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SBAS avionics compared to GBAS on-board equipment

Jakub Machuta[1]; Jakub Kraus[1]*

[1]Department of Air Transport, Faculty of Transportation Sciences, Czech Technical University in Prague, Prague, Czech Republic

***Corresponding author**: Czech Technical University in Prague, Faculty of Transportation Sciences, Department of Air Transport, Horská 3, 128 03 Prague, Czech Republic, Email: kraus@fd.cvut.cz

Abstract

Global Navigation Satellite System (GNSS) has become an integral part of air navigation. Delay of the GNSS signal in ionospheric layer is one of the most serious problems in using GNSS. Not only accuracy but also the safety is very important in air navigation, and for that reason the augmentation of basic GNSS is used to meet higher requirements of aviation industry. This paper discusses Satellite-Based Augmentation System (SBAS) avionics with special emphasis on correction of signal delay in ionospheric layer as one of the most significant error fixes and compares it with other GNSS based on-board equipment - with basic GNSS (GPS) in terms of accuracy and with Ground-Based Augmentation System (GBAS) generally. This article should therefore show reader the differences between the methods of calculating ionospheric corrections by SBAS and GBAS and explain the reasons of these methods, taking into account the area of intended use of both systems.

Keywords

Air navigation; Global Navigation Satellite System; Satellite-Based Augmentation System; Ground-Based Augmentation System; Avionics; Ionospheric Delays

1. Introduction

Satellite-Based Augmentation System, hereinafter SBAS, is system designed to augment the navigation system constellations by broadcasting additional signals from geostationary (GEO) satellites and thereby provides incomparably more accurate position information then basic GNSS. Therefore SBAS has begun to be used extensively in aeronautics in the last decade.

The origins of SBAS are associated with implementation of Wide Area Augmentation system WAAS in USA. As a result of the benefits provided by SBAS, it was implemented also in other parts of the world, for example European continent is covered by EGNOS service.

SBAS architecture consists of ground segment, space segment and user segment. The basic scheme of ground segment is a set of monitoring stations (at very well-known position) to receive GPS signals that will be processed in order to obtain some estimations of errors that are applicable to the users. Once these estimations have been computed, they are transmitted in the form of differential corrections by means of a GEO satellite - space segment to the user. User segment is, in fact, SBAS receiver, which is the part of aircraft avionics.[1][2]

Monitoring stations (RIMS 2) collect parameters for calculation of three basic corrections of GPS and send them to avionics via GEO satellite. The SBAS avionics then computes these corrections of pseudoranges and adjusts position, velocity, time (PVT) accordingly.[3][1]

Table 1 shows the error range, which is defined as the statistical difference between the distance measured by the receiver and the theoretical distance from the actual position

Table 1. GPS AND SBAS ACCURACY COMPARISON

Error Source	GPS value (m)	EGNOS value (m)
GPS SREW	4.0	2.3
Ionosphere (UIVD error)	2.0 to 5.0	0.5

of the satellite to the receiver. The error range is characterized by 2 parameters. Parameter SREW (Satellite Residual Error for the Worst User Location) in the relevant area6 includes satellite track/position error - ephemeris error and satellite clock error. The parameter UIVD (User Ionospheric vertical Delay) belongs to the ionospheric vertical delay and is relevant for the given satellite - receiver pair. This is a delay at the point where the satellite signal passes through the ionospheric layer. Other error sources such as multi-path signal propagation, receiver noise, or troposphere signal delay are always dependent on the type and quality of the receiver.[4]

From these three basic corrections that SBAS ensures, absolutely the most necessary and important is correction of signal delay in ionospheric layer. This correction makes SBAS so accurate at the vertical plane improves GPS standard vertical error range from $\pm 23m^{95\%}$ to $\pm 4m^{95\%}$ and allows using SBAS for LPV and LPV 2007 procedures during final approach.[3][5]

Since augmentation systems such SBAS and GBAS have been used in aviation, ionospheric gradient is the threat to these systems and has to be measured and reduced. Protection of the users from errors caused by ionospheric signal delay is vital for more advanced use of GNSS augmentation systems in air navigation. Purpose of this paper is to bring a closer look at methods of ionospheric correction and to provide comparison between SBAS's and GBAS's measures against this threat.

2. Materials and methods

2.1 Computing methodology of ionospheric errors by SBAS avionics

To estimate the ionospheric error, each receiver must identify the so-called Ionospheric Pierce Points IPPs. Location of each IPP is defined as the intersection between the atmospheric layer located at an altitude of 350 km and the line connecting the receiver position and GPS satellite. This position is defined by the latitude ϕ_{PP} and the longitude λ_{PP} in WGS84 coordinates (see Fig. 1).

Corrections are transmitted for each of the points on the virtual grid located at an altitude of 350 km. We call this Ionospheric Grid Points (IGP), see Fig 2. The final correction for a given IPP is the result of interpolation of individual IGPs. The receiver knows the status of these specific points (IGPs) with an estimated delay for each of them and is therefore able to estimate an ionospheric delay for each IPP and therefore for each pseudorange.

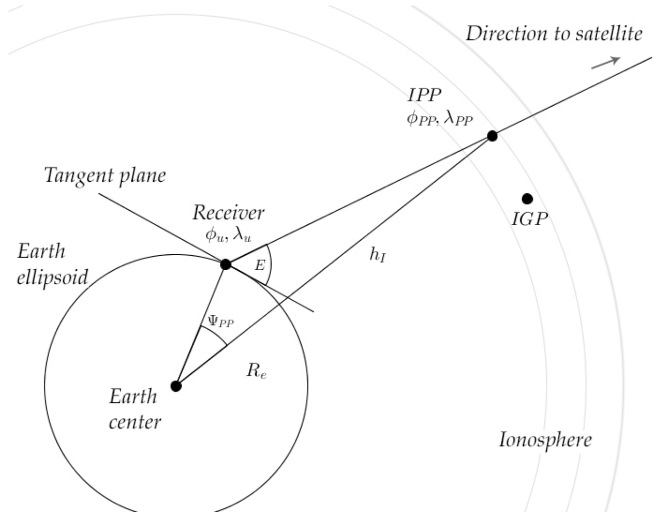

Figure 1. Principle of the IPP (Ionospheric Pierce Point).

The receiver must also take into account the Obliquity factor (ionosphere signal angle), see below. The transfer of ionospheric corrections parameters to the receiver allows SBAS avionics to calculate the estimation of ionospheric errors for a given IPP. These corrections are transmitted for each IGP grid point. From Fig. 1, we can get geometrically the latitude ϕ_{PP} and the longitude λ_{PP} for the given IPP. The following equations are based on this consideration.

$$\phi_{PP} = \sin^{-1}(\sin\phi_u \cos\Psi_{PP} + \cos\phi_u \sin\Psi_{PP} \cos A) \quad (1)$$

where

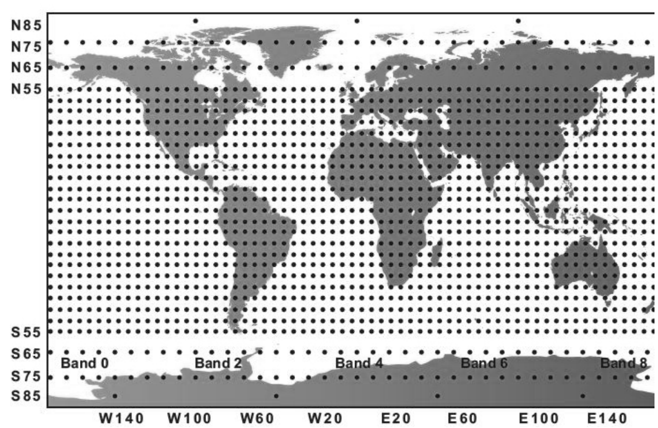

Figure 2. Ionospheric Grid Points (IGPS).

$$\Psi_{PP} = \frac{\pi}{2} - E - \sin^{-1}\left(\frac{R_e}{R_e + h_I}\cos E\right) \quad (2)$$

The result is expressed in radians. Ψ_{PP} corresponds to the angle between the user position and the direction of the IPP taken back towards the Earth center. The angle A corresponds to the azimuth of the satellite relative to the position of the receiver (ϕ_u, λ_u). E corresponds to the elevation angle of the satellite, that is the angle between the tangent plane and the line passing through the receiver and the satellite. R_e is an approximation of the Earth's radius (6,378 km) and h_I is the height of maximum electron density (350km).

After expressing the latitude ϕ_{PP} of IPP, we are able to calculate its longitude λ_{PP}, which is given by relations:

$$\lambda_{PP} = \lambda_u + \pi - \sin^{-1}\left(\frac{\sin\psi_{PP}\sin A}{\cos\phi_{PP}}\right) \quad (3)$$

for

$$\phi_u > 70^\circ \wedge \tan\psi\cos A > \tan\left(\frac{\pi}{2} - \phi_u\right) \quad (4)$$

and

$$\lambda_{PP} = \lambda_u + \pi + \sin^{-1}\left(\frac{\sin\psi_{PP}\sin A}{\cos\phi_{PP}}\right) \quad (5)$$

for

$$\phi_u < -70^\circ \wedge \tan\psi_{PP}\cos(A+\pi) > \tan\left(\frac{\pi}{2} - \phi_u\right). \quad (6)$$

Once IPP position is determined, it is chosen which IGPs will be used for interpolation, see Fig 3. The receiver must take into account the possibility that some IGPs will not be monitored. In such a situation, the interpolation is performed within a triangle that contains IPP. If two IGPs are not monitored, the interpolation area will expand, which obviously reduces accuracy.

To obtain ionospheric correction IC and to add it to the pseudorange measurement, the vertical error of the given IPP must be multiplied by the so-called Obliquity Factor F_{PP}.

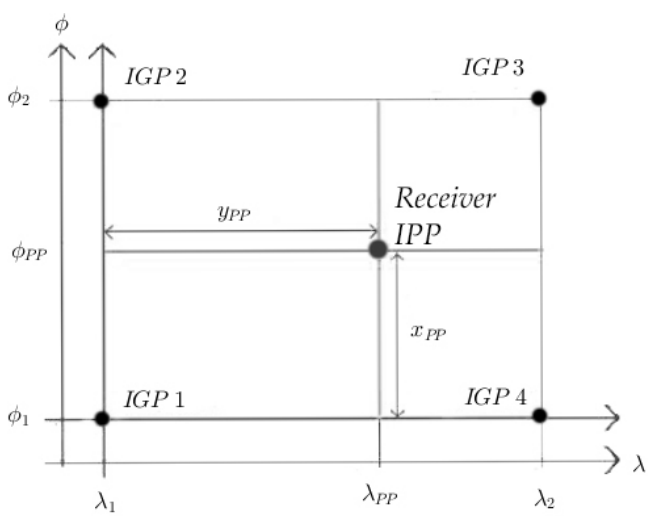

Figure 3. Principle of interpolation of the IPPs.

$$IC = F_{PP}\tau_{vpp}(\phi_{PP}, \lambda_{PP}) \quad (7)$$

where F_{PP} is defined as

$$F_{PP} = \left[1 - \left(\frac{R_e\cos E}{R_e + h_I}\right)^2\right]^{-\frac{1}{2}}. \quad (8)$$

SBAS message type 26 contains the data for the calculation of these corrections and is transmitted from *RIMS* via *GEO* satellite to aircraft avionics. There are two basic parameters in message type 26: *Grid Ionospheric Vertical Delay* (GIVD) and a parameter for estimating the accuracy of corrections (σ^2_{GIVE}) so-called *GIVE indicator(GIVEi)*.

Based on *GIVD* and σ^2_{GIVE} data provided for each GPS satellite in sight and by applying Obliquity Factor, the receiver obtains a slant range correction and a standard deviation value for the residual ionospheric error σ^2_{UIRE}.[1][2][6]

$$\sigma^2_{UIRE} = F^2_{PP}\cdot\sigma^2_{UIVE}. \quad (9)$$

2.2 GBAS, its avionics and ionospheric delays

Ground Based Augmentation System, hereinafter GBAS, is a GNSS based approach system with ground extension located in the airport area. On-board avionics monitors integrity and applies corrections through data obtained from the ground station located at the airport. Such ground extension has greatly increased the accuracy of satellite navigation system data and allowed GNSS to be applied in the *precision approach phase*. In a simplified way, we can say that GBAS is a regional SBAS. GBAS is one of the *unconventional precision approach* types *PA* and currently provides navigational performance for *CAT I*, but with planned textitGAST D certification it will support precision approaches up to *CAT III*. For this reason GBAS represents the future in the field of precision instrument approach at international airports and should be used as a suitable substitute for conventional ILS. In Europe, GBAS is already installed at airports in Bremen, Frankfurt, Palermo, Braunschweig, Toulouse or Malaga. LPV 200 approach can be taken as a possible alternative for GBAS, however, only for CAT I.

GBAS, like SBAS, also consists of *3 elements*: satellite constellation, ground stations and aircraft avionics. The ground station consists of one or more *VDB*[8] transmitters, broadcast antennas, several reference receivers and processing units, all located near the airport.[9][7]

Because GBAS ionospheric delays are, unlike SBAS, almost same in the psuedorange data received by GBAS reference stations and aircraft, most have been thought removable. But GBAS avionics uses smoothing process of code pseudoranges called Carrier-smoothing, which is achieved by simple algorithm called *Hatch filter*[1]0.

Carrier-smoothing uses a time constant of 100 seconds (30 seconds planned for GAST D), to correct some of the errors present in the code pseudorange based on the carrier phase of the GPS signal. If a *spatial ionospheric delay gradient* is encountered during the textitfinal approach segment FAS, it will affect GPS satellites passing over the region. The ionospheric gradient $dI = dx$ is expressed as rate of ionospheric delay change for each horizontal kilometer, and is indicated in mm/km units, see Fig. 4.

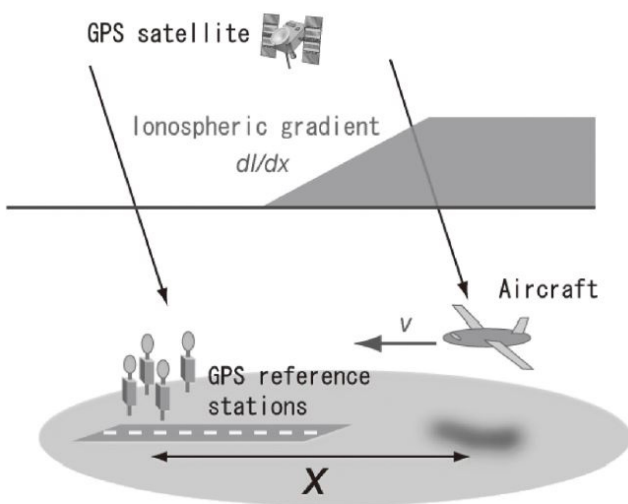

Figure 4. Spatial ionospheric delay gradient.

Assuming that the ionospheric gradient does not change over time, the maximum change δI of range errors in the satellite's line of sight (slant) direction shows *Eq. 10*.

$$\delta I = \frac{dI}{dx}(x + 2\tau v) \quad (10)$$

The first part of the Eq. 10 on the right side is a range error caused by spatial change in the ionospheric delay. The second part corresponds to the effect of carrier smoothing. τ (100s) is time constant.

Implemented GBAS safety design in USA is based on the settings of an ionospheric gradient maximum of 425mm/km and a horizontal distance of 6km from a GBAS reference station to the *decision height* (DH).[8][9][10][11]

3. Results and discussion

GBAS avionics receives messages at a frequency of 108 to 117.975MHz from the *VDB transmitter* located at the airport, unlike the SBAS receiving messages via GEO satellite on the *L1 band* (ie 1575.42MHz). SBAS provides correction for the entire *relevant area* intended for its use. GBAS provides corrections for multiple *RWYs* at one airport and in exceptional cases for nearby airports and heliports (GRAS[11]), and therefore doesn't use *ionospheric grid points* IGPs for correcting ionospheric delays because of small distances between aircraft and ground stations (airport). It follows that both systems (both avionics) use different methods of correcting the delay in the ionosphere and hence the calculation of the *pseudorange correction*.

SBAS uses the interpolation principle between IGPs and obtains parameters for pseudorange correction for a given IPP. Corrections are transmitted in a specially reserved *message type* 26[12] via GEO satellite for each IGP in *virtual grid* located at an altitude of 350 km. Ionospheric grid points masks are transmitted in *message type 18*.

GBAS avionics uses *Carrier-smoothing* process. The ionospheric parameter is transmitted in *type 2 messages* to model the ionosphere effects between the aircraft and the GBAS reference point. This error can be well characterized by a *normal distribution* with a zero mean value. GBAS also transmits construction data for *final approach segment FAS* in *message type 4*. So that's major difference from SBAS, which keeps FAS data for a specific approach in aircraft *avionics database*. SBAS procedures (for example LPV) can be selected through a channel number. This five-digit number is included in the final approach segment (FAS) data block in the database of procedures and must be published. Or, the procedure can be selected using the menu selection method.[12][4]

GBAS on-board equipment consists of GNSS and VDB receivers. While the GNSS receiver receives and decodes signals from the satellites, the VDB receiver is used to receive and decode the navigation messages transmitted from the GBAS ground system. On the basis of the received information, the on-board subsystem evaluates service availability and determines location and integrity. In basic mode, the GBAS receiver selects the highest service supported by both ground and on-board system. If the service is not available at the airport, the receiver automatically selects the lower available service. Similarly to SBAS or ILS approach, GBAS avionics provides both horizontal and vertical guidance to a defined *final approach course and a final approach glide path*.

Based on the received data, the receiver calculates and adjusts *position, velocity, time* (PVT), defines error boundaries and monitors possible threats in aerospace. This information is then transmitted from the receiver to a graphic on-board display via TCP/IP. Again, it is the same principle as SBAS, with the difference that SBAS corrections are transmitted using GEO satellites. For *GAST D, CAT III*, however, the above output data is not sufficient, and additional monitoring systems and new on-board integrity monitoring algorithms need to be implemented.

Interestingly, if a SBAS signal is available in a given location, GBAS is able to use correction data from GEO SBAS satellites and thus be even more accurate. Therefore, both systems can work together to create a "synergistic effect".

The disadvantages of the GBAS are to some extent similar to those of the SBAS: multi-path signal propagation problem, required signal availability, adequate monitoring and, in particular, ensuring sufficient integrity and early warning of the pilot about the malfunction of the system.

The aim of GBAS avionics manufacturers is to ensure the easiest installation on existing ILS equipment. Since GBAS is usually implemented at major international airports, its avionics is focused on large aircraft - mostly Boeing and Airbus fleets. SBAS avionics manufacturers focus mainly on regional or business aircraft as well as on private general aviation aircraft in the form of *stand-alone receivers*. Both

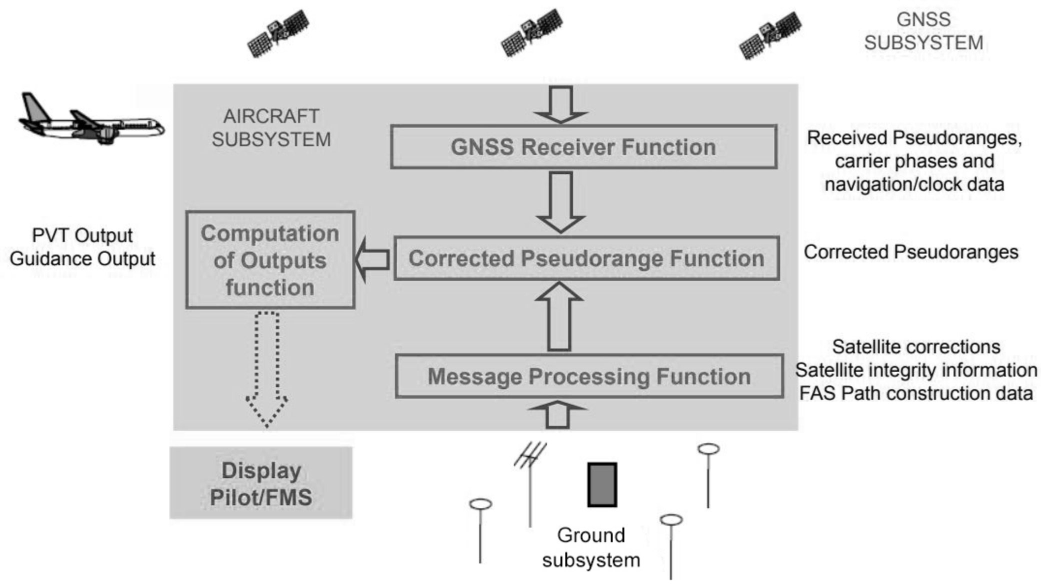

Figure 5. Data processing scheme of GBAS avionics.

SBAS and GBAS avionics are designed to match its interface as closely as possible to ILS, mainly because of the easy training of pilots for the transition to GNSS systems.

4. Conclusion

Recent years have shown a rapid advantage of using GPS-based navigation systems in the air navigation industry. Correction of ionospheric delays poses a key challenge relative to GPS usage. In air navigation, GPS-based systems have to be sufficiently accurate and safe. Assuring required integrity is also critical, because of practical needs of aviation. It must be available at any time and accessible to anybody. SBAS and GBAS uses different methods of generating differential corrections and integrity information for aviation users, both providing accurate and safe aircraft guidance. In the case of GNSS navigation, the local gradients of ionospheric delays are the hardest and also largest source of errors to control, when threatening safety. Both systems have implemented the protection against the threat of ionospheric gradients and secured safety margins to meet international standards.

Development of consistent ionospheric information system capable of detecting and correcting ionospheric errors efficiently could definitely help to simplify more advanced GNSS utilization in aviation.

GBAS avionics requirements, as SBAS, are standardized in ICAO *Annex 10/I* and MOPS (*MOPS RTCA/DO-253C*). Because GBAS for CAT II and CAT III is currently under development, the GBAS avionics standards13 will need to be modified to achieve the required accuracy and integrity. This will include, in particular, more consistent verification of satellite geometry, the new requirements for additional information from the ground system the new requirements for broadcasting protocols, requirements for monitoring the ionospheric gradient (30 seconds time constant during smoothing), the additional requirements for monitoring the failures of the reference receiver and more.

SBAS today supports the performance of *LPV 200*, which is the equivalent of *precision approach CAT I*. Even though SBAS avionics manufacturers (such as Garmin, Honeywell or Thales) are still improving their products, no major changes in avionics standards are planned.

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