To cite this version :

Authié, Thierry and Dall'Orso, Mickael and Trilles, Sébastien and Choi, Heonho and Kim, Heesung and Lee, Jae-Eun and Lee, Eunsung and Nam, Gi-Wook Performances Monitoring and Analysis for KASS. (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).

Performances Monitoring and Analysis for KASS

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ABSTRACT

The Korea Augmentation Satellite System (KASS) is the future SBAS of the Republic of Korea. It is developed by the Korea Aerospace research Institute (KARI) for the government of the Republic of Korea, and Thales Alenia Space is the industry prime contractor of this development. The function of the KASS is to decompose all possible range error sources and to distribute corrections and/or alerts to its users by means of geostationary satellites.

The KASS Processing Station (KPS) is the component of KASS in charge of computing the orbit, clock and ionosphere correction and alert information (below 'Navigation Overlay Frame', NOF) using data from a set of reference stations. The KPS is composed of two independent elements: the Processing Set (PS) and the Check Set (CS). The first element is responsible of computing the complete navigation context for the GNSS constellation (orbits and clock) and the ionosphere model, then to prepare and send the NOF to be broadcast to the users. The second element acts as a super user by applying the NOF to the GPS messages checking that this is consistent with an independent set of measurement to control and insure the integrity.

The KPS-PS component plays a key role in the KASS performance achievement where the APV-1 service level is required. To feed the KPS, the KASS has specific KASS Reference Station (KRS) located on the Rep. of Korea land masses. Compared to other SBAS, this leads to a very concentrated station network. This particularity makes a specific algorithm adaptation of the KPS-PS necessary, as compared to the EGNOS solution, to provide the desired APV-1 performance. These adaptations regard both orbit determination and all the more ionosphere corrections due to the very low number of Ionosphere Grid Points (IPG) that need be modeled and monitored.

To cope with these KASS specificities, Thales Alenia Space has designed, developed and qualified a new complete real time navigation algorithm chain that provides MOPS-compliant NOF messages. The ionosphere model is different from the EGNOS one that favors a local analysis counter to a global approach as the TRIN model [2] used in EGNOS.

This new algorithm chain provides the specified APV-1 performance, particularly in the case of strong ionosphere activity, with a very good level of integrity margin.
This paper presents the overall KASS system architecture as well as the results obtained using this new algorithm chain under different ionosphere contexts. The APV-1 service availability level is presented and the maximum of safety index on each monitored IGP and satellite is discussed.

INTRODUCTION

The KASS is the planned Satellite-Based Augmentation System (SBAS) in Korea. An SBAS is a Global Navigation Satellite System (GNSS) augmentation system standardized in Annex 10, Volume 1, to the International Convention on Civil Aviation published and maintained by the International Civil Aviation Organization (ICAO). The KASS is a system that will provide safety-critical services for the Civil aviation as well as an Open service, usable by other forms of transportation and possibly other position, navigation and timing (PNT) applications.

The KASS will provide improved GNSS navigation services for suitably equipped users in the agreed service areas of the Republic of Korea by broadcasting an augmentation signal to the US Global Positioning System (GPS) Standard Positioning Service (SPS). The augmentation signal provides corrections to ranging measurements from GPS satellites clock & orbits and integrity bounds on the residual ranging errors, as well as corrections and integrity bounds for ionosphere delays. The augmentation signal will be broadcast by two Geostationary Earth Orbiting (GEO) satellites and will be used by GPS/SBAS user equipment to compute a navigation solution.

The KASS is a project of the Korean Ministry of Land, Infrastructure and Transport (MOLIT). The KASS procurement is being managed by a KASS Program Office (KPO) within the Korea Aerospace Research Institute (KARI). The KARI is the primary entity of the Republic of Korea in the sphere of space exploration. The KARI is a developer, manufacturer and operator of various types of spacecraft and mission. Once commissioned for operational use, the KASS will be maintained and operated by the MOLIT. Thales Alenia Space in France is the industry prime contractor of the KASS development.

The KASS is designed to be a system-of-systems including hardware and software to fulfill the following functions.

- Collect GPS and GEO satellite data at various locations in the Republic of Korea (and possibly in other States in the future),
- Transmit these data to redundant KASS Processing Stations (KPSs) where the contents of the augmentation signal are generated, and redundant KASS Control Stations (KCSs) where operators monitor and control the system,
- Compute corrections and associated integrity bounds for ranging measurements from GPS and possibly GEO satellites in view of the KASS,
- Format messages compliant with the SBAS user interface standardized in ICAO SARPS Annex 10 and the RTCA MOPS 229-D change 1 [1],
- Uplink a signal carrying these messages to navigation payloads on the KASS GEOs, and
- Broadcast the signal to the users after frequency-conversion to the L1 band.

The Navigation services provided to the aviation community by the KASS support the implementation of Performance-Based Navigation (PBN) in the Republic of Korea by providing navigation services for the following phases of flight:. *En route* (oceanic and domestic), *terminal area*, *non-precision approach* (also called LNAV, lateral navigation), *approach with vertical guidance type I* (APV-I), *departure, and Required Navigation Performance* (RNP) operations. The KASS may also be used to support *Automatic Dependent Surveillance – Broadcast* (ADS-B) applications.

The KASS ensures the integrity of the broadcast corrections in case of possible failures of the GPS constellation, of some of its hardware components or possible latent faults of some of its software components, and promptly alerts the users whenever the integrity of the broadcast corrections cannot be assured.

The global overview of the system is given in the Figure 1.

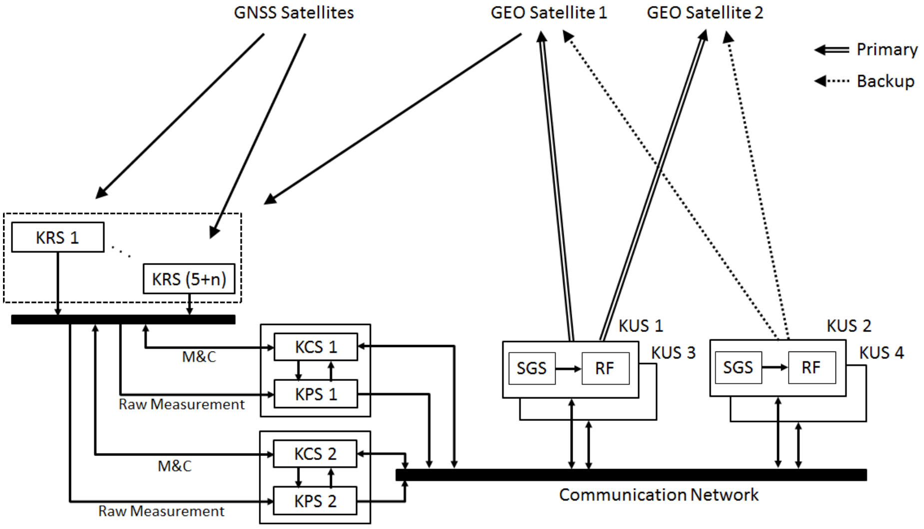


Figure 1: KASS architecture overview

The ground segment will comprise the following subsystems .

- The network of KRSs (KASS Reference Stations), with two independent receivers at each KRS site;
- The redundant KPSs (KASS Processing Sets) and KCSs (KASS Control Stations), and the KUSs (KASS Uplink Stations); and
- The communication network between all system components distributed across Korea (WAN).

The space segment will include the GEOs satellites and the navigation payloads onboard these GEOs.

Using measurements from the KRS spread over the KASS coverage area, the KPS derives the information necessary to support the generation of the KASS broadcast messages. Each message is transmitted to the KUS to uplink them to the KASS GEO satellites for onwards transmission to the users.

To achieve the required overall KASS availability and continuity performance, it is necessary to have several redundant KPS which are collocated with the KCS to share communication lines. The KPSs at all sites will all be active (i.e. simultaneously operational). The selection of the KPS channel to be used as the user data message provider will be made at the KUS, using status validation data from each KPSs check functions as well as control information from the KCS.

The KPS computation processing set (KPS-PS) determines the user data information (corrections, confidence intervals, etc.) using measurements from one of the receivers of each KRS site. The integrity of the derived information is then assessed by the KPS check set (KPS-CS) using data from at least one other group of independent receiver from each KRS site. The status information generated from the integrity assessment is transmitted to the KUS for use in selecting the KPS to be used as the user data provider.
A KPS channel is made of one Processing Set and one Check Set.

The KPS Processing Set is responsible for computing the necessary GNSS corrections and integrity data to be broadcast to the user (Messages Types 2-6, 25, for the satellites and 26 for the ionosphere), and for selecting and formatting the most appropriate sequence of messages in which this information must be sent. Additionally, the KPS Processing Set must incorporate some means of verifying the correctness of its performance.

The Integrity data are formed by User Differential Range Error (UDRE) and Grid Ionospheric Vertical Error (GIVE) for each satellite and Ionosphere Grid Point (IGP) respectively. The UDRE bounds the non-modelled orbit and clock error once applied the satellite KASS corrections. The GIVE bounds the vertical ionospheric delay error the Grid Ionosphere Vertical Delay (GIVD) once has been applied. According the MOPS [1], the UDRE and GIVE values are linked to the standard deviation of a normal distribution that overbound the residual errors at the desired confidence level, after application of SBAS corrections:

- $UDRE = 3.29 \cdot \sigma_{UDRE} \cdot \delta UDRE$, where $\delta UDRE$ value is defined in Message Type 27, and
- $GIVE = 3.29 \cdot \sigma_{GIVE}$.

The functional description of the processing set is divided in several sub-sets. They include the pre-processing of the data, the computation of the main corrections, i.e. ephemeris, clocks and ionosphere, the computation of the UDRE, the GIVE and the selection and formatting of the messages. This set is also responsible to establish the KASS Network Time (KNT) that represent the internal reference time scale on which all clocks are synchronized (stations and satellites). The KNT is steered towards the GPS time scale by the KPS Processing Set design. The steering shall be closer than 50ns by requirement, but in practice the gap between the two time references is below 3ns (see [3]). The message the KPS Processing Set sends is the NOF Up Link (UP).

The KPS Check Set is responsible for verifying the integrity of the NOF coming from the Signal In Space (SIS). There are five KPS cycles between the NOF-UP emission event and the NOF-SIS reception event. For each monitored satellite defined in the PRN mask (Message Type 1), the KPS Check Set computes the Satellite Residual Error at the Worst user location (SREW) and compares it to the broadcast UDRE in the NOF-SIS. For each monitored IGP defined in the IGP mask (Message Type 18) the KPS Check Set computes the GIVD error and compares it to the broadcast GIVE in the NOF-SIS. The KPS Check Set send a ‘do not use’ alarm to the KPS Processing Set for injection inside the very next NOF-UP in case an anomaly is detected.

The Figure 2 provides details on the data flows exchanged between Subsystems and between KPS sets.

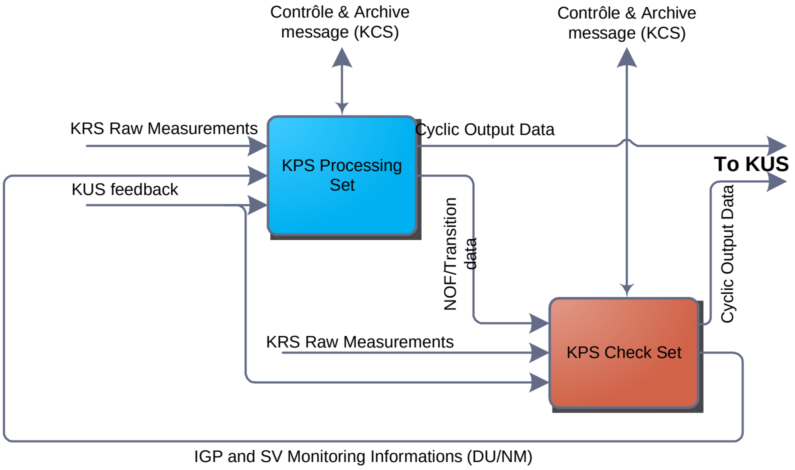


Figure 2: KPS data flows

The interface between the KPS Processing Set and KPS Check Set consists in the following:

- Internal and operational NOF computed by the Processing Set and sent to the Check Set for independent verifications,
- Transition information sent by the Processing Set to the Check Set in order to recover from SV/IGP NM/DU periods through the NOF-SIS,
- NM/DU flags requested by the Check Set for inclusion in the NOF-UP to be send by the Processing Set to the KUS
- Communication test performed during the initialization phase of the KPS

The proposed KRS network for KASS are located on the Rep. of Korea land masses. The specificity of this stations network is the geographic colocalisation. This led to important KPS algorithms adaptations regarding on orbit determination and ionosphere corrections for KPS-PS and integrity assessment for KPS-CS. Although the final location of the KRS is not finalized and depend on site survey the positions that are used from now are depicted below.

KRS ID	**Location**	**Latitude**			**Longitude**			**Altitude**
		(deg)	*(Min)*	*(Sec)*	*(deg)*	*(Min)*	*(Sec)*	*(m)*
1	Incheon	37	28	47.56	126	27	12.70	12
2	Yeong-do	35	3	45.08	129	4	14.67	135
3	Jeongsuk	33	23	53.59	126	42	47.12	346
4	Mara-do	33	7	02.84	126	16	09.73	26
5	Ulleung-do	37	31	04.11	130	47	56.02	182
6	Muan	34	59	36.69	126	23	16.49	15
7	Yangyang	38	3	31.70	128	39	46.90	76

Tableau 1: KRS proposed location

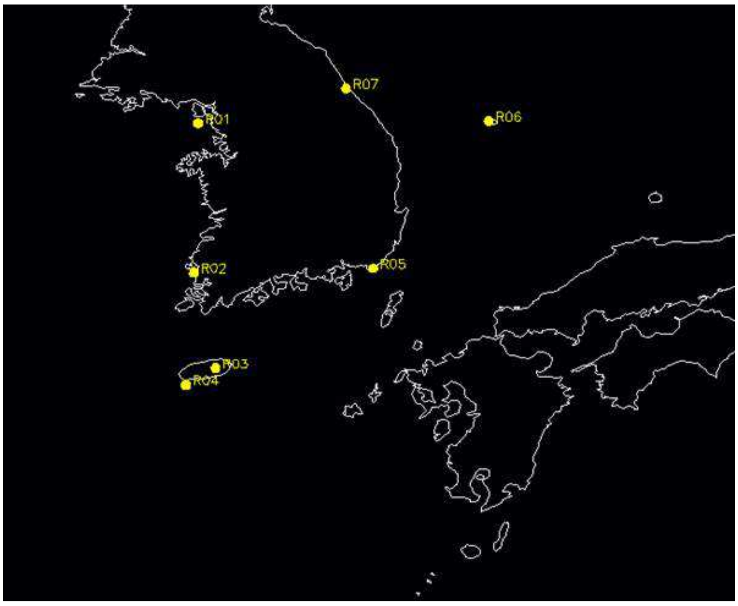


Figure 3: KRS proposed network for KASS

PERFORMANCE OF THE KPS

There are four levels of service for KASS. These service levels are listed below:

- **En Route**: Any level flight segment after arrival at initial cruise altitude until the start of descent to the destination
- **Terminal**: Descent from cruise to either Initial Approach Fix
- **NPA**: For non-precision approaches (NPA) in aviation an instrument approach and landing which utilizes lateral guidance but does not utilize vertical guidance
- **APV-I**: For precision approaches with vertical guidance

Figure 4 shows the definition of Incheon Flight Information Region (FIR) and the Republic of Korea land masses.

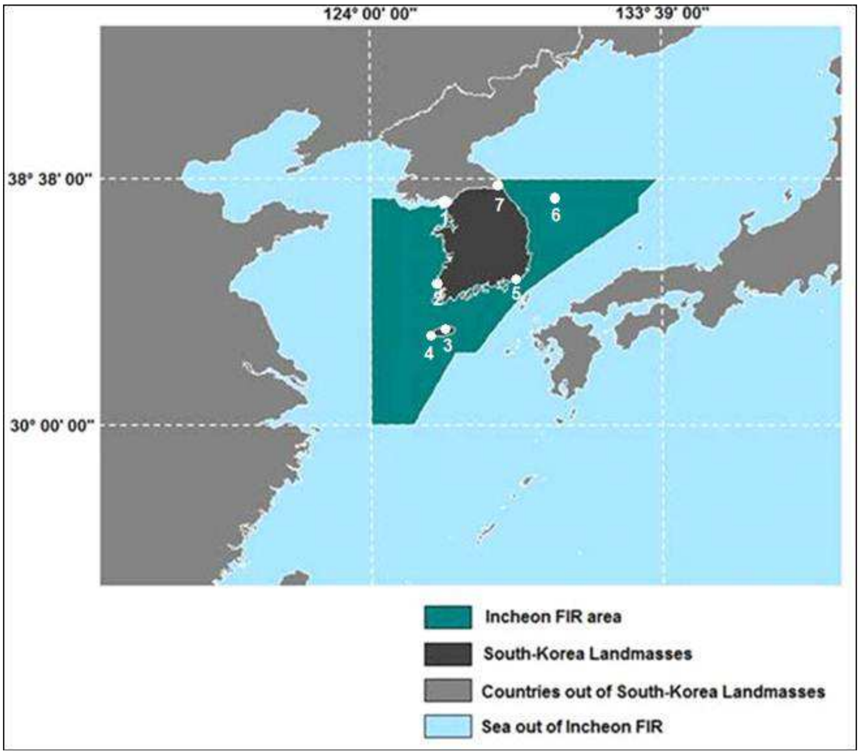


Figure 4: KASS service area

The KASS service area for Open service is given by:

30 deg. North < latitude < 39 deg. North
124 deg. West < longitude < 134 deg. East

The performance of a satellite navigation system is expressed in four Criteria: Accuracy, Integrity, Continuity and Availability.

The Accuracy feature is the difference between the computed value and the actual value of the user position, speed and time.

The Integrity feature refers to the notion of trust that the user may have in the computed position. Integrity includes the ability of a system to provide confidence thresholds as well as Alarms within a known time-to-alert (TTA) in case of anomaly.

The Continuity feature defines the ability of a system to perform its function without interruption during the operation planned by the user (for example landing phase of an aircraft). It is evaluated as the probability that from the moment when the criteria of precision and integrity are completed at the beginning of an operation, they remain so for the duration of the operation.

Finally the Availability feature is the percentage of time when, over a certain geographical area, the criteria of accuracy, integrity and continuity are met.

The System time to alert is defined as the time starting when an alarm condition occurs to the time that the alarm is displayed in the cockpit. The KASS is designed in such a way the TTA is always under 6 seconds as EGNOS.

Table below provides the various service levels and the associated performance requirement for KASS GPS L1 legacy.

Phase	**Service coverage**	**Availability**	**Continuity**	**TTA**	**Accuracy**		**Integrity**		
					HNE	**VNE**	**HAL**	**VAL**	**Risk P_{HMI}**
En Route	FIRs of Incheon	99.0%	10^{-5}/hour	5 mn	3.7 km	N/A	3.7 km	N/A	10^{-7}/h
Terminal	FIRs of Incheon	99.0%	10^{-5}/hour	15 s	740 m	NA	1.85 km	N/A	10^{-7}/h
NPA	FIRs of Incheon	99.0%	10^{-5}/hour	10 s	220 m	NA	556 m	N/A	10^{-7}/h
APV-I	Land-masses Korea + Jeju	99.0%	$8x10^{-6}$/15 s	10 s	16.0 m	20.0 m	40.0 m	50.0 m	$2x10^{-7}$/150 s

Table 1: KASS performance service levels

The performance features that are presented in this paper are the level of targeted APV-1 performance levels associated with integrity characteristics as Safety Index (SFI) on satellites and IGP. Because the KASS project is currently under preliminary design these performances features are assessed only on the base of synthetic scenarios at the date of the paper no real data coming from KRS are available.

However the synthetic data shall be representative of the ionosphere behaviour above the South Korea in nominal conditions but almost in case of strong ionosphere dynamic to warranty the integrity of the system. The accuracy, availability and continuity commitments are based on the nominal scenario. The integrity commitment is assessed whatever the environment situation thus in nominal and degraded ionosphere conditions. On degraded scenario the commitment is only to maintain integrity.

The synthetic scenario have to catch the real ionosphere and then then have been built based on a real data collection coming from a set of Korea stations and neighboured IGS stations. Having these datasets a dedicated methodology shall be developed to inject these ionosphere information in the synthetic scenarios. The description of this methodology is the scope of the following section.

IONOSPHERE MODELLING APPROACH FOR SYNTHETIC SCENARIO

The processing of the ionosphere is critical to the KASS system performance. In order to test the performance of the KASS system, and especially the capability for maintaining integrity during solar storm conditions, synthetic scenarios were produced. The scenarios were derived from actual observations of GPS receivers located in the Republic of Korea. The 3D distribution of electron density was created by deriving grid values of the ionosphere parameters, *foF2* and *M(3000)F2*, from observed data and by applying the NeQuick model to this grid ([4], [5]).

The NeQuick model (see [4] and [5]) is adapted to real ionospheric conditions by means of using the *Az* parameter. This will be the concept used to derive the scenarios by computing a grid of Az values.

The ionosphere conditions representative of the Korea environment have been simulated from actual observations of GPS receivers located in the Republic of Korea, complemented by some IGS stations located in neighbouring. IGS datasets are provided daily at a 30s sampling rate.

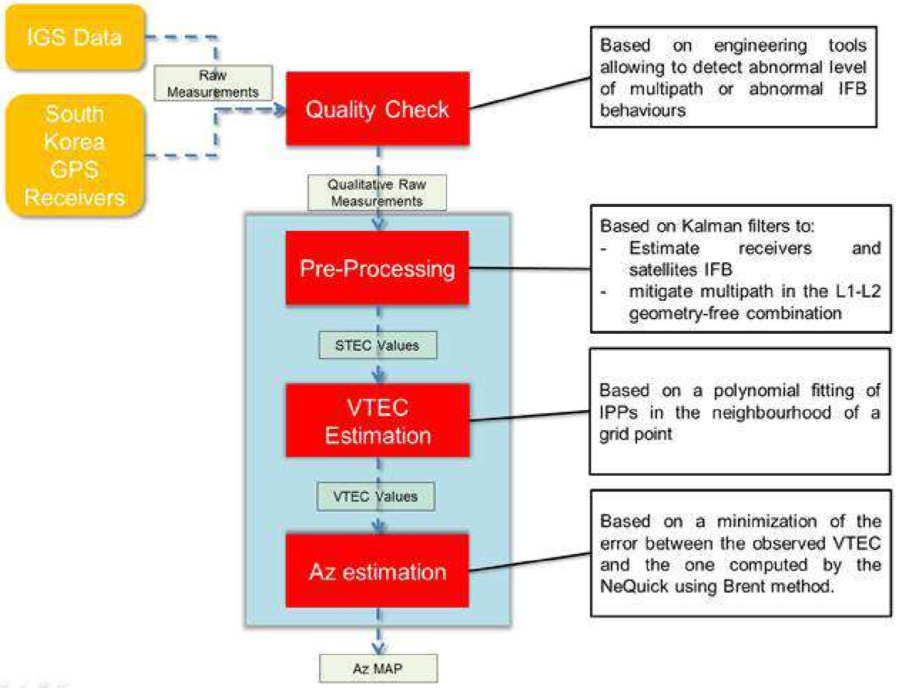
The first step is to assess the quality of the data of every receiver. In order to prevent any ionosphere mismodelling, the receiver measurements shall not contain any abnormal level of multipath or of IFB behaviour. Each receiver with such an anomaly has been discarded from the set of receivers used to elaborate the ionosphere model.

Then, the measurements of the remaining receivers have been pre-processed in order to separate the Slant Total Electron Content (STEC) from other sources of error. This algorithm chain implements filters that aim at mitigating the multipath error in the geometry-free L1/L2 combination and also estimates the satellite and receiver IFB. At the end of this process, the STEC values are obtained.

Once the STEC values have been computed, Vertical TEC (VTEC) values have been estimated over a thin layer grid of 1 degree latitude/longitude resolution. The approach consists in performing a local approximation of the vertical TEC variable in the vicinity of a given grid point of the thin layer considering a large set of Ionosphere Pierce Points. Around each grid point, the ionosphere has been modelled by a polynomial fit.

Finally, some NeQuick models have been calibrated in order to be able to reproduce an ionosphere environment consistent with the observed ionosphere delays from the measurements. For each grid point and each epoch the *Az* value has been computed. The methodology to compute the *Az* maps is based on minimizing, the error between the observed VTEC and the one computed by the NeQuick, using the Brent method. Hence, an *Az* map is obtained with the same sample as the input VTEC grid. These *Az* maps are finally used as input of engineering tools in order to generate an ionosphere scenario.

The Figure 5 presents the different steps of the methodology:



Based on engineering tools allowing to detect abnormal level of multipath or abnormal IFB behaviours

Based on Kalman filters to:
- Estimate receivers and satellites IFB
- mitigate multipath in the L1-L2 geometry-free combination

Based on a polynomial fitting of IPPs in the neighbourhood of a grid point

Based on a minimization of the error between the observed VTEC and the one computed by the NeQuick using Brent method.

Figure 5: Injection methodology of real ionosphere data in synthetic scenarios

At the end of this activity, the objective is to have two available scenarios, representative of the Korea ionosphere environment.

- One scenario representative of nominal conditions
- One scenario representative of degraded conditions

FAULT FREE SCENARIO DESCRIPTION

The nominal scenario has been built considering GPS measurements collected from the June 21st, 2015 to June 25th, 2015.

In order to describe the ionosphere state on this period, Fig 6 shows a map of the vertical delay on June 23rd, 2015 at 7 am UTC, that corresponds to the period when the spatial gradients are strongest.

The values of maximal temporal and spatial gradients are the followings:

<u>Spatial Gradient Maximum:</u> **0.238m/deg**
<u>Temporal Gradient Maximum:</u> **1.7mm/s**

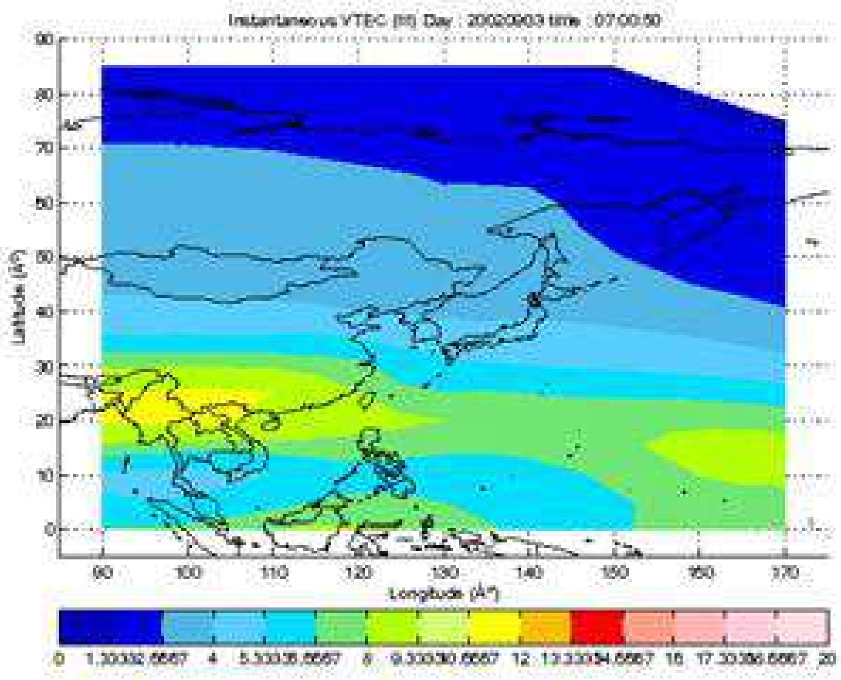


Figure 6: Vertical ionospheric delay (m) when spatial gradient is maximum

The degraded scenario has been built considering GPS measurements collected on some different periods:

- October 29th, 2003
- From March 7th to 9th, 2014
- November 10th, 2004

The first two periods (October 2003 and March 2014) show wide ionosphere events. Figs 7-10 show a series of maps of the vertical delay on each day of the degraded scenario at the time when the ionosphere gradients are the highest.

The maximal of amplitude of spatial and temporal gradient are the followings:

<u>Spatial Gradient Maximum:</u> **1.6m/deg**
<u>Temporal Gradient Maximum:</u> **10mm/s**

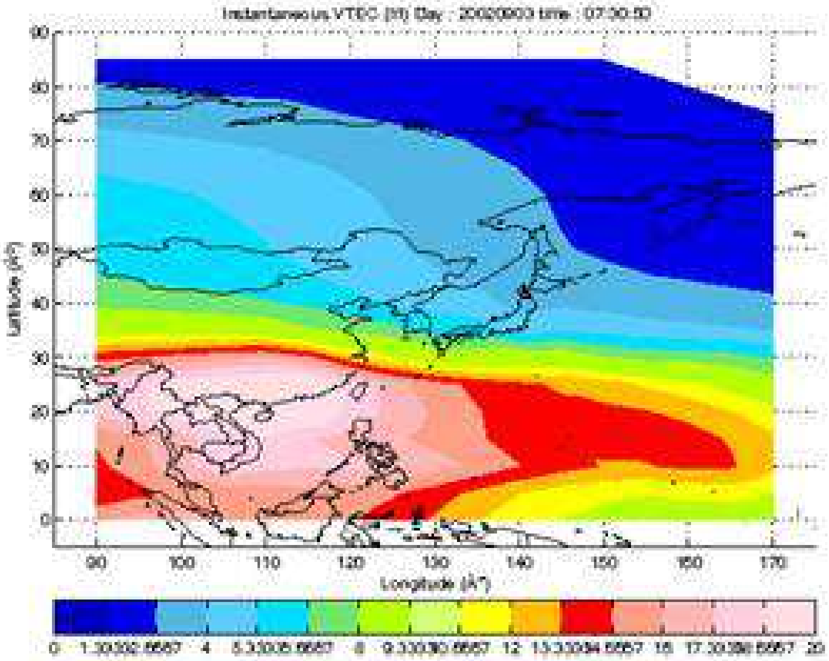


Figure 7: DAY3 (03/09/2002): Representative of the 29/10/2003

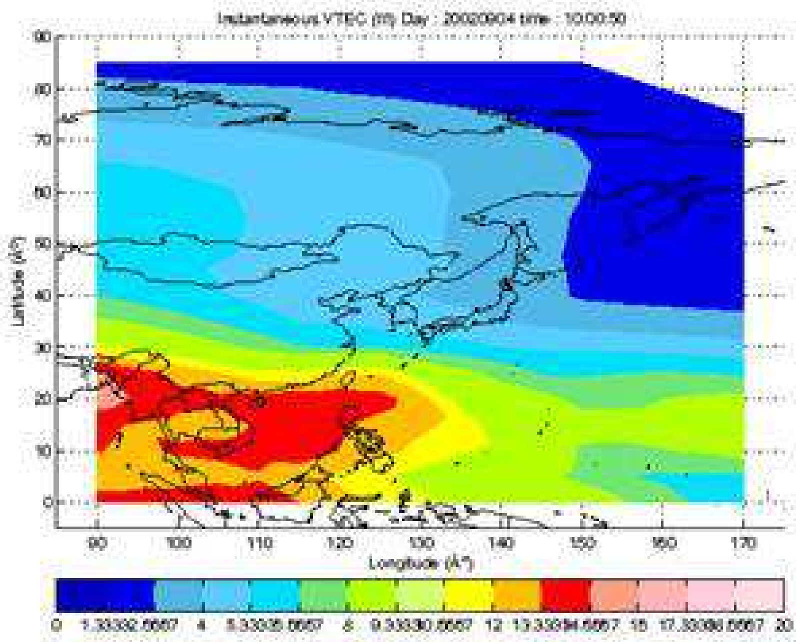


Figure 8: DAY4 (04/09/2002): Representative of the 07/03/2014

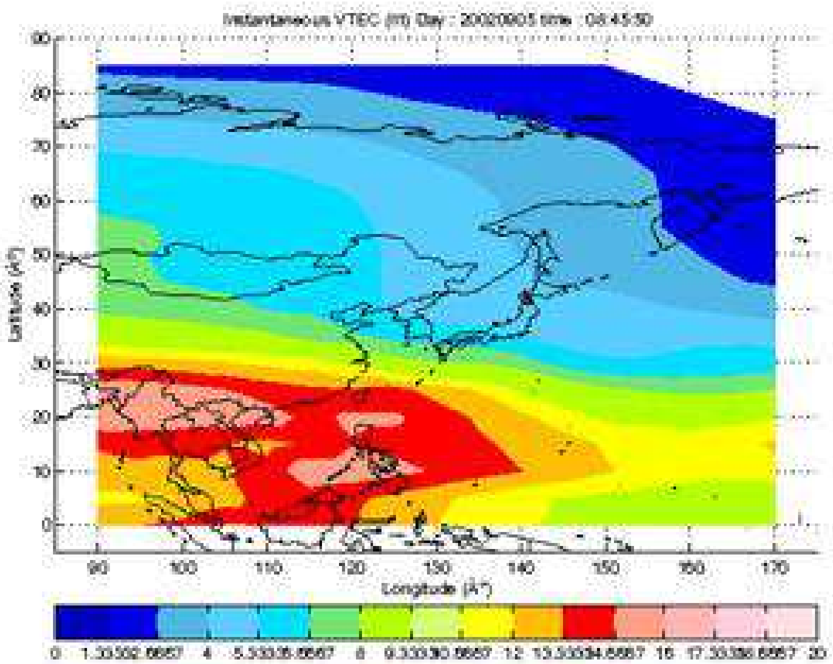


Figure 9: DAY5 (05/09/2002): Representative of the 08/03/2014

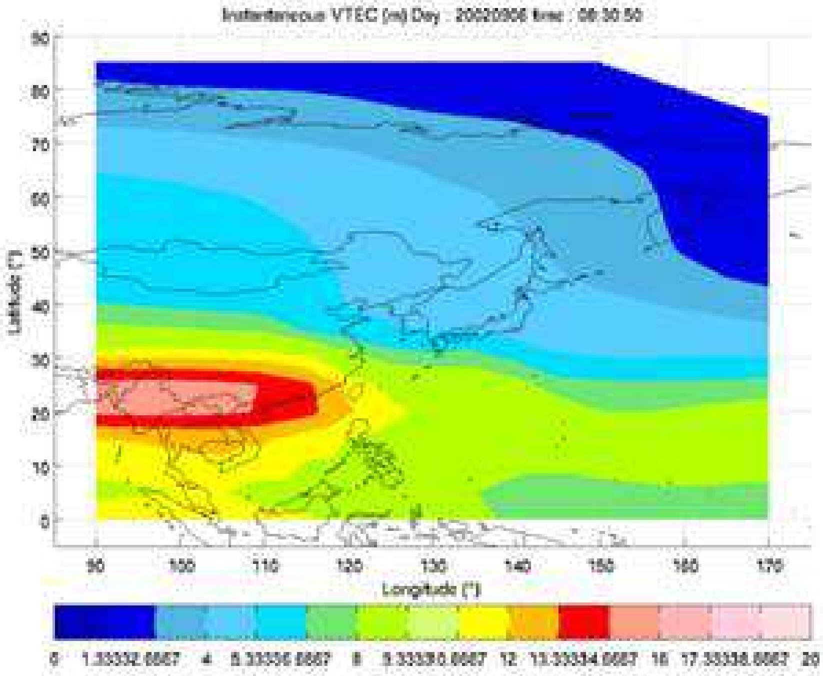


Figure 10: DAY6 (06/09/2002): Representative of the 09/03/2014

The last day of the scenario (November 10th , 2004) shows local ionosphere events. Figure 11 shows a map of the vertical delay on the last day of the degraded scenario at the time the ionosphere gradients are the higher.

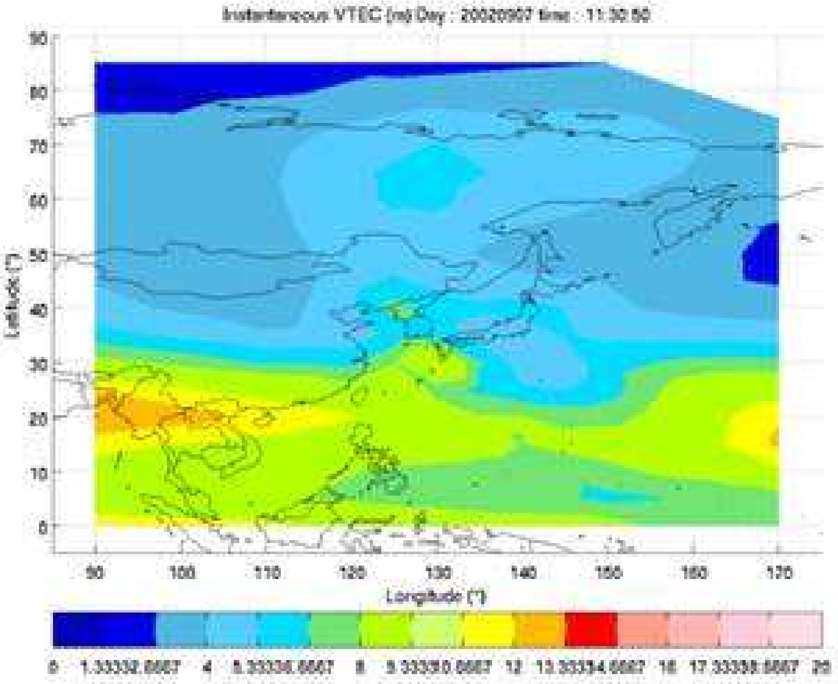


Figure 11: DAY7 (07/09/2002): Representative of the 10/11/2004

INTEGRITY PERFORMANCE ASSESSMENT METHODOLOGY

The alarm limit is the maximum allowable error in the user position solution before an alarm is to be raised within the specific TTA. The Horizontal Alarm Limit (HAL) and Vertical Alarm Limit (VAL) define the alarm box (see Figure 12) .

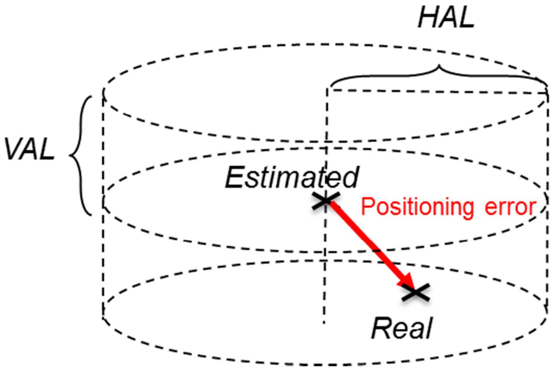


Figure 12: Alarm Limit box

This alarm limit is dependent on the flight phase (see Table).

The definition of the integrity risk is the probability during the period of operation that an error, whatever is the source, might result in a computed position error, where H_{err} and V_{err} note its horizontal and vertical components, exceeding the Alarm Limit, and the user be not informed within the specific TTA.

The integrity is maintained while

$$P(\{H_{err} < HAL\} \wedge \{V_{err} < VAL\}) > 1 - P_{HMI}$$

Where $P_{HMI} = 2 \times 10^{-7}/150$ s for APV-1 service level for instance.

In case the previous inequation does not hold at a time t, an alarm shall be received by the user before $t + TTA$. In case the alarm in not received under TTA a non-integer situation occurs.

The Horizontal and Vertical Protection Level (HPL and VPL) are the values computed by the user receiver which estimates the bound on the actual Navigation System Error using data transmitted by the SBAS signal (UDRE, GIVE) and pre-determined bounds. The HPL and VPL shall bound the positioning error with a probability equal to 0.9999999.

The HPL and VPL are calculated on the basis of the integrity data provided by the SBAS and standardized assumption on the budget of local errors.

The integrity assessment is apportioned in two parts.

- The nominal condition i.e. without failure named the Fault Free condition,
- The degraded condition corresponding to an exposition to Feared Event.

The total budget is equally allocated between this two features, the nominal and degraded conditions.
Under nominal or Fault Free (FF) condition the KPS design shall guaranty that

$$P_{FF} = P(\{H_{err} > HAL\} \vee \{V_{err} > VAL\}) < \frac{1}{2} P_{HMI}$$

The integrity is insured by design: the σ_{UDRE} and σ_{GIVE} time series are computed in such a way the non-modeled residual error are bounded up to $5.33\sigma_{UDRE}$ or $5.33\sigma_{GIVE}$ corresponding to the required confidence level (10^{-7} for SL3 service level). For APV1 service level the budget of $2 \times 10^{-7}/150\,\mathrm{s}$ is allocated to the whole KASS system: it must be declined to the sub-systems. The KPS Processing Set and the Check Set are two filters that can stop an integrity event, and they are supposed independent. Indeed, they don't process the same measurements, and their algorithms are different; even their HW and SW are independent.

The integrity is verified at pseudorange level by measuring at each sample time the safety index on both satellite (SV) and IGP defined as:

$$SFI_{SV} = \frac{SREW}{\sigma_{UDRE}} \quad \text{and} \quad SFI_{IGP} = \frac{GIVD_{error}}{\sqrt{\sigma_{GIVE}^2 - \Delta\mathrm{GIVE}^2}}$$

where ΔGIVE is the additional GIVE contribution allocated for the Hatch filter user smoothing and computed with the specified MOPS ionosphere gradient of $10\,\mathrm{mm/s}$. This contribution shall be removed from σ_{GIVE} because it is assumed that it is completely consumed by the user so it cannot be considered as a protection against ionosphere errors i.e. GIVD error ($GIVD_{error}$).

While $SFI_{SV} < 5.33$ and $SFI_{IGP} < 5.33$ the pseudorange integrity is warranty and then the integrity at user level is warranty. On a nominal system condition without failure (Fault Free) integrity is verified by tests and checking that the maximum safety index are always inferior to 5.33.

Under degraded condition the KPS design shall guaranty that, for the set of all Feared Event (FE), then

$$P_{FE} < \frac{1}{2} P_{HMI}$$

The probability of non-integrity is case of feared event is the sum of each integrity risk in front of each feared event FE_i. The probability P_{FE_i} is a conditional probability of impact that, under the FE_i has occurred, a missed detection has an impact at user level. The system failure modes associated with feared events are defined with a certain probability of occurrence P_{occ}. Taking into account this probability of occurrence the integrity risk associated at the degraded condition is:

$$P_{FE} = \sum_i P_{occ}(FE_i) \cdot P_{FE_i}$$

The general equation used to evaluate the integrity risk is given by the previous probability figures weighted by the time exposure time, namely the probability of occurrence to be either in nominal or degraded condition :

$$P_{NI} = P_{occ}(FF) \cdot P_{FF} + P_{FE} < P_{HMI}$$

where $P_{occ}(FF)$ is the exposure probability (closed to 1) to the nominal condition regime and P_{NI} is the total budget of Non-Integrity that has to be below the requirement given in Table .

In the following only the integrity performance P_{FF} figure in nominal condition is mentioned because the integrity risk in case of feared event is currently under assessment.

RESULTS AND DISCUSSION

This section presents the first preliminary results of the KASS performance on accuracy, integrity and availability.

A. Availability performances

The availability performance map that are presented are built as an average on the five days of the nominal scenario considering the extended 27 SPS08 GPS constellation with a probability of failures.

For APVI, the colored area of Figure 13 shows the users for which the availability is above 99%.

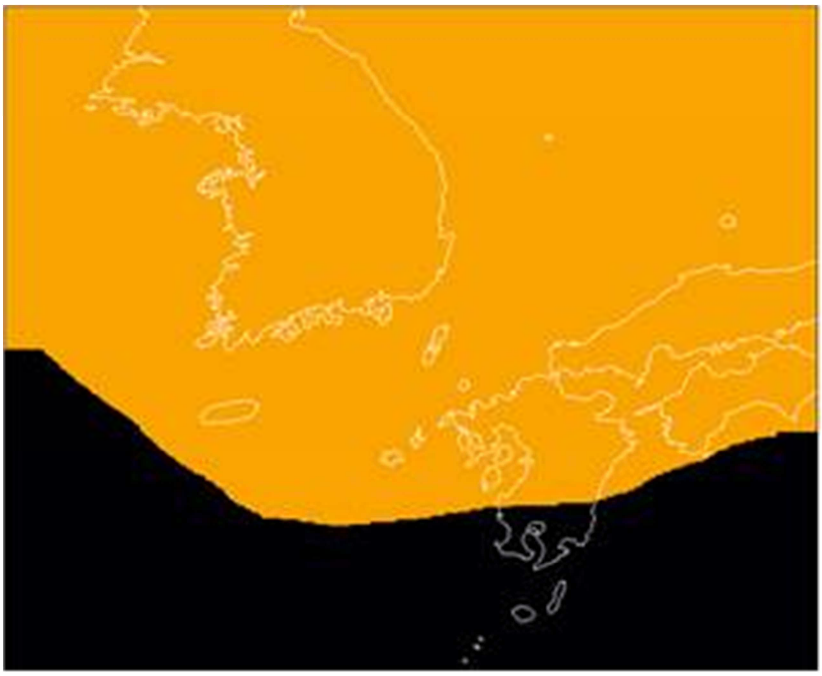


Figure 13: Availability for APV1 service level

The Korea land masses and Jeju are covered with a good margin.

Figure 14: Availability for NPA , Terminal , En-Route services level

The Figure 14 shows the availability performance for the other services level. The coverage over the FIRs of Incheon is 100% everywhere.

B. Accuracy performance

In our simulation conditions, the accuracy is estimated using the Navigation System Error (NSE).
The NSE is the 95th percentile of the the position error distribution at a specific .
The following Figure 15 and Figure 16 present the 95th percentile of the five days of the nominal scenario for both horizontal and vertical accuracy for APV-1 service level.

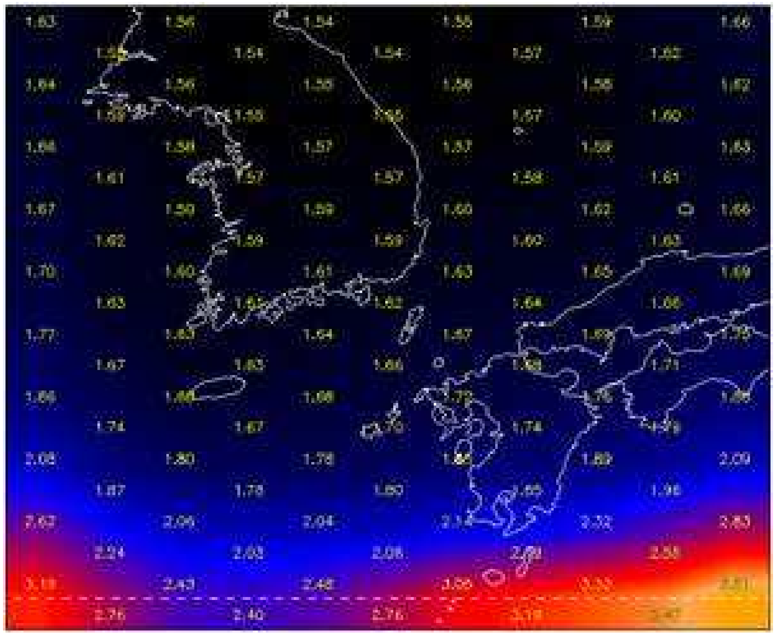


Figure 15: Horizontal NSE for APV1 service level

The Horizontal NSE is below 1.60m, to be compared to the requirement of 16m over the Republic of Korea land masses. The following map shows the vertical accuracy performance.

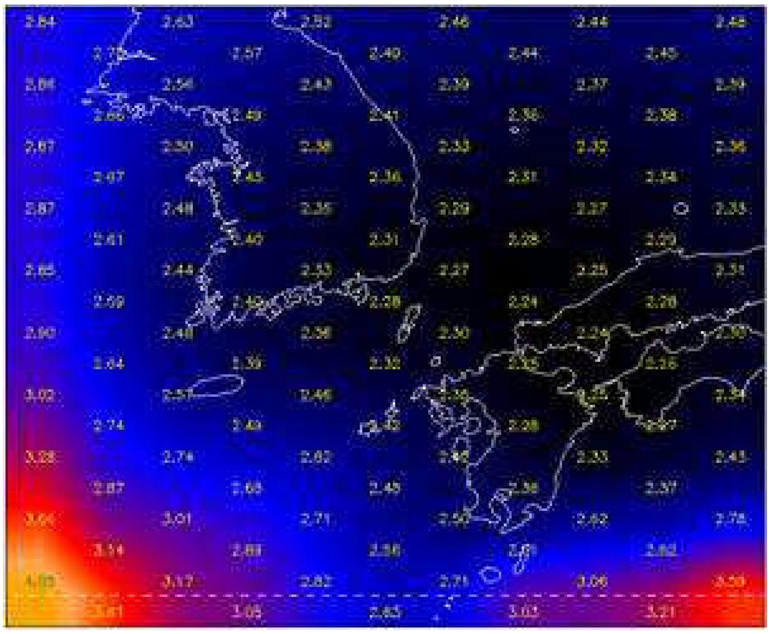


Figure 16: VNSE for APV1 service level

The vertical NSE is below 2.40m to be compared with the 20m requirement over the Korea land masses.

The accuracy of the ionosphere correction is given in Figure 17 for the day three of the nominal scenario.

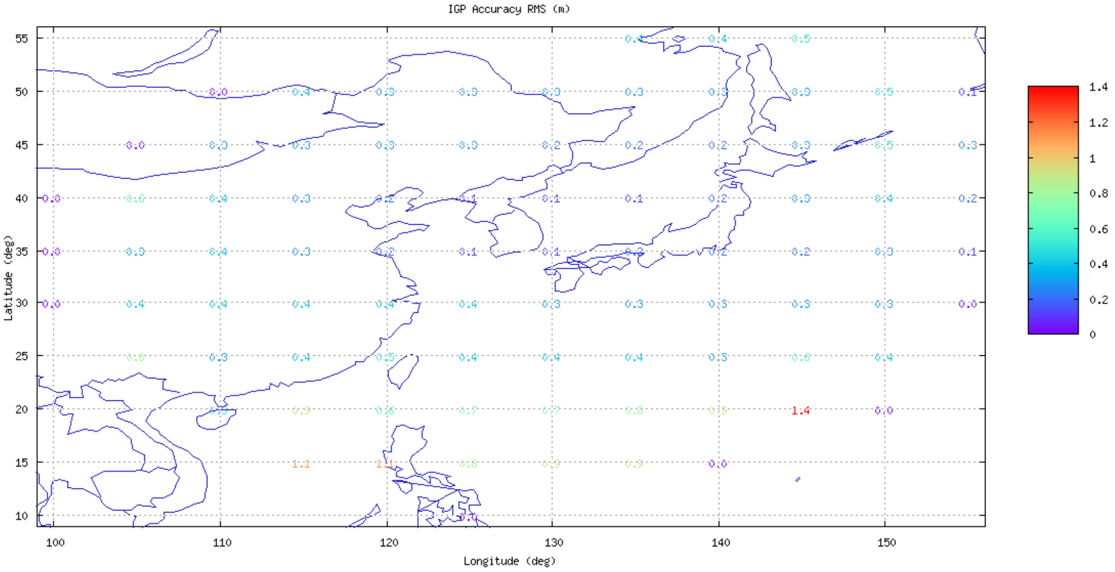


Figure 17: RMS GIVD error of DAY3 on nominal scenario

The RMS of vertical ionosphere error on the geographic square defined by the following coordinates,

20 deg. North < latitude < 50 deg. North
115 deg. West < longitude < 140 deg. East

is below 1m at the boundary and 10cm at the center of the square. The vertical ionosphere delay is thus well modeled over the Korea land masses. The gradient of the vertical ionosphere delay is mainly present along the South-North direction that is consistent with the real ionosphere gradient.

The Figure 18 shows the Horizontal NSE for the 5 days of the nominal scenario for En Route, Terminal and NPA services level (i.e. without using the ionosphere corrections).

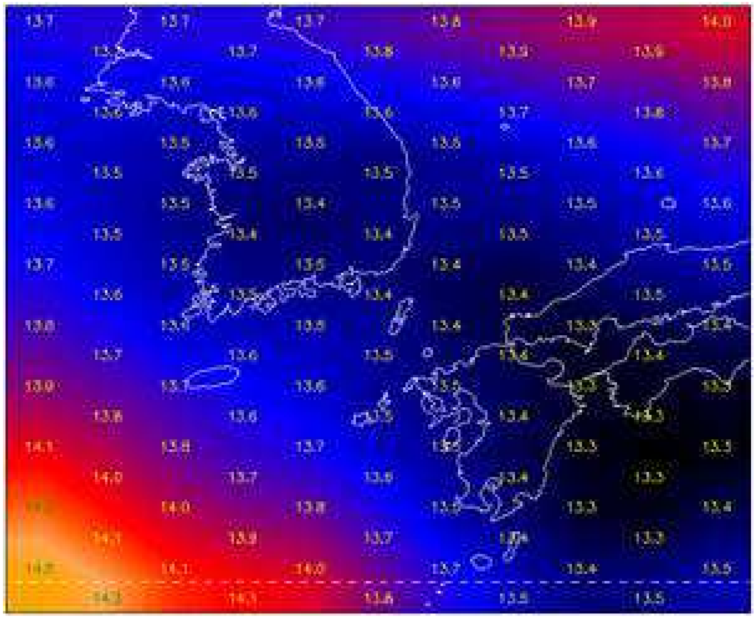


Figure 18: HNSE for NPA, Terminal, En-Route service level

The Horizontal NSE is below 13.7m, to be compared with the 3.7km requirement, for En Route, 740m for Terminal and 220m for NPA services level over the FIR of Incheon.

C. Integrity performance

As mentioned in section 11 this section presents the safety index (SFI) maps for both satellites and IGP. The safety index is defined as the maximum over the scenario of ratio of the observed error to the 1-sigma bound value. These maps are focused on days 3 of the nominal and degraded scenario, that are representative of the overall days of each.

For the nominal scenario, Figure 19 presents the maximum of the SFI per monitored IGP. The maximum that is obtained is 1.33 (to be compared to the 5.33 requirement) and is reached at two IGP of 30 deg North of latitude and 125 deg, 130 deg of longitude. These IGPs are monitored 100% of time, whereas it is not the case for the IGPs located further South. Indeed the less an IGP is monitored, the lower the integrity risk is.

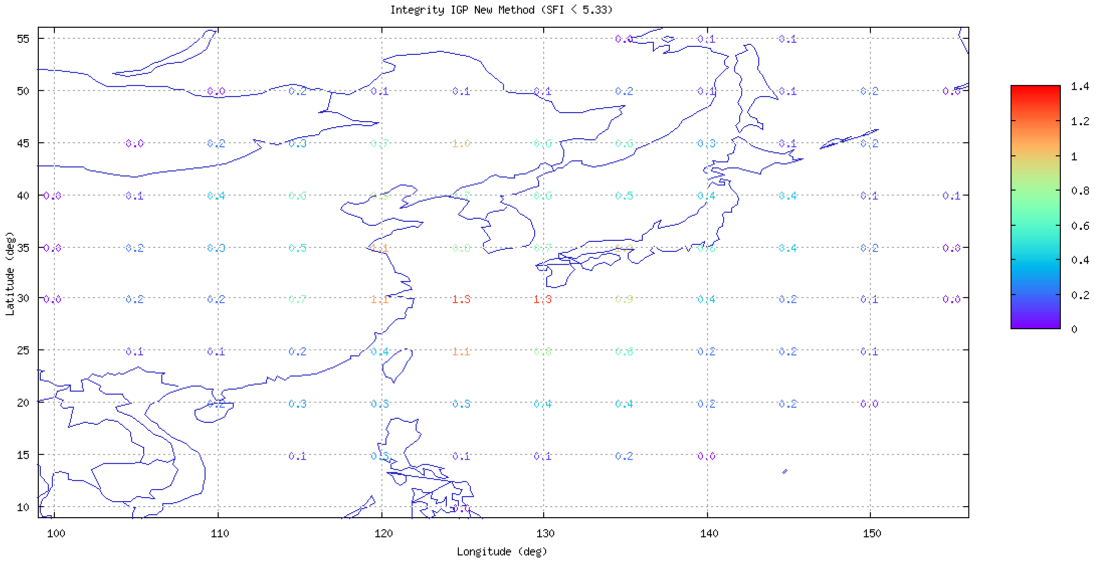


Figure 19: SFI max per IGP, nominal scenario, day 3

Figure 20 shows the IGP SFI max time series that highlight a very good integrity margin as well a very stable behavior along time.

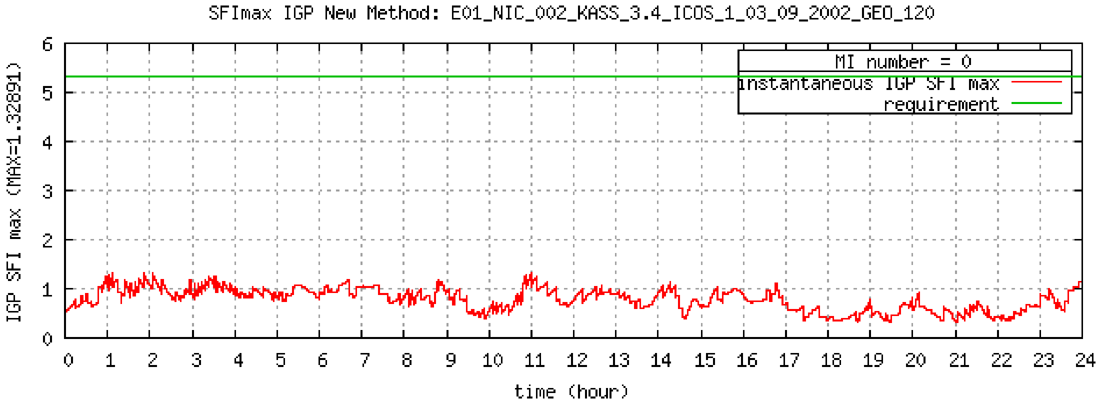


Figure 20: IGP SFI max time series, nominal condition, day 3

Figure 21 presents the maximum of SFI per monitored satellite. The figures are homogenous for each satellite and the integrity margin is very good. The maximum of SFI reached is 1.2 (to be compared to the 5.33 requirement) by PRN 28.

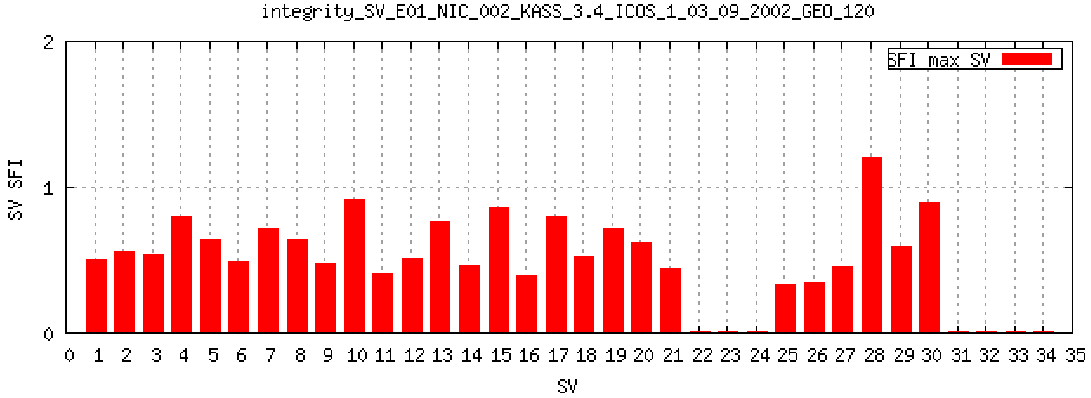


Figure 21: SFI max per satellite, nominal condition, day 3

Figure 22 shows the satellites SFI max time series and highlights a very good behavior stability. Some geometric pattern may be noted due to the GPS orbital period (i.e. twice a day).

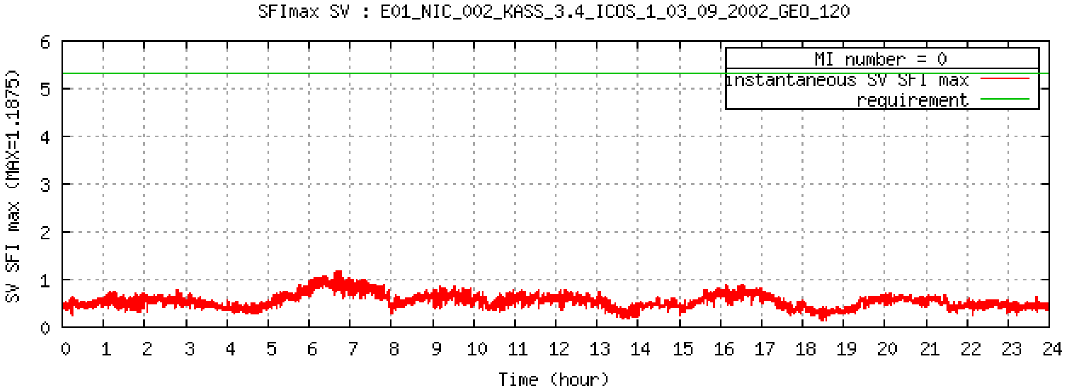


Figure 22: Satellite SFI max time series, nominal condition, day 3

For the degraded scenario, the figures below shows the maximum Safety Index per IGP on the degraded scenario for a few days.

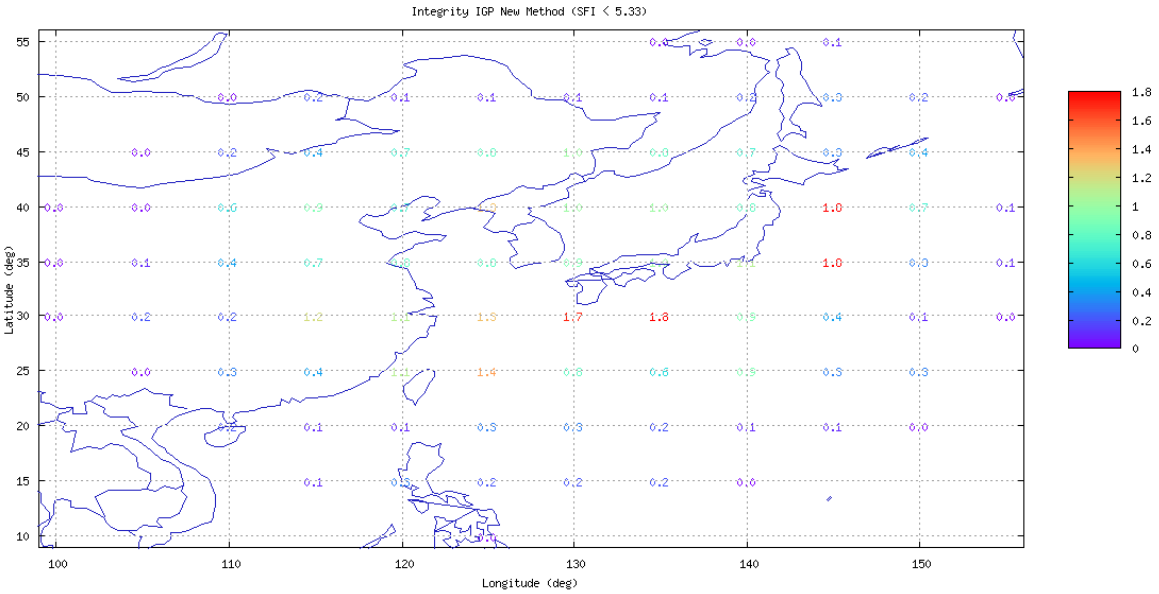


Figure 23: SFI max per IGP, degraded scenario, day 3

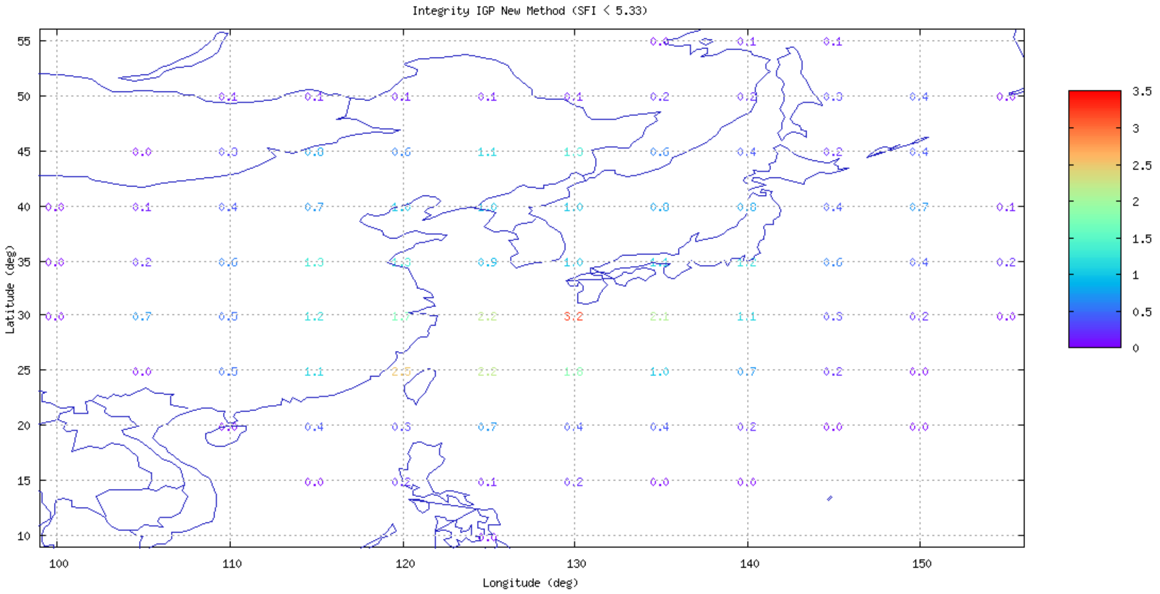


Figure 24: SFI max per IGP, degraded scenario, day 4

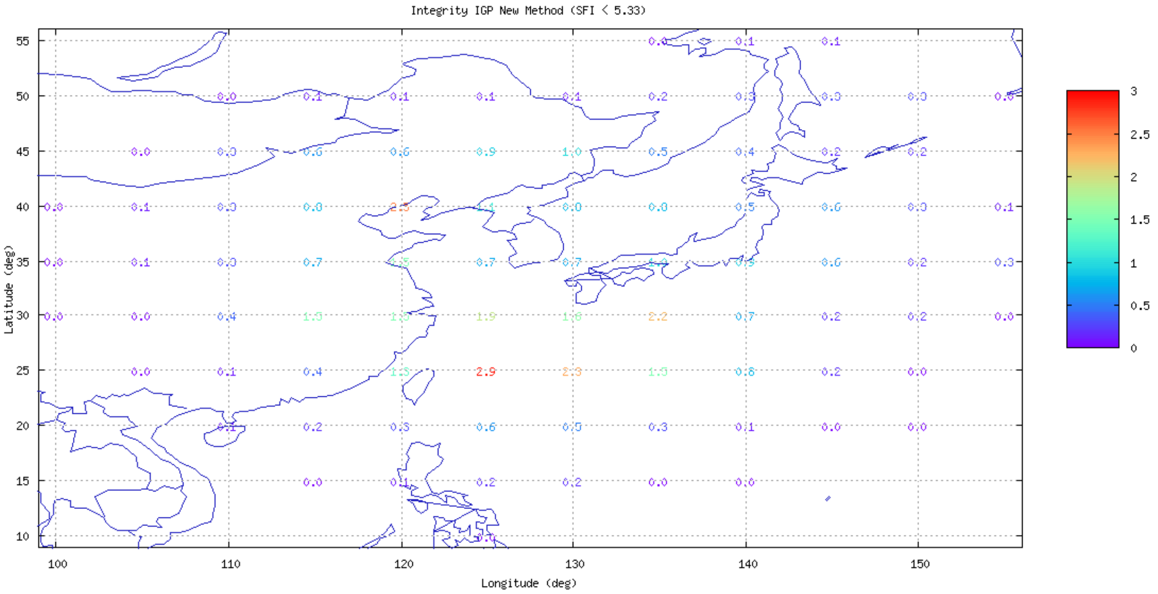


Figure 25: SFI max per IGP, degraded scenario, day 5

Overall, the maximum SFI on the whole scenario is 3.2, which leaves a good integrity margin, despite the very degraded ionospheric conditions. These conditions are reflected through the evolution of the maximum SFI over time, which is shown below:

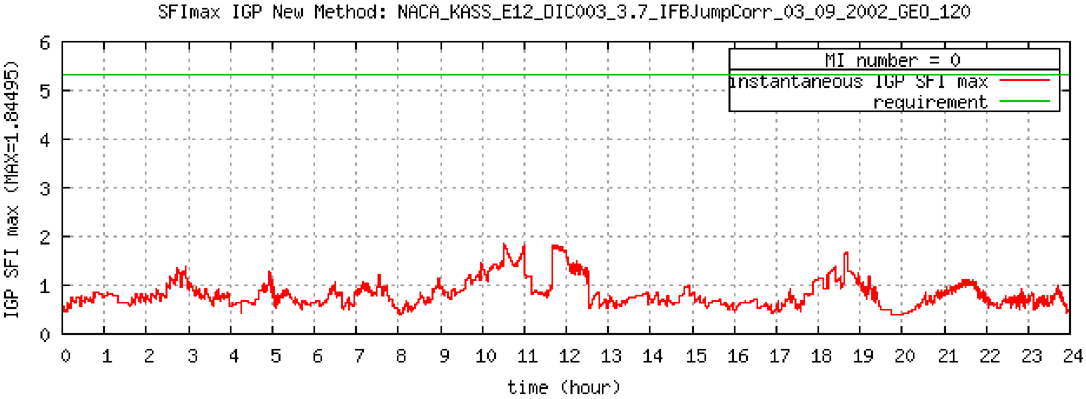


Figure 26: IGP SFI max time series, degraded condition, day 3

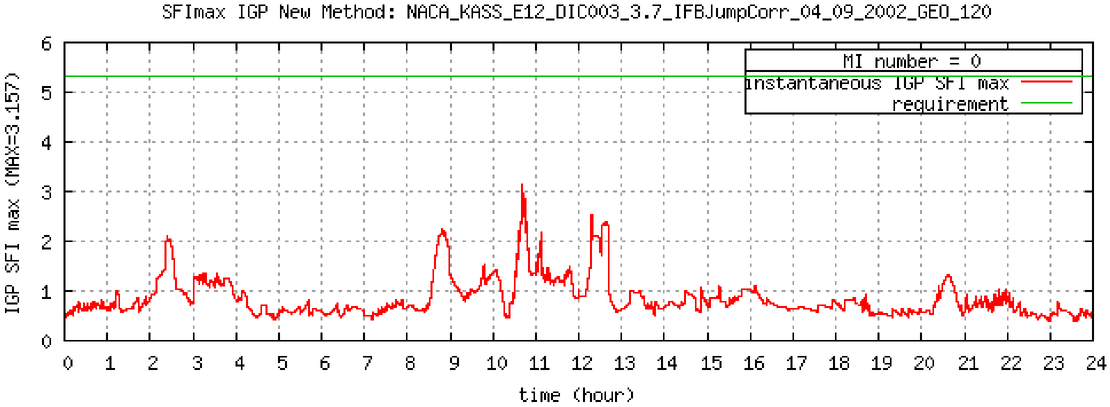


Figure 27: IGP SFI max time series, degraded condition, day 4

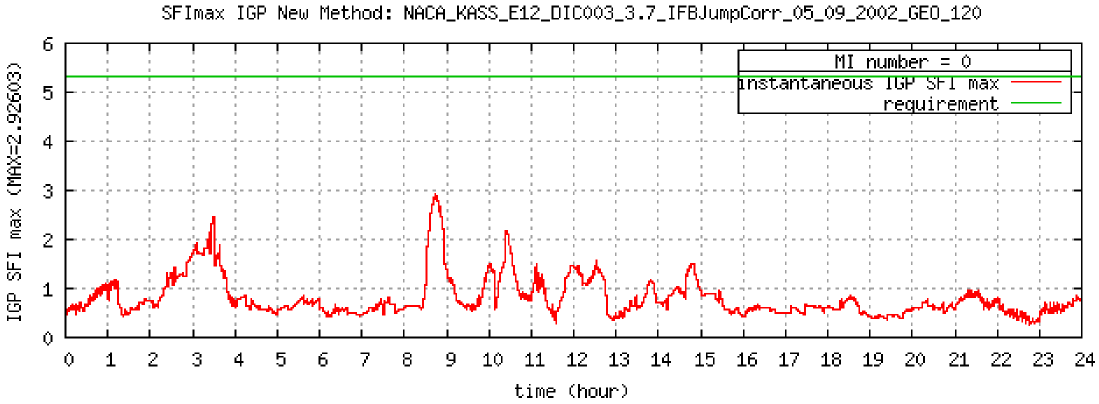


Figure 28: IGP SFI max time series, degraded condition, day 5

The maximum Safety Index shows variations due to the rapid evolution of the ionospheric conditions over Korea for this scenario. However, the ionospheric corrections calculated allow to always bound the error with a good margin.

The maximum Safety Index for the satellites shows, just like the nominal scenario, a large integrity margin, the maximum value for day 3 being 1.1. The results for the other days of the scenario are very similar.

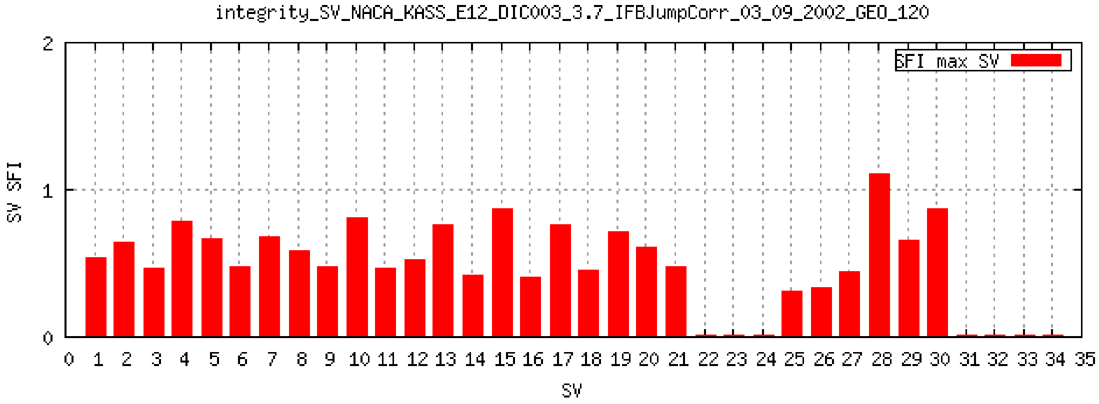


Figure 29: SFI max per satellite, degraded condition, day 3

Like the nominal scenario, the satellite maximum SFI remains very stable over time:

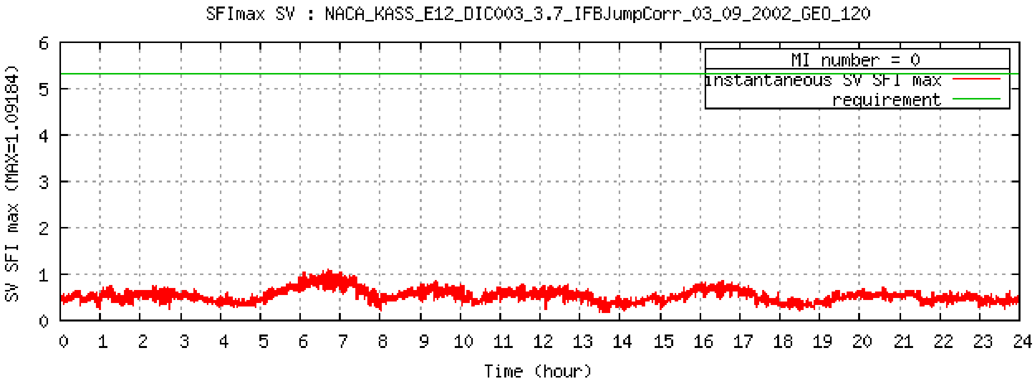


Figure 30: Satellite SFI max time series, degraded condition, day 3

1. CONCLUSIONS

The KASS design and the KPS algorithms design prototype allows reaching a very good level of accuracy, integrity and availability performance features. The summary of our results is given in Table 2.

Phase	Service coverage	Availability	TTA	Accuracy		Integrity
				HNE	VNE	Risk P_{HMI}
En Route	FIRs of Incheon	100% in Fault Free + GPS failures System Failures not included yet	6 s	13.7 m	N/A	Good margin in Fault Free Feared Event budget currently under assessment
Terminal	FIRs of Incheon	100% in Fault Free + GPS failures System Failures not included yet	6 s	13.7 m	NA	Good margin in Fault Free Feared Event budget currently under assessment
NPA	FIRs of Incheon	100% in Fault Free + GPS failures System Failures not included yet	6 s	13.7 m	NA	Good margin in Fault Free Feared Event budget currently under assessment
APV-I	Land-masses Korea + Jeju Island	99.83% in Fault Free + GPS failures System Failures not included yet	6 s	1.6 m	2.4 m	Good margin in Fault Free Feared Event budget currently under assessment

Table 2: Performance budget summary assessment

2. ACKNOWLEDGMENTS

The authors would like to thanks Mathias Van Den Bossche and Celine Benassy-Foch from Thales Alenia Space for their paper proofreading and benefit discussions.

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