - X_{OEP})^T (\tilde{A}W^{-1}\tilde{A})(\hat{X} - X_{OEP})}{\sum_{i=1}^n \varepsilon_i^2}$$

has a Ficher distribution with four and  $n - 4$  degrees of freedom:

$$T \sim F_{4, n-4}$$

The use of Ficher law is common in navigation (see [4] for instance).

By setting a confidence level  $1 - \alpha$  (eg 95%, 99%, ...), we determine a quantile  $r$  for the Fischer law followed by the random variable  $T$ . This allows to define a coherence test of the estimate of position to the second with the position given by OEP:

- If  $T < r$ , then the coherence between the OEP position and the estimate made is assured with the desired confidence level,
- If  $T > r$ , then there is an inconsistency between the OEP position and the estimate performed at time. This is the sign of that a Feared Event occur and can cause a reaction of the system.

The same reasoning can be formulated for the estimator of the clock. Only the number of degrees of freedom changes, one will obtain a Fischer's law at 1 and n-1 degrees of freedom. This gives a second coherence test.

In case of detection of Feared Event the orbit and clock covariance error matrix is no longer calculated since the covariance provided by OEP module and CEP module can no longer be considered reliable. Only the inflating factor  $\sigma_{UDRE}$  is calculated which allows, from the last matrix of covariance sent, to cover at 3.29 sigma the largest observed station residue.

## RESULTS AND DISCUSSION

The algorithms described have been integrated in the SPEED platform, and run on several different scenarios to assess the performance in terms of integrity and availability.

SPEED for ‘System Platform for EGNOS Evolutions & Demonstrations’ is an SBAS Operational Test-bed that fully represents EGNOS Performances in terms of accuracy, continuity, availability and integrity for Safety Of Life services.

The integrity is assessed on a pseudorange, by checking if the residual on every line of sight is lower than the UDRE calculated by the user using the MT28 matrix and the  $\sigma_{UDRE}^2$  in the fast corrections. This calculation is performed for every user in the Geostationary Broadcast Area.

The first scenario is made of EGNOS real data from the day November the 20<sup>th</sup> 2011. On this day, the conditions are nominal. The maximum Safety Index, defined as:

$$SFI = \frac{SREW}{\sigma_{UDRE}}$$

where the SREW (Satellite Residual for the Worst User Location) is searched for on the whole GBA, is calculated for all GPS satellites available this day:

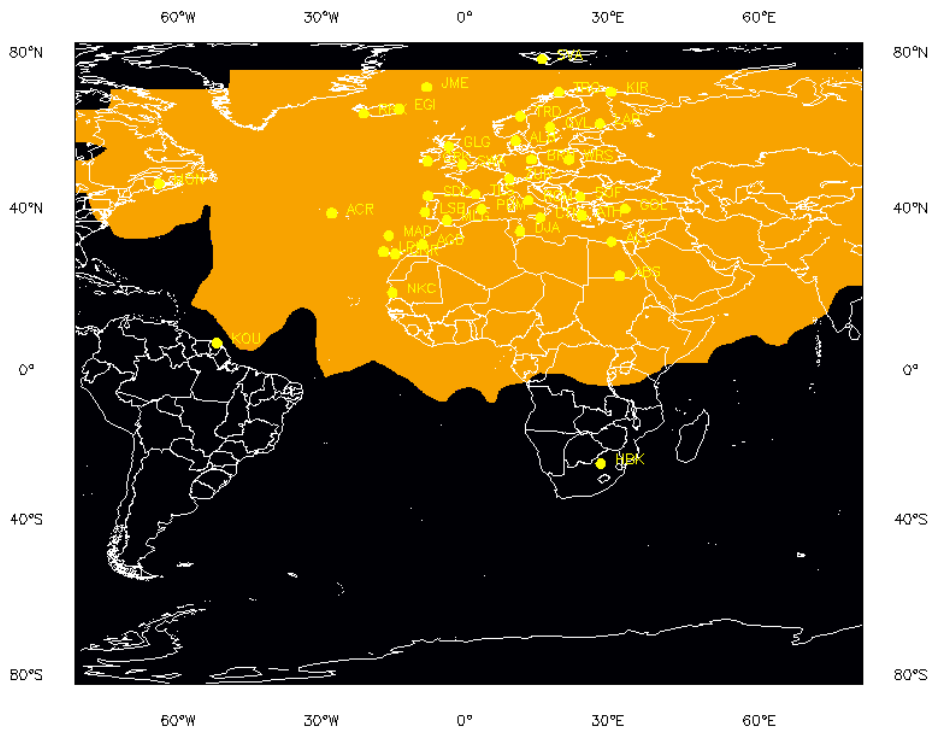
PRN	SFI max on GBA	PRN	SFI max on GBA
1	NA	17	2.30
2	2.76	18	2.13
3	3.08	19	2.68
4	2.95	20	2.31
5	3.03	21	3.08
6	3.12	22	2.76
7	2.80	23	2.78
8	4.52	24	NA
9	3.42	25	NA
10	2.41	26	3.93
11	3.50	27	NA
12	2.43	28	3.30
13	2.18	29	2.54
14	2.86	30	4.44
15	2.62	31	3.44
16	3.44	32	1.91

**Table 1: Satellites maximum SFI, 11/20/2011**

The integrity is ensured as long as the SFI remains below 5.33, which is the case here. Some satellites show high levels of SFI, but this problem can be overcome by fine tuning the orbitography estimation process, which has a tendency to underestimate the covariance.

The availability has also been estimated. Below is a representation of the area (within the GBA) where the APVI service level is ensured, which is the case whenever the protection levels of a user are below 40m in horizontal plane, 50m in the vertical direction, 99% of the time.

The calculation has been performed without consideration of the ionospheric delay, so implicitly this is valid for bifrequency users.



**Figure 3: APVI availability area, bifrequency users, 11/20/2011**

The availability area is very large, and covers most of the northern hemisphere within the GBA.

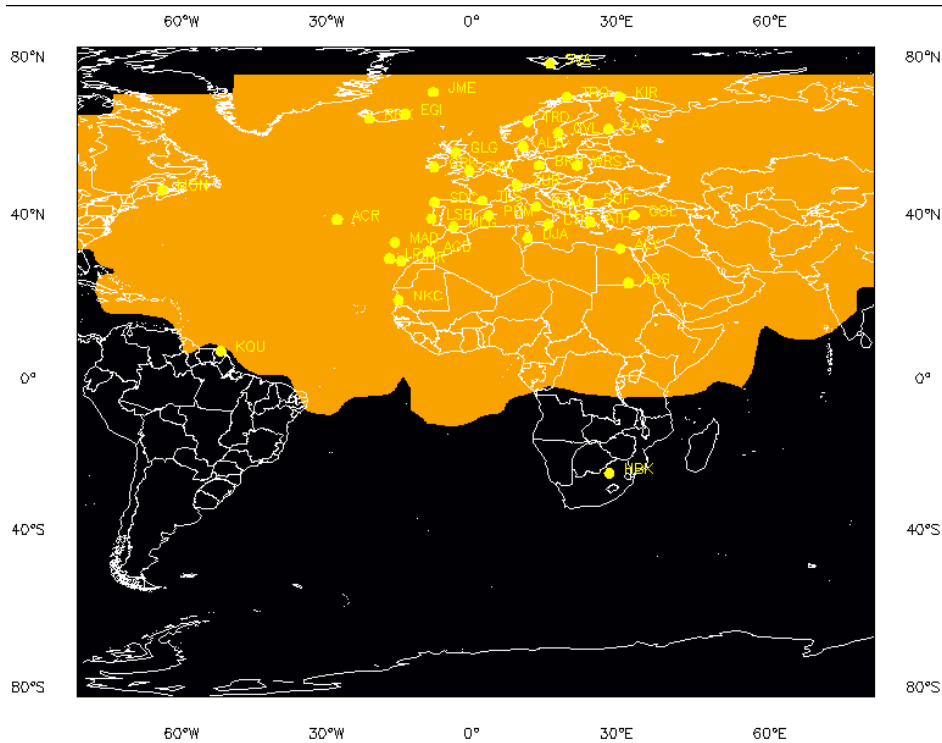
Another scenario, made of real EGNOS data on the day August 14<sup>th</sup> 2014, is assessed here. The levels of SFI maximum for every satellite, in the GBA are given in the table below:

<b>PRN</b>	<b>SFI max on GBA</b>	<b>PRN</b>	<b>SFI max on GBA</b>
<b>1</b>	4.69	<b>17</b>	3.13
<b>2</b>	3.32	<b>18</b>	2.96
<b>3</b>	5.11	<b>19</b>	3.13
<b>4</b>	3.65	<b>20</b>	3.08
<b>5</b>	4.12	<b>21</b>	3.86
<b>6</b>	4.24	<b>22</b>	3.19
<b>7</b>	3.12	<b>23</b>	3.73
<b>8</b>	4.88	<b>24</b>	3.97
<b>9</b>	2.91	<b>25</b>	3.91
<b>10</b>	2.96	<b>26</b>	3.43
<b>11</b>	2.40	<b>27</b>	2.93
<b>12</b>	2.85	<b>28</b>	NA
<b>13</b>	3.31	<b>29</b>	2.58
<b>14</b>	2.34	<b>30</b>	2.68
<b>15</b>	3.18	<b>31</b>	NA
<b>16</b>	3.13	<b>32</b>	3.11

**Table 2: Satellites maximum SFI, 08/14/2014**

Again the SFI are always below 5.33, even if sometimes high.

The APVI availability for bifrequency users is shown in Figure 4:



**Figure 4: APVI availability area, bifrequency users, 08/14/2014**

On a third scenario, made of EGNOS real data on the January the 1<sup>st</sup> 2014, the PRN1 showed an erratic behavior of its clock on this period. The clock would, for some hours fluctuate, before coming back to a nominal behavior. This scenario allows to check the robustness of the algorithm to this kind of Feared Event.

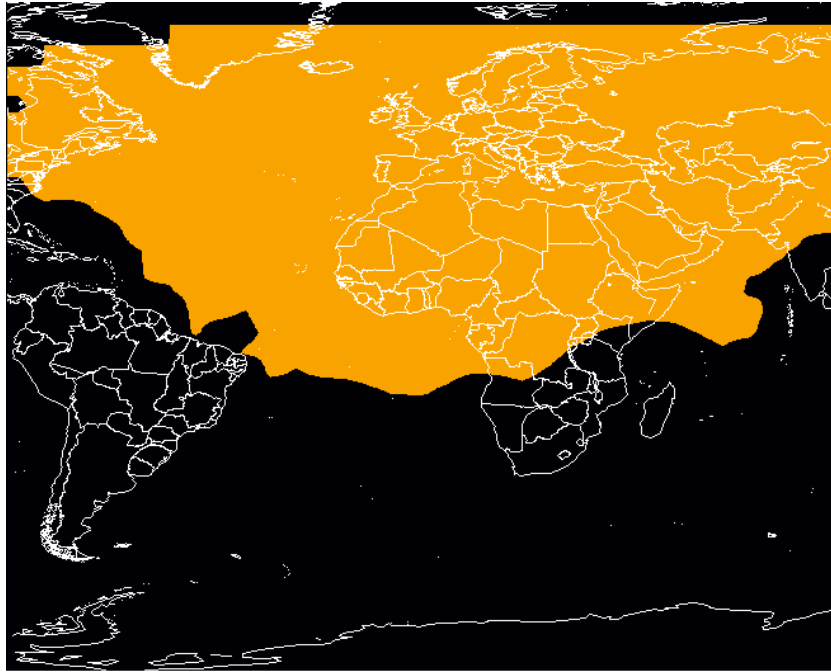
The integrity, evaluated on the GBA, is given below:

PRN	SFI max on GBA	PRN	SFI max on GBA
1	1.30	17	2.34
2	1.96	18	1.84
3	2.04	19	2.08
4	1.54	20	1.85
5	2.50	21	2.29
6	2.36	22	1.79
7	2.51	23	1.38
8	2.57	24	1.87
9	2.53	25	1.69
10	2.81	26	2.04
11	1.92	27	2.62
12	1.73	28	1.84
13	2.22	29	2.83
14	2.92	30	NA
15	1.82	31	2.30
16	2.17	32	2.13

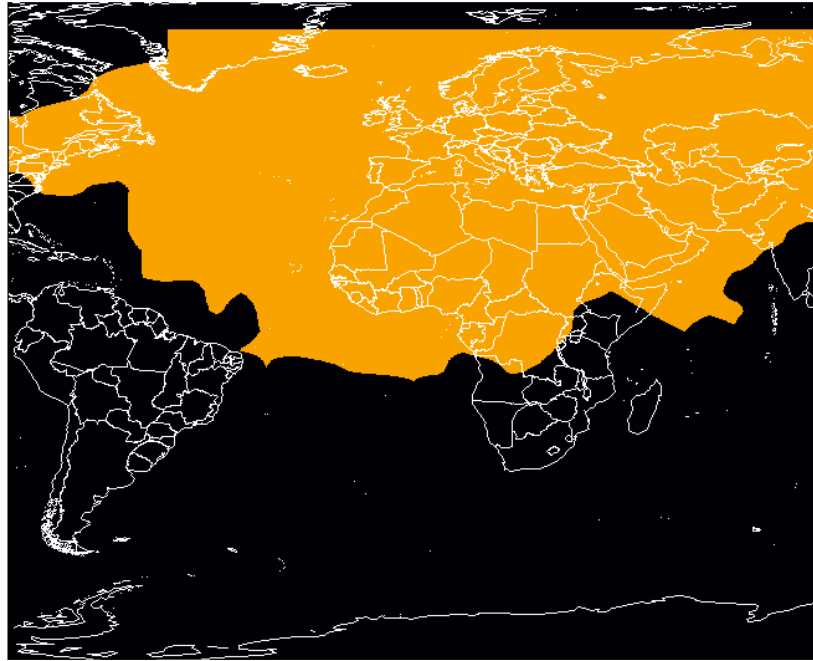
**Table 3: Satellites maximum SFI, 01/01/2014**

The integrity is always ensured. The monitoring of the PRN1, showing the unexpected behavior of its clock is lost after 9.40 am on this day, when its clock starts fluctuating. The algorithms detected the problem and consequently, no calculation of the MT28 was performed for that period, the satellite was not monitored.

Despite the loss of the PRN1, the availability region is still very large, as shown below:



**Figure 5: APVI availability area, bifrequency users, 01/01/2014**



**Figure 6: LPV200 availability area, bifrequency users, 01/01/2014**

## **CONCLUSIONS AND PERSPECTIVES**

A new method for the calculation of the MT28 based on a priori knowledge of satellite orbit and clock covariance has been designed. The method also implements the calculation of the  $\sigma_{U_{DRE}}^2$  term transmitted in the fast corrections. The algorithm has been tested on different scenarios, in nominal conditions and degraded conditions, with satellite clock events, and shows that the satellite integrity is ensured on the whole GBA, while giving a very good level of service availability, both APVI and LPV200.

## **ACKNOWLEDGMENTS**

The authors would like to gratefully acknowledge the CNES navigation team for supporting this work under CNES contract 160062 of the framework 12212.

The opinions expressed in this paper are the authors'. CNES is not liable for the use of any of the information included herein. The authors would like to thank Norbert Suard from CNES from private communication regarding event occurred on PRN1 during December 2013 and January 2014.

The authors would also like to thank Celine Renazé at Thales Alenia Space for the complete software development of the MT28 algorithm inside the Thales Navigation Kernel and for the experimentations on SPEED.

## 1. REFERENCES

- [1] *Minimum operational performance standards for Global positioning system / wide area augmentation system airborne equipment*, DO-229D rev 1, Jan. 2013, RTCA ed. Washington, DC.
- [2] T. WALTER, A. HANSEN, P. ENGE, *Message Type 28 : ION NTM 2001*, Long Beach (Virginia), 522–532
- [3] A. ROUANET LABE, R. LEMBACHAR, T. AUTHIE, S. TRILLES, F. MERCIER. *New Orbit Determination and Clock synchronisation modules for EGNOS*. ION GNSS+ 2016, Portland (Oregon), 3189 – 3196
- [4] A. LEICK. *GPS SATELLITE SURVEYING*, Wiley