SATELLITE-BASED NAVIGATION ARCHITECTURE STUDY FOR AIRCRAFT CATEGORY III LANDINGS

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Abstract

As a result of the rapid increase in air travel, satellite navigation is playing an increasingly important role in facilitating increase in capacity and efficiency without compromising the safety of aircraft flight operations. ANASTASIA (Airborne New and Advanced Satellite techniques and Technologies in A System Integrated Approach) is a European Commission project within the Sixth Framework Program, with the basic objectives to define and implement future (beyond 2010) communication and navigation avionics based on satellite services. The objectives are to be achieved by exploiting the multi-constellation and multi-frequency architectures in combination with multiple onboard sensors, to provide a worldwide gate-to-gate service.

Studies have shown that stand-alone Global Navigation Satellite Systems (GNSS - GPS and GALILEO) or stand-alone GNSS augmented by Space Based Augmentation Systems (SBAS) cannot satisfy the demanding performance requirements of precision approaches. To satisfy these requirements, Ground Based Augmentation Systems (GBAS) are needed. For Category I approaches the navigation performance requirements are well established and the required ground based architecture is currently in the advanced stages of development. However, in order to be able to satisfy the performance requirements of the most stringent phase of flight (landings under Category III weather conditions), adaptation of this architecture, both in terms of hardware and software, is required.

This paper addresses some of the key technical aspects of the modifications required at the hardware and software levels to enhance the performance of a Category I satellite-based navigation architecture to the anticipated level where Category III landings can be achieved using a satellite-based navigation architecture.

1 Introduction

As a result of the rapid increase in air travel, there is an urgent need to increase the capacity of gate-to-gate travel under all weather conditions [1]. A typical flight consists of eight stages of operation (as shown in Fig. 1), preceded and followed by Airport Surface Movement (ASM), also often referred to as "taxiing".

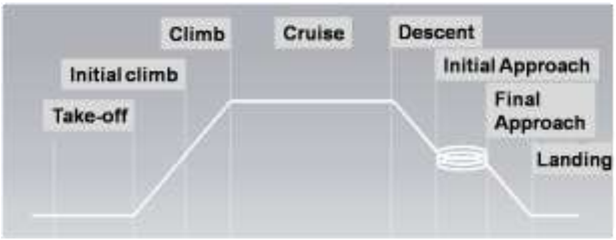

Fig. 1: Phases of flight

In order to be able to perform the final approach and landing phases under adverse weather conditions, aircraft need to carry out the so-called precision approaches, divided into Category I, II and III (often referred to as CAT I, II and III). Whilst there is currently no agreement at this stage between EUROCAE (Europe) and the RTCA (USA) in respect of the CAT III requirements [2], it is clear nonetheless that CAT III approaches and landings have significantly more stringent navigation requirements than CAT I and, together with ASM, are currently the major bottlenecks in the chain of gate-to-gate operation. In this paper, the CAT III requirements developed by EUROCAE [3] will be used as the basis, given that these requirements were derived from existing landing systems that have been validated through many years of operational experience, thereby guaranteeing the safety of the CAT III operations.

Airspace volume can clearly not be increased and airport surface areas are limited. Therefore, in order to increase capacity, minimum separation between aircraft must be decreased (as shown in Fig. 2). In order to maintain (or improve) safety, improved positioning and navigation technologies are thus required. In line with recommendations issued by SESAR [4], the European Air Traffic Management (ATM) modernisation programme, Global Navigation Satellite System (GNSS) is expected to be at the core of novel high-precision positioning and navigation systems.

GPS (as the only mature GNSS) and its augmentations are already in use for the en-route, terminal and initial approach phases of flight. The augmentations enhance GPS performance to support the phases of flight with relatively stringent requirements.

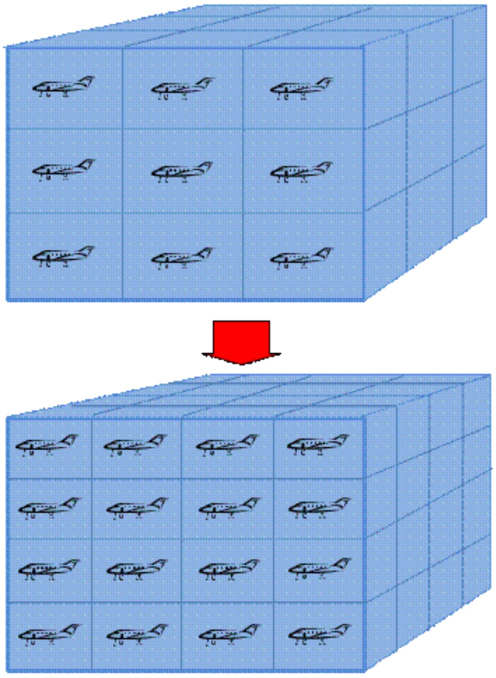

Fig. 2: Airspace Capacity

For CAT I approaches, ground Gased Based Augmentation Systems (GBAS) are currently under development. However, various aspects of the CAT I GBAS architecture limit its usefulness for CAT III approaches. This paper investigates the limitations of the current architecture and proposes one that has the potential to overcome these limitations.

2 Background

2.1 GBAS Principle

The general principle of GBAS is to compute the distance between a reference station on the ground and the GNSS satellites and use that information to compute a correction for the errors in that signal, at a time interval depending on the characteristics of the errors. The corrections for the relevant satellites are then sent to the receiver on the aircraft which uses them to improve its own measurements (see Fig. 3).

One of the crucial assumptions made in using such a system is that the errors between the satellites and the GBAS Ground System are sufficiently correlated with the errors between the satellites and the GBAS airborne system (i.e. the aircraft). A number of factors can potentially cause significant decorrelations, requiring thus to make conservative assumptions in order to guarantee system safety. Whilst this approach is sufficient to meet CAT I requirements, these assumptions make such architecture unsuitable for the CAT III phase of the approach, which has significantly more stringent requirements than CAT I.

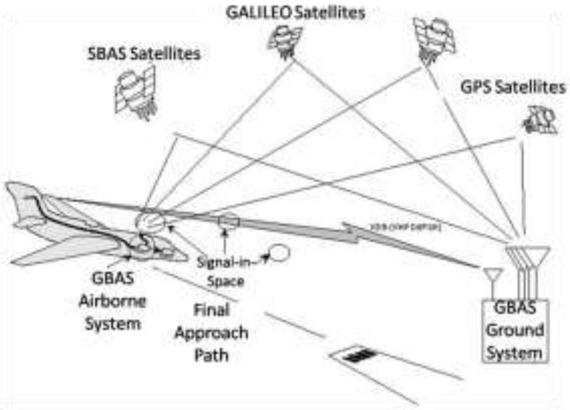

Fig. 3: GBAS Principle

2.2 GBAS Limitations

Various factors contribute to the decorrelation of errors measured at the GBAS Ground System (GGS) and the aircraft. These include residual receiver clock errors, multipath, noise, the troposphere and the ionosphere. In this paper the emphasis is on the ionosphere component, which is potentially a very serious threat to CAT III landings.

It is well known that although generally accepted to exhibit a high level spatial correlation during benign solar activities, the ionosphere can be highly variable as a result of high solar activity, leading notably to localised ionosphere fronts. The extent to which signals from satellites passing through the ionosphere are affected depends upon the location at which they pass through the ionosphere. Current assumptions are that the rate of decorrelation equivalent to 0.4 m (range error) per kilometer between the GGS and the aircraft can occur [5]. With a typical anticipated distance of 5 km between the GGS and the aircraft, this leads to a potential range error of about 2 m. This is larger than the requirements for CAT III landings developed in Europe even without considering the effect of geometry [2]. Therefore, it is necessary to mitigate the risk posed by the effects of the ionosphere.

3 Novel GBAS Architecture

In order to mitigate the limitations above, a dual-frequency architecture could be used to compute the ionosphere contributions at aircraft level and at ground-level separately. However, the use of carrier-phase smoothed dual-frequency code-measurements to directly estimate the ionosphere delays has been shown to be inadequate due to the relatively large noise and multipath on the code-observables. This leads to various undetectable scenarios, requiring conservative assumptions about potential decorrelations to be made, and results in a GBAS performance that is not sufficient to meet the EUROCAE CAT III requirements and is also not expected to be sufficient to meet the RTCA CAT III requirements.

3.1 Operational Architecture - Considerations

In order to minimise the noise and multipath, an option is to use the carrier-phase observables only in the determination of the ionosphere-induced delays. The difficulty of this approach lies in the reliability of extracting and validating the number of integer wavelengths (also referred to as the integer ambiguity) between the satellites and the aircraft or GBAS Ground Station (GGS) receivers, as well as the robust detection and repair of cycle slips.

In static-mode however, dual-frequency carrier-phase measurements are expected to be able to very accurately and reliably extract the ionosphere delays. To mitigate the risks by the ionosphere, an option is therefore to introduce a ground-based monitor (or network of ground-based monitors) in the vicinity of the airport to derive accurate ionosphere delays and measurement residuals. If placed strategically, these monitors also allow to reduce the effective "decorrelation" distance between the aircraft and the GGS (i.e. the tolerable distance between the aircraft and the GGS increases due to relatively local errors being accounted for). Various factors need to be taken into consideration in the development of such a monitoring architecture, which we have called Extended-GBAS (or E-GBAS), in order to be able to meet the requirements of CAT III approaches:

- Performance constraints
- Operational constraints and
- Financial constraints.

Performance constraints: the architecture must be designed such as to meet the CAT III performance requirements. The performance of GBAS is essentially determined by the uncertainties of the differentially corrected range measurements at aircraft level. These uncertainties are a function of the measurements used as well as the level of error correlation between the GGS and the aircraft (which varies with distance). The emphasis in this paper is on the detection of ionosphere-induced errors as a result of ionosphere fronts. Since the proposed architecture is ground-based only, to minimise integrity risks and maximise availability, the effective distance between the aircraft and the nearest monitor (or nearest baseline joining two monitors) should be minimised. Simultaneously, to maximise the monitor sensitivity, the GGS-to-GM (Ground Monitor) distances should be maximised. The distances should be chosen such that ionosphere fronts cannot 'slip in between' two GMs. Last but not least, in order to guarantee that the GGS cannot be affected by the ionosphere without at least one monitor being affected, the monitors should 'cover' the GGS.

Operational constraints: it is important to place the monitors such that multipath and masking by other aircraft and buildings is minimised. This implies that monitors need to be placed sufficiently far from taxiways and terminal areas as well as approach paths.

Financial considerations: amongst others, the overall monitoring infrastructure should be limited to the minimum possible.

The optimal architecture is a trade-off of these various constraints. From a performance perspective, the minimum number of monitors required is two (such that the two GMs and the GGS form a straight line) in order to ensure that the GGS cannot be affected by the ionosphere without at least one GM being affected.

However, such configuration may still suffer from significant decorrelations as a result of the relatively large distances between the aircraft on the CAT III approach and the closest point on the monitor baseline. Therefore, an improved architecture would consist of three GMs (see Fig. 4). From a performance perspective, placing the monitors such that the baselines pass through all the points with the most stringent requirements would be optimal. However, cost and logistics will have to be carefully traded with performance requirements expected from such architecture. The ultimate choice of the GM geometry layout will have to be determined for each airport physical layout individually.

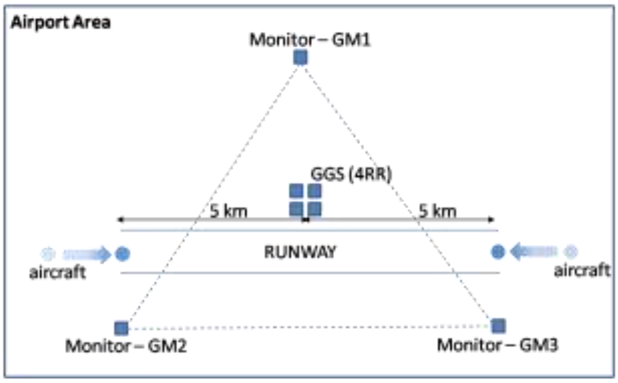

Fig. 4: E-GBAS – Physical Layout (Sample)

The next section describes the functional architecture associated with the proposed physical architecture.

3.2 Functional Architecture

The E-GBAS architecture fulfills two functions (summarised in Fig. 5): firstly, it allows the accurate computation of the ionosphere delays at the GGS as well as at the GMs. Using this information, improved differential corrections are sent to the aircraft. This reduces the need for overly conservative decorrelation assumptions and increases overall system availability. Secondly, the E-GBAS architecture allows an additional increase in system availability for the following reasons: currently a selection of monitors at the GGS determines the existence of a failure by comparing the test statistics to pre-defined thresholds. If any of these monitors determines the existence of a failure, the system becomes unavailable. Yet, it is entirely possible to have a scenario where one of the errors slightly exceeds its threshold and all others are significantly below their threshold. The E-GBAS architecture provides a means to compute the overall measurement error between all potential sources of failure and thereby eliminates the aforementioned limitations.

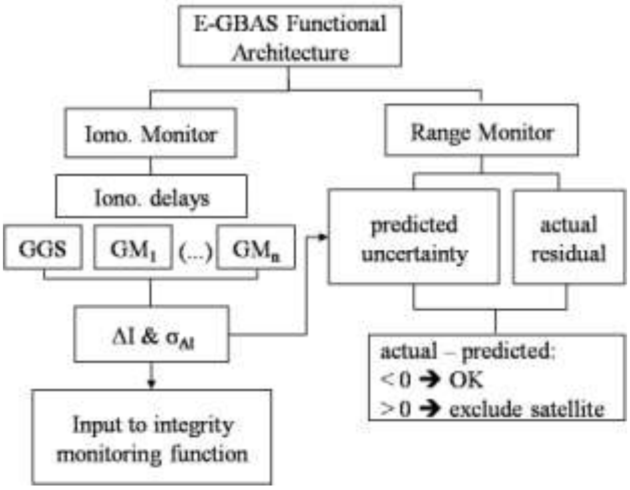

Fig. 5: E-GBAS – Functional Architecture

The ionosphere monitoring algorithm computes the ionosphere delays at the GGS and the GMs using dual-frequency carrier-phase measurements:

$$\tilde{I}(t) = \frac{\phi_2(t) - \phi_1(t)}{\alpha}$$

$$= I^i_{1,j}(t) + \frac{\tau^i_{21}(t) + IFB_{21,j}(t) + \Delta\nu^i_{21,j}(t) + \Delta N^i_{21,j}(t)}{\alpha}$$

where

α = $1 - f_1^2 / f_2^2$

ϕ = carrier-phase observables

$I^i_{1,j}$ = ionosphere-advance of L1 carrier

τ^i_{21} = hardware group delay between L1&L2

$IFB_{21,j}$ = interfrequency bias between L1&L2

$\Delta\nu^i_{21,j}$ = difference in carrier-phase noise and multipath

$\Delta N^i_{21,j}$ = difference in carrier-phase ambiguity

Since the difference in ionosphere delays between the GGS and the GMs is of interest, the satellite hardware group delay τ_{21} disappears:

$$\Delta_{GM_n-GGS}\tilde{I}(t) = \tilde{I}_{GM_n}(t) - \tilde{I}_{GGS}(t)$$

$$= \Delta_{GM_n-GGS} I^i_{1,j}(t) + \frac{1}{\alpha}\begin{pmatrix} \Delta_{GM_n-GGS} IFB_{21,j}(t) \\ + \nabla_{GM_n GGS}\Delta\nu^i_{21,j}(t) \\ + \nabla_{GM_n-GGS}\Delta N^i_{21,j}(t) \end{pmatrix}$$

Given that both the GGS and the GMs are stationary, reliable ambiguity resolution and cycle slip detection is straightforward. The uncertainty in the estimation of the difference in ionosphere delay between the GGS and the GM's is given by:

$$\sigma^2_{\Delta I} = \sigma^2_{\Delta IFB} + \sigma^2_{\nabla\Delta\nu}$$

The uncertainties associated with the Inter-Frequency Bias (IFB) are of the order of a few millimeters for carrier-phase L1 and L2 [6] and can therefore be neglected. The uncertainty in the difference in ionosphere-delay estimations is thus essentially determined by the carrier-phase noise and multipath. Both of these are significantly smaller than the noise and multipath associated with the smoothed code observations used in current state-of-the-art monitoring systems, and thus allows a significant improvement in the ionosphere estimation.

The expected ionosphere bias between the GGS and the aircraft as well as the remaining uncertainties can be extrapolated from the individual ionosphere delay measurements at the GMs and the GGS. The bias is corrected for in the positioning algorithm, and the uncertainty used in the computation of the solution integrity. A more conservative method would be to use the maximum gradient within the coverage area to compute the maximum bias in ionosphere delay between the GGS and the aircraft in the computation of the solution integrity.

In addition to the monitoring of the ionosphere, the E-GBAS architecture can be used as an additional safeguard, with the potential to increase service availability for those cases in which a given failure is detected and exceeds its maximum tolerable limit whilst the overall error is below the maximum tolerable limit (as a result of the other errors being below their maximum limits). Each GM compares the true range to the satellite (from the known GM location) with the computed range using the GGS information, to compute the actual residual error. This is compared to the estimated residual error, computed based upon the measurement noise, multipath, as well as the ionosphere and troposphere uncertainties. Provided that the measured residual error is smaller than the estimated residual error, the satellite is considered healthy. Otherwise, the satellite is excluded.

An initial performance analysis suggests that the E-GBAS architecture used in combination with the European Galileo satellite system has the potential to meet the CAT III precision approach requirements. However, further experiments (as described in the next section) are required to confirm these results.

4 Performance Assessment

In order to test the E-GBAS architecture in environments representative of the CAT III approach scenario, advanced simulations and real flight trials are in the process of being carried out. This section provides a brief overview of the methodology used to characterise the architecture performance.

Simulations are carried out using a SPIRENT hardware simulator, analysing precision approach specificities, with special emphasis on the operational environment (multipath), slow ramp errors and potential decorrelations between reference station and aircraft as a result of ionosphere induced anomalies.

In addition to the simulations, a set of 10 CAT III approaches will be carried out at Braunschweig airport, using a test aircraft (see Fig. 6) provided by the Technical University in Braunschweig (TUBS). The test aircraft is equipped with a dual-frequency GPS L1/L2 receiver and recording devices to record both code and carrier-phase measurements.

Fig. 6: Test Aircraft (TUBS) [Picture by Christophe Ramos]

A set of four GPS L1/L2 reference receivers, with baselines from the aircraft to the reference varying between 400 m and 5000 m at the aircraft CAT III decision height, is used on the ground (see Fig. 7).

Navigation algorithms developed at Imperial College London process these data in post-processing mode and produce position and integrity solutions. In order to characterise the algorithm performance, these solutions must be compared to the true position of the aircraft for each time-point. A reference system is thus required. This reference system must be more accurate than the expected performance of the algorithms (at the sub-metre level). A laser tracker was chosen as a suitable candidate. By comparing the position solutions obtained with the navigation software with the reference position (representing the "truth"), an accurate performance characterisation of the navigation software can be achieved.

The results of these analyses will be published in [7].

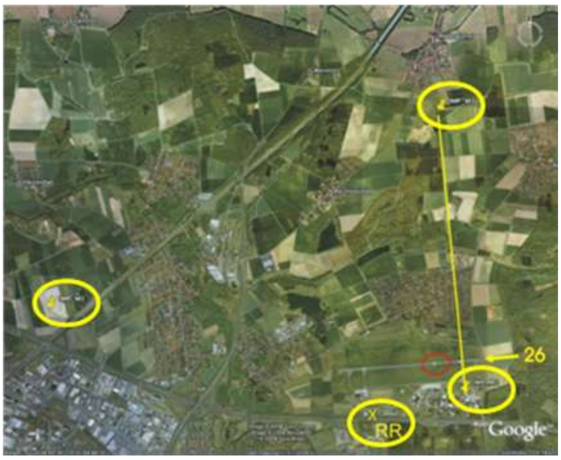

Fig. 7: E-GBAS layout at Braunschweig Airport [Source - Google Earth]

5 Conclusion

As a result of the rapid increase in air travel, airspace capacity limits have been reached, with precision approach and surface movement being major bottlenecks in the chain of gate-to-gate aircraft operations under adverse weather conditions. Therefore, there is an urgent need to develop novel technologies for gate-to-gate aircraft positioning and navigation. These technologies are expected to be based upon the Global Navigation Satellite System (GNSS), and enhancements to current augmentation architectures are required to address current system deficiencies. This paper proposes a novel E-GBAS architecture which has the potential to meet CAT III performance requirements. A detailed performance characterisation study is currently in progress to validate the initial findings.

Acknowledgement

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