Operational Evaluation of a GBAS System

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ABSTRACT

Satellite navigation (GNSS) is a worldwide available technology that represents a full range of opportunities. For civil aviation, these systems represent a new era, as they have the potential to provide an all-weather gate-to-gate guidance within a global coverage, and will allow decommissioning most traditional navigation aids. Their sole performance, however, is not compliant with the requirements for the most demanding civil aviation operations, as GNSS systems particularly fail to grant integrity to the navigation solution they are providing, and therefore they require augmentation.

The Ground-Based Augmentation System (GBAS) intends to help GNSS meet the requirements for Precision Approach operations, this way fulfilling the objective of gate-to-gate navigation. As an additional feature, GBAS systems will also provide a Positioning service that will allow GNSS-supported Departure, Landing and Surface Movements operations.

This dissertation presents the process of operational evaluation of a GBAS system, by simulation of a GBAS ground station at the Lisbon International Airport. This simulation will be performed using PEGASUS, a program developed intentionally for the purpose of augmentation systems operational evaluation. GBAS state-of-the-art is also presented and it is seen that GBAS systems are already being acknowledged as a valid alternative to CAT-I ILS and are expected to be the primary system to support CAT-I Precision Approach operations by 2015.

INTRODUCTION

Satellite navigation is becoming a well-known technology of society in general. Its applications range from transportation systems to agriculture and fisheries, passing by supporting other sciences and offering innumerable benefits to society, not disregarding leisure applications [1]. The first impulse to such technologies was given by the United States’ Global Positioning System (GPS) that is now available to worldwide users. Europe is currently developing its own satellite navigation system, Galileo, to enter a market that is predicted to achieve €400 billion by 2025 [3].

Civil aviation is one of society sectors that will take great advantage from these systems, as satellite navigation has already been envisaged by the International Civil Aviation Organization
Global Navigation Satellite Systems (GNSS) are expected to be introduced in an evolutionary manner with increasing benefits that shall culminate in sole-means operation, as stated in the ICAO Global Air Navigation Plan. As a sole-means navigation system, GNSS must allow aircrafts to meet, for a given operation or flight phase, the performance requirements defined by ICAO for that same operation, which will be expressed in terms of Accuracy, Integrity, Availability and Continuity [8].

Currently active satellite navigation systems, GPS and the Russian GLONASS, however, fail to meet the requirements for sole-means operations. Besides the effect of several error sources that degrade the positioning Accuracy obtained with these systems, they particularly fail to meet the Integrity requirements. Integrity of a system is its ability to provide timely warnings to users when it is providing erroneous information and should not be used for navigation [9]. Although GPS and GLONASS satellites transmit an Integrity message, assuring that their signals are correct, these messages can be more than one hour late, a delay too long for aviation use.

Augmentation Systems help to improve the safety of satellite navigation systems, by aiding them to meet the performance requirements for civil aviation operations, particularly Integrity. These systems are classified in three different categories: Aircraft-Based (ABAS), Satellite-Based (SBAS) and Ground-Based (GBAS). Besides Integrity, SBAS and GBAS systems will also improve their Accuracy and possibly Availability and Continuity [8].

Being different by concept, each augmentation type is also conceived to support different flight phases. ABAS systems are essential for GNSS application in civil aviation, as the decisive system Integrity checker, and must be used during all flight phases and operations. SBAS systems, being capable of providing service over a wide area, are intended to support mostly En-route and Terminal Area operations, and may also be used in Non-Precision and Precision Approaches, down to Category-I (CAT-I) operations [10].

GBAS systems provide local GNSS augmentation and are intended to support all types of Precision Approach, from CAT-I to CAT-III operations. This way, GBAS systems are foreseen as going to play a key role in the consummation of the objective of GNSS functioning as an all-weather gate-to-gate service. GBAS systems will provide two services, a Precision Approach and a Positioning service. The Precision Approach service is intended to provide deviation guidance for Final Approach Segments, while the Positioning service enhances the GNSS positioning Accuracy [5].

In order for GNSS systems to be certified for use in the aviation domain it has to be performed the operational validation of the system. This validation intends to demonstrate that the system is compliant with the requirements defined for the flight phases and operations that it is meant to support [5]. These requirements are defined in the ICAO GNSS Standards and Recommended Practices (SARPs) document [9].

**Research Objectives**

The main research objective of this dissertation was to perform a first evaluation of the performance that would be achieved with a GBAS station installed at the Lisbon International Airport. This assessment was performed by simulating the GBAS ground facility using a set of fixed-based GNSS receivers and the software PEGASUS, developed by the European Organisation for the Safety of Air Navigation (EUROCONTROL).
The research focus in the operational evaluation of the simulated GBAS, which involves establishing the performance of the system that would be experienced by a potential user and verifying the stability of the performance in a certain time period,

Besides the main objective, several other essential research topics are approached in this dissertation:

- Clarifying the role of satellite navigation systems in the future of civil aviation;
- Introducing the Global Navigation Satellite System and its components;
- Presenting the performance requirements for GNSS operations; and
- The relevance of Augmentation Systems in the fulfilment of these requirements;
- Understanding the principle behind the GBAS;
- Gaining experience with GBAS systems and their operation modes; and
- Familiarizing with data analysis software, as PEGASUS, and with the operational evaluation methodologies.

This work was realized in cooperation with the Portuguese Flight Test Workgroup (Grupo de Trabalho de Ensaios em Voo – GTEV) from the Technical University of Lisbon, the Portuguese Air Force (PoAF), the Portuguese Air Traffic Service Provider, NAV Portugal, and EUROCONTROL.

GROUND-BASED AUGMENTATION SYSTEM

Mission

GBAS Systems are mainly intended to support Precision Approach (PA) operations, from CAT-I to CAT-III PAs. The PA service will act by first establishing a Final Approach Segment (FAS), which is the Instrument Approach phase where alignment and descent for landing are accomplished, and by afterwards providing deviation guidance from this FAS, in an ILS look-alike form.

GBAS PA service benefits over ILS will be significant. One of the most noteworthy is the fact that, unlike ILS, which has to be working for every runway end, a sole GBAS station can easily provide multiple approaches not only to all the runways at the airport on which it is installed but also to nearby airports, this way reducing the land requirements at each airport. Furthermore, GBAS will also provide more stable signals in space than ILS as it is a digital transmission and not a beam. ILS signals can be considerably attenuated by adverse weather conditions and even by other aircrafts in the Terminal area, which does not occur with GBAS. Among other GBAS PA benefits it can be noted the possibility of conducting curved or segmented approaches and the capability to change or create approach procedures and touch down points without infrastructure changes.

Besides the PA service, GBAS stations will also provide a Positioning service that will support other Terminal Area operations as Departure, Landing and Surface Movements. This service will provide users with corrections and Integrity data, therefore improving GNSS performance in the surrounding airspace and may also be used to provide guidance in Area Navigation operations. Moreover it is expected that GBAS stations will provide a ranging service, similar to the one from GNSS constellation.

Table 1 summarizes some of the most relevant GBAS characteristics and benefits for both Air Traffic Service Providers (ATSPs) and Airline operators.

In a phased introduction, the first ICAO GNSS SARPs provide guidelines and requirements for GBAS operations to support CAT-I PAs and for the GBAS Positioning service. As so, GBAS CAT-I will firstly constitute an alternative to ILS CAT-I service and is expected to allow the phased decommission of this system. This way, both ATSPs and airline operators will gain experience with the system, while the more stringent CAT-II
and CAT-III requirements are prepared by ICAO [10].

Table 1 – GBAS benefits [6].

<table>
<thead>
<tr>
<th>ATSPs</th>
<th>Airlines</th>
</tr>
</thead>
<tbody>
<tr>
<td>Potentially supports all-type Precision Approaches</td>
<td>Reduced track miles</td>
</tr>
<tr>
<td>Single station provides approaches to multiple runway ends</td>
<td>Schedule reliability</td>
</tr>
<tr>
<td>Highly reliable Positioning service enabling to: — increase airport capacity; — avoid congested airspace; — avoid obstacles; — avoid noise/environmentally sensitive areas</td>
<td>Increased signal stability</td>
</tr>
<tr>
<td>Reduced ground infrastructure</td>
<td>No false lobes/ghosts</td>
</tr>
<tr>
<td>Less maintenance required than ILS</td>
<td>Low visibility takeoff</td>
</tr>
<tr>
<td>Improves Terminal area surveillance</td>
<td>Minimal retraining</td>
</tr>
<tr>
<td>Reduces Flight inspection costs</td>
<td></td>
</tr>
</tbody>
</table>

As referred in the ECAC Navigation Strategy, it is expected that by 2015 GBAS facilities have already widespread replacing ILS as the main provider of CAT-I capability at airports [10].

Architecture of the GBAS System

The overall architecture of the GBAS system is divided in three subsystems, as can be observed in Figure 1.

- Satellite Subsystem
- Ground Subsystem
- Aircraft Subsystem

The Satellite Subsystem is composed by the GNSS ranging sources and produces the ranging signals and navigation messages. These ranging sources include the GPS and GLONASS constellations and SBAS satellites. It should be noted that in case of SBAS satellites, it is only used the ranging function.

Figure 1 – Overall GBAS architecture.

The Ground Subsystem is the central part of GBAS systems. One Ground Subsystem can support unlimited Aircraft Subsystems within its area of coverage. The Ground Subsystem shall monitor all GNSS ranging sources and provide users with:

- Pseudorange Corrections;
- Integrity Information; and
- Final Approach Segment data.

The Ground Subsystem is yet divided into three smaller units and comprises an Integrity Monitoring function, as illustrated in Figure 2.

The Receiving Unit’s role is to collect pseudorange measurements and navigation data from all ranging sources in line-of-sight. This unit is formed by the set of two or more Reference Receivers (RRs) that are fixed-based receivers of which we have a very precise knowledge of its position, clock error deviation and surrounding environment characteristics.

The redundant pseudorange measurements made by the Receiving Unit are afterwards supplied to the Processing Unit. By combining this information with other that it has stored, as the precise location of the Reference Receivers, the Processing Unit computes pseudorange corrections and other GBAS data and arranges it into messages, known as GBAS messages.
Figure 2 – Ground Subsystem organization.

Data broadcast is carried out by the Transmission Unit, using a Very High Frequency (VHF) Data Broadcast (VDB) in the band 108 to 117.975 MHz. The nominal coverage of the GBAS VDB transmission shall be omnidirectional of at least 23 nautical miles (43 Km), but in practice may be extended to provide a larger area for the Positioning service.

The primary functions of the Aircraft Subsystem are to:

- Receive and decode GNSS and GBAS signals;
- Assess system Availability to support the flight operation in progress;
- Determine aircraft position and Integrity; and
- Provide guidance signals and Integrity information.

The Aircraft Subsystem includes the antennas to receive the GNSS and VDB signals and a Multi-Mode Receiver (MMR). The MMR is a new type of receiver that was conceived to cope with the various types of PA that will coexist for a certain period. The MMR will perform all the required calculations and procedures and supplies the output information to the Flight Control System and to the Primary Flight Display.

**GBAS OPERATIONAL EVALUATION IN LISBON**

**Research Considerations**

This research had as basis the execution of static and dynamic data collections in order to evaluate GBAS performance in both these situations, in post-processing. However, several major constraints led to a significant deviation from the original idea, particularly in what concerns the dynamic data collection.

First of all, it has to be noted that, mostly due to the complex and long-lasting process of meeting all the involved parts in the procedure of planning and setting up an experimental station at the Lisbon Airport, at the time of writing the set of RRs that was idealized had not yet been deployed. This fact had a great impact in what concerns daily performance evaluation and, as will be seen further, the system’s static evaluation was performed with a set of data not deliberately collected for this purpose, which will cause the results that will be shown to be unreliable.

As for the dynamic data collection, the initial proposal was to perform it using an instrumented Dassault Falcon 50 from the Portuguese Air Force (PoAF). This aircraft however, was experiencing problems and was unavailable during a long period of time. Although the PoAF fleet incorporates other Falcon 50 aircrafts, no other was used as they were not properly instrumented and the GNSS signal reception was deteriorated. Following these constraints, there were established contacts with a Portuguese Air Transport company, so that it could be used a Dassault Falcon 900, belonging to this company, to perform the dynamic data collections. However, this cooperation experienced some delays and this way the Falcon 900 was also unavailable. After a few months, the PoAF instrumented Falcon 50 returned from maintenance and, although not being yet fully operational, was available to carry the flight tests. As the aircraft was prepared to perform a flight test in the Lisbon area, it was installed a Septentrio PolaRX-2 receiver on-board and it was prepared a set of RRs to collect the reference data. However, only after the flight it was noticed that the Septentrio receiver was not working properly and, as so, there turned out to be no dynamic data collections performed to carry out this evaluation.
For the reasons here presented, this research turned out to be a first study about the GBAS system and how to perform the GBAS Positioning service evaluation using PEGASUS.

Simulation of the GBAS System

The GBAS Ground and Aircraft subsystems were simulated using the EUROCONTROL Prototype EGNOS and GBAS Analysis System Using SAPPHIRE (PEGASUS). PEGASUS is a processing tool which allows analysis of GNSS data collected from different SBAS and GBAS systems using only algorithms contained in the published standards. The tool has been developed in the frame of the EUROCONTROL European Geostationary Navigation Overlay Service (EGNOS) [3] operational validation activity and was enhanced with the GBAS Modular Analysis and Research System (MARS). With this module PEGASUS now supports GBAS data processing needs and activities, particularly assisting ATSPs to obtain operational approval of a GBAS installation [11].

The PEGASUS software is a modular tool and, as so, it is possible to define a sequence of tasks to be processed. The scenarios that were implemented to perform this study were:

- Scenario 1 – GBAS Messages Processing; and
- Scenario 2 – GBAS Messages Application.

As their names indicate, Scenario 1 is used to obtain the GBAS messages from the RRs data and Scenario 2 will be used to apply these messages over the raw data collected by the RoR. These scenarios are based on scenarios 001 and 007 from the GBAS MARS Tutorial [12].

Data Evaluation

The procedure followed in the GBAS navigation solution performance evaluation is different in static and dynamic situations. In static evaluations, PEGASUS allows to calculate the GBAS navigation solution deviation from a chosen point and this functionality is used to assess directly the Navigation System Error (NSE).

In dynamic evaluations, however, other approach to obtain the NSE has to be used. As so, the Trimble Total Control (TTC) Differential GPS (DGPS) software is used. This software allows to correct GNSS positions using DGPS algorithms and will be used to assess the aircraft truth reference trajectory against which will be compared the GBAS navigation solution.

For each case it was developed a Matlab function that allows assessing the GBAS navigation solution RNP parameters, so they can be compared against the appropriate performance requirements presented in Table 2. Integrity and Continuity will be evaluated in terms of events occurrence.

Table 2 – GNSS performance requirements.

<table>
<thead>
<tr>
<th>Operat.</th>
<th>Accuracy (95%)</th>
<th>Alert Limit</th>
<th>Availability</th>
</tr>
</thead>
<tbody>
<tr>
<td>APV-I</td>
<td>220 m</td>
<td>20 m</td>
<td>556 m</td>
</tr>
<tr>
<td>APV-II</td>
<td>16.0 m</td>
<td>8.0 m</td>
<td>40 m</td>
</tr>
<tr>
<td>CAT-I</td>
<td>16.0 m</td>
<td>6.0 m</td>
<td>40 m</td>
</tr>
</tbody>
</table>

Static Evaluation

Due to the constraints referred, this section will only illustrate the procedure for static GBAS performance evaluation and the results here presented can not be seen as representative of the potential performance of a future GBAS station.

For this exemplification two Septentrio receivers were used, a PolaRx-2 and a PolaRx-2E. Following the procedure presented previously, both GBAS messages processing and application
was accomplished recurring to PEGASUS, and Matlab was used to perform the results evaluation. However, this data collection was not performed on purpose for GBAS evaluation purposes and at the time of data collection only two receivers were available, when a minimum of two is required to act as the GBAS Ground Subsystem RRs. As so, the GBAS messages application had to be done over the data collected by one of the RRs, what considerably damages the reliability of the conclusions that may be drawn from this test.

To quantify the errors that affect the GBAS ranging errors, it was chosen an Aircraft Accuracy Designator (AAD) of A and the Ground Accuracy Designator (GAD) is obtained from PEGASUS, which automatically calculates it with basis on the reference receiver observations.

The GBAS navigation solution Accuracy is evaluated by comparing it with the true receiver location. Figure 3 and Figure 4 show the obtained Horizontal and Vertical Position Errors, HPE and VPE, as well as the Horizontal and Vertical Protection Levels, HPL and VPL, and the number of ranging sources used to generate the GBAS navigation solution, NSV, including GPS and EGNOS satellites.

The first conclusion that may be drawn from these figures is that no Integrity events occurred, as the NSE was correctly bounded by the Protection Levels during all the analysis time. It is also noticeable that both HPE and VPE were well below 2 meters for most of the evaluation time, with a 95th percentile of 0.54 meters for HPE and of 0.63 meters for VPE. The obtained Protection Levels are also noteworthy with 99th percentiles of 6.63 meters for HPL and 10.13 meters for VPL. It is also observable from the graphics that a very high percentage of CAT-I Availability is experienced, as the VPL only exceeds the VAL during a short period of time and the HPL never exceeds the corresponding HAL.

The static evaluation results are summarized in Table 3. A valid comparison with EGNOS was also looked-for but EGNOS performance in the evaluated time period was rather uncharacteristic, with the HPL and VPL 99th percentiles well above the 100 meters.

Once again, these results cannot be used to conclude about the performance of a real GBAS station.

### Table 3 – GBAS static performance.

<table>
<thead>
<tr>
<th>Accuracy</th>
<th>Integrity</th>
<th>Availability</th>
</tr>
</thead>
<tbody>
<tr>
<td>HPE (95%)</td>
<td>VPE (95%)</td>
<td>HPL (99%)</td>
</tr>
<tr>
<td>0.54 m</td>
<td>0.63 m</td>
<td>6.63 m</td>
</tr>
</tbody>
</table>

### Dynamic Evaluation

As was referred previously, there turned out to be no dynamic data collections for the GBAS
performance evaluation purpose, due to the mentioned constraints. As so, to illustrate the process of GBAS dynamic performance evaluation, it will be used a set of data collected on other flight. The main constraint of this evaluation is that, simultaneously to the in-flight data collection, only one ground receiver was collecting data and, as is already known, GBAS systems must have at least two RRs in order to generate the GBAS corrections. This way, a second RR had to be simulated in order to accomplish the procedure.

The dynamic data was collected during a Vienna (Austria) – Lisbon flight, which took place in July 12, 2007, by a Septentrio PolaRx-2 receiver. The aircraft was the instrumented PoAF Falcon 50 (Figure 5). The static data collection was achieved using a Septentrio PolaRx-2E.

Following the procedure presented previously, GBAS messages processing and application over the aircraft receiver was executed using PEGASUS and the aircraft truth reference trajectory was assessed using TTC. The outputs of both programs were then processed with a Matlab program to obtain the results that will be presented next. It should be noted that during this processing it was just considered the dynamic data collected within the nominal range of a real GBAS station, of approximately 43 Km and it was used an AAD-A.

The GBAS navigation solution Accuracy is evaluated by comparing it with the truth aircraft reference trajectory. Figure 6 and Figure 7 illustrate the obtained NSE and Protection Levels.

As in the static evaluation no Integrity events occurred. The above figures show that the HPE and VPE were inferior to 2 meters for most of the evaluation time and that the HPL and VPL exhibit an outstanding performance, allowing CAT-I Availability during the whole flight phase within the nominal coverage of the simulated GBAS station, as is shown in Figure 8. It has to be reminded, however, that this evaluation cannot be used to assess the true GBAS capabilities.

Furthermore it can be compared the GBAS navigation solution performance with the ones obtained with EGNOS and stand-alone GPS (Table 4).

The results from Table 4 essentially show that the Availability obtained with GBAS superposes to the one obtained with EGNOS, as there is a full contrast in their apparent ability to support CAT-I operations. However, the results for this poor EGNOS performance led to a more deep analysis.
of the in-flight collected data and it was noticed that several anomalous events were experienced, indicating that the receiver was in a pre-failure status, that would be confirmed in the flight that was supposed to collect the data for the GBAS evaluation.

It started by giving an overview of the whole concept of satellite navigation, and what it is expected to represent in the future of civil aviation, and continued by introducing the currently active and future satellite navigation systems. The Integrity issue was then raised to exemplify GNSS incapability to provide service for safety-of-life operations, as civil aviation, and Augmentation Systems were introduced as a means to grant the required Integrity to GNSS and also to help them meet other performance requirements.

From the three types of existing GNSS augmentation, this work focused in ground-based augmentation. The principle behind GBAS systems was introduced and it was seen how these systems improve the GNSS positioning Accuracy by removing the effect of several error sources affecting pseudorange measurements. Furthermore it was also described how they grant them Integrity by providing high-confidence bounds for the positioning errors.

A more technical description of the architecture and characterization of a GBAS system was also given and a complete demonstration of the GBAS Precision Approach and Positioning services was presented.

Finally, the methodology to be followed in order to perform the operational evaluation of a simulated GBAS station was introduced. Results from the application of this methodology to a virtual GBAS station at the Lisbon International Airport were sought but, due to the mentioned constraints, valid results were not obtained. Even though, some results are shown as a means to exemplify the process of data evaluation.

CONCLUSIONS AND FINAL REMARKS

Summary

This dissertation focused in the use of satellite navigation technologies in civil aviation, particularly applied to Precision Approach operations.

Table 4 – GBAS dynamic performance.

<table>
<thead>
<tr>
<th>RNP Parameters</th>
<th>GBAS</th>
<th>EGNOS</th>
<th>GPS</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Accuracy</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HPE (95%)</td>
<td>1.06 m</td>
<td>1.43 m</td>
<td>3.71 m</td>
</tr>
<tr>
<td>VPE (95%)</td>
<td>1.86 m</td>
<td>1.08 m</td>
<td>1.81 m</td>
</tr>
<tr>
<td><strong>Integrity</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HPL (99%)</td>
<td>4.43 m</td>
<td>27.23 m</td>
<td>–</td>
</tr>
<tr>
<td>VPL (99%)</td>
<td>7.18 m</td>
<td>22.78 m</td>
<td>–</td>
</tr>
<tr>
<td><strong>Availability</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>APV-II</td>
<td>100.0%</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>APV-I</td>
<td>42.3%</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>CAT-I</td>
<td>0.0%</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td><strong>Continuity (Continuity Events)</strong></td>
<td>1</td>
<td>13</td>
<td>–</td>
</tr>
<tr>
<td>APV-II</td>
<td>1</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>APV-I</td>
<td>13</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>CAT-I</td>
<td>0</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>

Figure 8 – GBAS flight trajectory.
major constraints that affected the data collection activities.

However, other research objectives were achieved, being the two most significant the compilation of a document that fully describes Ground-Based Augmentation Systems principle of work, operational capabilities, state-of-the-art, architecture and operations, and the successful elaboration of the procedure for both static and dynamic GBAS performance evaluation that shall be used in the evolution of the Lisbon GBAS activities.

GBAS systems are being tested and implemented all over the world with results showing that GBAS Precision Approach service easily meets the performance requirements for CAT-I operations and it is expected that by 2015 GBAS shall be the primary instrument to support these operations.

The GBAS Positioning service will be an extra advantage of GBAS systems, capable of providing GNSS augmentation for other operations, as Landing, Departure and Surface movements.

Future work

The future work proposals are various. As a lot remained undone within the scope of the research theme, future work proposals are divided between guidelines to be followed in order to accomplish the research objective and the proposals for further investigation.

The proposals to complete the process of evaluation of the GBAS Positioning service performance are:

- To establish the location and deploy a set of Reference Receivers to collect GNSS data and generate GBAS messages corrections in a continuous basis for static performance evaluation; and
- To perform flight tests for dynamic performance evaluation.

Furthermore, future work proposals would be to acquire the required equipment to set up a GBAS ground station and a Multi-Mode Receiver in order to advance to the operational evaluation of the GBAS Precision Approach service.

REFERENCES


