Assessment of EGNOS continuity from position to range domain

X. Derambure, J.M. Piéplu, D. Flament, J.C. Levy, E. Sales, *Alcatel Space Industries*
J. Ventura-Traveset, *European Space Agency*

BIOGRAPHY

Alcatel Space Industries is the prime contractor of EGNOS whose development contract has been signed between Alcatel and ESA on 16th.06.1999.
X. Derambure: System Engineer; EGNOS Service Volume modelling and analysis.
J.C. Levy: System Engineer; EGNOS algorithms performance specification.
E. Sales: System Engineer; EGNOS End to End simulations with EGNOS algorithms prototypes.
J.M. Piéplu: EGNOS Performance and Modelling Team Leader.
D. Flament: EGNOS System Engineering Team Leader.

The European Space Agency (ESA) is the responsible within the European Tripartite Group (European Commission, ESA, Eurocontrol) of the design, development and qualification of an Advanced Operational Capability (AOC) of the EGNOS system.
J. Ventura-Traveset is the EGNOS Principal System Engineer at the ESA Project Team.

ABSTRACT

The EGNOS system is being developed in Europe to provide GPS and GLONASS regional augmentation services to aviation, maritime and land users. EGNOS is a major element of the European Satellite Navigation Program, which is jointly being implemented by the Commission of the European Union, the European Space Agency and EUROCONTROL [4].
The EGNOS system, as any other Wide Area Augmentation System, relies on the broadcast of correction and integrity information in the pseudo-range domain, which are then used to provide a solution in the position domain service.
The EGNOS System Performance Requirements, and in particular the Continuity of Service, are specified in the position domain. A key process in the allocation and verification of EGNOS system and sub-systems performances is therefore the relationship between the Continuity of Service and the Continuity characteristics of the broadcast corrections and integrity information.
This paper describes a theoretical approach on this issue and associated simulation results, as currently achieved in the frame of the EGNOS implementation phase. In particular, it identifies the major sources of non continuity in the EGNOS service and describes in probabilistic terms the impact of EGNOS integrity bounds instabilities on the User level Continuity of Service.

INTRODUCTION

For any navigation system, the continuity of Service is the probability that the service remains available during an operation time assuming that it is provided at the beginning of this operation time.

The starting point to define EGNOS continuity performance is then the list of conditions at user level for entering into EGNOS Precision and Non Approach Services and then, for interrupting this Service.

User will commonly enter a precision or non precision approach at **T0** if all the following conditions are fulfilled:

Condition 1: Sufficient number of satellites ranging signals tracked and predicted to be available over the next operation period for the computation of a navigation solution;
Condition 2: Sufficient number of EGNOS GEO satellites messages tracked and predicted to be available over the next operation period for the reception of the navigation correction and integrity messages;
Condition 3: No alarm is raised: The computed protection level is below the alert limit.

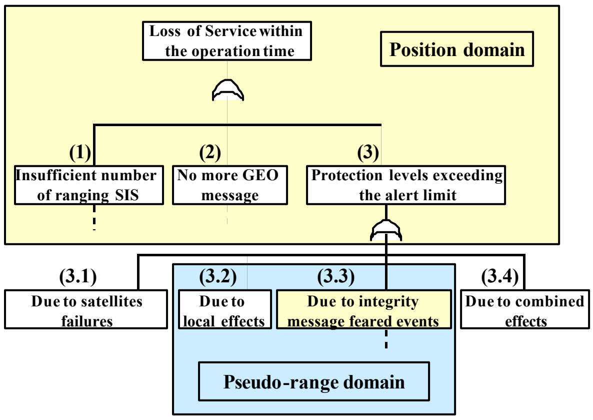
In the same way, a user will interrupt a precision approach at a given time, say ***t***, in case any of the following events occurs:
Service Event 1: Insufficient number of ranging signals;
Service Event 2: No EGNOS GEO satellites message is tracked anymore;
Service Event 3: An alarm is raised: The computed horizontal or vertical protection level exceed the corresponding alert limits.

From these conditions and feared events a continuity apportionment tree can be elaborated so as to:

- highlight the different levels of severity of continuity of service feared events vis-à-vis the operational use of EGNOS services;
- to allow the quantification of the tree;
- to identify the different types of feared events in the tree and in particular EGNOS integrity bounds

instabilities.

This has resulted into the Continuity apportionment tree presented hereafter:



The continuity performance of cells 1 and 2 can be expressed directly in the position domain and can be directly computed from the satellites outages and restoration figures (E.g. MTBF, MTTR ; [1] and [2]). On the contrary the cell 3 corresponds to discontinuity in the position domain but can be derived into the following sub-feared events: Increase of the protection level due to satellites failures (3.1), local effects (3.2) or integrity bounds instabilities --expressed in the pseudo-range domain: (3.3)-- or due to combined effects (3.4).

Note that EGNOS discontinuity due to an increase of the protection level due to satellites failures (3.1) can be assessed from the satellites outages and restoration figures (E.g. MTBF, MTTR ; [1] and [2])

This decomposition of feared events into those caused directly by the ground segment (integrity bounds instabilities) and those caused externally allows a direct apportionment and verification of EGNOS continuity performance down to the characteristics of the broadcast corrections and integrity information.

The purpose of this paper is to focus on the loss of service due to these integrity message feared events such as UDRE or GIVE instabilities.

In a first step, the global approach for EGNOS continuity assessment from position to range domain is presented after the identification of the integrity message feared events.

In a second step, a mathematical modelling of the impact of these feared events on EGNOS continuity and the way to implement this model in a service volume simulator is proposed.

Some service volume results for EGNOS CAT I precision approach are finally presented and discussed in a last step.

Non continuity sources in the pseudo-range domain

As seen in the previous paragraph, only the non continuity sources in the pseudo-range domain induced directly by the ground segment are being considered here.
The horizontal and vertical protection levels are computed according to the MOPS Protection Level algorithm [3] and are basically function of the satellites geometry (DOP) and the estimation of the pseudo-range error bounds for each of the following error sources: Receiver noise, multipath and tropospheric error (External to the ground segment) and the ground segment computed and broadcast UDRE and GIVE.

Instabilities in the broadcast UDRE/GIVE may then lead to discontinuities at system levels and 4 UDRE and 1 GIVE feared events are defined hereafter:

- General UDRE excessive increments: The broadcast UDRE are suddenly increased for all monitored satellites;

- UDRE(GPS) excessive increments: At time T0, the broadcast UDRE on average over a subset of one or more than one monitored GPS satellites is lower or equal to the UDRE(GPS) broadcast upper bound nominal value and becomes higher (i.e. one or more quantisation steps above) than this upper bound specified value during the next operation period.

- UDRE(GEO) excessive increments: At time T0, the broadcast UDRE on average over a subset of one or more than one monitored GEO satellites is lower or equal to the UDRE(GEO) broadcast upper bound nominal value and becomes higher (i.e. one or more quantisation steps above) than this upper bound specified value during the next operation period.

- UDRE(GLO) excessive increments: At time T0, the broadcast UDRE on average over a subset of one or more than one monitored GLO satellites is lower or equal to the UDRE(GLO) broadcast upper bound nominal value and becomes higher (i.e. one or more quantisation steps above) than this upper bound specified value during the next operation period.

  Notes:
  1. operation period is assumed to be 1 hour for NPA and 150 sec. for Precision Approach.
  2. UDRE and GIVE quantisation steps are defined in the RTCA MOPS document [3].

- Multiple GIVE excessive increment: At time T0, the broadcast GIVE on average over a subset of more than one monitored IGP is lower or equal to the GIVE broadcast upper bound nominal value and becomes higher (i.e. one or more quantisation steps above) than this upper bound_specified value during the next 150 seconds.

Approach for EGNOS continuity assessment from position to range domain

As mentioned in the previous paragraph, the Continuity Performance is derived from the position to the pseudo-range domain according to a list of identified integrity message feared events.

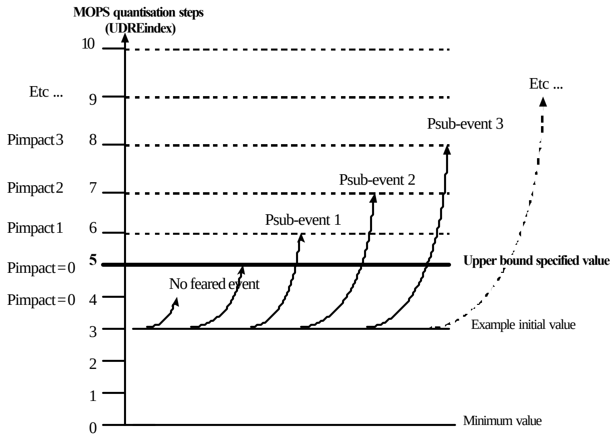
Each feared event can be characterised by a couple of probabilities: A system impact probability (P_{impact}) and an associated probability of occurrence (P_{event}).

By definition, the feared events 'UDRE or GIVE increments' are indeed implicitly expected to be at different values (e.g. increments which results into a UDRE/GIVE value of 20 cm., or 1 m. or 10 m. above the specified upper bound).

A probability of occurrence as function of the level of the UDRE/GIVE increment (P_{event}) can be therefore defined for each feared event.

In the same way, the global impact on the system continuity (P_{impact}) of EGNOS integrity bounds instabilities depends clearly on the amplitude of these instabilities:

This is illustrated in the following diagram for the UDRE where the associated system impact probability (Probability of service interruption) may vary from 0% to 100 % depending on the value of UDRE/GIVE reached after a sudden increment



The analytical expression of probability of service interruption can be therefore computed, for each of the feared events, from the 'event probability' and the 'System impact probability' as follows:

$$P_{service\text{-}interruption} = P_{event(1)} * P_{impact(1)} + P_{event(2)} * P_{impact(2)} + \ldots.. + P_{event(n)} * P_{impact(n)}$$

As these System Impact Probabilities vary greatly (from almost 0% to 100%), depending on the value of the UDRE/GIVE increments and the number of satellites affected by the event, they are specified as a curve, for which quantisation level is defined by the UDRE and GIVE messages quantisation steps specified in the RTCA MOPS (Message type 6) [3].

These System Impact Probabilities (Pi_{mpact}) must be combined at ground Segment Level with the Probabilities of occurrence of the Ground Segment outputs feared events (P_{event}) in order to verify that the continuity requirements are met at system level.

The less conservative way to combine these P_{impact} with the P_{event} is that the P_{event} are also a function of the UDRE and GIVE messages quantisation steps specified in the RTCA MOPS [3].

Note that this analytical formula has been settled for clarity considerations, but the actual implementation of this approach should be rather based on the implementation of this concept within Fault trees methodology and computations which allows to account for potential common events at lower levels.

This dual approach with 'System impact probabilities' and 'Probability of occurrence' for the continuity performance allocation and verification, allows then a flexibility in the assignment of the event probabilities at ground segment level as long as the overall Continuity requirement at system level can be shown to be met.

Major assumptions for the mathematical modelling

Due among others to the specific geometry encountered at each user location over time, EGNOS continuity performance is a priori submitted to variations over time and over users location. However, in order to obtain a pragmatic and workable translation from the ground segment (pseudo-range and IGP domain) to the System (Position domain) performance, it is necessary to obtain an unique (not time varying, not user location dependent) equation relating position and pseudo-range domains through Service interruption probabilities.

Therefore, it is assumed that the Navigation System Continuity performance can be assessed through computations of P_{impact} relying on averaging over time (typically 24 hours to average geometrical effects), but considering the worst location of this average over the Service area. Another typical assumption for the continuity performance assessment with respect to Precision approach requirements is to consider a constant geometry during the operation time (CAT I phase of flight = 150s).

Assuming finally that UDRE increments generated by the ground segment are identical for each affected monitored satellites, the following equation represents the general formula assessing EGNOS continuity performance in case of UDRE increments on the monitored GPS , GEO and GLONASS satellites during the operation time.

$$P_{\substack{Service \\ Interruption}} = \sum_{i=0}^{\overline{M}_{GPS}} \sum_{j=0}^{\overline{M}_{GEO}} \sum_{k=0}^{\overline{M}_{GLO}} \int_{x=0}^{+\infty} \frac{\partial P_{event}}{\partial x}(i,j,k,x) \cdot P_{impact}(i,j,k,x)\,dx$$

where

- $P_{\substack{Service \\ interruption}}$ is the probability of service interruption due to UDRE increments applied on GPS, GEO or GLONASS satellites during the operation time assuming the full availability of service at the beginning of the operation time.

- $P_{event}(i,j,k,x)$ is the probability during the operation time of producing an UDRE increment less than x meters (UDRE increment < x) on i monitored GPS, j monitored GEO and k monitored GLONASS satellites assuming no UDRE increment at the beginning of the operation time.

- $P_{impact}(i,j,k,x)$ is the probability that an UDRE increment of x meters applied on i monitored GPS, j monitored GEO and k monitored GLONASS satellites produces an interruption of the service.

- $\overline{M}_{GPS}$, $\overline{M}_{GEO}$ $\overline{M}_{GLO}$ are respectively the average number of monitored GPS , GEO and GLONASS satellites

In order to assess EGNOS continuity performance due to UDRE increments on monitored satellites, it is then necessary to compute $P_{impact}(i,j,k,x)$ for each combination of i, j, k and x.

For a specific i, j, k, x combination, this probability shall be moreover representative of every EGNOS users all over the service area at any time step and shall take into account the different possibilities N_{ijk} of i,j,k GPS, GEO and GLONASS satellites affected by the UDRE increment out of the monitored satellites.

Due to this large number of combinations and constraints, the computation of these probabilities can be therefore only computed by service volume simulations analysis.

Note however that $P_{impact}(i,j,k,x)$ is bounded by 100% which is achieved for instance when an infinite UDRE increment is applied on all monitored satellites.

In a more general way, it is clear that $P_{impact}(i,j,k,x)$ increases with x Considering i GPS, j GEO and k GLONASS, the probability of service interruption with an UDRE increment of 10 meters applied on these satellites $P_{impact}(i,j,k,x)$ is obviously superior to the probability of service interruption with an UDRE increment of 1 meters.

In the same way, the probability of service interruption $P_{impact}(i,j,k,x)$ increases with the number of satellites affected by the UDRE increment x.
In a more general way, it emerges from the definition of $P_{impact}(i,j,k,x)$ that

$$\begin{cases} \forall(i_1,i_2) \\ \forall(j_1,j_2) \\ \forall(k_1,k_2) \\ \forall(x,y) \end{cases} : \begin{cases} i_1 \le i_2 \\ j_1 \le j_2 \\ k_1 \le k_2 \\ x \le y \end{cases} \Rightarrow P_{impact}(i_1,j_1,k_1,x) \le P_{impact}(i_2,j_2,k_2,y)$$

This last equation allows to reduce the range of UDRE increment for the computation of $P_{impact}(i,j,k,x)$ to $[0,x_0]$ where x_0 is the lowest UDRE increment where $P_{impact}(i,j,k,x_0) = 100\%$

Implementation for the service volume

The algorithm used for the computation of the probabilities of service interruption is based on the availability algorithm [1].
The basic principle is to compute exhaustively for each user the instantaneous decrease of service availability between the nominal case where all satellites UDRE are under their specified values and a degraded case where some monitored satellites are affected by an increase of UDRE.
Assuming an UDRE increments x on a GPS , *b* GEO and *c* GLONASS out of the visible satellites from a specific user u at a time step t and considering the navigation requirement R,

$$K_{a,b,c}^{x}(u,R,t) = \frac{1}{N_{a,b,c}} \sum_{n=1}^{N_{a,b,c}} bool\left[R_x(a,b,c;n)\right]$$

corresponds to the average instantaneous availability considering all configurations n of a GPS , *b* GEO and *c* GLONASS affected by an UDRE increment of x meters out of the visible satellites.

The boolean function $bool\left[R_x(a,b,c;n)\right]$ value is computed as follows:

- $bool\left[R_x(a,b,c;n)\right] = 0$ if the *navigation requirement* ***R*** is not met in the configuration number n of a GPS, b GEO and c GLONASS out of the visible satellites, affected by an UDRE increment of x meters.

- $bool\left[R_x\left(a,b,c;n\right)\right] = 1$ if the *navigation requirement* ***R*** is met in the configuration number *n* of a GPS, b GEO and c GLONASS out of the visible satellites, affected by an UDRE increment of x meters.

Notes:

1. The UDRE increment x is taken into account in the broadcast UDRE
2. As the impact of the satellites failures on the continuity performance correspond to a specific feared event, the satellites RAMS figures (MTBF, MTTR) shall not be taken into account for the computation of the probability of service interruption due to EGNOS integrity bounds instabilities.

The instantaneous service interruption probability $P^x_{a,b,c}(u,R,t)$ for a specific user u at a time step t considering the RNP R is defined as the instantaneous decrease of availability due to an UDRE increment of x meters on a GPS, b GEO and c GLONASS out of the **visible** satellites:

$$P^x_{a,b,c}(u,R,t) = K^x_{a,b,c}(u,R,t) - K^x_{0,0,0}(u,R,t)$$

Note that $P_{impact}(i,j,k,x)$ relies on the number of **monitored** GPS, GEO and GLONASS satellites whereas $P^x_{a,b,c}(u,R,t)$ relies on the number of **monitored and visible** satellites.

The instantaneous service interruption probability $P^x_{impact_{i,j,k}}(u,R,t)$ for a user u at a time step t and the RNP R is defined thus as the instantaneous decrease of availability due to an UDRE increment of x meters on i GPS, j GEO and k GLONASS out of the **monitored** satellites and is computed by the following equation:

$$P^x_{impact_{i,j,k}}(u,R,t) = \sum_{a=0}^{i}\sum_{b=0}^{j}\sum_{c=0}^{k} P^x_{a,b,c}(u,R,t).Q^{i,M_{GPS}}_{a,V_{GPS}}.Q^{j,M_{EEO}}_{b,V_{GEO}}.Q^{k,M_{GLO}}_{c,V_{GLO}}$$

where $Q^{i,M_{GPS}}_{a,V_{GPS}}, Q^{j,M_{GEO}}_{b,V_{GEO}}, Q^{k,M_{GLO}}_{c,V_{GLO}}$ are the conditional probabilities that a GPS, b GEO and c GLONASS out of the V_{GPS}, V_{GEO} and V_{GLO} **visible** satellites are affected by an UDRE increment considering that i GPS, j GEO and k GLONASS are affected by an UDRE increment out of the M_{GPS}, M_{GEO} and M_{GLO} **monitored** satellites.

These probabilities depends on the instantaneous number of visible and monitored satellites and are computed by the following equations:

$$Q^{V_{GPS}}_{i,a} = \frac{\begin{bmatrix} i \\ a \end{bmatrix}\begin{bmatrix} M_{GPS} - i \\ V_{GPS} - a \end{bmatrix}}{\begin{bmatrix} M_{GPS} \\ V_{GPS} \end{bmatrix}}$$

where M_{GPS} is the instantaneous number of monitored GPS and i is the number of monitored GPS affected by an UDRE increment

$$Q^{V_{GEO}}_{j,b} = \frac{\begin{bmatrix} j \\ b \end{bmatrix}\begin{bmatrix} M_{GEO} - j \\ V_{GEO} - b \end{bmatrix}}{\begin{bmatrix} M_{GEO} \\ V_{GEO} \end{bmatrix}}$$

where M_{GEO} is the instantaneous number of monitored GEO satellites and j is the total number of monitored GEO satellites affected by an UDRE increment

$$Q^{V_{GLO}}_{k,c} = \frac{\begin{bmatrix} k \\ c \end{bmatrix}\begin{bmatrix} M_{GLO} - k \\ V_{GLO} - c \end{bmatrix}}{\begin{bmatrix} M_{GLO} \\ V_{GLO} \end{bmatrix}}$$

where M_{GLO} is the instantaneous number of monitored GLONASS and k is the total number of monitored GLONASS affected by an UDRE increment.

As the geometry of satellite is predictable and approximately constant during CAT I operation times, the instantaneous service interruption probability is averaged for each user over T=24h (GPS or GLONASS ground tracks period).

This avoids among others a very conservative approach and an over specification due to the systematic consideration of satellites geometry worst cases.

On the contrary, as the continuity requirement shall be met for every users of EGNOS service area, the global service interruption probability $P_{impact}(i,j,k,x)$ is computed as the maximum of the average service interruption probabilities of all EGNOS users.

For simulation purposes, considering N_T, the total number or time step of the simulation period, this last equation becomes:

$$P_{impact}(i,j,k,x) = \max_u\left[\frac{1}{N_T}\sum_{t=0}^{N_T} P^x_{impact_{i,j,k}}(u,R,t)\right]$$

Note that this last equation can be simplified for the computation of $P_{impact}(i,0,0,x)$, $P_{impact}(0,j,0,x)$, $P_{impact}(0,0,k,x)$ and $P_{impact}(all,all,all,x)$ according to the identified feared events.

$$P_{impact}(i,0,0,x) = \max_u \left[\frac{1}{N_T} \sum_{t=0}^{N_T} \left(\sum_{a=0}^{i} P^x_{a,0,0}(u,R,t).Q^{i,M_{GPS}}_{a,V_{GPS}} \right) \right]$$

$$P_{impact}(0,j,0,x) = \max_u \left[\frac{1}{N_T} \sum_{t=0}^{N_T} \left(\sum_{b=0}^{j} P^x_{0,b,0}(u,R,t).Q^{j,M_{GEO}}_{b,V_{GEO}} \right) \right]$$

$$P_{impact}(0,0,k,x) = \max_u \left[\frac{1}{N_T} \sum_{t=0}^{N_T} \left(\sum_{c=0}^{k} P^x_{0,0,c}(u,R,t).Q^{k,M_{GLO}}_{c,V_{GLO}} \right) \right]$$

$$P_{impact}(all,all,all,x) = \max_u \left[\frac{1}{N_T} \sum_{t=0}^{N_T} P^x_{all,all,all}(u,R,t) \right]$$

Results for CAT I Precision approach

This algorithm has been implemented in Alcatel DIP-SVM Service Volume Simulator for the computation of the probabilities of service interruption.

As the UDRE values are limited to a list of discrete values according to the UDRE index defined in the RTCA MOPS [3], the UDRE increment can be characterised directly by the variation of this index above the nominal value.

Figure 1 represents then the probability of service interruption when the UDRE index of 1 or 2 GEO is increased from the nominal value up to 15 during the phase of flight.

Figure 2 represents then the probability of service interruption when the UDRE index of n =1 to all GPS is increased from the nominal value up to 15 during the phase of flight.

Figure 3 represents then the probability of service interruption when the UDRE index of all monitored satellites is increased from the nominal value up to 15 during the phase of flight.

It emerges clearly from these figures that the probability of service interruption increases with the UDRE increment and the number of affected monitored satellites.
Note also that according to the second condition to declare the service available, the probability of service interruption reaches 100% when the UDRE index of all GEO is greater than 14 (Do not use or Not monitored).

In order to compute the global contribution of EGNOS ground segment to the continuity performance, these curves shall be finally combined with the ground segment probabilities of producing such increases of UDRE during the phase of flight under nominal external conditions.

Conclusion

In this paper a theoretical approach on the relationship between the Continuity of Service and the Continuity characteristics of the broadcast corrections and integrity information has been developed. It is proposed to assess in probabilistic terms the impact of EGNOS integrity bounds instabilities on the User level Continuity of Service.

The major advantage of this approach is the decomposition of feared events into those caused directly by the ground segment (integrity bounds instabilities) and those caused externally. This allows a direct apportionment and verification of EGNOS continuity performance down to the characteristics of the broadcast corrections and integrity information.

A mathematical formula implemented allowing to compute the probability of service interruption due to UDRE increments has been therefore developed and implemented in a Service volume simulator. Some associated simulation results, as currently achieved in the frame of the EGNOS implementation phase, have been presented.

From these results, the global contribution under nominal external conditions of EGNOS ground segment to the continuity performance can be assessed in the pseudo-range domain.

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FIGURES

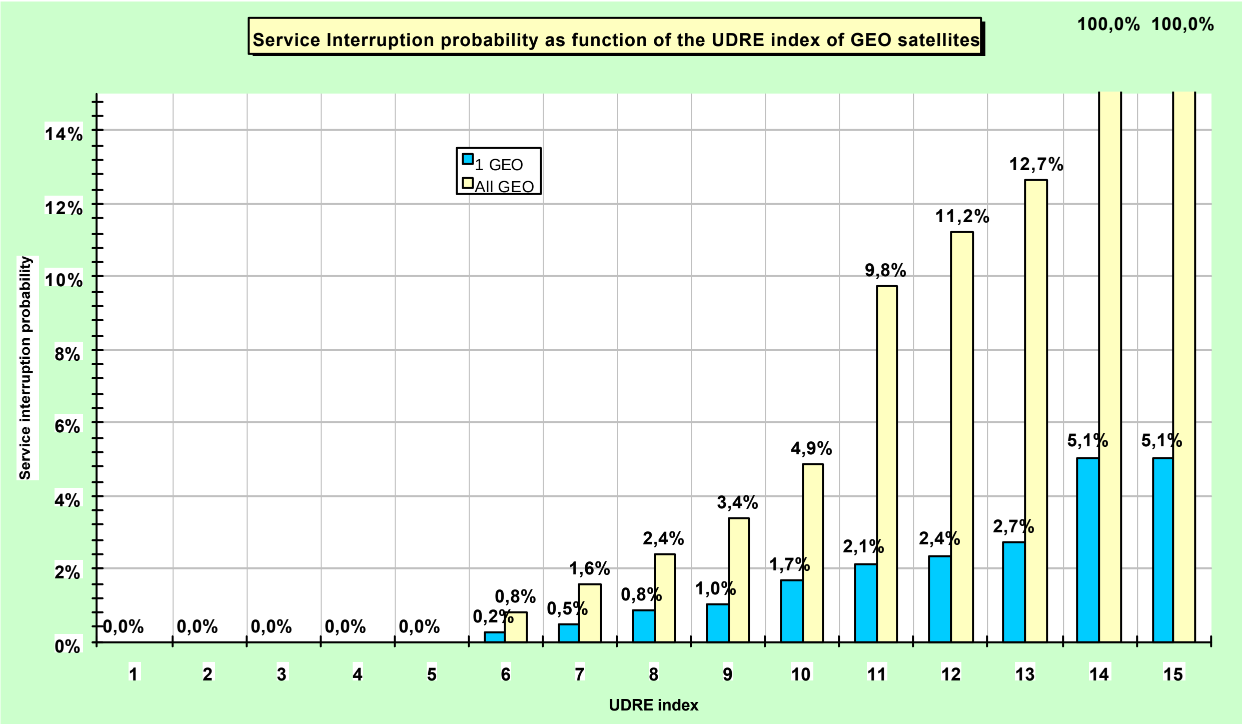

Figure 1 Precision Approach: Example of Service interruption probability due to UDRE increments on GEO satellites (2 GEO: IOR & AOR-E)

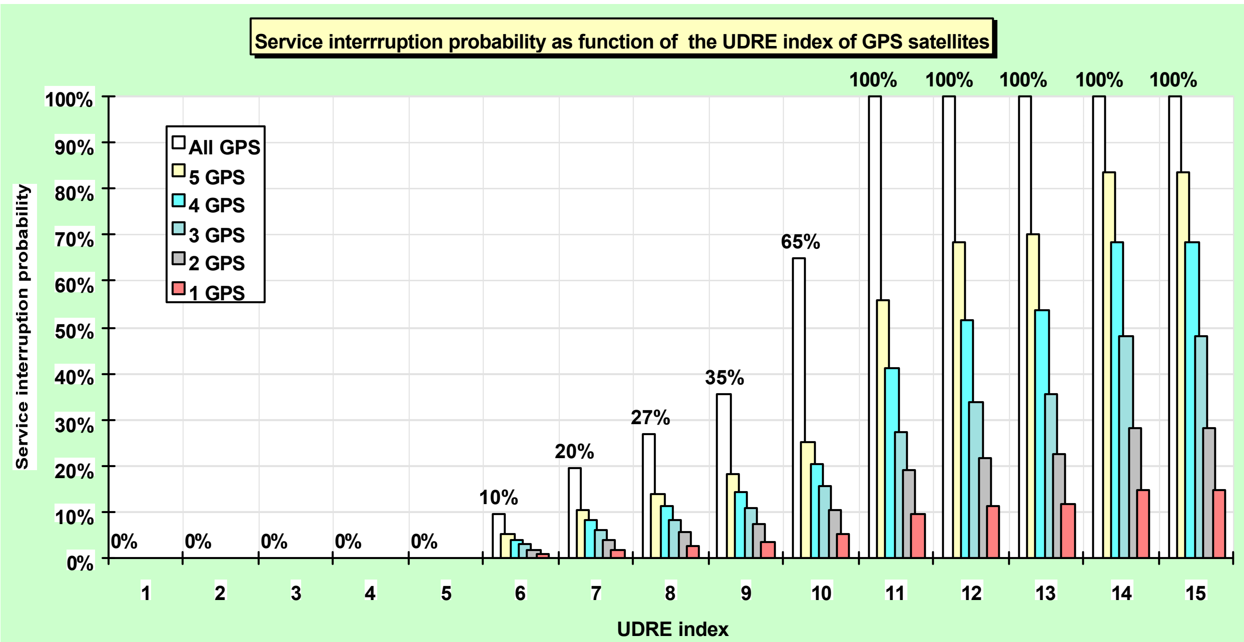

Figure 2 Precision Approach: Example of Service interruption probability due to UDRE increment on monitored GPS satellites

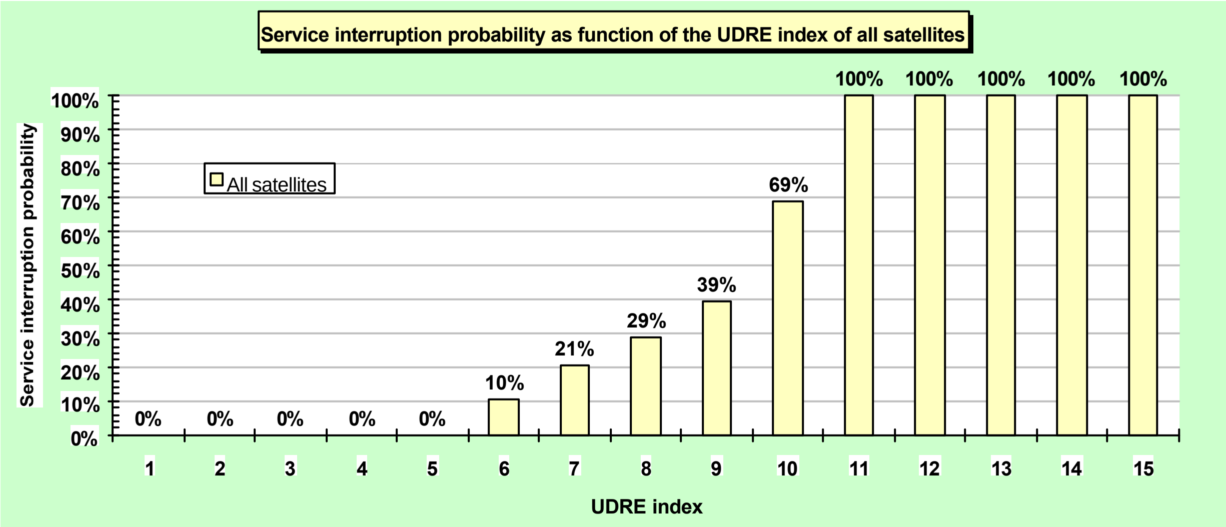

Figure 3 Precision Approach: Example of Service interruption probability due to UDRE increment on all satellites

SYMBOL	DEFINITION	RANGE
$P_{Discontinuity}$	Probability of service interruption due to UDRE increments applied on GPS, GEO or GLONASS satellites during the operation time assuming the full availability of service at the beginning of the operation time	[0% ; 100%]
$P_{incr}(i,j,k,x)$	Probability during the operation time of producing an UDRE increment less than x meters (UDRE increment < x) on i monitored GPS, j monitored GEO and k monitored GLONASS satellites assuming no UDRE increment at the beginning of the operation time	[0% ; 100%]
$P_{inter}(i,j,k,x)$	Probability that an UDRE increment of x meters applied on i monitored GPS, j monitored GEO and k monitored GLONASS satellites produces an interruption of the service	[0% ; 100%]
M_{GPS}	Instantaneous number of monitored GPS satellites	[0 ; 24]
M_{GEO}	Instantaneous number of monitored GEO satellites	[0 ; 2]
M_{GLO}	Instantaneous number of monitored GLONASS satellites	[0 ; 24]
R	Navigation Requirement	-
t	Time of Day	s
u	Particular user located over EGNOS Service area	
$K^{x}_{a,b,c}(u,R,t)$	Average instantaneous availability considering all configurations n of a GPS , b GEO and c GLONASS affected by an UDRE increment of x meters out of the visible satellites	[0% ; 100%]
$P^{x}_{a,b,c}(u,R,t)$	Instantaneous probability of service interruption due to an UDRE increment of x meters on a GPS, b GEO and c GLONASS out of the visible satellites for a specific user u at a time step t considering the RNP R	[0% ; 100%]
V_{GPS}	Instantaneous number of visible monitored GPS satellites for the user u	[0 ; 24]
V_{GEO}	Instantaneous number of visible monitored GEO satellites for the user u	[0 ; 2]
V_{GLO}	Instantaneous number of visible monitored GLONASS satellites for the user u	[0 ; 24]
$Q^{i,M_{GPS}}_{a,V_{GPS}}$	Conditional probabilities that a GPS out of the V_{GPS} **visible** satellites are affected by an UDRE increment considering that i GPS are affected by an UDRE increment out of the M_{GPS} **monitored** satellites	[0% ; 100%]
$Q^{j,M_{GEO}}_{b,V_{GEO}}$	Conditional probabilities that b GEO out of the V_{GEO} **visible** satellites are affected by an UDRE increment considering that j GEO are affected by an UDRE increment out of the M_{GEO} **monitored** satellites	[0% ; 100%]
$Q^{k,M_{GLO}}_{c,V_{GLO}}$	Conditional probabilities that c GLONASS out of the V_{GLO} **visible** satellites are affected by an UDRE increment considering that k GLONASS are affected by an UDRE increment out of the M_{GLO} **monitored** GLONASS	[0% ; 100%]

Table 1 List of mathematical Symbols