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ELEVENTH AIR NAVIGATION CONFERENCE

Montreal, 22 September to 3 October 2003

(DRAFT) REPORT OF COMMITTEE B ON AGENDA ITEM 6

The attached draft which constitutes a part of the report on Agenda Item 6 (sub-item 6.2) is presented for approval by Committee B for submission to the Plenary.

(20 pages)

Agenda Item 6 : Aeronautical navigation issues

6.2 NAVIGATION POLICY ISSUES IN THE LIGHT OF PRESENT AND ENVISAGED GNSS SERVICES AND ARCHITECTURES, INTEGRATION AND BACK-UP OPTIONS

6.2.1 Introduction

6.2.1.1 The current ICAO strategy for the introduction of communications, navigation, and surveillance/air traffic management (CNS/ATM) systems envisages a gradual transition from the current terrestrial navigation infrastructure to the increased use of a satellite navigation infrastructure. The initial step of this transition has been supported by the development of ICAO Standards and Recommended Practices (SARPs) for the global navigation satellite system (GNSS) and publication of procedures and criteria for operations using Basic GNSS receiver.[1]

6.2.1.2 GPS is already being used onboard many aircraft, in particular, in Europe, as a means of compliance with basic area navigation (RNAV) requirements. SBAS is coming on-line with the commissioning of the United States' Wide Area Augmentation System (WAAS) and the introduction into operation after SBASs in Europe, Japan and India in the 2004 - 2006 time frame. GBAS developments are progressing, initially to support Category I precision approach.

6.2.2 The role of GNSS in provision of aeronautical navigation services and transition strategy considerations

6.2.2.1 The meeting received information on developments in States indicating an increasing role satellite navigation was playing in provision of air navigation services. One State presented its plans for phasing out some existing terrestrial facilities, beginning with the decommissioning of non-directional radio beacons (NDPs) as the equipage of commercial fleets and general aviation progresses. Several other States also indicated their planning for gradual decommissioning of terrestrial navaids as the reliance on satellite navigation increases.

6.2.2.2 The meeting was also informed of a common aviation position in the European region which was being developed with the participation of airspace users and air navigation service providers. The ultimate goal envisaged was a sole navigation service to be achieved with GNSS provided that this service would be proven to be safe, secure and the most cost beneficial solution.

6.2.2.3 This information was supplemented by the airline position on aeronautical navigation needs which supported GNSS as the primary radio navigation system for positioning and timing in the near future. The airspace users urged States, in close collaboration with airspace users, to move rapidly from the current

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[1] The term "Basic GNSS receiver" designates GNSS avionics that at least meet requirements for a GPS receiver in Annex 10, Volume I, and specifications of RTCA DO-208 or EUROCAE ED-72A, as amended by FAA TSO-C129A or JAA TSO C129 (or equivalent).

ground-based system to a cost-effective, harmonized and interoperable space-based radio navigation system capable of being used in all airspace during all phases of flight. Airlines position also encouraged implementation of GNSS procedures, in a coordinated manner, with a view to achieving as soon as possible worldwide navigation capability from en-route down to at least Category I minima.

6.2.2.4 Based on the general consensus to expedite transition to satellite navigation the meeting discussed a proposal for the development of a strategy that sets the basis for transition to a future worldwide navigation service centred around the use of GNSS. It was recognized however that the *Global Air Navigation Plan for CNS/ATM Systems* (Doc 9750) and the Regional Air Navigation Plans represent strategic documents that meet the intent of such a proposal. The meeting however agreed to reconfirm the transition objectives and established a set of conditions to be met in the course of transition.

6.2.2.5 The meeting addressed near-term objectives in the transition process. It was noted from information presented on the status of GNSS development that one satellite-based augmentation system, namely the United States WAAS became operational in mid-2003, and three other SBASs were planned to become operational in the 2004 - 2006 time frame. The meeting reviewed information presented on the planned implementation of approaches with vertical guidance (APV) in one State. The programme in this State envisaged the deployment of such approaches in phases. The work being carried out with a view to complementing conventional approach and landing aids, in particular the instrument landing system (ILS), would involve:

a) approval of non-precision approaches based on the use of ABAS;

b) evaluation of the use of APV procedures with barometric vertical guidance; and

c) lastly, the operational benefits provided through the use of APV approach and landing procedures with SBAS vertical guidance for all airspace users.

6.2.2.6 In addition, several States reported on significant activities in the Caribbean, South American and African Regions to evaluate SBAS performance using WAAS and EGNOS test bed. Support to these trials rendered by service providers and preliminary results were appreciated, and the meeting agreed that these activities should be promoted

6.2.2.7 Based on the above, a proposal was made that the airspace users should be encouraged to equip with SBAS receivers[2] to take advantage of their superior performance over Basic GNSS receivers and improved service availability. Another proposal was also presented advocating the adoption of SBAS-based APV-1 operations as a global requirement. The intent of the proposals was supported and the meeting agreed to encourage States and service providers, airspace users and the manufacturing industry to work together towards the above goals. The meeting therefore developed the following recommendation:

Recommendation 6/1 — Transition to satellite-based air navigation

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[2] The term "SBAS receiver"designates GNSS avionics that at least meet requirements for a SBAS receiver in Annex 10, Volume I, and specifications of RTCA DO-229C, as amended by FAA TSO-C145A/146A (or equivalent).

That:

a) ICAO continue to develop as necessary provisions which would support seamless GNSS guidance for all phases of flight and facilitate transition to satellite-based sole navigation service with due consideration of safety of flight, technical, operational and economics factors;

b) air navigation service providers move rapidly, in coordination with airspace users, with a view to achieving, as soon as possible, worldwide navigation capability to at least APV performance; and

c) States and airspace users take note of the available and upcoming SBAS navigation services providing for APV operations and take necessary steps towards installation and certification of SBAS capable avionics.

6.2.3 GNSS vulnerabilities and sole navigation service

6.2.3.1 The meeting was presented with a navigation strategy for the area of the ECAC Member States which identified a transition to an area navigation (RNAV) environment supported by global navigation satellite system (GNSS). Consideration of the costs of the transition to such an environment together with the need to ensure failure survival indicated that there would, for the foreseeable future, remain a need for ground-based navigation aids and the consequent requirement to ensure continued spectrum protection for these aids.

6.2.3.2 Having agreed that spectrum availability aspects of the strategy should be addressed, as necessary, under its Agenda Item 5, the meeting discussed the GNSS potential to become the sole navigation service. The discussion focussed on some uncertainties that remain in respect to the GNSS potential to become the sole navigation service due to its potential failure modes, their corresponding impact on the ATM operations of the ECAC Member States, and mitigation possibilities.

6.2.3.3 The meeting was made aware that the Global Positioning System (GPS) without any external augmentation had already been accepted as a means of providing a basic RNAV capability en-route throughout the ECAC area. This has been possible because of the ability to revert to conventional navigation using ground navigation aids such as VOR/NDB. The availability of GALILEO as a second satellite system complementing GPS, both having additional navigation signals, was expected to allow further reliance upon GNSS, thereby enabling VOR/NDB decommissioning and relying upon RNAV based upon GNSS and DME.

6.2.3.4 However, whilst the GPS plus GALILEO might provide the basis upon which a total RNAV environment might be predicated, it had still to be proven that such a solution would be cost effective in the light of the potential need for carrying dual RNAV systems to meet continuity and availability requirements. Since many aircraft were equipped with only single RNAV or flight management system (FMS) equipment, the timescale by which a cost-effective transition to a total RNAV environment could therefore be considerably extended.

6.2.3.5 It was noted that even with dual on-board systems, meeting the requirement for the acceptable risk of total loss of navigation capability might still require two different sensor inputs, e.g. GNSS aided by INS or DME. If this was required, DME coverage would need to be improved with an overall increase in DMEs in the ECAC area over the next 10 - 20 years.

6.2.3.6 Studies in the European Region had suggested that, in the 2010 - 2015 time-scale, it might be more cost-effective to ensure the required level of continuity of service by retaining the current VOR environment to support reversionary navigation using dual VOR avionics installations on the aircraft than it would be with dual RNAV/FMS equipment and dual sensor input. If these initial results were confirmed, the expected decommissioning of VOR in that period might not be possible.

6.2.3.7 Having reviewed this information, the meeting recognized that, although future developments were expected to considerably reduce the risks associated with a sole GNSS service, some failure modes would remain that could prevent a total reliance upon GNSS. It was noted that in the context of operations within the ECAC area, there was work on-going to identify means and associated mitigation strategy by which a gradual move towards sole service might become possible. However, the ability to reach that ultimate objective and the time-scale by which this could be achieved remain uncertain at this point in time.

6.2.3.8 The meeting then reviewed the results of GNSS vulnerability study carried out by the Global Navigation Satellite System Panel (GNSSP) at the request by the Air Navigation Commission. It was observed that studies had been carried out over the recent years by several highly qualified institutions addressing GPS vulnerabilities while the report presented to the meeting attempted to consider same issues in the context of GNSS, GPS being one of the core elements of GNSS. Various vulnerabilities of GNSS, evaluation of operational risks, means of prevention of system outages and guidance on mitigation of such outages were presented and appreciated.

6.2.3.9 The conclusion of the study that, to date, no vulnerabilities had been identified that compromise the ultimate goal of transition to GNSS as a global system for all phases of flight was noted by the meeting, with the understanding that the assessment of GNSS vulnerability aspects and mitigation alternatives should continue. It was agreed that the study results presented to the meeting could serve as useful guidance for States in assessing the GNSS vulnerability and selecting appropriate mitigations. The meeting therefore developed the following recommendation:

Recommendation 6/2 — Guidelines on mitigation of GNSS vulnerabilities

That States in their planning and introduction of GNSS services:

a) assess the likelihood and effects of GNSS vulnerabilities in their airspace and utilize, as necessary, the mitigation methods as outlined in the guidelines contained in the appendix to the report on Agenda Item 6;

b) provide effective spectrum management and protection of GNSS frequencies to reduce the possibility of unintentional interference;

c) take full advantage of on-board mitigation techniques, particularly inertial navigation;

d) where determined that terrestrial navigation aids need to be retained as part of an evolutionary transition to GNSS, give priority to retention of DME in support of INS/DME or DME/DME RNAV for en-route and terminal operations, and of ILS or MLS in support of precision approach operations at selected runways; and

e) take full advantage of the future contribution of new GNSS signals and constellations in the reduction of GNSS vulnerabilities.

6.2.3.10 It was suggested that the recommended guidelines should be considered for inclusion in the GNSS Manual which, in its draft form, was made available to the meeting for information. The suggestion was noted by the Secretariat.

6.2.3.11 During the review of GNSS vulnerabilities, a number of concerns was raised in regard to the effects of non-planar ionospheric spacial gradients and scintillations in equatorial regions. Several States reported that they had established data collection programmes and proposed that ICAO assess the results of such studies and provide appropriated guidance to States. The meeting encouraged continuation of these efforts and exchange of data between States and regions, noting that such data exchange was already taking place in some international expert groups, e.g. the SBAS Interoperability Working Group (IWG). The meeting therefore developed the following recommendation:

Recommendation 6/3 — Assessment of atmospheric effects on SBAS performance in equatorial regions

That ICAO, in order to aid the work on mitigation of atmospheric effects on SBAS performance, assess the results of data collection being carried out in States and develop appropriated guidance material.

6.2.3.12 The meeting also reviewed a proposal to consider the need for standardization of an automated means to report GNSS outages and determine the effects of an outage on GNSS operations. In this regard, the meeting noted information on the example software posted on the ICAO Web site to demonstrate a prediction tool which can support flight planning and NOTAM generation. Having appreciated this initiative, the meeting was of the opinion that a uniform application of such tools was essential and developed the following recommendation:

Recommendation 6/4 — Automated means for reporting and assessing the effects of outages on GNSS operations

That ICAO consider standardization of an automated means of reporting GNSS outages and assessing their effects on GNSS operations and develop, as necessary, the requisite provisions.

6.2.4 RNP and RNAV issues

6.2.4.1 The meeting was informed of a number of open issues surrounding different definitions and concepts related to required navigation performance (RNP) and area navigation (RNAV). Further concerns were raised that, despite efforts to develop and implement a cost-effective global definition of RNP, it was unlikely that the harmonization of the concept and requirements in this area could be achieved in the near future. The rationale for these concerns included dependance of most RNAV systems upon ground infrastructure which was location dependent, the potential for a variety of required RNAV functionalities associated with the same RNP types in various ATC environments, and avionics versatility driven by cost effectiveness considerations or resulting from evolutionary development of RNAV/FMS systems. The meeting recognized the complexity of the issues involved and shared these concerns.

6.2.4.2 In this regard, one State informed the meeting that it was currently implementing performance-based RNAV procedures and airspace restructuring to take advantage of aircraft navigation capabilities to fly more accurate and predictable flight paths through its airspace. Performance-based RNAV would result in increased levels of navigation accuracy and flight path predictability, leading to improved efficiency and capacity. This State was also implementing required navigation performance (RNP) approach procedures and developing a strategy for the introduction of RNP for other phases of flight. In the context of the above, it also expressed concern about a state of affairs with RNP and RNAV concepts.

6.2.4.3 The meeting was informed that on 10 June 2003, during consideration of the report of the fourth meeting of the Global Navigation Satellite System Panel (GNSSP/4), the Air Navigation Commission had agreed that, as proposed in GNSSP/4 Recommendation 1/1, action should be taken to establish a focal point for the resolution of the issues identified. It had been noted during consideration of this matter that there was an urgent need to address these issues in order to ensure a harmonized approach to the further development of RNP and RNAV. Accordingly, a new air navigation study group named as the Required Navigation Performance Study Group (RNPSG) had been established. Several States and international organizations attending the meeting expressed their commitment to support the work of RNPSG.

6.2.4.4 In supporting the above action, the meeting also noted that air navigation service providers were making investments in their navigation infrastructure as they implement new RNAV and RNP procedures. As these procedures were developed and used, States were modifying separation standards to account for enhanced aircraft navigation capability, and redesigning airspace for best use of these new procedures. The schedule for implementation of new requirements should be coordinated to align with infrastructure investments and to allow operators sufficient time to equip with the needed capabilities. In this connection, the meeting stressed an urgent need for global harmonization of performance-based navigation concepts and requirements and the leading role of ICAO in this harmonization activities. It was suggested that by the end of 2004, a framework should be developed for the resolution of issues identified by GNSSP/4 and other issues relating to the implementation of performance-based navigation operations. By the end of 2005, the operations approval criteria, the obstacle clearance criteria, and the separation criteria for performance-based navigation operations should be defined or updated, as appropriate. Accordingly, the meeting developed the following recommendation:

Recommendation 6/5 — Early resolution of issues arising from implementation of RNAV and RNP operations

That ICAO as a matter of urgency address and progress the issues associated with the introduction of RNP and RNAV operations.

6.2.5 **Advanced GNSS capabilities and new technology alternatives**

6.2.5.1 The meeting was presented with information on the status of initial GNSS implementation in one State. It was stressed that the key motivation for the introduction of satellite navigation services was the ability of new services to solve airspace issues and increase the availability of instrumental flight procedures. Considering the mountainous terrain environment of major airports in this State, a number of distinctive features of GNSS was elaborated as enablers of improvements in terms of accessibility, flexibility in terminal area operations and RNAV coverage. Accordingly, the meeting was presented with a proposal that ICAO needs to focus on updating and development of Standards and procedures providing for realization of GNSS operational and safety benefits including those associated with advanced system capabilities.

6.2.5.2 The meeting was cautioned that the current state of development of ICAO technical Standards was still insufficiently advanced to support those capabilities in the near term. Specifically, the meeting was informed that the development of the relevant GNSS performance requirements for such capabilities currently underway within the Navigation Systems Panel (NSP) was expected to be completed in 2007. Hence, development of the corresponding GNSS SARPs could only be completed after 2007 with procedures and criteria to follow. Concerns were also expressed that some of the additional developments that were proposed might entail substantial indirect costs to the user community. However, the meeting noted that not all the proposed developments were necessarily of a challenging technical nature and that some States were already engaged in studies of proposed capabilities. The meeting therefore developed the following recommendations:

Recommendation 6/6 — Advanced GNSS procedure design

That ICAO develop procedures for both fixed and rotary wing aircraft, enabling GNSS-based RNAV procedures to lower minimas in obstacle rich environments.

Recommendation 6/7 — Curved GBAS RNAV procedures

That ICAO develop GBAS procedures for fixed wing aircraft, providing RNAV procedures with high track and velocity keeping accuracy through curves to enable flexible approach line-ups.

6.2.5.3 In follow-up to the above discussion, the meeting's attention was drawn to the significant inertial capability that existed in the world's aircraft and to benefits that can be derived from integrated GNSS/INS applications. It was recalled that such applications were recognized as a valuable mitigation in meeting deliberations of GNSS vulnerabilities. It was also noted that many aircraft used inertial data to complement performance of ILS in precision approach and landing operations, and, similarly, the integration of GNSS with INS can enhance navigation performance in terms of accuracy, integrity, availability and continuity.

6.2.5.4 The meeting noted, however, that realization of full benefits of GNSS/INS integration was constrained by the lack of standardization of system capabilities and its characteristics, particularly coasting times that constitute an essential factor of risk assessment and mitigation strategies. The meeting, therefore, developed the following recommendation:

Recommendation 6/8 — GNSS/INS integration

That ICAO develop provisions for the integration of GNSS/INS in order to reduce the vulnerability of GNSS to RFI interference and aid the development of advanced GBAS capabilities.

6.2.5.5 The meeting reviewed the feasibility assessment of GNSS-based Category II/III approach and landing and aerodrome surface operations. It was recalled that the current Standards and Recommended Practices (SARPs) for GBAS provide augmentation to the core satellite constellations of GLONASS and GPS and support Category I precision approach. Galileo would be added to the core satellite constellations and its local component would be standardized as an amendment to the GBAS SARPs at a later date. It was also noted that a goal of GBAS development in support of Category II/III operations was to enable the evolution of the basic Category I architecture to Category III minimizing changes to the basic system and ensuring backwards compatibility with existing Category I avionics.

6.2.5.6 The meeting was also made aware of current studies in States in support of Advanced Surface Movement Guidance and Control (A-SMGCS) and the work in the Navigation Systems Panel which was focussing on the application of GNSS as a position sensor for A-SMGCS.

6.2.5.7 The assessment results had indicated that Category II/III capability would be achieved in the 2010-2015 time frame depending on the GBAS architecture and performance requirements. The final outcome of the ongoing development of the performance requirements and standards would also influence the complexity of the future GBAS architecture supporting Category II/III approach and landing operations and when it would be generally available. Expressing concerns over possible complexity of the future GBAS architecture, the meeting however supported a conclusion that the benefits of having a single system which can provide guidance in all phases of flight justified continued work on the resolution of technical and operational issues involved.

6.2.6 **Pre-operational experiences**

6.2.6.1 The meeting received information from a number of States and regional organizations regarding trials being carried out in the Caribbean, South American and African Regions at the regional and national levels to collect data for the definition of the GNSS architectures in these regions. A three-stage GNSS implementation strategy in the AFI Region and the initial results of the EGNOS test bed trials were reported to the meeting. The meeting was also presented with the information on trials involving WAAS and EGNOS test beds in the CAR/SAM States.

6.2.6.2 The lessons learnt and proposals stemming from the experiences gained were reviewed by the meeting. These concerned a broad range of issues, including human resources, regional training capabilities, the need for integration of technical cooperation projects and financing aspects. The meeting was made aware of ICAO activities and groups addressing these issues. The meeting also noted with appreciation the support States involved in the development of WAAS and EGNOS were providing within the framework of the SBAS test bed trials. To encourage the continuation of these activities, the meeting developed the following recommendation:

Recommendation 6/9 — Support and participation in SBAS pre-operational implementation activities

That:

a) States that develop and introduce satellite-based augmentation systems and other SBAS service providers continue to provide their support and participation in the activities leading to the extension of their SBAS service areas into neighbouring States and Regions; and

b) States participating in SBAS implementation activities coordinate with other participating States to optimize their effort and facilitate participation of service providers.

6.2.7 **OTHER RELATED ISSUES**

6.2.7.1 Concerning the issue of legal and institutional aspects of GNSS referred to in working papers 143, 153 and 160, the meeting agreed that neither the scope nor the agenda presented a suitable opportunity for discussions on those topics. Therefore, the meeting, assisted by the President of the Council, Dr. A. Kotaite and the Director of the Legal Bureau, agreed to note the information and views contained in the above referenced papers and agreed that they should be referred to the ICAO Council for consideration and action as deemed appropriate by that ICAO body.

6.2.7.2 Regarding a proposal concerning the need for reliable free GNSS service in working paper 107, the meeting was informed that a study on the allocation of GNSS costs was being undertaken by the Secretariat with the assistance of the Air Navigation Services Economics Panel (ANSEP) and that its completion was expected by the end of 2004. The meeting noted some principles and assumptions endorsed by ANSEP to be applied for cost allocation between civil aviation and other users, in particular that basic GNSS services should be provided free of charge and that any cost allocation of GNSS services should take place at the regional level. The meeting concluded that the need for reliable GNSS service to be provided free of direct users charges should be brought to the attention of ANSEP and considered in its further work.

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APPENDIX

GUIDELINES ON GNSS VULNERABILITY AND MITIGATION METHODS INCLUDING TERRESTRIAL, AIRBORNE AND PROCEDURAL SOLUTIONS

1. INTRODUCTION

1.1 GNSS is being progressively introduced throughout the world and has the potential to meet performance requirements for all phases of flight, obtaining safety and efficiency benefits through the navigation domain. As GNSS operations become prevalent, it is essential that the service providers identify the vulnerabilities of this system and develop the necessary mitigations. This paper identifies the vulnerabilities of GNSS and the corresponding mitigations that can be applied when appropriate. In developing this paper, several other vulnerability studies have been considered and their concerns and recommendations addressed. Most vulnerabilities discussed are common to other navigation systems providing aeronautical radio navigation service, but those systems are outside the scope of this paper.

2. GNSS SIGNAL VULNERABILITIES

2.1 Interference

2.1.1 GNSS core satellite constellations and satellite-based augmentation system (SBAS) signals are vulnerable due to their relatively low received signal power since GNSS signals originate from satellites and each satellite's signal covers a large fraction of the Earth's surface. While the very high frequency (VHF) data broadcast of a ground-based augmentation system (GBAS) is more difficult to interfere (its signal power is similar to that of terrestrial navigation aids), GBAS service depends on the core satellite signals. Interfering signals are limited to line-of-sight propagation. For example, the interference region at 600 m (2 000 ft) above ground level is inherently limited to approximately 110 km (60 NM) for a ground-based interferer.

2.1.2 The GNSS Standards and Recommended Practices (SARPs) require a specified level of performance in the presence of levels of interference as defined by the receiver interference mask. These interference levels are generally consistent with the International Telecommunication Union (ITU) regulations. Interference at levels above the mask may cause loss of service but such interference is not allowed to result in hazardous or misleading information.

2.1.3 *Unintentional interference*. The majority of reported GNSS interference events have been traced to on-board systems, and experience with GNSS installation has identified several sources of unintentional interference (e.g. spurious emissions or harmonics of VHF communications equipment and the out-of-band and spurious emissions from satellite communications equipment). Portable electronic devices can also cause interference to GNSS and other navigation systems.

2.1.3.1 Ground-based sources of interference currently include mobile and fixed VHF communications, point-to-point radio links operating in the GNSS frequency band, harmonics of television stations, certain radar systems, mobile satellite communication systems and military systems. The likelihood of such interference depends on State spectrum regulation, frequency management and enforcement within each State or region.

2.1.4 *Intentional interference*. Because of the low power of GNSS signals, it is possible for low power transmitters to jam the GNSS signal. While there have been no recorded instances of intentional jamming directed at civil aircraft, the possibility of intentional interference must be considered and evaluated as a threat.

2.2 **Spoofing**

2.2.1 Spoofing is the intentional corruption of the navigation signals to cause aircraft to deviate and follow a false flight path. Spoofing of satellite-based GNSS signals is technologically much more complex than spoofing of conventional ground-based navigation aids. Spoofing of the GBAS data broadcast is as difficult as spoofing conventional landing aids.

2.2.2 While spoofing can theoretically cause misleading navigation for a particular aircraft, it is very likely to be detected through normal procedures (e.g. by monitoring of flight path and distance to waypoints and by radar surveillance). Ground proximity warning systems (GPWS) and aircraft collision avoidance systems (ACAS) provide additional protection against collision with the ground and with other aircraft. In view of the difficulty in spoofing GNSS and the fact that unique operational mitigations are not deemed necessary, spoofing is not further addressed in this paper.

2.3 **Atmospheric effects**

2.3.1 Heavy precipitation attenuates GNSS satellite signals by only a small fraction of 1 dB and does not impact operations. Tropospheric effects are addressed by system design and do not represent a vulnerability issue. There are two ionospheric phenomena that must be considered: rapid and large ionospheric changes, and scintillation. Ionospheric changes result in range errors that must be accounted for in system design. Scintillation may result in temporary loss of GNSS signals from one or more satellites.

2.4 **Other vulnerabilities**

2.4.1 The GNSS ground and space segment vulnerabilities also need to be considered. There is a risk of an insufficient number of satellites in a given constellation due to lack of resources to maintain a constellation, launch failure(s) or satellite failure. Control segment failure or human error can potentially cause the failure of multiple satellites within a constellation.

2.4.2 Another risk is service interruption or degradation during a national emergency situation, where each State has the freedom of action as authorized by the Convention on International Civil Aviation (Article 89 refers). If signal denial is limited to a specific area, jamming of all civil GNSS signals would occur but the affected airspace would be closed to civil air traffic regardless. Another less likely situation would involve degradation or denial of core satellite or satellite augmentation signals throughout the coverage area.

3. ASSESSING GNSS OUTAGE RISKS

3.1 There are two principal aspects to be considered in the evaluation of the operational risks associated with GNSS vulnerabilities:

a) the likelihood of GNSS outage; and

b) the impact of GNSS outage.

3.2 By considering these aspects as a function of airspace, air navigation service providers can determine whether mitigation is required and, if so, to what level. Mitigation is required for outages with major impacts having a moderate to high likelihood of occurrence.

3.3 Assessing likelihood of GNSS outage

Interference

3.3.1 *Unintentional interference*. Operational experience is the best way to assess this risk. The likelihood of unintentional interference is often a function of geography. Large cities with significant radio frequency (RF) interference sources, industrial sites, etc., are more prone to the unintentional interference than remote regions. This interference is very unlikely in remote regions.

3.3.2 *Intentional interference*. Each State must consider the motivation to interfere with GNSS in determining the likelihood of intentional interference. The motivation may be driven by potential damage to a region and the operational impact on aviation and non-aviation applications. If there is minimal impact, the threat potential is low since there is no motivation to interfere. The extent of potential impacts may grow as applications using GNSS expand and the dependence on GNSS increases.

Atmospheric effects (ionosphere)

3.3.3 Rapid and large changes in the ionosphere are frequently observed near the geomagnetic equator, but their effect is not large enough to impact en-route through non-precision approach operations. For approach with vertical guidance (APV) and precision approach (PA) operations, the effects of these changes can be assessed and mitigated when designing augmentation systems. In equatorial regions, the availability of APV and PA operations using a single GNSS frequency may be limited.

3.3.4 Ionospheric scintillation is insignificant at mid-latitudes. In equatorial regions, and to a lesser extent at high latitudes, scintillation may result in the temporary loss of one or more satellite signals. Operational experience in equatorial regions has shown that the probability of loss of existing GNSS service is remote due to the relatively large number of satellites in view. Scintillation can interrupt reception of broadcasts from a SBAS geostationary orbit (GEO) satellite.

3.4 Assessing impact of GNSS outage

3.4.1 The impact of a GNSS outage on navigation services depends on the following factors:

a) type of airspace: remedial action timing is more critical for a terminal area than for high altitude en-route airspace, and, for en-route airspace, is more critical for airspace where more stringent separation minima is established;

b) air traffic density: in regions with high traffic density, reliance on radar vectoring or pilot procedures may be impractical due to workload;

c) level of service: for less demanding operations dead reckoning may be all that is required to proceed to an area where GNSS service is available;

d) availability and equipage of other navigation systems: aircraft that can navigate with other means will not be affected;

e) radar surveillance: if primary or secondary radar is available, ATC will be able to provide more assistance to assure separation and divert to alternate airports;

f) extent of outage: the geographic extent and duration of a service interruption;

g) outage assessment: the ability of the air navigation service provider to quickly assess the extent of the service outage; and

h) weather conditions: while it is prudent to assume instrument meteorological conditions (IMC) when assessing outage impacts, the geographic extent of IMC and the meteorological parameters assumed in any analysis should be realistic.

3.4.2 The impact of a GNSS outage on other services should also be considered. GNSS is frequently used as a source of precision timing information within communication and radar systems, and may be used for automatic dependent surveillance (ADS) services. Timing vulnerabilities can be addressed through system design, and ADS applications are outside the scope of this paper.

4. REDUCING THE LIKELIHOOD OF GNSS OUTAGES

4.1 Installation and operation

4.1.1 On-aircraft interference can be prevented by proper installation of GNSS equipment, its integration with other aircraft systems (e.g. shielding, antenna separation, out-of-band filtering) and restrictions on the use of portable electronic devices on board aircraft.

4.2 Spectrum management

4.2.1 *Spectrum management.* Effective spectrum management is the primary means of mitigating unintentional interference from man-made transmitters. Operational experience has indicated that the threat of unintentional interference can be virtually eliminated by applying effective spectrum management. There are three aspects of effective spectrum management:

a) creation of regulations/laws that control the use of spectrum;

b) enforcement of those regulations/laws; and

c) vigilance in evaluating new RF sources (new systems) to ensure that they do not interfere with GNSS.

4.2.2 *Interference location and termination.* The ability to locate the interferer and terminate the interference to GNSS without delay is a critical aspect. The primary method of detecting interference is through pilot reporting. As many aircraft may experience outage simultaneously when interference first occurs, an automated method of reporting the outage (e.g. an automatic data link message) would reduce workload and facilitate defining the outage area and locating the interferer. Interference detection systems may be implemented in aircraft and on the ground.

4.3 New signals and constellations

4.3.1 New signals and core satellite constellations will significantly reduce the vulnerability of GNSS. The use of the stronger signals and diverse frequencies planned for GPS, GLONASS and Galileo will effectively eliminate the risk of unintentional interference, since it is highly unlikely that such an interference source would simultaneously affect more than one frequency. Additional satellites (including multiple constellations) will eliminate the risk of the complete outage of GNSS due to scintillation, and multiple frequencies will mitigate the impact of ionospheric changes. Future GEO satellites will mitigate the effect of ionosphere on SBAS by using satellites which lines of sight are separated by at least 45°. More robust GNSS signals and new frequencies make it more difficult to intentionally interfere with all GNSS services. Additional core satellite constellations mitigate the risk of system failure, operational errors or discontinuance of service. They may also continue to provide global service in the unlikely event that a provider of one GNSS element modifies or denies service due to a national emergency situation.

4.3.2 Robust system management and funding are essential to continued operation of GNSS services and mitigate the system vulnerabilities identified in paragraph 2.4, except for the potential for global interruption of service due to a national emergency. An effective means of avoiding a global interruption of service is for service providers to adopt a policy of specific area denial in the event of national emergency.

5. MITIGATING THE EFFECTS OF GNSS OUTAGES

5.1 Introduction

5.1.1 There are three principal methods currently available to mitigate the effects of GNSS outages on aircraft operations:

a) by taking advantage of inertial navigation systems and GNSS receiver technologies;

b) by employing procedural (pilot or ATC) methods; and

c) by taking advantage of terrestrial radio navigation aids used as a backup to GNSS or integrated with GNSS.

5.1.2 By adopting an effective strategy using one or more methods identified in this section, a service provider will not only ensure safe aircraft operations in case of GNSS outages but will also discourage the attempts of intentional interference by reducing the potential effects of these attempts.

5.2 Inertial navigation systems and receiver technologies

5.2.1 Inertial navigation system (INS) provides a short-term area navigation capability after the loss of GNSS or other position updating. Many air transport aircraft are already equipped with INSs and inertial systems become more affordable and accessible to operators with smaller, regional aircraft. This capability should therefore be considered when evaluating the need for terrestrial aids as mitigations for GNSS outages.

5.2.2 There are also technologies that add robustness to GNSS receivers to mitigate interference. Anti-jam technologies include advanced antennas (e.g. spatial nulling) and receiver signal processing techniques. As the cost of these technologies decreases, they may become more affordable alternatives to inertial navigation systems for small aircraft.

5.3 Procedural methods

5.3.1 If there is no other navigation system available in case of GNSS outage in non-radar airspace, aircraft can revert to dead reckoning, as most new aircraft navigation systems include an automatic dead reckoning capability. When possible, pilots can revert to visual navigation, exit the affected area or land at a suitable airport. In the event the GNSS capability is lost, ATC can assess the potential for loss of lateral separation and, where possible, use vertical separation instead.

5.3.2 The same procedures can be used in radar airspace, with the additional possibility for ATC to vector aircraft through the affected area, depending on the ATC workload and the number of impacted aircraft. For many current terminal operations, aircraft are already radar vectored to intercept a precision approach path.

5.3.3 In uncontrolled non-radar airspace, pilots can communicate with each other via air-to-air channel to maintain separation and attempt to determine the geographical extent of the outage.

5.3.4 Successful reliance on procedural means to assure separation and diversion depends upon all of the factors in paragraph 3.4. The most significant consideration is the extent to which aircraft are equipped with another means of navigation, such as inertial navigation.

5.3.5 Procedures and training for pilots and air traffic controllers should address the vulnerability of GNSS and identify how to respond effectively to interference and implement alternative procedures, and to report interference occurances and their location.

5.4 **Terrestrial radio navigation aids**

5.4.1 Currently, one of the most effective means of mitigating a GNSS outage is for aircraft to revert to using terrestrial navigation systems. As the transition to GNSS is accomplished and the terrestrial infrastructure is reduced, increased reliance will be placed on the other mitigation techniques. The operational capability required from a terrestrial infrastructure will evolve as GNSS operations become predominant and airspace and procedures rely increasingly on area navigation (RNAV) operations. A DME infrastructure can be used to provide an area navigation service for en-route and terminal operations for aircraft equipped with flight management systems that use multiple DMEs. This same capability can be used for RNAV approach operations if the DME coverage is sufficient.

5.4.2 For those cases where reversionary navigation does not provide an RNAV capability, the workload to transition to alternative routes and procedures must be considered. However, once the operations on these alternative routes are established, operations can continue as long as required in the event of sustained interference.

5.4.3 If it is determined that an alternate precision approach service is needed, instrument landing system (ILS) or microwave landing system (MLS) may be used. This would likely entail retaining a minimum number of such systems at an airport or within an area under consideration.

6. **CONCLUSIONS**

6.1 *Unintentional interference*. The likelihood and operational effect of interference varies with the environment. Unintentional interference is not considered a significant threat provided that States exercise proper control and protection over the electromagnetic spectrum for both existing and new frequency allocations. Furthermore, the introduction of GNSS signals on new frequencies will ensure that unintentional interference does not cause the complete loss of GNSS service.

6.2 *Intentional interference*. The risk of intentional interference depends upon issues that must be addressed by States. For States that determine that the risk is unacceptable in specific areas, safety and efficiency can be maintained by adopting an effective mitigation strategy through a combination of on-board mitigation techniques (e.g. use of INS), procedural methods and terrestrial navigation aids.

6.3 *Ionosphere*. Scintillation can cause loss of GNSS satellite signals in the equatorial and auroral regions, but is unlikely to cause complete loss of GNSS service and will be mitigated with the addition of new GNSS signals and satellites. Ionospheric changes may limit the SBAS and GBAS services that can be provided in the equatorial region using a single GNSS frequency, and must be considered when designing the augmentation systems.

6.4 *Other vulnerabilities*. Independently managed constellations, funding, and robust system design will significantly mitigate system failure, operational errors, and discontinuance of service.

6.5 States should assess the GNSS vulnerability for their airspace and select appropriate mitigations depending on the airspace in question and the operations that must be supported. These mitigations can ensure safe operations in transition to GNSS and enable States to avoid the provision of new terrestrial navigation aids, reduce existing terrestrial navigation aids, and discontinue them in certain areas.

ATTACHMENT

EXAMPLE GNSS VULNERABILITY ASSESSMENT

Guidelines for evaluating the impact and likelihood of a GNSS outage is provided in section 3 of this paper. This appendix provides two examples of how this methodology can be applied to existing GNSS operations. These examples do not take into account future GNSS signals or constellations.

1. **Congested airspace — Mid-latitudes.** The following example applies to the existing GNSS operations in airspace with a high density of aircraft operations, and a mid-latitude region with effective spectrum management.

1.1 *Unintentional interference.* Unintentional interference has been encountered in North America and Europe. In North America, there have been seven confirmed cases of interference to GPS in the last few years. Based on operational experience, unintentional interference is unlikely but cannot be neglected.

1.2 *Intentional interference.* For current operations, there is no significant motivation to deliberately interfere with GNSS. No case of intentional interference in civil environment has been reported so far. The likelihood of this interference is negligible for existing operations. The threat of intentional interference may change over time as reliance on GNSS increases.

1.3 The impact of interference is to cause a GNSS outage within the line of sight of the interferer. The majority of air carrier operators in these regions are equipped with inertial navigation and/or an FMS with a DME/DME RNAV capability. DME facilities are available in the majority of airspace. While some aircraft are not equipped with an independent RNAV capability, safety for these aircraft can be maintained and operations can continue, perhaps with reduced efficiency. Therefore, a unintentional and intentional interference have a moderate impact.

1.4 *Spoofing.* There is no significant threat due to spoofing, and the impact would be moderate.

1.5 *Ionospheric effects.* For mid-latitudes, ionospheric scintillation that causes loss of GNSS positioning has never been experienced, so the likelihood of occurrence is negligible. There would be no operational impact due to the short duration of the event and the available terrestrial navigation aids and high level of equipage to use those aids.

1.6 *Summary.* Table 1 summarizes the likelihood and operational impact of the vulnerabilities that have been identified. The table maps the likelihood of occurrence against the operational impact. The State should mitigate any vulnerability that is remote and has a severe impact, or probable and has any impact. In addition, consideration should be given to vulnerabilities that are remote and have a moderate impact.

2. **Remote areas — Equatorial.** The following example applies to the existing GNSS operations in remote airspace with a low density of aircraft operations in an equatorial region with effective spectrum management.

2.1 *Unintentional interference.* Most sources of unintentional interference are less likely in remote regions. With effective spectrum management, the likelihood of interference in these areas may be negligible. The impact of outage may be moderate to severe due to unavailability of radar services.

2.2 *Intentional interference.* Intentional interference has not been encountered, and there is no significant motivation to deliberately interfere with GNSS given the low density of operations and the remote areas. The likelihood of this interference is considered to be negligible for existing operations. The threat of intentional interference may change over time as reliance on GNSS increases. The impact of intentional interference is the same as unintentional interference.

2.3 *Spoofing.* There is no significant threat due to spoofing, and the impact would be moderate.

2.4 *Ionospheric effects.* For equatorial regions, ionospheric scintillation that impacts GNSS performance is likely to occur. The operational effect is moderate, since it is typically a degradation in performance and not a complete loss of navigation capability. In the event that a complete loss of positioning occurs, it does not persist for very long and the low density of operations ensures continued safety.

2.5 *Summary.* Table 2 summarizes the likelihood and operational impact of the vulnerabilities that have been identified. The most significant issue is the potential for ionospheric scintillation. States should take action to reduce the impact of this effect. This can be accomplished through:

a) operational procedures that ensure continued operation during brief GNSS outages; and

b) continued research on the duration and likelihood of severe scintillation.

Table 1. Congested airspace — Mid-latitudes

		Operational impact		
		No impact	Moderate impact	Severe impact
Likelihood	Negligible	Ionospheric effects	Intentional interference; Spoofing;	
	Remote		Unintentional interference	
	Probable			

Table 2. Remote areas — Equatorial

		Operational impact		
		No impact	Moderate impact	Severe impact
Likelihood	Negligible		Unintentional and Intentional interference; Spoofing	
	Remote			
	Probable		Ionospheric effects	

3. When the analysis shows there is no critical vulnerabilities, implementation of spectrum management measures is still essential to reduce, as much as possible, the occurrences of service interruptions.

— END —