SBAS Error Modelling for Category I Autoland

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BIOGRAPHY (IES)

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ABSTRACT

Several Satellite Based Augmentation Systems are currently being used by the aviation community or under development around the world. WAAS which covers US airspace currently provides the capability to perform LPV operations with 200ft minima, equivalent to Cat I performance as defined by ICAO. Airbus continues to equip new aircraft with SBAS receivers to provide the capability of LPV200 without ground-based navaids. SBAS receivers are required to meet standards defined in the ICAO SARPs and RTCA DO229D and such receivers have been shown in flight trials to have the potential to autoland under CAT I conditions as certified using GBAS. Autoland is attractive to crews to alleviate the issues associated with flight crew fatigue and unfavourable operational conditions.

In the frame of GBAS CAT III R&D, a Navigation System Error model has been developed by the GNSS community which has been endorsed by AWOHWG (All Weather Operations Harmonization Working Group). This NSE model is a necessary input to the GBAS enabled CAT I autoland certification.

The demonstration of Autoland performance for CAT I operations using GBAS was based on Monte Carlo simulation and flight tests. The simulation must account for both the average risk with all parameters (wind, weight, runway conditions, NSE) varying nominal in a statistical sense and the limit case risk which sets one such parameter to its limit worst case value. These simulations provide results in terms of the aircraft parameters whose regulations [CS AWO 131] will then determine if the intended operations are airworthy.

This paper presents the initial work in developing the GBAS approach for an SBAS enabled CAT I autoland capability. A model of the SBAS NSE is required in the nominal and limit case, as well as in the malfunction case, to be used as an input to autoland simulations. The NSE is a function of the user-satellite geometry and the corrected and smoothed pseudorange errors. Instead of the classical approach of implementing statistical variation in the pseudorange errors, the GBAS autoland methodology determines offline, through auxiliary simulation a direct model of the position domain error. The success of this approach is in reducing the number of statistical parameters varied within the autoland simulation platform. This paper presents the same methodology in the case of SBAS NSE modelling and introduces the requirements in developing an SBAS NSE model for the malfunction case.

INTRODUCTION

Several Satellite Based Augmentation Systems are currently in use by the aviation community and a number of others are under development. WAAS covers the US Air Space, whereas EGNOS covers European Civil

Aviation Conference Airspace, MSAS the Japanese Airspace, GAGAN the Indian Airspace and SDCM the Russian Airspace. WAAS currently offers the capability to perform RNAV operations with Localizer Performance with Vertical Guidance (LPV) 200 ft minima in US National Airspace, corresponding to Category I minimum performance defined by ICAO SARPS [ICAO, 2006]. The EGNOS Safety of Life service, established in 2011 to provide LPV capability, will offer, in the near term, the same minima capability in Europe, that is to say 200 ft.

Airbus has decided to equip its A350 XWB with SBAS receivers, in order to offer to its customers the capability to fly published RNAV GPS approaches with LPV 200 minima, without navigation ground infrastructure in the airport vicinity and providing a geometric vertical guidance free of temperature and barometric setting errors. Future GNSS evolutions like Galileo or second GPS frequency will enable the coverage extension of RNAV with LPV 200 ft minima. On the other hand, current SBAS standards such as ICAO SARPS and RTCA DO-229D, provide the minimum performance requirements offering the potential to perform autoland under Category I conditions equivalent to GBAS as shown by several flight trials.

Automatic landing, otherwise named autoland, starts "from the beginning of the landing flare until aircraft exits the landing runway, comes to a stop on the runway, or when power is applied for takeoff in the case of a touch-and-go landing" [ICAO-CAST, 2010]. Autoland is attractive for crews in case of flight crew fatigue after a long night flight, unfavourable operational conditions (e.g. high wind) including poor visual conditions such as a low rising sun aligned on the runway axis or crew incapacitation. Autoland Category I has been certified on Airbus aircraft using GBAS.

In the frame of GBAS Category III R&D, a Navigation System Error model has been developed by the GNSS community and further expanded and validated within an Airbus thesis [NERI, 2011] to incorporate GBAS ICAO SARPS GAST (GBAS Approach Service Types) level D specificities. This model has been endorsed by AWO HWG (All Weather Operations Harmonization Working Group) [AWO36, 2010], a Working Group with EASA and FAA in order to develop harmonized regulations for Low Visibility Operations.

The autoland performance demonstration for certification is based on simulation and on flight tests. As far as simulation is concerned, a statistical approach is requested by the regulation (CS AWO 131 for EASA). This statistical demonstration is based on Monte-Carlo method and identifies two types of risks to be demonstrated: The average risk and the limit risk.

From these simulations, statistical results are obtained on the main aircraft parameters at touchdown and Regulation [AWO] gives different probabilities objectives not to exceed for each aircraft parameter for both average and limit risks.

In order to conduct this performance demonstration, it is necessary to know the Navigation System Error (NSE) of the system. GBAS or SBAS NSEs are dependent of the satellite geometry retained or available at the time of the approach and on the residual pseudorange measurement errors. As a consequence, it is necessary to develop a SBAS noise model to feed Monte-Carlo simulations and representing the NSE for nominal and limit cases. In addition, the modelling of the SBAS fault modes, such as GPS ranging source failures or reference station failures effects, must be identified in order to cover the malfunction case as required by regulations.

This paper presents the modelling of SBAS errors by reutilizing the methods that were used to design a GBAS NSE model for autoland simulations. The purpose of this model is to represent the nominal and limit GPS L1 C/A SBAS NSE to feed aircraft simulators for autoland simulations. The classical way to do so in GNSS is to model pseudorange measurement errors and then project these in the position domain. The method previously used to model GBAS NSE for autoland simulations, aims at reducing the number of parameters necessary by directly generating the NSE in the position domain instead of the pseudorange domain. The idea here is thus to use the same methodology to derive the SBAS NSE model.

After introducing the SBAS systems and their incorporation on Airbus, the RNAV with LPV minima operations and the requirements applicable to Category I autoland certification, this paper describes the structure of the error model. Then, simulations assumptions are discussed and validated. Potential variations of the error model due to discrepancies, if any, between EGNOS and WAAS for instance will be identified. These error models focusing on nominal and steps errors, will be based on simulations to identify distributions, using standardized SBAS errors contributors defined in ICAO SARPS and DO229D. Modelling results will be confronted with real SBAS recorded data. Finally, recommendations will be expressed towards industry and SBAS service providers to provide a model for SBAS fault modes, necessary to complete autoland certification.

SBAS STATUS

SBAS is a system standardized in ICAO SARPS [ICAO, 2006] and in RTCA DO229D [RTCA, 2006], which enables in theory interoperability between the airborne receivers and the various SBASs, shown in Figure 1.

Interoperability refers to the ability, by applying the same international standards, to obtain the same level of service and performance, and the same positioning, navigation, and timing functionalities when interfacing a DO229D receiver with any SBAS around the world. SBAS being a relatively new system – WAAS was commissioned in

2003 - still possesses interoperabilities issues. Notable examples include the use of MT27 in Europe and MT28 in the US, and the absence of the ranging capabilities WAAS offers within EGNOS [AZOULAI, 2010]. In addition, the level of service might not be equivalent, for example MSAS is yet to offer vertical guidance due to the threat of ionospheric storms present in the Japanese geographic region.

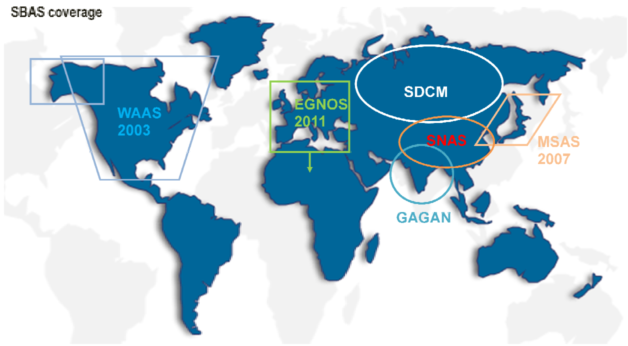

Figure 1: SBAS active or under development

Currently, WAAS offers the capability to perform RNAV operations with Localizer Performance with Vertical Guidance (LPV) 200 ft minima at a majority of airports in US National Airspace, corresponding to Category I minimum performance defined by ICAO SARPS [ICAO, 2006], with nearly 3000 LPV approaches at the date of writing of this paper [FAA, 2012]..

WAAS Performance Analysis Network (PAN) reports provide a statistical analysis of the WAAS performance over three months. The July 2012 report [WAAS PAN, 2012] (April 1st to June 30th 2012) observed accuracies within the LPV performance requirements, that is to say HPL below 40 m and VPL below 50 m. the maximum values observed are 1.63m horizontally and 1.98 m vertically. Therefore, WAAS appears to be a good candidate for autoland feasibility demonstration and we suggest to develop a model based on WAAS specification and data.

In Europe, EGNOS serving the ECAC (European Civil Aviation Conference) airspace has been commissioned in 2011 and has initiated deployment of LPV approaches, not yet below 250 ft. Indeed, before being able to propose LPV 200, the EGNOS service provider must demonstrate several years of performance compatible with requirements set by ICAO to authorize LPV 200. In the meantime, EGNOS has shown performance potentially compatible with autoland and observed during Airbus flight trials and data collection campaign. In [AZOULAI, 2010], we observed, during four flights trials on July 9, July 27, Sept 24 and Oct 6, 2009, on A380, with SBAS MMRs prototypes developed against RTCA DO229D**,** a horizontal accuracy (95%) of 1,4 m and a vertical accuracy of 1,92 m with HPL (respectively VPL) lower than 40 m (respectively 35 m). In [AZOULAI, 2009], we also compared the behavior of SBAS and GBAS LOCALIZER and GLIDE SLOPE deviations, showing that data feeding autopilot with both systems.

EGNOS appears to be a good candidate for autoland feasibility demonstration and we suggest to develop a model based on EGNOS specification and data. Obviously, the aim is to have only one model for certification and we should in the future define, if possible an envelope model as well as pave the way by identifying key characteristics necessary for the other existing or future SBAS systems to be part of the NSE autoland model. In agreement with ESSP, we decided to initiate the model identification from February 2012 where a new EGNOS version (V2.3.1P) has been put in place [ESSP, 2012].

Concerning the other SBAS, MSAS covering the Japanese FIR doesn't provide vertical guidance and we are forced to exclude for the moment this system from our baseline model. Upon availability of vertical guidance, we will be able to include MSAS into an envelope model. The other systems such as GAGAN from India and SDCM in Russia are still under development and no data are available to feed our study.

Concerning aircraft equipage, Airbus has decided to equip its A350 XWB with SBAS receivers, in order to offer to its customers the capability to fly published RNAV GPS approaches with LPV 200 minima, without navigation ground infrastructure in the airport vicinity and providing a geometric vertical guidance free of temperature and barometric setting errors. Future GNSS evolutions such as a secondary constellation in Galileo or secondary civil GPS frequency will enable the coverage extension of RNAV with LPV 200 ft minima. On the other hand, current SBAS standards such as ICAO SARPS [ICAO, 2006] and RTCA DO-229D [RTCA, 2006], provide minimum performance requirements offering the potential to perform autoland under Category I conditions equivalent to GBAS. Indeed, GNSS Signal-in-Space performance applicable to Category I operations is now the same considered for SBAS and GBAS. Even if we cannot evacuate the fact that GBAS technology has always been considered potential to serve Category III operations, showing accuracy performance on the order of a meter, GBAS Category I autoland has been certified on Airbus aircraft, based on the fact that ICAO SARPS GBAS performance is actually metric performance derived from ILS Category I angular performance [EUROCAE, 2007], thus GBAS NSE is considered ILS look-alike. This certification has consisted of applying autoland certification requirements applicable to Category III certification, except that visual conditions are available below 200 ft, enabling to rely on the crew to take over the aircraft in case of abnormal error conditions. Other choices linked to the nature of GBAS errors have been considered and the method applied will be discussed later in this paper to help define the SBAS error model. Therefore, the SBAS NSE model is independent of the aircraft as it depends on the nature of the errors affecting the signal-in-space and the receiver. The interface of the model with the aircraft lies in the integration of the outputs of the receiver with the aircraft systems such as the auto flight system.

As a conclusion of this chapter, we can reasonably expect that the SBAS errors will be compatible with autoland and that is what we would like to demonstrate through this paper.

AUTOLAND REQUIREMENTS

The autoland performance demonstration for certification, summarized in table 1, is based on simulations and on flight tests. As far as simulation is concerned, a statistical approach is requested by the regulation ([AWO] for EASA and AC120-28D [FAA, 1999] for FAA). This statistical demonstration is based on Monte-Carlo method and identifies two types of risks to be covered:

- The average risk which corresponds to the result of 2000 simulated autolands with all dimensioning parameters (wind, weight, CG, flap settings, runway conditions, NSE) varying according to their distribution.

- The limit risks which correspond to several sets of 200 simulated autolands where a dimensioning parameter is put at its limit value (for instance max head wind = 30kts), and all other remaining dimensioning parameters vary according to their distribution.

From these simulations, statistical results are obtained on the main aircraft parameters at touchdown (X distance from the runway threshold, Y distance from the runway centerline, vertical speed, bank angle and sideslip) and Regulation [AWO] gives probabilities objectives not to exceed for each aircraft parameter for both average and limit risks, using what is called the landing box or touchdown box as defined in figures 2 and 3.

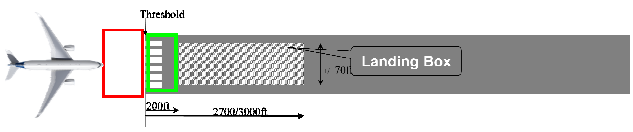

Figure 2 : Aircraft, Runway and Landing box

As far as X distance parameter is concerned, the following probabilities have to be demonstrated:

- "Short Landing": Probability to land prior runway threshold plus 60m (200 ft) shall be lower than 10^{-6} for the average risk, and lower than 10^{-5} for the limit risks.
- "Long Landing": Probability to land beyond runway threshold plus 823m (2700 ft) shall be lower than 10^{-6} for the average risk, and the probability to land beyond runway threshold plus 914m (3000 ft) shall be lower than 10^{-5} for the limit risks.

On the lateral axis, the following probabilities have to be demonstrated:

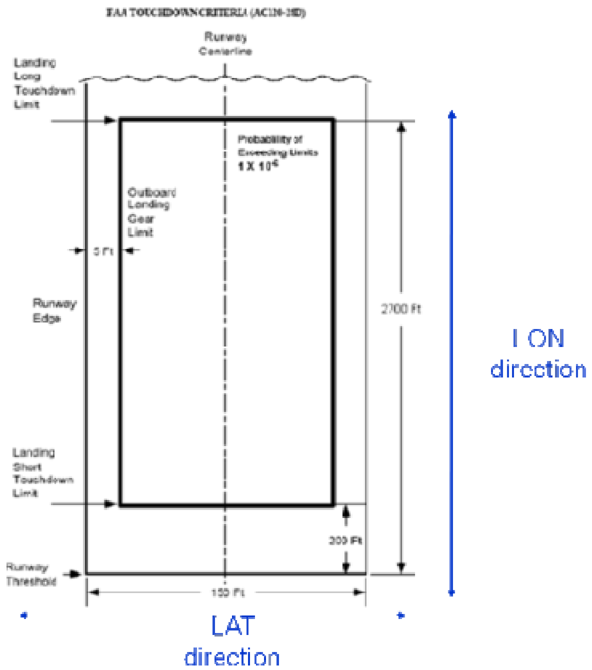

Figure 3: Touchdown Box definition (source FAA)

- Lateral touchdown considering the outboard landing gear: Probability to land at a distance greater than 21 m (70 ft) from the runway centreline shall be lower than 10^{-6} for the average risk, and lower than 10^{-5} for the limit risks.

The navigation system and more particularly the signal-in-space used to guide the aircraft are subject to errors inherent to their nature (noise like) and faults. In order to achieve the autoland performance demonstration, it is necessary to characterize the Navigation System Error (NSE) of the system utilized, which is dependent of the satellite geometry retained or available at the time of the approach and on the residual pseudorange measurement errors. This SBAS error model must represent the NSE for the nominal and the limit cases. In addition, modelling the effects of the SBAS fault modes, such as GPS ranging source failures or reference and processing station failures, must be achieved in order to cover the malfunction case as required by the regulations. This will be discussed in a subsequent section.

Coming back to the nature of SBAS errors and the choice to make in deciding which kind of errors must be modelled, we must understand the rationale and the implication of the autoland requirements, in particular in terms of probability. Recall that the probability requirement to land outside the touchdown box for the average risk is set to 10^{-6}.

The 10^{-6} figure has an historical background. It relates to the observed statistics recorded in the 1960's of having a catastrophic accident during a landing in manual conditions. French and English aviation authorities considered at that time that the risk of having a catastrophic accident during an automatic landing should be at least ten times lower i.e. less than 10^{-7}. This risk included not only the average risk but also the particular risk to have an extreme condition such as wind and failure events [Grossin, 1981]. This condition could be assimilated to what the regulations today call the limit case. Indeed, this makes sense if we can identify a probability of occurrence for extreme conditions, which requires a good history of observations. For some cases, it is difficult to estimate this figure such as for ionospheric storm conditions.

On the other hand, US authorities considered that any single failure or combination of single failures leading to a catastrophic event shall be less probable than 10^{-9} and that the risk to have the aircraft land outside the landing box shall be improbable that is to say less than 10^{-6} [Grossin, 1981]. We can note that this is still the applicable approach harmonized between FAA and JAA, now EASA for ILS and MLS. The only thing that has been modified since then is the introduction of the limit case, pushed by Europeans through JAA and the way the failures which are actually more probable than 10-9, must be shown to not have a catastrophic consequence for the aircraft. The question currently under discussion in AWO HARC (Harmonization Aviation Rulemaking Committee), is whether this approach, applicable to ILS, can be extended to Cat III operations with automatic landing, using another technology GPS-based such as GBAS, without modifications. A first step has been done with GBAS for Category I and we aim to extend it to SBAS.

Another justification of the 10^{-6} figure for the average risk could be considered and drive the errors to be modelled. If we consider autoland under Category I or Category III operations, environmental (i.e. runway profile and configuration) and aircraft conditions except for the signal-in-space performance, have no reason to be different except for the absence of visual cues for the crew in Category III and disregarding the choice to apply a limitation compared to ILS or tentative to take advantage of more modern technology to enhance the operational envelope. The remaining part is composed of the signal-in-space errors and fault modes. In order to demonstrate autoland, we said earlier that we must run at least 2000 simulations for the average risk with the intent to extrapolate the results to 10^{-6}. Therefore, events with lower probabilities of occurrence are unlikely to be drawn and should be discarded from the model. Events with probabilities between 10^{-5} and 10^{-9} are usually considered as fault modes within GNSS. [DOD, 2008] states the probability to have URE exceeding the Not To Exceed tolerance without a timely alert for one GPS satellite failure must be lower than 10-5/hour. Moreover, Category I continuity risk, applicable to LPV approaches is 8.10-6/in any 15 seconds [ICAO, 2006]. More generally, electronic hardware reliability usually possesses loss probability figures of 10^{-4} to 10^{-6}, except for very simple electronic devices such as antennas . Therefore, looking at a risk probability on the order of 10^{-6} to land outside the touchdown box, the receiver is more likely to be affected by a hardware failure than the nominal noise. It implies that since this case is covered by the malfunction case demonstration, it is useless to model errors in the nominal case that are not fault free and that are less probable than 10^{-5} to 10^{-6} or in other words, we don't need to know what are the noise-like errors at this level of probability.

In case we need to account for a fault mode, assuming we have statistical data or the effect of such fault mode is not significant, assessed by engineering judgement, we could consider this fault mode be part of the limit case, because this is the frontier between the nominal case and the malfunction case. On the other hand, a fault mode that has significant effects or is impossible to predict should neither be part of the nominal case nor the limit case.

Another question that is raised when comparing autoland certification methodology and signal-in-space integrity schemes used in SBAS and GBAS, is the way we consider individual risks (single failure case) and a combination of these risks (multiple failure case).

In the case of autoland, the average risk considers the Monte-Carlo methods with the involved parameters varying in their distribution. This definition is also considered in [Walter, 2011]. But in the limit case, only one parameter is put at its limit while the others are allowed to vary with their distribution. In other words, we could say that the limit condition, such as a cross wind of 30 knots has a probability of one. This could be defined as a specific risk like in [Walter, 2011]. Indeed, we never cumulate max weight and max wind for instance. But, when we consider integrity scheme applying to SBAS or GBAS, each contributing source of errors is overbound by a Gaussian distribution zero-biased, assuming they are independent processes and so the resulting computed protection level is extremely conservative by not factoring or not limiting the unexpected combination of all extreme values from their distribution because the overbound is not the reality. Therefore, when we want to define the SBAS NSE model to be used in nominal conditions, we would be overly conservative, compared to the autoland demonstration, if we use the standard deviations taken into account in the protection levels equations rather than using values closer to the reality, that would be experienced by a user. In other words, it would be like all contributors to the SBAS error such as multipath, troposphere, ionosphere, clock and ephemeris errors are set at their extreme values and then the sum of all these errors feeds the Monte-Carlo simulations. Assessing the different possibilities offered to us to model SBAS NSE, we will be confronted to be more or less conservative whether we have access to conservative pre-defined modelled sigmas or statistics from observations or a combination of both.

Condition	FAA Criteria	EASA Criteria	Pass Condition
Nominal	AC 120-28D §6.3.1	CS AWO 131	Safe Landing $1\text{-}10^{-6}$
Limit	N/A	CS AWO 131	Safe Landing $1\text{-}10^{-5}$
Malfunction	AC 120-28D §6.4.1	CS AWO 161	For failures with probability $>10^{-9}$ Safe Landing 1

Table 1: Autoland Certification requirements summary

GBAS AUTOLAND NSE MODEL

In order to maintain a simple structure to the autoland simulation model it was proposed to use an independent GBAS NSE simulator that would generate a distribution of errors according to a pre-defined set of parameters. Following this the characteristic points of this distribution can be integrated in the autoland simulator. The autoland simulator's NSE generator element is shown in Figure 4.

The model time step size of the autoland simulation ΔT and a master *Seed* which are used to determine the three Gaussian error sequences. These three zero mean unit variance random generated sequences are then filtered by a 2nd order Butterworth filter. The Butterworth filter mimics the effect of the code tracking loop and carrier smoothing performed within the receiver. In doing so it introduces temporal correlation by defining the spectral content of the sequence. Validation of this approach was undertaken in [Murphy *et al.*, 2005] and showed the frequency response of the model to be an appropriate yet conservative representation of real GBAS receivers. An equivalent model must be validated in the SBAS case considered in this paper.

The three sequences which ultimately will define the NSE in the vertical, along and cross track directions are scaled by the compensation gain to normalize the effect of the filter and return the variance to unity. Finally the sequences are multiplied by three K values representing the standard deviations in each component. Models of the distribution of K values for the SBAS case are considered in this paper.

The GBAS error model, previously presented in [NERI, 2010] has the following characteristics.

- Sigma errors, characterizing the errors distributions and the geometry, are in line with latest GBAS GAST D and GAST C overbounding errors.
- GPS Constellation state probabilities are coherent with [RTCA, 2004]
- Vertical and Horizontal distributions have been generated independently:
  - Distributions are limited by a ratio between horizontal and vertical.
  - Horizontal error distribution based on the worst direction

The model is limited to airports located between 70° of Latitude North and South.

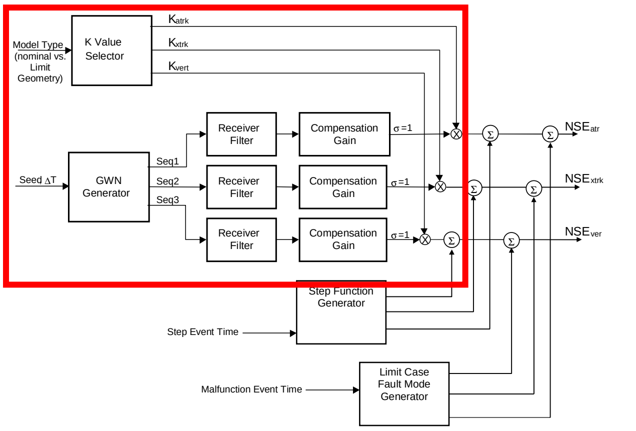

Figure 4: GBAS NSE generator

The distributions obtained for the vertical and the horizontal are provided in figure 5 and 6. They are satisfactory to be able to demonstrate autoland performance compliant with the average risk set by the regulations. We don't expect SBAS NSE to show the same performance but it provides a good basis to compare with SBAS NSE model.

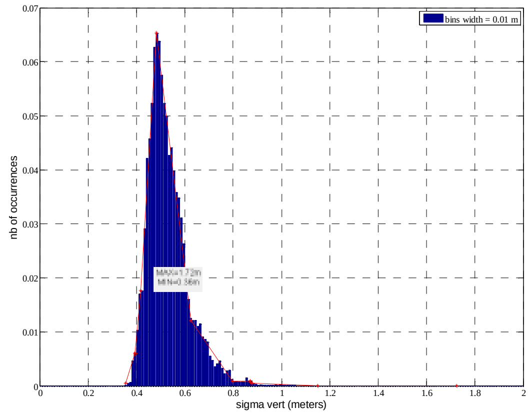

Figure 5: Sigma vert for GBAS GAST C

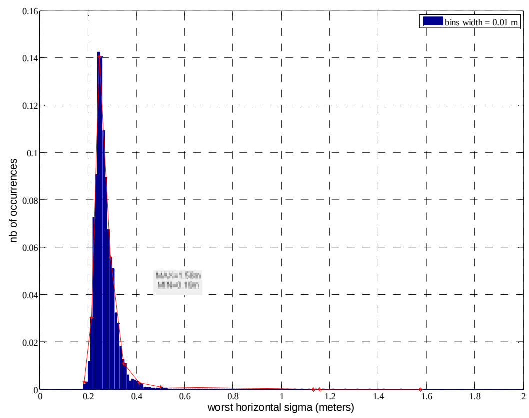

Figure 6: Worst horizontal sigma for GBAS GAST C

SBAS NSE MODEL DERIVATION

As the GBAS approach to modelling the NSE was successful in greatly reducing the number of influent parameters, the NSE generation model shown in Figure 4 is adopted here also. A review of the methodology undertaken for GBAS highlighted a number of steps to be taken to extend the methodology to SBAS NSE modelling:

- identify reasonable assumptions to be made in offline simulations used to determine K_{vert}, K_{atrk} and K_{xtrk} distributions
- formulate a nominal SBAS pseudorange error model to be used in offline simulations and derivation of K_{vert}, K_{atrk} and K_{xtrk}
- derive K_{vert}, K_{atrk} and K_{xtrk} distributions
- analyse correlation between K_{vert} and K_{atrk}, K_{xtrk}
- determine the step effects of satellite geometry changes
- validate the use of the 2nd Order filter for a DO229D receiver
- confirm that the three Gaussian sequences may be generated without including the effects of error correlation

In this paper we focus on the derivation of the K factors and model of the receiver spectral characteristics. In the following section we present the assumed pseudorange error models with a discussion on the difficulties that arise to define a standard model for SBAS nominal performance. The expected NSE sigma distributions for WAAS are then presented followed by a discussion of the the steps to be taken to derive NSE sigma distributions in the case of EGNOS.

SBAS PSEUDORANGE ERROR MODEL

The pseudorange error models are key to determining the NSE variance distribution. For each satellite measurement, the standardised SBAS residual error model will be assumed [DO-229D]:

$$\sigma_i^2 = \sigma_{i,flt}^2 + \sigma_{i,UIRE}^2 + \sigma_{i,air}^2 + \sigma_{i,tropo}^2$$

where:

σ_i	standard deviation of satellite measurement *i*
$\sigma_{i,flt}$	standard deviation of the fast and long term corrections
$\sigma_{i,UIRE}$	standard deviation of the ionosphere delay estimation error
$\sigma_{i,air}$	standard deviation of the receiver noise and multipath modeled Gaussian white sequence
$\sigma_{i,tropo}$	standard deviation of the troposphere delay estimation error

Each of these error model terms may be expressed in greater detail as described below.

The fast and long term corrections are defined in the SBAS MOPS as follows:

$$\sigma_{i,flt}^2 = \begin{cases} \left[\sigma_{i,UDRE}.\delta UDRE + \varepsilon_{fc} + \varepsilon_{rrc} + \varepsilon_{ltc} + \varepsilon_{er}\right]^2 & ,if\ RSS_{UDRE} = 0 \\ \left[\sigma_{i,UDRE}.\delta UDRE\right]^2 + \varepsilon_{fc}^2 + \varepsilon_{rrc}^2 + \varepsilon_{ltc}^2 + \varepsilon_{er}^2, & if\ RSS_{UDRE} = 1 \end{cases}$$

where:

- RSS_{UDRE} flag in MT10
- σ_{UDRE} model parameter from Message Type 2-6,24
- $\delta UDRE$ user location factor in MT27 MT28, otherwise $\delta UDRE = 1$
- ε_{fc} fast correction degradation parameter
- ε_{rrc} range rate correction degradation parameter
- ε_{ltc} long term correction degradation parameter
- ε_{er} non-precision operations degradation parameter

In the case of EGNOS, MT27 is broadcasted by the EGNOS operational system to increase the UDRE in selected geographical areas.

Only one area is defined in EGNOS:

(-40° < longitude < 40°; 20° < latitude < 70°) and MT27 values are fixed as follows:

- Inside: δUDRE = 1 (ECAC),
- Outside: δUDRE = 100 (maximum value defined in the MOPS [RTCA, 2006]).

In this feasibility study we have naturally restricted our regions of interest to airports within the core SBAS coverage areas. Therefore, it is assumed that δUDRE = 1 in all cases.

In the case of WAAS, proprietary error models have been developed at Stanford University which express the nominal $\sigma_{i,UDRE}$ for each of the broadcast UDRE index. These models were used in the generation of the nominal position error sigmas shown in the following section.

The ionosphere residual error variance is determined using the following model [DO-229D]:

$$\sigma_{i,UIRE}^2 = F_{pp}^2 \sigma_{UIVE}^2$$

$$F_{pp} = \left[1 - \left(\frac{R_e \cos\theta_i}{R_e + h_I}\right)\right]^{-\frac{1}{2}}$$

where:

- θ_i is the satellite elevation angle
- R_e is 6378136.0m
- h_I is 350000.0m

- F_{pp} is the obliquity factor which relates the vertical ionosphere delay to the slant ionosphere delay along the line-of-sight vector

At the user receiver the $\sigma_{i,UIRE}$ is derived from interpolating the broadcast $\sigma_{i,GIVE}$values for the neighbouring ionosphere grid points (IGP).

For these two terms, the question raised before with regard to the conservatism applied to the modelling is fully applicable. Indeed, these two terms or their index are broadcast by WAAS and EGNOS tailored to meet the integrity requirements set by the ICAO and feeding the protection levels equations. Using these values might lead to a NSE model not compatible with autoland feasibility. Unfortunately, these values are not modelled in ICAO SARPS [ICAO, 2006] unlike all the other terms for GBAS.

This flexibility enables SBAS service providers to allocate the integrity risk within their system accounting for differences in the regional ionosphere environment. Therefore, we must redefine the methodology utilized for GBAS and utilise nominal error models not defined in the relevant standards [ICAO, 2006] [RTCA, 2004]. This may be challenging due to SBAS proprietary issues and would likely require different models for each SBAS.

For WAAS, a large volume of data has been collected between 2003 and 2006 for the purpose of justifying the publication of LPV 200 approaches. [DeCleene, 2007] Proprietary models for WAAS have been developed using the large volume of data to express the σ_{UIVE} and $\sigma_{i,UDRE}$.

Another assumption that we must make is the fact that we reasonably believe that SBAS systems continuously improve in terms of end-user performance. Indeed, the GPS constellation has shown improvement in terms of the estimation of orbit ephemeris and clocks. In addition, SBAS systems improve algorithms to monitor ionosphere and increase the number of reference stations (RIMS for EGNOS and WRS for WAAS). There might be outliers observed occasionally which must be explained. But, it seems a fair statement and this has been confirmed by SBAS stakeholders [WALTER, CHATRE, 2012]

The model of the airborne receiver residual errors follows the MOPS formulation exactly, namely:

$$\sigma_{i,air} = \left(\sigma_{i,noise}{}^2 + \sigma_{i,multipath}{}^2 + \sigma_{i,divg}{}^2\right)^{1/2}$$

$$\sigma_{i,multipath} = 0.13 + 0.53.e^{-\theta_i/10\,deg}\ \text{m}$$

$$\left(\sigma_{i,noise}{}^2 + \sigma_{i,divg}{}^2\right)^{1/2} \leq 0.36\text{m (AAD-A)}$$
$$\left(\sigma_{i,noise}{}^2 + \sigma_{i,divg}{}^2\right)^{1/2} \leq 0.15\text{m (AAD-B)}$$

where AAD is the Airborne Accuracy Designator [DO-229D].

Similarly for the residual tropospheric error, the MOPS models are adopted:

$$\sigma_{i,tropo} = \sigma_{TVE}.m(\theta_i)$$
$$m(\theta_i) = \frac{1.001}{\sqrt{0.002001 + \sin^2(\theta_i)}}$$

where $\sigma_{TVE} = 0.12$m.

Given the pseudorange models outlined above, like the GBAS NSE model, it would be possible to assess the impact of geometry variations on the nominal NSE variance. Implementing the adopted models and making the assumptions outlined above, simulations can only be run to obtain sample Cumulative Distribution Functions (CDF).

WAAS NSE MODEL

Distributions for the vertical and worst case horizontal direction NSE sigmas are shown in Figures 7 and 8. These results were obtained by selecting 5000 times points randomly from a sidereal day and at nine airport locations within CONUS. As stated above, GPS constellation state probabilities from [RTCA, 2004] were assumed which equates to a 95% probability for the full 24 satellite GPS baseline, 3% for the 23 satellite degraded constellation and 2% for the 22 satellite degraded constellation.

Agreed WAAS Stanford University.FAA proprietary nominal error models for the WAAS UDRE and GIVE were employed to maintain performance estimates as close to reality as is feasible. Comparison of Figures 7 and 8 for WAAS to the GBAS case in Figures 5 and 6 shows remarkable agreement between the two systems. The conformity of these initial results suggests that SBAS autoland may be feasible, at least for the average risk demonstration part. However, these results are preliminary and the impacts of geometry step changes remain to be investigated.

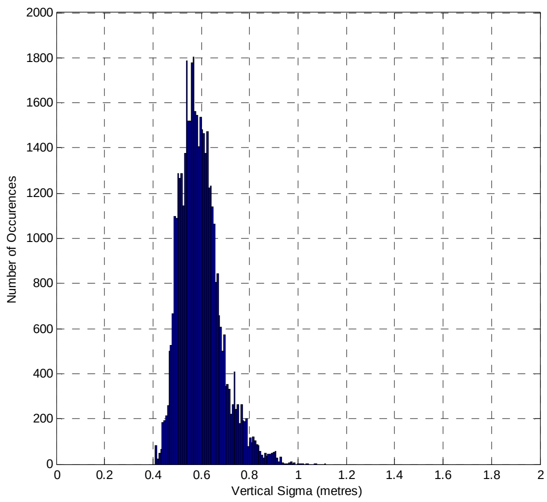

Figure 7 : WAAS Vertical Sigma Histogram

In addition, reminding that the GBAS error terms standardized and used in the GBAS NSE model are tailored to meet integrity requirements, we can explain why the SBAS errors seem so homogeneous with the GBAS errors. It is because the GBAS NSE model is actually conservative and using the same methodology used for SBAS in this paper with GBAS should probably lead to an improved accuracy characterization.

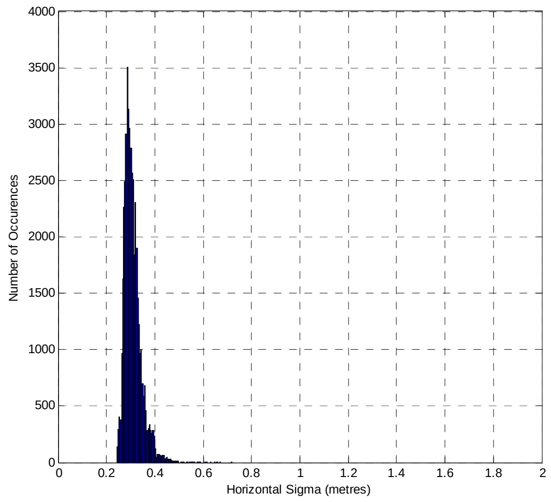

Figure 8 : WAAS Horizontal Sigma Histogram

In order to assess the degree of correlation between the vertical and horizontal NSE sigmas Figure 9 displays the same distributions as a 2D histogram. Notably a lack of correlation is observed which suggests that drawing the distributions and independently of as was implemented for GBAS in [NERI, 2011] may be preferred to employing a fixed ratio as proposed in [MURPHY, 2009].

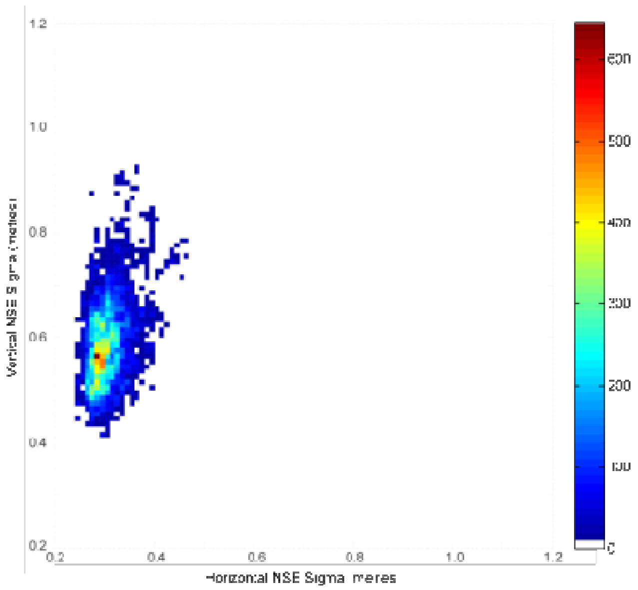

Figure 9. WAAS NSE Sigma Correlation

EGNOS NSE MODELLING

In the case of EGNOS, nominal NSE models have not yet been formulated and validated for the UDRE and GIVE components. As with WAAS, the preferred solution is to utilise a model of the observed UDRE and GIVE as a function of the broadcast indices for each of these errors as well as the network's observability of the constellation. This approach allows the expected error distribution to be determined in offline simulations whilst applying weightings of the receiver processing in terms of the assumed broadcast sigmas.

Since EGNOS is targeting to publish LPV 200 procedures from 2014, a process of collecting and analyzing data is on-going and upon their availability, we will be able to derive a NSE model for EGNOS. This will be the subject of future work.

RECEIVER FILTER CHARACTERISTICS

The aim of this filter is to reproduce the effects of the receiver signal and measurement processing. It assumes that the spectral content of the error is determined by two processes: the code tracking loop (DLL) filtering and the carrier smoothing. The positioning algorithm is a linear process and as such does not influence the spectral content of the position error. The relevant processes are shown in Figure 10.

Figure 10: Receiver Processes

Based on GBAS Cat I standards [RTCA MOPS DO253], the filter accounts for a 100 seconds time constant for the code carrier smoothing. The expression of the filter is as follows:

$$H(s) = \frac{\omega_n^2}{s^2 + \sqrt{2}\omega_n.s + \omega_n^2}$$

with $\omega_n = 0.01$

The same assumptions can be made for the SBAS RTCA DO229D case, that the spectral content of the error is determined by two processes: the code tracking loop (DLL) filtering and the carrier smoothing. Indeed:

- A common SBAS/GBAS receiver is the standard,
- The smoothing time constant is the same for both LPV/Cat I cases : 100 s,
- The tracking constraint regions are harmonized.

It should be noted that this filter model employed within the autoland simulation is also intended to account for spectral content in the pseudorange measurements input

(Figure 10). In the following analysis we check no errors sources with unfavourable correlation properties are present.

We investigate here whether employing the assumption of this 2nd order filter is valid in the case of SBAS. In order to determine the temporal behaviour for SBAS, three DO229D receivers connected to the same antenna were employed to generate position error data sets of 24 hours for six days at surveyed ground locations. Unfortunately due to the data logging process of one of the manufacturer's receivers, these datasets were unavailable for the analysis. Results obtained for the two remaining receivers were found to show no discernible difference and as such only a single DO229D receiver's datasets are presented

Figures 11 and 12 show the horizontal and vertical position error time series for each of the days in parallel. The standard deviations in the horizontal and vertical domains are 0.32 and 0.64 over each data set which show excellent performance in line with the distributions displayed in Figures 7 and 8. However, some correlation between the time series of each day is observed. This suggests sidereal repeated error components are present, potentially as a result of local multipath, geometry variations or the effects of long term EGNOS corrections.

The Power Spectrum Density of the horizontal and vertical position errors are estimated using the Welch estimator within MATLAB. Sample periods of 16384 (2^{14}) samples were used with overlaps of 50% (8192). Figures 13 and 14 show the horizontal and vertical deviations over the six days in a semilog (in decibels) plot.

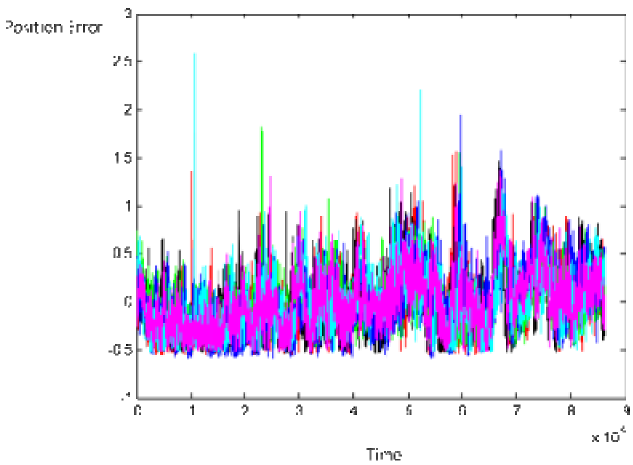

Figure 11: Horizontal Position Error Time Series

A key observation from these figures is the presence of a peak at 0.25Hz which equates to a 4s period. This has been identified as the usual refresh rate of the fast corrections and UDRE values within EGNOS [SUARD, 2012]. Over the nominal four second applicability period a linear function is applied which likely gives rise to this artefact of the spectrum [RTCA, 2006]. The impact of this peak and neighbouring frequency power is naturally reduced by the smoothing of the low pass carrier smoothing filter. As such the higher frequency components are found to lie at approximately -20dB from the lower frequency components which contribute most of the error variation.

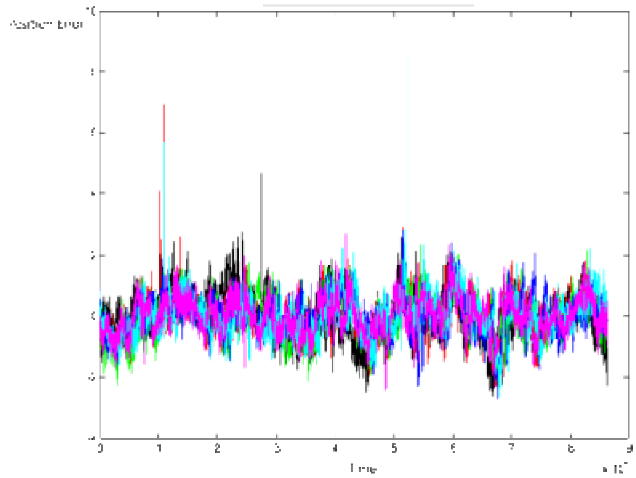
Figure 12: Vertical Position Error Time Series

A number of shorter Airbus flight datasets were also analysed within this work. Although, the sample sizes were not sufficient to make substantive conclusions regarding the correctness of the filter used, the corresponding spectral analysis showed remarkably similar forms with identical peaks at 0.25Hz.

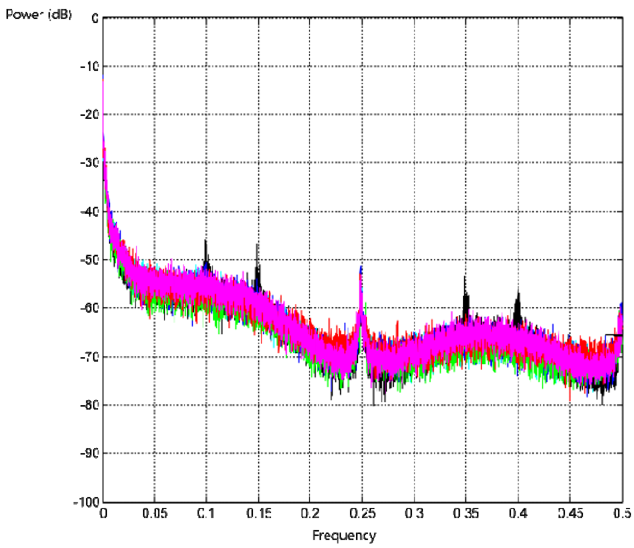

Figure 13: Horizontal Position Error PSD

Figures 15 and 16 show the horizontal and vertical deviations over the six days in a loglog plot. In addition the PSD resulting from the transfer function of the canonical 2nd Order filter is shown in yellow and of a 1st Order filter in orange. These plots show that a 1st order filter matches better the empirical frequency response than the 2nd order filter used for GBAS. The 1st order filter fits well the frequency response of the DO229D receiver over the range 7×10^{-4} to 4×10^{-2}, which equates to components with periods of 25 seconds to 23 minutes.

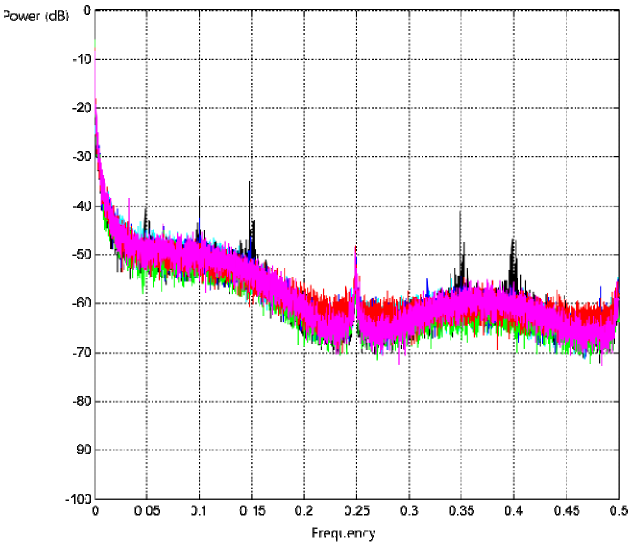

Figure 14: Vertical Position Error PSD

. Lower frequency components above the model may be understood to be a result of the sidereal repeating elements observed in Figures 11 and 12 above. In terms of Figure 10 these may be understood to be due to temporal correlations in the input pseudorange sequence or as a result of geometry variations. It is not clear whether these properties arise due to the static ground installation of the receivers and as such are not be observed in flight or are due to elements of the SBAS processing as cross checking of the datasets has not been performed as yet. However, as these lower frequency components relate periods far longer than the length of an autoland approach they would only introduce biases or very gradual ramp changes to the position error, beyond the duration of each autoland Monte-Carlo draw, thus should not be considered in the properties of the filter model.

At the higher end of the frequency spectrum, further variations to the 1st and 2nd order models are noted in Figures 15 and 16. However, as the models place higher power at the lower critical frequencies this will result in a conservative approach. Therefore, the same reasoning is applied as was taken in the case of GBAS [MURPHY, 2009] yet greater variation of the spectrum at the higher frequencies is observed than for GBAS due to the nature of the SBAS corrections and residual error characteristics. It should also be noted that some variation in the relative levels of the 1st and 2nd order theoretical models with respect to the empirical data is observed if the range of frequencies is varied. The sensitivity to the lower frequency end point was investigated for validation purposes but no significant change was found to revise the conclusions made.

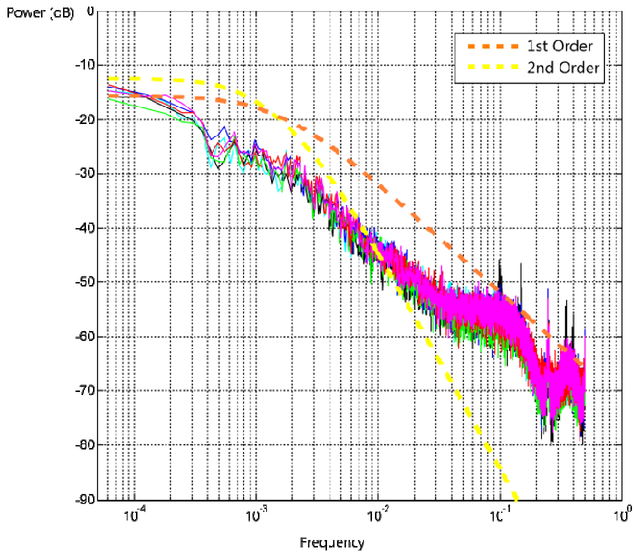

Figure 15: Horizontal Position Error loglog PSD

We conclude on this limited dataset that a 1st order filter reflects the real data response most closely. Further investigation is needed to understand this phenomenon better. It may be that the tracking loop has only minimal effect on the frequency range considered and as a result the cascade appears first order rather than second order or it may be that large correlation in the pseudorange input sequence are not sufficiently filtered resulting in much larger magnitudes than expected for a 2nd order system.

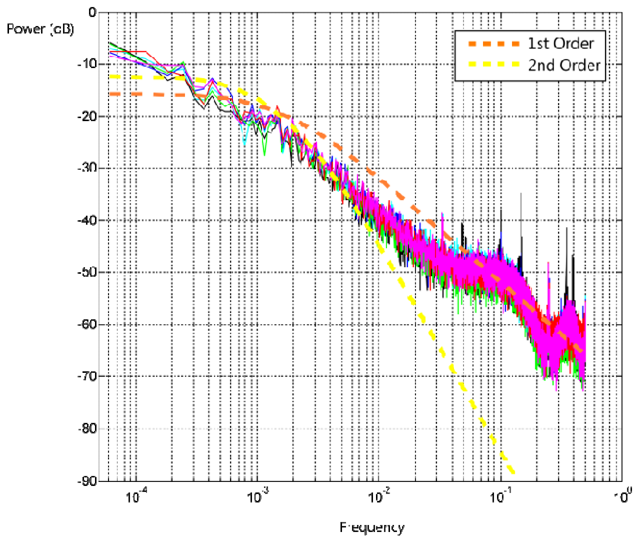

Figure 16: Vertical Position Error loglog PSD

FAULT MODEL REQUIREMENTS

In the frame of aircraft certification for Category III autoland operations including roll-out, there is a criterion that looks at performance in the presence of malfunction, with a probability higher than 10^{-9}, and more particularly successful landing inside the landing box or go-around evasive manoeuvre of the aircraft (e.g. go-around).

The airworthiness assessment has also the objective to provide a safety classification for the failure and to verify that the failure probability is in accordance with the classification of the failure (Minor, Major, Hazardous, Catastrophic).

Due to particular characteristics of SBAS since the system is metric and not angular and the sources of malfunction cases (ranging source or ground station failures) are different compared to ILS, it is thus required to identify the SBAS failure effects, potentially by defining their root cause, and above all assess their effect (Hazardous Misleading Information or continuity loss) on the guidance of the aircraft as well as determine if the safety classification is adequate compared to the probability of failure.

There might be some cases like in the case of ionospheric anomalies caused by solar storms, that the SBAS is affected by large changes in error over relatively short baselines. A lack of hindsight and a lack of sufficient historical data prohibit using a statistical approach to demonstrate airworthiness during large ionospheric events. This phenomenon is obviously not caused by a system failure and thus is considered as an environmental constraint (i.e. external to the SBAS system including the aircraft). Furthermore since it is difficult to predict, it could be found adequate, like in the GBAS case, to consider this phenomenon as a malfunction event from the airworthiness point of view like any other SBAS hardware failures,

During GBAS autoland Category I, two points were considered to address the malfunction case. First of all, below 200 ft, the crew has external visual cues to detect and if needed take over the aircraft under an unsafe conditions due to a GBAS error. The autoland can only be performed under crew supervision. Secondly, since the GBAS signal-in-space was considered valid for Category I, which implied a requirement of guaranteed signal below 100 ft [ICAO, 2006], GBAS errors could be anything whilst staying within the alert limits that are 40 m in the lateral domain and 10 m in the vertical domain. Therefore, the certification requirements consisted in assimilating GBAS errors below 200 ft as bias of any size up to the alert limits and to demonstrate that the crew could detect these errors and take over the aircraft. This approach has been adopted by the airworthiness authorities and the GBAS autoland Category I was granted on Airbus aircraft.

As a consequence, we have two alternatives for the malfunction case demonstration with SBAS:

- SBAS fault modes can be assimilated as bias of any size below 200 ft up to the alert limits. But, these biases must be limited to 10 m like GBAS where the value was directly derived from the Vertical alert limit whereas SBAS VAL for LPV200 is currently 35 m.
- SBAS fault modes effects are precisely identified with the following characteristics given by figure 17. This approach was taken for GBAS Cat III R&D and is documented in [MURPHY, 2010]:

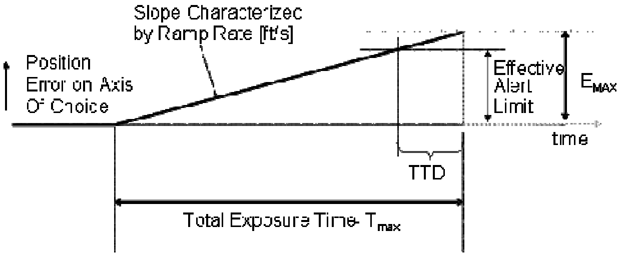

Figure 17: Fault diagram

Both approaches require assistance of SBAS manufacturers, without infringing proprietary aspects and commitments from Air Navigation Service Providers customers of SBAS to ensure certification feasibility. Anyhow, the best approach would be to document it in ICAO SARPS. But one difficulty lies with the first approach since the vertical alert limit applied to SBAS to support LPV 200 approaches is set to 35 m which seems too large to ensure autoland under malfunction case demonstration. Therefore, if first approach is adopted, we would need to have requirements to ensure failures induced errors are closer to 10-15 m than 35 m, like GBAS Category I and ILS Category I. This trade-off and the analysis of the SBAS failure modes will be the subject of future work.

CONCLUSIONS

Cat III autoland is a basic functionality on Air Transport Aircraft, using ILS with an incredible in service experience of nearly 50 years. GBAS Cat I Autoland has been certified on Airbus aircraft using a GBAS NSE model. SBAS NSE show similar errors than GBAS Category I for the fault free case. Autoland requirements have been described and require a SBAS NSE model.

Unlike GBAS, SBAS errors distributions linked to clock/ephemeris and ionosphere are not publicly available and are tailored to the compliance of integrity requirements set in ICAO SARPS.

SBAS NSE model thus requires a large amount of real data in order to get the confidence in the model for autoland demonstration.

We have derived a WAAS NSE model based on simulations using proprietary FAA/Stanford models in coherence with real data observed during 2003-2006 data collection campaign. The distributions appears compatible with the Category I autoland average risk demonstration.

We have initiated the identification of receiver filter characteristics based on observations of a limited dataset. A 1st order filter reflects the real data response most closely. Further investigation is needed to understand this phenomenon better, compared to GBAS receiver filter characteristics which is equivalent to a 2nd order filter.

Finally, we have described the malfunction case demonstration requirements and established a path, with two alternatives towards defining the SBAS failures effects, to be covered during an autoland under Category I conditions demonstration, both requiring assistance from SBAS manufacturers.

Future works include:

- To collect data and derive error distributions for EGNOS based on the methodology used for WAAS and derive a nominal envelope model for both WAAS/EGNOS
- Identify scenarios for step changes in the position domain and characterize their size
- Complete identification of receiver filter characteristics
- Identify fault mode characteristics for each SBAS eligible for autoland
- Perform autoland simulations using SBAS NSE model to show autoland Category I feasibility with SBAS

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REFERENCES

[ICAO, 2006]: "Annex 10 to the Convention on International Civil Aviation, Aeronautical Telecommunications, Volume I Radio Navigation Aids", International Civil Aviation Organization, Sixth Edition, July 2006, Amendment 85.

[AZOULAI, 2010] "Multi SBAS Interoperability Flight Trials with A380", L. Azoulai, S. Virag, R. Leinekugel-Le-Cocq, C. Germa, B. Charlot, ION GNSS 2010, September 21 - 24, 2010 Portland, Oregon

[ICAO-CAST, 2010]: "Phase of flight definitions and usage notes", Commercial Aviation Safety Team and International Civil Aviation Organization, June 2010

[NERI, 2010] "GBAS NSE MODEL FOR CAT II/III AUTOLAND SIMULATIONS", Neri, P, Macabiau, C, Azoulai, L, Muller, J, PLANS 2010

[NERI, 2011] "Use of GNSS signals and their augmentations for Civil Aviation Navigation during Approaches with Vertical Guidance and Precision Approaches", PhD Thesis, INPT, 2011

[AWO36, 2010] Minutes of AWO HWG 36th Meeting, Brussels, 2010.

[GROSSIN, 1981] Systèmes de commande automatique du vol C.A.D.V. – J.Grossin - ENSICA – 1981

[RTCA, 2006] “Minimum Operational Performance Standards for Global Positioning System/Wide Area Augmentation System Airborne Equipment”, DO229-D, RTCA SC-159, 2006

[WAAS PAN, 2012] WAAS Performance Analysis Report, Report #41, Reporting Period: April 1 to June 30, 2012, July 2012, FAA/William J. Hughes Technical Center NSTB/WAAS T&E Team

[AZOULAI, 2009] Experimental flight tests with EGNOS on A380 to support RNAV LPV operations, Laurent Azoulai, Sébastien Virag, Romain Leinekugel-Le Cocq, Airbus, Cyril Germa, Bernard Charlot, Thales Alenia Space, Pierre Durel, SII, ION GNSS 2009 proceedings, September 22 - 25, 2009, Savannah, GA

[ESSP, 2012] EGNOS Service Notice #3: EGNOS upgrades deployed in the first quarter of 2012 – ESSP - April 2012

[EUROCAE, 2007] High-level performance requirements for a global navigation satellite system/ground based augmentation system to supprt precision approach operations, ED-144, October, 2007

[AWO] EASA, CS AWO 1, “Joint Aviation Requirements – All Weather Operations”, Subpart 1, “Automatic Landing Systems”

[FAA, 1999] FAA Advisory Circular 120-28D, “Criteria for Approval of Category III Weather Minima for Takeoff, Landing and Rollout” dated July 13, 1999

[DOD, 2008] GPS Standard Positioning Service Performance Standard – US DoD – 4th Edition September 2008

[Walter, 2011] SBAS and GBAS Integrity for Non-Aviation Users: Moving Away from “Specific Risk”, Sam Pullen, Todd Walter and Per Enge, Stanford University, International Technical Meeting of the Institute of Navigation, San Diego, CA, January 24-26, 2011

[RTCA, 2004] Minimum aviation system performance standards for the local area augmentation system (LAAS), RTCA DO-245A, December 2004

[MURPHY, 2009] ICAO SARPS Support for Airworthiness Assessments GLS Signal Modeling

[FAA, 2012] http://www.faa.gov/about/office_org/headquarters_offices/ato/service_units/techops/navservices/gnss/approaches/index.cfm

[MURPHY, 2010] T. Murphy, M. Harris, C. Shively, L. Azoulai, M. Brenner, "Fault modeling for GBAS airworthiness assessments", Proc. of the ION GNSS conference, Portland, Oregon, 2010

[WALTER, CHATRE, 2012] Private conversation with Todd Walter (Stanford University) and Eric Chatre (European Commission)]

[DeCleene, 2007] NSP Mar07/WG1&2/WP15 Approval to Conduct WAAS-Based LPV Approaches to Lower Minima

[SUARD, MILNER, 2012] Personal communication between Norbert Suard (CNES) and Carl Milner (ENAC)