GPS / Galileo Performance Assessment

Aircraft Precision Approach

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GPS and Galileo are expected to serve as navigation sources for a variety of applications. The most stringent performance requirements are derived from safety critical applications including aviation precision approach operations. The precision approach operation will be realised using Ground Based Augmentation Systems (GBAS) and/or future Galileo Local Elements.

Safety and efficiency considerations in air traffic demand a precise and global navigation system that is available 24 hours a day in all weather conditions. The fulfilment of the stringent requirements for precision approaches down to CAT III asks for a careful analysis of System Integrity, Availability, Continuity of Service and Accuracy during precision approaches and automatic landings.

The GBAS performance assessment and validation is done using the methods

- service volume simulation (SVS) and prediction
- real time system and performance monitoring using an Independent GBAS Monitor (IGM)
- evaluation of the monitored data in history mode and post-processing.

Introduction

The advantages of implementing satellite based navigation systems for en-route and their Ground Based Augmentation Systems (GBAS) at airports are:

- one navigation system for all phases of flight
- one system per airport instead of one system per runway end
- support of an unlimited number of users
- parallel and segmented approaches possible
- all-weather landing capability
- ground taxiing guidance
- airport surface movement guidance and control
- etc.

Today, there are no certified and operational GBAS ground systems available, but the performance of such GPS based GBAS systems can be observed and evaluated using pre-operational systems. NavPos Systems GmbH develops an Independent GBAS Monitor (IGM) based on the specification of the German Air Navigation Services (DFS Deutsche Flugsicherung GmbH) to support the operational validation of such GBAS ground systems for the precision approach Category I (CAT-I). DFS has installed two prototype GBAS ground stations at Frankfurt and Bremen airport. The Bremen installation will be used for restricted operational use starting in 2007. The prototype ground station will be replaced by a certified GBAS CAT-I ground station in 2008.

Using Service Volume Simulation (SVS) it is possible to predict the GBAS performance for any location or in a grid over an area and thus to detect geographical dependencies. In addition, the expected GBAS performance using future combined GPS and Galileo measurements can be simulated. The presented service volume simulations and predictions were generated in the frame of the NavPos Systems R&D projects GalTeC and GALILEA.

GBAS Concept

The Ground-Based Augmentation System (GBAS) is a safety critical system that augments the GPS Standard Positioning Service and provides enhanced levels of service supporting all phases of approach, landing, departure and surface operations within its service area. GBAS will initially be applied as an alternative to ILS CAT I. The GBAS system consists of three primary subsystems:

- The GNSS satellite subsystem is producing the ranging signals and navigation messages. The satellite signals received by the GNSS receivers are affected by various error sources. A substantial part of these error sources can be corrected through the use of differential techniques in the

GBAS system. The GNSS satellite subsystem may include GPS, GLONASS and SBAS satellites.

- The GBAS ground subsystem consist of:
  - o two to four GNSS reference receivers at surveyed positions
  - o GBAS processing unit, which collects pseudoranges for all GNSS satellites in view from all reference receivers, computes and broadcasts differential corrections and relevant integrity – related information
  - o VDB transmitter. The corrections are transmitted from the ground system via a Very High Frequency (VHF) Data Broadcast (VDB) in the frequency band 108 to 117.975 MHz. The transmitter broadcasts pseudorange corrections, integrity parameters and local data such as Final Approach Segment (FAS) data, referenced to the WGS-84 geodetic system. If a transmitting antenna has an omni directional pattern then the ground station is capable to support multiple runway end approaches.
- The GBAS aircraft subsystems within the area of coverage of the ground may use the broadcast differential corrections to enhance integrity and accuracy of positioning. After selecting the desired FAS for the landing runway, the differentially corrected position is transformed into navigation guidance signals which are:
  - o lateral and vertical deviations from the selected FAS
  - o distance to the threshold crossing point of the selected FAS
  - o integrity flags.

GBAS Required Performance

A Navigation and Flight-Guidance System has to fulfil stringent requirements regarding Accuracy, Integrity, Continuity of Service and Availability. GPS SIS integrity is determined by RAIM and/or augmentation systems like WAAS (Wide Area Augmentation System) and EGNOS (European Geostationary Navigation Overlay Service). The requirements are different for the different phases of flight. GPS based RAIM fulfils the performance requirements from En-Route down to the lateral guidance for non-precision approach operations globally. On a regional scale, the satellite based augmentation systems WAAS, EGNOS and others will provide vertical navigation guidance down to APV-I and APV-II. The Galileo baseline architecture specifies a global integrity concept which will

GBAS Service Level	Typical operation(s) which may be supported by this level of service
A	Approach operations with vertical guidance (performance of APV-I designation)
B	Approach operations with vertical guidance (performance of APV-II designation)
C	Precision Approach to lowest Category I minima
D	Precision Approach to lowest Category IIIb minima, when augmented with other Airborne equipment
E	Precision Approach to lowest Category II/IIIa minima
F	Precision Approach to lowest Category IIIb minima

Table 1 - GSL for Approach Services [1].

Performance Requirements	GBAS Service Level	Accuracy		Integrity				Continuity
		Lateral NSE 95%	Vertical NSE 95%	Integrity Probability	Time to Alert	Lateral Alert Limit	Vertical Alert Limit	Continuity Probability
CAT I	C	16.0 m (52 ft)	4.0 m (13 ft)	$1\text{-}2 \times 10^{-7}$ In any 150s	6 s	40 m (130 ft)	10 m (33 ft)	$1\text{-}8 \times 10^{-6}$ In any 15 s
CAT II/III TBD – requirements not finalised yet	F	5.0 m (16 ft)	2.9 m (10 ft)	$1\text{-}1 \times 10^{-9}$ In any 15 s vert. , 30 s lat	2 s	17 m (56 ft)	<=10m	$1\text{-}8 \times 10^{-6}$ In any 15s vert, 30s lat

Table 2 - GSL Required Performance [1], [4].

In order to provide smooth implementation of the aircraft GBAS equipment, and to ease entry into regular operations the guidance data output is developed consistent with existing ILS requirements ("ILS look-alike"). This reduces the certification effort of the Multi-Mode Receivers (MMR), which includes a GBAS aircraft subsystem named hereafter GBAS Rx.

fulfil APV-II requirements.

For take off and landing the criteria are much more stringent than for en-route navigation. The most stringent requirements to the flight guidance system are given for automatic landings. The precision approach operation will be realised using Ground Based Augmentation Systems (GBAS) and/or future Galileo Local Elements.

GBAS service levels are classified according to the required operations as illustrated in Table 1. In this analysis the focus is on GBAS CAT-1 Service Level C and GBAS CAT-IIIb Service Level F. The required GBAS performance for the Service Levels C and F are summarised in Table 2 as derived from RTCA Sources.

GBAS Integrity Monitoring Algorithms and Definitions

This section describes the GBAS integrity algorithms which are based on the continuous computation of vertical/lateral protection levels and comparison with the vertical/horizontal alert limits.

Computation of Protection Levels

According to [1] the GBAS integrity vertical and lateral protection levels are calculated from the following:

$$VPL_{H0} = K_{ffmd}\sqrt{\sum_{i=1}^{N} s^2_{Apr\_vert,i}\sigma_i^2}$$

$$LPL_{H0} = K_{ffmd}\sqrt{\sum_{i=1}^{N} s^2_{Apr\_lat,i}\sigma_i^2} \quad \text{(Eq. 1)}$$

where:

$s_{Apr\_vert,i} = s_{vert,i} + s_{x,i} * \tan\theta_{GS}$ = projection of the vertical component and translation of the along-track errors into the vertical for i^{th} ranging source

$s_{Apr\_lat,i} = s_{lat,i} = s_{y,i}$ = projection of the lateral component for i^{th} ranging source

$s_{vert,i}$, $s_{lat,i}$ projections of the vertical/lateral components for i^{th} ranging source from the projection matrix S

K_{ffmd} = predefined multiplier which determines the probability of fault-free missed detection

θ_{GS} = glidepath angle for the final approach path

N = number of ranging sources used in the position solution

i = ranging source index

σ_i^2 = the standard deviation of overall UDRE error after applying GBAS differential corrections pertaining to satellite i which is presented as

$$\sigma_i^2 = \sigma^2_{pr\_gnd}[i] + \sigma^2_{tropo}[i] + \sigma^2_{air}[i] + \sigma^2_{iono}[i] \quad \text{(Eq. 2)}$$

where

$\sigma_{pr\_gnd}[i]$ is the total (post correction) fault-free noise term provided by the ground function (via the VDB) for satellite i

$\sigma_{tropo}[i]$ is a term computed by the airborne equipment to cover the residual tropospheric error for satellite i

$\sigma_{air}[i]$ is the (post correction) fault-free noise term for satellite i.

$\sigma_{iono}[i]$ is the residual ionospheric delay uncertainty for satellite i.

Besides VPL_{H0}, LPL_{H0} the GBAS integrity monitoring requires to estimate ephemeris error position bounds VEB and LEB:

$VEB = MAX\{VEB_j\}$, $LEB = MAX\{LEB_j\}, j = 1,N$

The vertical and lateral ephemeris error position bounds for the j-th core satellite constellation ranging source used in the position solution is computed as, [1]:

$$VEB_j = |s_{Apr\_vert,j}|\, x_{air} P_j + K_{md\_e}\sqrt{\sum_{i=1}^{N} s^2_{Apr\_vert,i}\sigma_i^2}$$

$$VEB_j = |s_{Apr\_vert,j}|\, x_{air} P_j + K_{md\_e}\sqrt{\sum_{i=1}^{N} s^2_{Apr\_vert,i}\sigma_i^2} \quad \text{(Eq. 3)}$$

where:

P_j is the broadcast ephemeris decorrelation parameter for the j-th ranging source

K_{md_e} is the appropriate broadcast ephemeris missed detection multiplier for the approach associated with the satellite constellation for the j-th ranging source.

The UDRE error components in Eq.2 consist of

$\sigma^2_{pr\_gnd}[i]$, $\sigma^2_{tropo}[i]$, $\sigma^2_{air}[i]$ and $\sigma^2_{iono}[i]$.

GBAS Ground Error, $\sigma^2_{pr\_gnd}[i]$

The RMS of the total non-aircraft contribution to the GBAS error as a function of the elevation angle as given in [1] is

$$RMS_{pr\_gnd}(\theta_i) \le \sqrt{\frac{(a_0 + a_1 e^{-\theta_i/\theta_0})^2}{M} + (a_2)^2} \quad \text{(Eq. 4)}$$

GBAS Accuracy Designator letter	θ_i (deg)	a_0 (m)	a_1 (m)	θ_0 (deg)	a_2 (m)
A	> 5	0.5	1.65	14.3	0.08
B	> 5	0.16	1.07	15.5	0.08
C	> 35	0.15	0.84	15.5	0.04
	=<35	0.24	0	-	0.04

Table 3 - RMS_{pr_gnd}

Tropospheric Residual Error, $\sigma^2_{tropo}[i]$

The tropospheric uncertainty as defined in [1] is

$$\sigma_{tropo}[i] = \sigma_N h_0 \frac{10^{-6}}{\sqrt{0.002 + \sin^2(\theta_i)}}(1 - e^{\frac{-\Delta h}{h_0}}) \text{ mtr} \quad \text{(Eq. 5)}$$

where

σ_N = refractivity uncertainty transmitted by ground subsystem in Message Type 2

h_0 = troposphere scale height transmitted by the ground subsystem

Δh = difference in altitude between airborne and ground subsystems

θ_i = elevation angle for the i^{th} ranging source

Airborne Pseudorange Performance: $\sigma^2_{pr\_air}[i]$

Airborne Accuracy Designator letter	θ_0 (degrees)	a_0 (meters)	a_1 (meters)
A	6.9	0.15	0.43
B	4.0	0.11	0.13

Table 4 - RMS_{pr_air}

The RMS of the total airborne contribution to the error in a corrected pseudorange [1] is

$$\sigma_{air,i} = \sqrt{\sigma^2_{receiver}(\theta_i) + \sigma^2_{multipath}(\theta_i)}$$

where

$\sigma_{receiver}(\theta_i)$ is the airborne receiver contribution, $\sigma_{receiver}(\theta_i) = RMS_{pr\_air,GPS} \le a_0 + a_1 e^{-\theta_i/\theta_0}$
with a_0, a_1, θ_0 and given in Table 4.

$\sigma_{multipath}(\theta_i)$ is the RMS of the installed multipath error contribution as defined in [1] is for Airframe Multipath Designator A

$$\sigma_{multipath}[i] = 0.13 + 0.53 e^{(-\theta[i]/10\deg)}$$ in metres

for Airframe Multipath Designator B

$$\sigma_{multipath}[i] = (0.13 + 0.53 e^{(-\theta[i]/10\deg)})/2.0$$ in metres

Ionospheric Residual Error, $\sigma_{iono}[i]$

According to [2], the model of the Ionospheric Residual Uncertainty is written as

$$\sigma_{iono} = F_{PP} \times \sigma_{vert\_iono\_gradient} \times (x_{air} + 2 \times \tau \times V_{air}) \quad \text{(Eq. 6)}$$

where:

F_{pp}= the vertical-to-slant obliquity factor for given satellite and

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

R_e = radius of the earth
h_i = ionosphere shell height
θ = satellite elevation
$\sigma_{vert\_iono\_gradient}$ = the standard deviation of a normal distribution associated with the residual ionospheric uncertainty due to a spatial decorrelation (a parameter broadcast by the ground subsystem in Message Type 2)
x_{air} = distance(slant range) between aircraft and the GBAS reference point
τ = the time constant of the smoothing filter
V_{air} = the horizontal speed of the aircraft

GBAS Performance Observation using the Independent GBAS Monitor (IGM)

The Independent GBAS Monitor (IGM) is used to permanently monitor the Ground-Based Augmentation System (GBAS) in real time together with all the needed data to restore historical system states and to support post-processing GBAS performance assessment. The system is specified to fulfil the ICAO requirements [4], [5] for

- GNSS data recording
- GNSS performance assessment
- GBAS ground testing.

The IGM System includes

- 1 GPS/SBAS Dual Frequency (DF) Rx,
- 1 GPS Single Frequency (SF) Rx
- 1 VDB Rx (Telerad)
- Server and Storage devices
- Uninterruptable Power Supply.

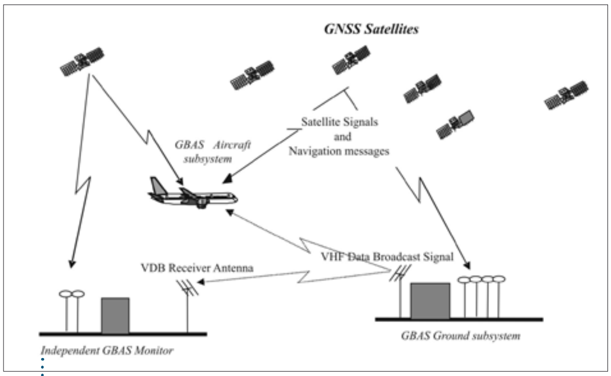


Figure 1 - GBAS Architecture plus Independent GBAS Monitor (IGM).

Figure 2 - IGM Hardware and Graphical User Interface - System Overview.

The IGM architecture (see Figure 1) that supports above ICAO requirements optionally includes a GBAS Rx which is a certified airborne Multi-Mode-Receiver (MMR). Alternatively, the monitoring of the GBAS Rx performance is accomplished by simulating GBAS Rx outputs on the basis of real data from one of the GNSS receivers and the VDB receiver.

The IGM user can select numerical and graphical views to display the observed data in real time or access the recorded data in history mode. Since the IGM GUI is implemented as a web service, it is possible to login into the IGM from any user PC within a protected network using a standard web browser. The statistical evaluation of observation time spans is provided in the form of the number of visible satellites, xDOPs and xNSE/xPL diagrams and also Stanford Plots, Ground Accuracy Designator (GAD) plots and Cumulative Distribution Function (CDF) graphs. In addition to the data and performance monitoring of the GBAS, the IGM System is continuously recording its own IGM system status, the GPS and SBAS satellite constellation status, the GPS receiver states and observations. It also performs online monitoring of parameters and system states against user-defined thresholds. User groups are alerted by Email, if defined performance thresholds are exceeded. In addition all kind of anomalies are recorded in a protocol file and a daily GBAS performance report is generated automatically. Figure 2 shows the IGM System Overview. Figure 3 presents the Polar Plots of both GNSS receivers. The IGM generates GAD plots (see Figure 4) as a performance assessment indicator of the GBAS ground station. As part of the IGM standard operations a permanent on-line GBAS Rx simulation process is implemented (see Figure 5).

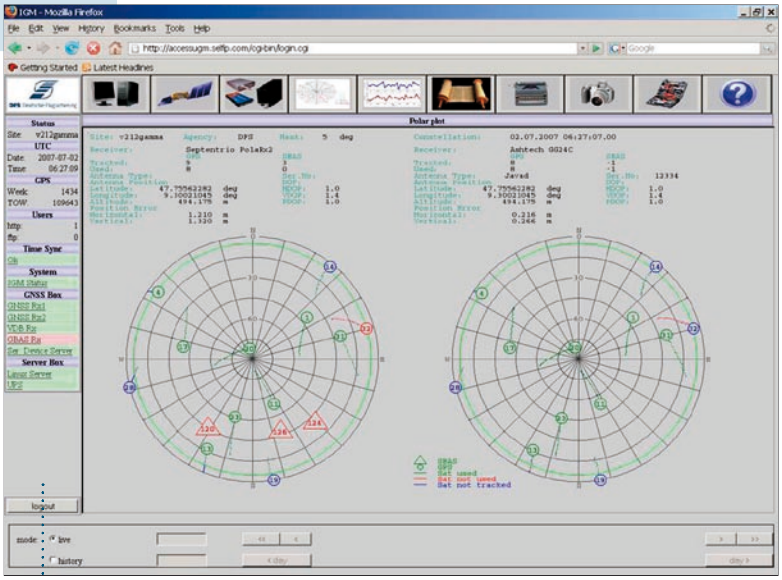


Figure 3 - GNSS Status as Polar Plot (live mode).

As shown with Figure 4 and Figure 5, the IGM monitors the GNSS and GBAS performance in real time. It also supports the assessment of historical data and the creation of statistical graphs. Figure 5 also shows the GBAS Rx Simulator GUI of the IGM which includes a simplified Course Deviation Indicator (CDI) display. The GBAS Rx simulator implementation follows the algorithmic definitions of the airborne standards. All GBAS, GNSS and IGM Monitoring data are recorded to support data investigation in history mode and post-processing.

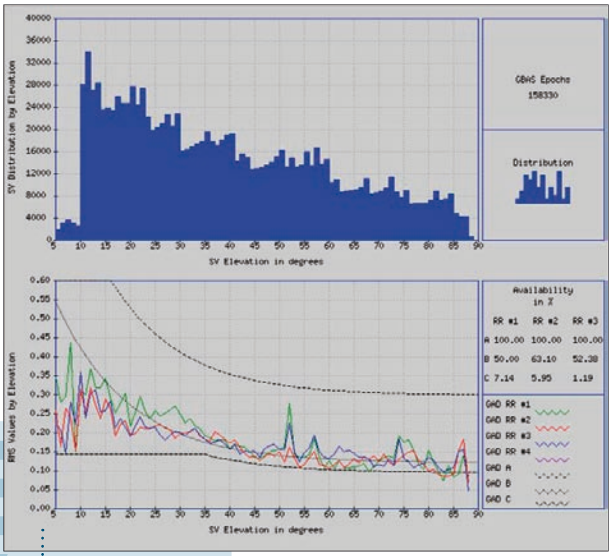


Figure 4 - GBAS Observations showing Distribution of Satellites by Elevation and Ground Accuracy Designators Performances.

GBAS Performance Prediction and Analysis using SVS

Using the IGM, the GPS based CAT-I GBAS data are monitored in real time and evaluated in post-processing. The results can be compared with the Service Volume Simulations to adjust the SVS settings. Using the SVS it is then possible to predict the GBAS performance for other locations or in a grid over an area and to detect geographical dependencies. It is further possible to expand the simulations

Figure 5 - GBAS Receiver Simulator Performance of the IGM.

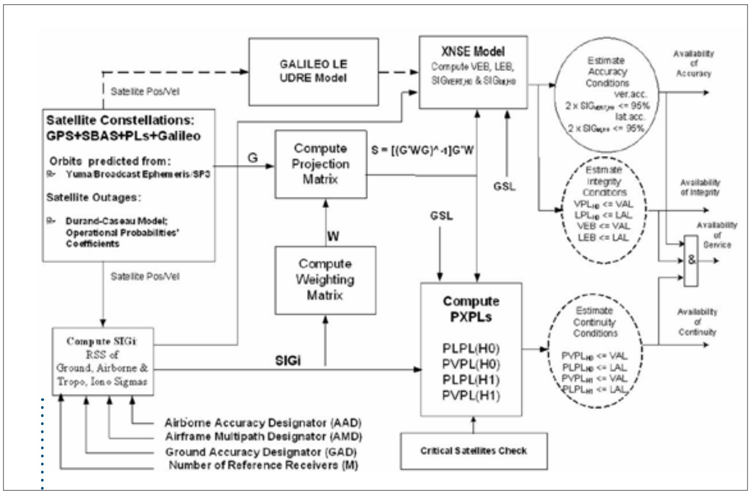


Figure 6 - Block scheme of the AVIGA GBAS SVS Module.

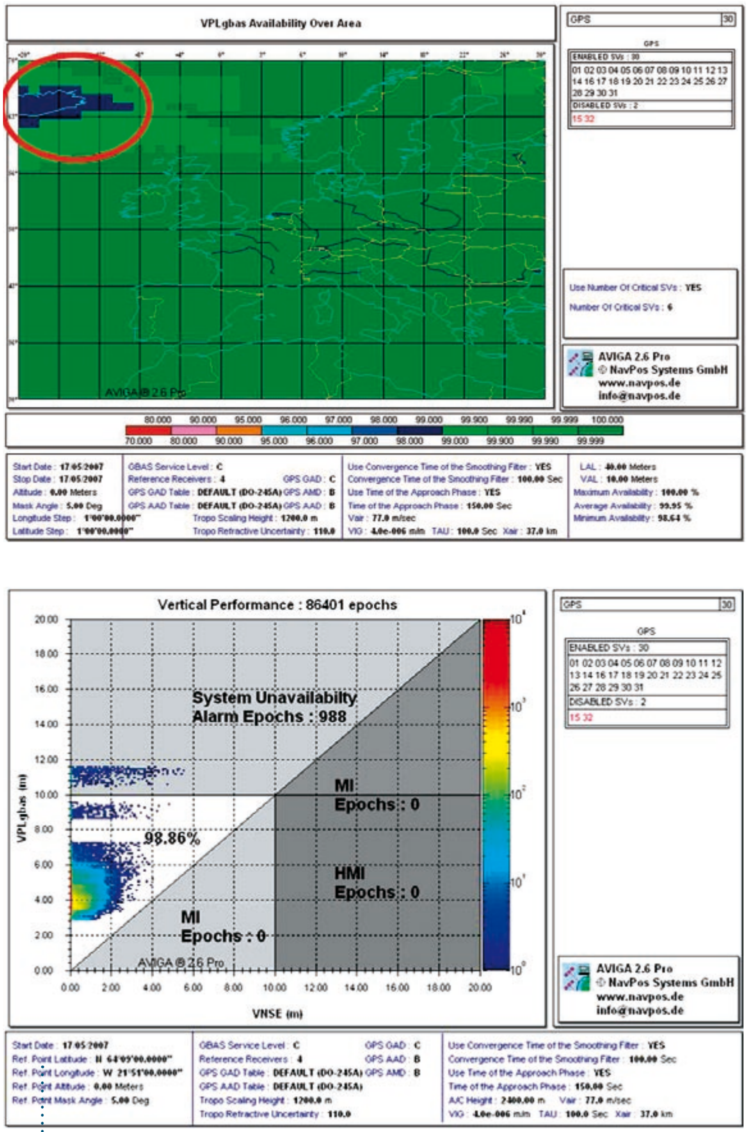


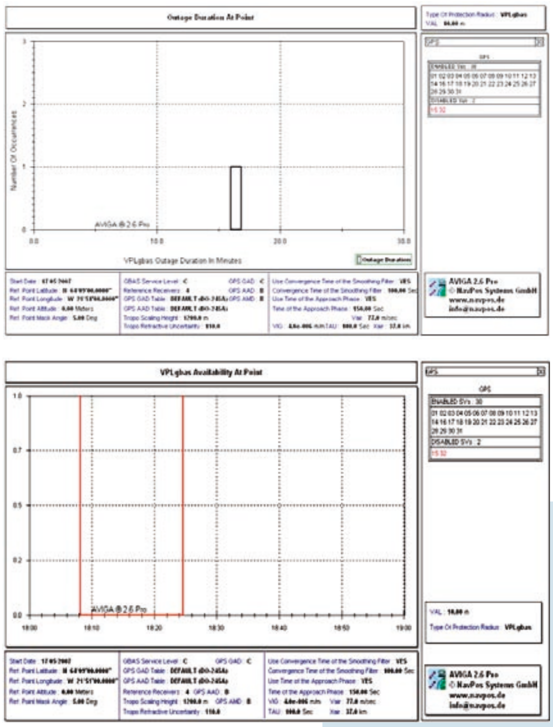
Figure 7 - GBAS CAT-I Service Level C Using GPS Broadcast Ephemeris of 17th May 2007.

to GBAS Service Level F to predict and investigate the combined GPS and Galileo performance.

Using the GBAS and Galileo Local Element modules of the AVIGA Service Volume Simulation and Prediction tool, it is possible to analyse availability of Accuracy, Integrity and Continuity of GBAS and Galileo Local Element systems. Figure 6 shows the block diagram of the implemented GBAS module, which allows to simulate the status and availabilities of past, current and future GNSS constellations. The following two performance levels were investigated:

- GBAS CAT-I Service Level C using GPS actual constellation of day 17th May 2007
- GBAS CAT-IIIb Service Level F using GPS+Galileo nominal constellations.

Figure 7 shows the Service Volume Simulation for GBAS CAT-I Service Level C using the GPS Constella-



tion of day 17th May 2007 with 30 active and healthy satellites. GPS Broadcast Ephemeris were used to determine the satellite trajectories. The analysis can be done at a defined point (e.g. an airport) or in a grid over an area. The VPLgbas Availability Analysis was done over an area using a grid spacing of 1° x 1°. The selected time resolution was 1 min. The minimum GBAS service range is 37km. Therefore the used distance between GBAS and aircraft Xair was also set to 37km. The aircraft velocity was assumed with 77m/s. The convergence times of the smoothing filters were considered with 100s and no geometry changes were allowed during approach times of 150s.

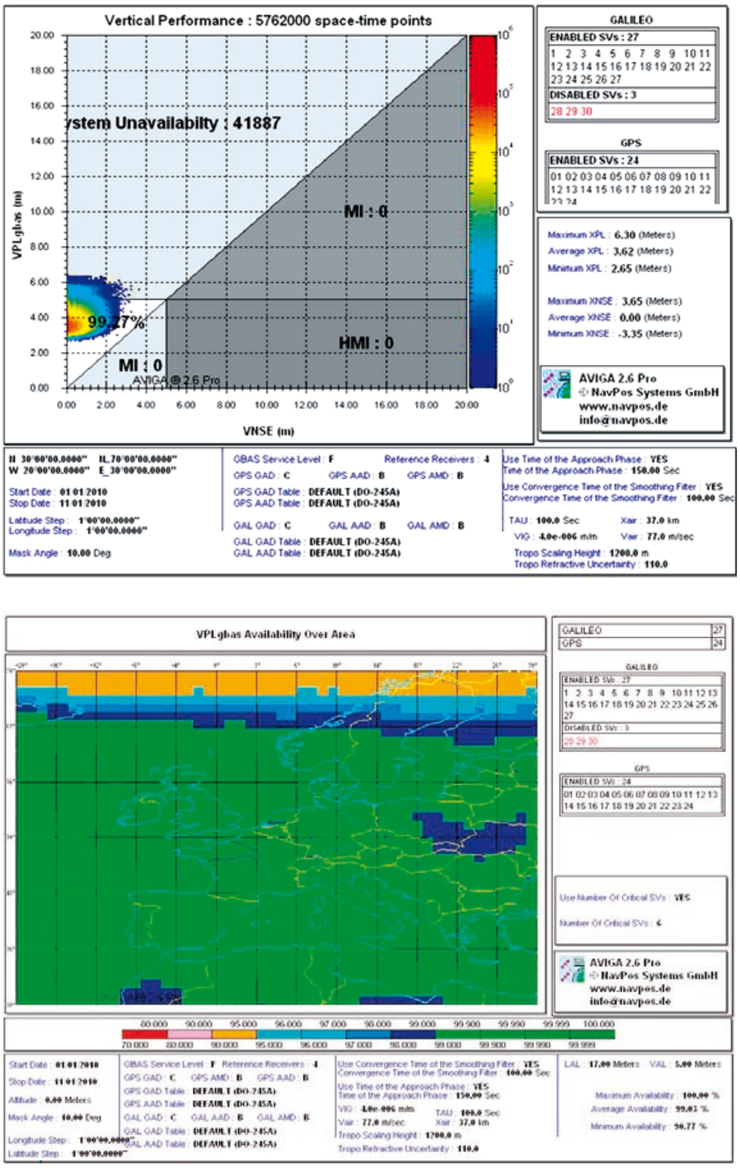


Figure 8 - GBAS CAT-IIIb Service Level F Using GPS+Galileo Nominal Constellations.

The VPLgbas Availability over Area Plot shows the geographical variation of the GBAS performance. In most grid points of the selected area, the availability during that day is 100%. However there exist some areas where the GBAS availability drops to 98.64%. These regions and possible outage times can be predicted using GBAS Service Volume Simulations. On 17th May 2007 the region of Reykjavik showed a lower Availability. Therefore a VPL/VNSE analysis in the form of a Stanford plot (see Figure 7) was calculated for Reykjavik using time steps of 1s. It identifies an availability of 98.86%. It was determined that only one outage with a duration of 17min occurred on that day. These spots occur as a function of the satellite geometry and also move with time. An Independent GBAS Performance Prediction and Monitoring could be added at each GBAS equipped airport to predict, record and validate the GBAS performance during operation. Then GBAS CAT-IIIb Service Level F was investigated using the nominal constellations of combined GPS and Galileo. Figure 8 shows the result of the VPL/VNSE estimation in form of a Stanford Plot and also in a 1°x1° grid over area. The time step is 5min and the duration is 10days which reflects the Galileo Repeat Orbit. Since the GBAS CAT-II/III standardisation is not finalised yet, a Vertical Alert Limit of 5m was selected as threshold parameter for the Service Volume Simulations. Considering such a very stringent VAL, the VPLgbas Availability still shows a very good average availability of 99%.

Conclusions

The use of GBAS for navigation and precision approach down to CAT-I is feasible and efficient. The expansion of the GBAS CAT-I to CAT-IIIB Autoland Capability seems to be achievable using combined GPS and GALILEO signals.

The performance parameters Accuracy, Continuity of Service, Integrity and their respective Availability can be investigated using the methods

- service volume simulation (SVS) and prediction,
- real time system and performance monitoring, and
- evaluation of the monitored data in history mode and post-processing of the recorded data.

Since the GPS constellation and its geometry is changing over time, a prediction of the GBAS CAT-I performance using actual GPS orbit and status data can detect critical satellite geometries beforehand by Service Volume Simulation.

The status and the performance of GNSS and GBAS is monitored in real time by the IGM. The recorded data of this system can be used for incident/exident investigations as well as for online and detailed offline data analysis. The capability of the IGM to re-visit the recorded data in history mode simplifies and shortens the response time to internal and external user requests.

The fulfilment of the stringent requirements for precision approaches down to CAT-IIIb asks for a careful examination of System Integrity, Availability, Continuity of Service and Accuracy. The service volume simulations show the great potential of combined GPS and Galileo for aircraft precision approaches and automatic landings.

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- Galileo Local Elements research was supported by the European GNSS Supervisory Authority (GSA) as part of the co-funded GALILEA study.

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Biographies of the Authors

Eduarda Blomenhofer is Managing Director of NavPos Systems GmbH (In Oberwiesen 16, 88682 Salem), a German SME which specialized in satellite navigation related systems engineering and software development. She owns an Engineer Degree in Surveying/Geodesy from the Porto University, Portugal. She is working in satellite navigation since 1990 developing real time systems, data processing software and service volume simulation tools for GPS, GLONASS, GBAS, SBAS and Galileo.

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Dr. Winfried Dunkel graduated as an engineer in aerospace technology at the Technical University of Braunschweig in 1989. He then worked as research and flight test engineer at the Institute of Flight Guidance and Control of the TU Braunschweig where he finished with the doctor degree. Since 1995 he is working in the satellite navigation department of the German Air Navigation Services DFS Deutsche Flugsicherung GmbH being responsible for several GBAS and Galileo related projects. He is member of European (EUROCONTROL, EUROCAE) and International GBAS working groups and technical advisor for the German ICAO panel member in the Navigation Systems Panel.