Application of Satellite Based Augmentation Systems to Altitude Separation

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This paper presents the application of GNSS1, or more precisely of Satellite Based Augmentation Systems (SBAS), to vertical separation for en-route, approach and landing operations. Potential improvements in terms of operational benefit and of safety are described for two main applications. First, vertical separation between en-route aircraft, which requires a system available across wide areas. SBAS (EGNOS, WAAS, and MSAS) are very well suited for this purpose before GNSS2 becomes available. And secondly, vertical separation from the ground during approach and landing, for which preliminary design principles of instrument approach procedures and safety issues are presented. Approach and landing phases are the subject of discussions within ICAO GNSS-P. En-route phases have been listed as GNSS-P future work and by RTCA for development of new equipments.

1. BACKGROUND. The main objective of the Navigation and Surveillance functions of Air Traffic Management is to prevent collisions by providing: safe separation between aircraft (corresponding failure is called air-to-air collision); and safe separation from the ground (corresponding failure is called ground collision, but is also known as Controlled Flight Into Terrain (CFIT) because the aircraft is controlled but navigation or interpretation errors result in a crash). Satellite Based Augmentation Systems, EGNOS, WAAS, MSAS, and possibly GNSS-2 (GPS Block IIF and Galileo) a decade later, will be capable of providing excellent performance across very wide areas. In particular, the vertical accuracy and high level of integrity they provide will enable new applications for en-route altitude separation and precision approaches throughout their coverage areas.

2. EN-ROUTE SEPARATION BETWEEN AIRCRAFT.

2.1. *Altitude Separation*. Current regulations require altitude separation between aircraft of 1000 ft up to FL290 (29000 ft) and 2000 ft above FL290 except, as explained later, for some aircraft in areas where a Reduced Vertical Separation Minimum (RVSM) has been introduced. The barometric altitude system currently used for vertical separation has reduced accuracy at higher altitudes, where safe separation requires greater margins. For example, at FL 300/30000 ft, 1 hPa error corresponds to 100 ft, while at sea level, it equates to only 30 ft. The aircraft barometric system is also used by secondary radar transponders, and the recently introduced Automatic Dependent Surveillance (ADS) systems, to report altitude to Air Traffic Control (ATC). Therefore, the same altitude errors affect both navigation and surveillance functions. For performance reasons, Flight Levels between 300 and 400 are in the most demand. For modern jet airliners, lower Flight Levels are less fuel efficient and higher levels (over FL400) are beyond the performance and certification

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envelope of most civilian aircraft except Concorde. The operational consequence of the 2000 ft spacing is that fewer Flight Levels are available, which increases bottlenecks in airways. Attempts to make better use of these Flight Levels has led to the new airworthiness directive JAR-OPS 1·872, and the associated operational and ATC aspects. The intention is to improve barometric systems, and the associated autopilot functions, so that altitudes are flown more accurately, thus permitting Reduced Vertical Separation Minimum (RVSM) of 1000 ft above FL 290. Airbus, Boeing and others have introduced the improved standard for new aircraft, but it is costly and in some cases uneconomic to retrofit older aircraft. Therefore, only a minority of aircraft are likely to satisfy RVSM criteria for some years to come. However, airway congestion will only be relieved if the majority of aircraft are compliant with the new requirements.

There are also serious concerns about barometric system integrity, which can be affected by many events such as aircraft maintenance, icing, and altimeter setting errors. Civil Aviation authorities are about to set up 'Height Monitoring Units' using radar data to check aircraft systems and pilots' compliance with the new rules. These local systems are very limited in coverage, and there is some consideration of using GPS to check altitudes. But it is clear that GPS, in its current form, cannot meet either the accuracy or integrity requirements. For example, two aircraft in close proximity could have an error difference of 300 m in GPS altitude using receivers without augmentation; this is clearly not acceptable. SBAS (EGNOS – WAAS) can provide the required accuracy (7–10 m vertical) to permit continuous altitude monitoring everywhere in their respective coverage areas. Between adjacent SBAS areas (e.g. in the Atlantic Ocean between WAAS and EGNOS), performance will be dependent on interoperability agreements, but will be much better than non-augmented GPS. GNSS2 will be designed to provide the worldwide accuracy required.

2.2. *Horizontal Situation Surveillance*. It is important to mention that SBAS will improve lateral separation control in airways through the availability of more accurate position information. Horizontal situation/separation is well measured in areas where good radar surveillance is available, but poor in the others; many secondary radars are less accurate than 1nm. SBAS will also bring significant improvement to future (Enhanced) TCAS (Traffic Collision Avoidance Systems) by providing GNSS 3D position for transmission to other aircraft.

2.3. *Possible Implementation*. Pilots could continue to fly barometric levels. Changing this fundamental practice requires a significant transition period for updating on-board equipment of all aircraft and revising ATC procedures. However, SBAS (EGNOS) data would be used by individual aircraft:

(i) To enable more accurate horizontal navigation.
(ii) For transmitting GNSS 3D information to ATC, it should be very easy to add this information to the Automatic Dependent Surveillance (ADS) message.
(iii) To broadcast GNSS 3D position data to all aircraft in the vicinity.
(iv) For pilots to cross-check barometric data against GNSS altitude using atmospheric corrections provided by ATC.

Air Traffic Control centres, or aircraft, receiving these GNSS 3D messages can use them to implement surveillance functions such as:

(i) *Vertical Separation Surveillance Function* (VSSF). ATC computers can verify that the 'delta altitude' between converging aircraft provides a safe separation, then display this 'delta altitude' to controllers and raise alarms in due time. Once implemented, this function would provide ATC with continuous and accurate surveillance of aircraft altitude separation.

(ii) *Height Monitoring Function* (HMF). ATC computers can perform additional analysis of ADS data to detect aircraft presenting altitude anomalies by cross verifying between barometric altitude and GNSS altitude. EGNOS, WAAS or MTSAT are capable of providing the necessary monitoring accuracy in their coverage areas.

(iii) *ADS Broadcast and ETCAS*. Aircraft receiving the ADS Broadcast can use it for an Enhanced Traffic Collision Avoidance System and so benefit from much more accurate and reliable position data. This is a step forward for free flight.

3. SEPARATION FROM THE GROUND.

3.1. *Terminal Area Operations*. As for en-route surveillance, controlling separation between aircraft is also a major issue in Terminal Areas (TMA). Density of traffic and interaction of complex departure and arrival trajectories and, for smaller airfields, insufficient radar availability can make the situation critical. To add to this problem, many runways have no precision approach (no vertical guidance). 150 accidents in the past 10 years have been identified as CFIT, where the aircrew had not lost control of the aircraft but had made navigation errors. These include several types of altitude errors for which SBAS can provide an independent altitude reference for use by both aircrew and ATC. Barometric altitude errors include: altimeter setting errors; aircraft system errors; local atmospheric differences from Standard Atmosphere (these differences are normally taken care of, but errors occur in establishing the corrections); misreading of approach plates with altitude confusion; and other technical errors along the flight path. In many cases, a timely warning provided by ATC and/or provided by reliable on-board systems could have prevented the crash. Forty percent of CFIT accidents occur during Non-Precision Approaches (NPA) with no vertical guidance. Replacing all NPA by SBAS approaches would further contribute to reducing the CFIT accident rate. The SBAS contribution to enhancing safety in TMAs has three components:

(i) Improving Enhanced Ground Proximity Warning Systems and making them cheaper.
(ii) Improving TMA operations by using GNSS 3D data in the ADS message.
(iii) Replacing all Non-Precision Approaches by Approaches with vertical guidance.

3.1.1. *Enhanced Ground Collision Avoidance System*. Existing Ground Proximity Warning Systems (GPWS) are based on radar altitude measurements and have been discredited by unacceptable false alarm rates. In many accidents, aircrew have simply disregarded true alarms due to this loss of credibility. In others, a warning was raised too late and/or did not provide the pilot with situation awareness information or possible escape trajectories. A new generation of Enhanced GPWS (EGPWS) have been developed and are beginning to equip many airliners. The new systems provide earlier warning, situation awareness and reduced false alarm rates. They use Terrain Reference Models and require accurate horizontal positioning usually provided by Flight Management Systems (FMS) fed by multiple Inertial Reference Systems (IRS), which are very expensive. At present, only 20–25% of aircraft have these complex positioning systems. SBAS will provide a better and much cheaper 3D position

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without the need for IRS and can therefore provide a cheap improvement to EGPWS. This would be a major safety improvement for all types of aircraft.

3.1.2. *TMA Operations*. In TMAs without radar (many approach control centres are not equipped), ATC cannot monitor altitudes and therefore cannot detect navigation errors or provide warnings to pilots when obstacle clearance or vertical separation between aircraft is insufficient and becoming dangerous. In TMAs with secondary radar, altitude reporting relies on the aircraft's barometric system. In both cases, transmission to ATC of GNSS 3D position data would allow ATC to monitor the clearance between individual aircraft and the ground/obstacles and the separation between adjacent aircraft. These processes could be automated by using a computer in which terrain reference models, obstacle data and associated minimum descent altitudes are stored for the local area. The stored data would, of course, need to be referenced to the GNSS datum – WGS84. Such a system would not suffer from the continual variations associated with barometric pressure.

3.1.3. *Instrument Approach Procedures*. SBAS (EGNOS) is capable of replacing all non-precision approaches (VOR, VOR/DME, ADF) – which, as mentioned earlier, are major contributors to CFIT – by Category 1 Precision Approaches (CAT1), or by NPV (Non Precision approach with Vertical guidance). NPV-I and NPV-II have recently been introduced by the ICAO GNSS-P to support operations by providing vertical guidance where availability of CAT1 performances is reduced. This is the case outside SBAS coverage areas, where various levels of degradation are expected. NPV-II, in terms of achievable minima, is very close to CAT1 but doesn't require the costly CAT-1 runway lighting system; it is therefore very attractive even within the SBAS coverage area. However, when used for approach and landing, a GNSS presents specific features which are very different from ILS, such as linear sensitivity (instead of angular), very stable guidance (no scalloping effect) etc. These features must be considered when designing approach procedures; a specific methodology is needed to ensure the highest level of safety.

3.1.3.1. *Creating a SBAS CAT1 Procedure*. A new concept has been presented by the ESA to the ICAO GNSS-P for replacing 'ILS look-alike considerations'. It is based on a common-sense concept that safe instrument approach and landing requires TWO fundamental conditions: obstacle clearance, and accurate positioning of the aircraft at decision height for easy and safe visual landing. It solves the ambiguity between non-precision and precision approach design methods. To be more explicit, a non-precision approach (NPA) such as LOC/DME is permitting a Decision Height (DH) of 250 ft; if ILS procedure design rules were applied to SBAS, the DH would be much higher. This ambiguity has led to various incorrect statements about SBAS CAT1 performance.

The methodology proposed by the ESA is to establish a GNSS protection surface based on all GNSS characteristics (error spectrum, linear accuracy, integrity, and continuity of service) and to introduce GNSS failure modes effects. By generating in simulations and flight tests an accumulation of low probability events, evaluation of aircraft position at the required confidence level of 10^{-7} (5σ) can be used to establish a protection surface. It is an end-to-end process starting with possible degradations to the navigation system (adverse conditions, failures…), simulation of the subsequent effect on the navigation function, establishing navigation system errors spectrum and evaluation of pilot and aircraft reactions. The process is very similar to modern engineering and certification methods applied to aircraft and to all 'High

Reliability Systems' (such as Nuclear Energy). It is called Risk Assessment and Validation Model (RAVAM). The FAA are presently conducting tests accordingly.

The method differs from ILS Collision Risk Model (CRM), which was based on experimental results (3000 approaches). The ESA considers that we cannot afford to wait for years of experimental results and believe that it is the only sensible way to demonstrate the confidence level of a new 'High Reliability System'. Corresponding flight simulations will be run for existing approaches and also for various types of other instrument approaches. Segmented approaches, and indirect approaches adapted to various airfield environments not possible with ILS, will be tested.

4. CONCLUSIONS. SBAS, and later (possibly by 2010) GNSS2, will bring tremendous advantages for airborne navigation and surveillance.

4.1. *For En-Route Traffic*. Using reasonably cheap aircraft equipment, SBAS will enable the introduction of ATC capabilities such as Vertical Separation Surveillance Function (VSSF), and Height Monitoring Function (HMF), which will allow reduced vertical separation and so double airways capacity above FL 290 with continuous safety monitoring. These services could be made available for all controlled airspace in ECAC (EGNOS) and CONUS (WAAS) areas using VHF ADS in the continental areas or SAT/COM ADS in oceanic or desert regions.

4.2. *For Terminal Areas*. In TMAs with or without radar, the use of SBAS associated with ADS would provide improved aircraft spacing and safety warnings. ATC would be able to monitor aircraft vertical separation and raise an alarm whenever an aircraft is deviating from a safe altitude.

SBAS would also provide better and cheaper 3D position for use in Enhanced TCAS and Enhanced Ground Proximity Warning Systems (EGPWS) for all types of aircraft.

4.3. *For Precision Approaches*. SBAS will enable Cat 1 precision approaches to be introduced at all airfields in the coverage areas, and Non Precision approaches with Vertical guidance outside coverage, so bringing significant operational and safety benefits by reducing CFIT. Design and safety rules presented here have been defined for preparing implementation.

4.4. *For All Applications*. The SBAS service (en-route and TMA) will be available everywhere within GNSS-1 coverage (ECAC area for EGNOS) without additional costs. Levels of service between two adjacent SBAS (e.g. the Atlantic area) can also provide significant improvements over non-augmented GPS, but this depends on agreements between the national authorities operating the SBAS.

KEY WORDS

1. GNSS. 2. Air Traffic Control. 3. Safety.