International Civil Aviation Organization

WORKING PAPER

AN-Conf/12-WP/21
26/5/12

TWELFTH AIR NAVIGATION CONFERENCE

Montréal, 19 to 30 November 2012

Agenda Item 6: Future direction
6.1: Implementation plans and methodologies

GLOBAL NAVIGATION SATELLITE SYSTEM (GNSS) IMPLEMENTATION ISSUES

(Presented by the Secretariat)

EXECUTIVE SUMMARY

This working paper discusses two issues related to global navigation satellite system (GNSS) implementation:

a) GNSS signals are vulnerable to intentional and unintentional sources of interference and to other effects. The paper suggest measures to reduce the likelihood that GNSS-based services will be disrupted and to mitigate the impact on aircraft operations in the event of the temporary loss of GNSS signals; and

b) new and enhanced core GNSS constellations offer the potential for increased GNSS benefits. The paper discusses the potential benefits and implementation challenges of a multi-constellation/multi-frequency GNSS environment.

Action: The Conference is invited to agree to the recommendations in this working paper.

Strategic Objectives:	This working paper relates to the Safety and Environmental Protection and Sustainable Development of Air Transport Strategic Objectives.
Financial implications:	The benefits of implementing multi-constellation/multi-frequency global navigation satellite system (GNSS) will be significant for navigation performance. The cost impact would be mainly associated with the need for new avionics. Failure to mitigate effectively the vulnerability of GNSS would prevent the full fruition of the potential safety and efficiency benefits of GNSS-based services. The cost impact of implementation of mitigation measures would be minimal for all stakeholders, except for the implementation of an alternative position, navigation and timing (APNT) system (2.5.2), whose cost impact could be substantial if introduction of new technology is required.
References:	Annex 10 — *Aeronautical Telecommunications*, Volume I — *Radio Navigation Aids* Doc 9849, *Global Navigation Satellite System (GNSS) Manual*

1. INTRODUCTION

1.1 Over the last decades, gradual implementation of the global navigation satellite system (GNSS) has taken place around the world. GNSS is today a cornerstone of the communications, navigation, and surveillance (CNS) infrastructure and forms the basis for the introduction of performance-based navigation (PBN). This paper discusses two issues that have emerged in the course of GNSS implementation: the intrinsic vulnerability of the GNSS signals; and the challenges associated with securing the benefits arising from the availability of multiple GNSS constellations.

2. MITIGATING GNSS VULNERABILITIES

2.1 Background

2.1.1 The very low strength of GNSS signals received from satellites makes GNSS vulnerable to interference and other effects that have the potential to affect multiple aircraft over a wide area. To date, no vulnerabilities have been identified that compromise the ultimate use of GNSS as a global system for all phases of flight. However, States and air navigation service providers (ANSPs) should implement mitigation strategies to reduce the likelihood of disruption of GNSS-based service.

2.2 Sources of GNSS vulnerabilities

2.2.1 The sources of GNSS vulnerabilities can be categorized as follows:

a) unintentional interference;

b) intentional interference;

c) effects of the ionosphere and solar activity (space weather); and

d) others.

2.2.2 They are briefly discussed below. See Appendix A for additional information.

2.2.3 Unintentional interference to GNSS signals can arise from several sources, operating in the same bands as GNSS or in other bands. A non-exhaustive list would include mobile and fixed VHF communications, television signals, certain radars, mobile satellite communications, military systems, point-to-point microwave links, GNSS repeaters and pseudolites[1], and systems on-board aircraft (both avionics and passenger devices).

2.2.4 Intentional interference to GNSS signals ("jamming") so far has typically targeted non-aviation users, but it may affect aviation users as well. One significant example is the proliferation of "personal privacy" jamming devices designed to defeat vehicle-tracking systems, which in some cases have disrupted aviation applications. The threat from intentional interference could increase as reliance on GNSS increases in aviation and other fields.

2.2.5 The ionosphere is a region of the upper atmosphere that is partially ionized by solar radiation from the Sun. GNSS signals are delayed as a function of the density of ionized particles in the ionosphere, which varies depending on the intensity of solar activity. Two effects on GNSS signals must

---

[1] GNSS repeaters and pseudolites are systems that transmit signals to supplement GNSS coverage in buildings and other areas where normal GNSS signals cannot be readily received.

be considered: rapid and large ionosphere delay changes; and scintillation (rapid amplitude and phase fluctuations). Ionosphere delay changes result in satellite range measurement errors that must be addressed by system design. Severe scintillation can result in temporary loss of one or more satellite signals.

2.2.6 In general, space weather can have a direct impact on GNSS. Space weather can be defined as the conditions on the sun and in the solar wind, magnetosphere, ionosphere, and thermosphere that can influence the performance and reliability of space-borne and ground-based technological systems and can endanger human life or health of aviation flight crews and passengers.

2.2.7 Other GNSS vulnerabilities include programmatic issues (including lack of resources to maintain a GNSS constellation, launch failures, or unanticipated satellite failures) and possible interruption or degradation of GNSS during a national emergency situation (Article 89 of the Chicago Convention refers) or for system testing purposes.

2.3 **Reducing the likelihood of GNSS signal disruption**

2.3.1 A number of measures can be taken to reduce the likelihood of GNSS signal disruption due to the sources described above.

2.3.2 The introduction of new constellations and frequencies for GNSS (see paragraph 3 of this paper) will significantly reduce the probability of loss of service caused by unintentional interference, by virtue of the diversity of frequencies and increased number of satellites in view. The availability of dual GNSS frequencies will also help compensate for the ionosphere delay effect. However, some residual impact of intentional interference will remain.

2.3.3 The primary means to reduce the likelihood of both intentional and unintentional interference is effective spectrum management. This involves the creation of a strong regulatory framework controlling the allocation and use of spectrum in such a way as to secure protection of GNSS frequencies. Such a framework would ensure that frequencies adjacent, or harmonically related, to GNSS bands are not used by systems that can interfere with GNSS receivers, that the use of GNSS repeaters and pseudolites is carefully regulated, and that purchase or use of devices that can cause intentional interference is forbidden. A capability to detect interference sources in support of enforcement programs should also be provided.

2.3.4 The International Telecommunication Union (ITU) is the specialized United Nations agency responsible for matters related to radio communications. The ITU Radio Regulations have the objective, inter alia, to ensure the availability and protection from harmful interference of the frequencies provided for safety of life services and to assist in the prevention and resolution of cases of harmful interference between radio services of different administrations.

2.3.5 Procedures for the prevention and resolution of harmful interference cases are detailed in Article 15 of the Radio Regulations, which in particular stipulate that "if there is a specialized international organizations for a particular service, reports of irregularities and of infractions relating to harmful interference caused or suffered by stations in this service may be addressed to such organizations at the same time as to the administrations concerned". Thus, reports of interference cases affecting aviation use of GNSS can be addressed to ICAO, which would then be in a position to alert ITU and appropriate UN bodies, with regard to the impact on aviation of the interference, with a view to facilitating a prompt resolution of the problem.

2.4 Risk assessment

2.4.1 Even though the likelihood of GNSS signal disruption can be significantly reduced as discussed above, disruption cannot be completely ruled out, and therefore ANSPs must be prepared to deal with potential loss of GNSS signals. This requires the completion of a risk assessment that will determine the residual likelihood of service outages and the impact of an outage in specific airspace.

2.4.2 The likelihood will be virtually non-existent in oceanic and sparsely settled areas and will be highest near major population centres. Impact assessment will consider the type of airspace, traffic levels and the availability of independent surveillance and communications services. The likelihood of disruption due to scintillation will depend on the geographic area and will require scientific assessment.

2.4.3 ANSPs must be prepared to act when pilot reports suggest interference. If analysis concludes that interference is present, ANS providers must identify the area affected, issue an appropriate NOTAM, apply mitigation as described below, and then locate and eliminate the source.

2.5 Mitigation strategies

2.5.1 The disruption of GNSS signals will require the application of realistic and effective mitigation strategies to ensure the safety and regularity of air services and to discourage those seeking to disrupt operations. Mitigation will include taking advantage of inertial systems, terrestrial aids and radar as well as air traffic control (ATC) and pilot procedures.

2.5.2 Several States have identified the need for an alternative position, navigation and timing (APNT) strategy, with the goal of maintaining air navigation services to the maximum extent possible in the event of a GNSS signal outage. Such a strategy should be coordinated globally (in this respect, ICAO involvement would be beneficial), be affordable and enable implementation within a relatively short time. This implies taking advantage of current systems, then defining a realistic evolution path. It is expected that VHF omni-directional radio range (VOR), distance measuring equipment (DME), instrument landing system (ILS) and inertial systems will be key elements, but new technology developments may be required, taking into account all the applications supported by GNSS.

2.5.3 Procedural mitigation can also be effective, taking account of the characteristics of the airspace, fleet equipage, pilot and ATC workload and alternative separation standards.

3. MULTI-CONSTELLATION/MULTI-FREQUENCY GNSS

3.1 Background

3.1.1 Today’s GNSS-based services rely for the most part on a single constellation, the global positioning system (GPS), providing service on a single frequency. However, another constellation, the GLObal NAvigation Satellite System (GLONASS), is already in operation, and more are being deployed (Galileo and BeiDou). All constellations will eventually operate in multiple frequency bands. Related developments are expected in the domain of GNSS augmentation systems. Additional information on the expected evolution of GNSS is provided in paragraph 1 of Appendix B.

3.1.2 Ultimately, the pace of transition to multi-constellation GNSS will depend on aircraft equipage, which in turn will depend on the business case for aircraft operators, as determined by the expected benefits, and the associated costs and challenges to be met.

3.2 Expected benefits

3.2.1 The use of GNSS signals from multiple constellations broadcasting in multiple frequency bands will improves GNSS technical performance. This offers the opportunity to realize operational benefits. These benefits include improved navigation performance, reduced likelihood of loss of service and increased service coverage.

3.2.2 Technical improvements associated with a multi-constellation, multi-frequency GNSS scenario are briefly discussed below. Additional information is provided in paragraph 2 of Appendix B.

3.2.3 GNSS performance is sensitive to the number of satellites in view. Multi-constellation GNSS will substantially increase that number. This will improve availability and continuity of service, particularly in areas where ionosphere scintillation can cause loss of lock on individual satellites. Furthermore, availability of more than thirty interoperable ranging sources will support an evolution of aircraft-based augmentation systems (ABAS) that could provide worldwide vertically guided approaches with minimal, or potentially no need for external augmentation signals in the long-term.

3.2.4 The availability of a second frequency will allow avionics to calculate ionosphere delay in real-time, effectively eliminating a major error source. Future satellite-based augmentation system (SBAS) systems would be able to support increased LPV service availability with minima as low as 200 ft decision height. Ground-based augmentation systems (GBAS) robustness and availability of Category II/III performance would also be improved. Moreover, as discussed in 2.3.2, frequency diversification is a very effective mitigation against unintentional interference, since it is highly unlikely that an unintentional interference source could simultaneously affect more than one GNSS frequency.

3.2.5 The availability of multiple independent constellations will provide redundancy to mitigate the risk of service loss due to a major system failure within a core constellation, and will address the concerns of some States about reliance on a single GNSS constellation outside their operational control.

3.3 Challenges

3.3.1 The introduction of multi-constellation, multi-frequency GNSS entails a number of new challenges beyond those already associated with current GNSS implementation. Examples of such challenges include: the need for signals of different GNSS constellations to be interoperable; legal liability concerns; the more complex role of augmentation systems potentially dealing with different combinations of GNSS constellations; and the increased complexity of avionics and aircraft integration and operational control (particularly if different States required or prohibited the use of different combinations of GNSS signals in their respective airspaces). A more detailed discussion is provided in paragraph 3 of Appendix B to this paper.

3.3.2 To realize multi-constellation benefits, ICAO, States, ANSPs, standardization bodies, manufacturers and aircraft operators need to coordinate activities to overcome these challenges. The ultimate goal is to establish an institutional and legal framework that would enable the unrestricted use of any GNSS element. Until then, ICAO and the aviation industry will have to develop pragmatic solutions to enable a gradual introduction of multi-constellation GNSS.

4. CONCLUSION

4.1.1 The discussion in section 2 of this paper highlighted the need for effective measures to reduce to the extent possible the likelihood of GNSS signal disruption and to mitigate any residual disruption. On this basis, the Conference is invited to agree to the following recommendations:

Recommendation 6/x – Assistance to States in mitigating global navigation satellite system (GNSS) vulnerabilities

The Conference request ICAO to:

a) continue technical evaluation of known threats to the global navigation satellite system, including space weather issues, and make the information available to States;

b) compile and publish more detailed guidance for States to use in the assessment of global navigation satellite system vulnerabilities;

c) develop a formal mechanism with the International Telecommunication Union and other appropriate UN bodies to address specific cases of harmful interference to the global navigation satellite system reported by States to ICAO; and

d) assess the need for and feasibility of an alternative position, navigation and timing system.

Recommendation 6/x – Planning for mitigation of global navigation satellite system (GNSS) vulnerabilities

The Conference request States to:

a) assess the likelihood and effects of global navigation satellite system vulnerabilities in their airspace and apply, as necessary, recognized and available mitigation methods;

b) provide effective spectrum management and protection of global navigation satellite system (GNSS) frequencies to reduce the likelihood of unintentional interference or degradation of GNSS performance;

c) report to ICAO cases of harmful interference to global navigation satellite system that may have an impact on international civil aviation operations;

d) develop and enforce a strong regulatory framework governing the use of global navigation satellite system repeaters, pseudolites, spoofers and jammers;

e) allow for realization of the full advantages of on-board mitigation techniques, particularly inertial navigation systems; and

f) where it is determined that terrestrial aids are needed as part of a mitigation strategy, give priority to retention of distance measuring equipment (DME) in support of inertial navigation system (INS)/DME or DME/DME area navigation, and of instrument landing system at selected runways.

4.1.2 The discussion in section 3 of this paper illustrated the significant potential benefits of the ongoing evolution of GNSS towards a multi-constellation, multi-frequency scenario. It also made it clear that several challenges need to be overcome in order to secure those benefits. On this basis, the Conference is invited to agree to the following recommendations:

Recommendation 6/x – ICAO work programme to support global navigation satellite system (GNSS) evolution

The Conference request ICAO to undertake a work programme to address:

a) technical interoperability of global navigation satellite system constellations and augmentation systems;

b) technical and operational solutions to address institutional and legal concerns;

c) identification of operational benefits to enable air navigation service providers and aircraft operators to quantify these benefits for their specific operational environment; and

d) continued development of Standards and Recommended Practices and guidance material for global navigation satellite system elements and encouraging the development of industry standards for avionics.

Recommendation 6/x – Use of multiple constellations

The Conference recommends that States, when defining their air navigation strategic plans and introducing new operations:

a) take advantage of the improved robustness and availability made possible by the existence of multiple global navigation satellite system constellations;

b) publish information specifying the global navigation satellite system elements that are approved for use in their airspace; and

c) adopt a performance-based approach with regard to the use of global navigation satellite system (GNSS) constellations, considering in particular the difficulties arising from limiting or mandating the use of specific GNSS elements.

— — — — — — — —

APPENDIX A

SOURCES OF GLOBAL NAVIGATION SATELLITE SYSTEM (GNSS) VULNERABILITIES

1. UNINTENTIONAL INTERFERENCE

1.1 The GNSS systems standardized by ICAO or under consideration for future standardization operate or are planned to operate in the bands 1559 – 1610 MHz (GPS, GLONASS, Galileo, BeiDou and SBAS); 108 – 117.975 MHz (GBAS); and 1164 – 1215 MHz (GPS, GLONASS, Galileo and BeiDou).

1.2 GNSS receivers in those bands must meet specified performance requirements in the presence of levels of interference defined by ICAO in Annex 10 — *Aeronautical Telecommunications* and used within the relevant International Telecommunication Union (ITU) recommendations. Interference above defined levels may cause degradation or loss of service, but avionics standards require that such interference shall not result in hazardously misleading information.

1.3 There are a number of sources of unintentional interference to GNSS from both in-band and out-of-band emitters, including mobile and fixed VHF communications, harmonics of television stations, certain radars, mobile satellite communications and military systems. Of specific concern is the use of the 1559 – 1610 MHz band by point-to-point microwave links that are allowed by a number of States. The use of these links is due to be phased out no later than 2015.

1.4 Additional sources of potential unintentional interference include GNSS repeaters and pseudolites (systems that transmit signals to supplement GNSS coverage in buildings and other areas where normal GNSS signals cannot be readily received), and aeronautical test equipment acting as a GNSS signal generator. When such equipment does not operate in accordance with specified conditions, it may interfere with GNSS avionics and CNS ground equipment. In some cases these systems can cause GNSS receivers within range to calculate erroneous positions. Such cases should be detectable because they would cause effects such as sudden, readily evident position shifts.

1.5 Many instances of reported GNSS interference events have been traced to on-board systems; experience has identified several sources, including VHF and satellite communications equipment and portable electronic devices. Such interference can be prevented by proper installation of GNSS avionics (e.g. shielding, antenna separation and out-of-band filtering), integration with other aircraft systems and restrictions on the use of portable electronic devices.

1.6 States can greatly reduce the threat of unintentional interference by applying effective spectrum management, as discussed in the body of this paper.

1.7 Current GNSS core constellations use a single frequency band (1559 – 1610 MHz). The introduction of GNSS signals on additional frequencies in the 1164 – 1215 MHz band will effectively eliminate the likelihood that unintentional interference would cause the complete loss of GNSS service. Enhanced services depending upon the availability of multiple frequencies could, however, be degraded by such interference.

1.8 The additional GNSS signals in the band 1164 - 1215 MHz to be broadcast by second-generation core satellites share the same frequency band as distance measuring equipment (DME) and TACtical air navigation system (TACAN). ITU rules require that DME/TACAN must be protected from interference. Compatibility studies based on the current DME/TACAN infrastructure concluded that the impact of radio frequency interference on the processing of the new GNSS signals is tolerable. The studies also concluded that a high density of DME/TACAN facilities operating in or near the new GNSS band could result in interference with GNSS signals at high altitudes. States should assess whether an increase of the DME/TACAN infrastructure is compatible with expanded use of GNSS or reallocate DME assignments away from GNSS frequencies.

2. INTENTIONAL INTERFERENCE AND SPOOFING

2.1 Today, essentially all conventional navigation aids remain in service, and all aircraft are still equipped to use them. Thus, there is little motivation to deliberately interfere with GNSS-based aviation services. As reliance on GNSS increases, however, the threat of intentional interference (“jamming”) could increase.

2.2 GNSS is used in many applications: financial, security and tracking, transportation, agriculture, communications, numerical weather prediction, scientific research, etc. Intentional threat analysis must consider all the applications of GNSS technology and the likelihood that jamming directed at non-aviation users would affect aircraft operations. It should also consider the mitigations put in place by non-aviation services. Of primary concern is the proliferation of personal privacy jammers designed to defeat vehicle-tracking systems.

2.3 States must evaluate and address the risk of intentional interference in their airspace. If States determine that the risk is unacceptable in specific areas, they can adopt a mitigation strategy as discussed in the body of the paper.

2.4 Spoofing is the broadcast of GNSS-like signals to cause GNSS avionics to calculate erroneous positions and provide false guidance. Spoofing of GNSS is less likely than the spoofing of traditional aids because it is technically much more complex. To avoid immediate detection, spoofing requires accurate, continuous aircraft position information. It is very difficult to match the spoofing signal to the dynamics of a target receiver and maintain sufficient signal strength to enable the receiver to remain locked to the spoofing signal. If the avionics did remain locked to a spoofing signal, there are various ways that it could be detected: integrated avionics could annunciate discrepancies between GNSS and INS or DME-DME positions; pilots could note deviations through normal monitoring of instruments and displays; and, in a radar environment, ATC could observe deviations. If an aircraft did deviate from track, ground proximity warning systems (GPWS) and aircraft collision avoidance systems (ACAS) would provide protection against collision with the ground and other aircraft.

2.5 Spoofing of the GBAS data broadcast is at least as difficult as spoofing conventional landing aids. To further protect GBAS an authentication scheme has been developed that will make spoofing virtually impossible.

3. EFFECTS OF THE IONOSPHERE AND SOLAR ACTIVITY

3.1 The ionosphere is a region of the upper atmosphere that is partially ionized by radiation from the sun. GNSS signals are delayed by a varying amount depending on the density of ionized particles in the ionosphere, which itself depends on the intensity of solar radiation and other solar bursts of energy. Two ionosphere phenomena must be considered: rapid and large ionosphere delay changes; and scintillation (rapid amplitude and phase fluctuations). Ionosphere delay changes result in range measurement errors that must be addressed by system design. Severe scintillation can result in temporary loss of one or more satellite signals.

3.2 The impact of ionosphere storms on en route through non-precision approach operations is negligible.

3.3 Severe scintillation can disrupt signals from satellites, but it does not affect wide areas of the ionosphere simultaneously; rather it occurs in patches. It therefore generally affects only a few of the satellites in view of a user. Losses of signal tracking due to scintillation are of short duration, but they may occur repeatedly during periods of several hours. Such losses can possibly cause GNSS service to be degraded or temporarily lost. One mitigation is the receiver's ability to rapidly reacquire a satellite signal following a scintillation event. Scintillation affects all GNSS frequencies, so multi-frequency receivers will not offer stronger protection. Another mitigation is the use of multiple constellations. If the receiver is able to track more satellites, the likelihood of service disruption is greatly reduced because more satellites would be unaffected.

3.4 Scintillation is virtually non-existent in mid-latitudes, except at low to moderate levels, which can occur during rare severe ionosphere storms. Severe scintillation is fairly common in equatorial regions where it typically occurs after sunset and before local midnight. Moderate scintillation occurs frequently in high-latitude regions, and can reach severe levels during ionosphere storms.

3.5 Ionosphere delay can be compensated by using dual GNSS frequencies. As the effects are frequency-dependant, the use of dual frequency allows the GNSS receivers to detect and compute these ionosphere delays.

3.6 SBAS can detect the effects of ionosphere storms that might threaten the integrity of broadcast corrections and can ensure that LPV operations do not continue when and where the broadcast ionospheric corrections may not adequately compensate for these effects. This type of mitigation is effective because ionosphere storms that are sufficiently severe to threaten the validity of SBAS corrections are infrequent (they are expected to affect LPV service about 1% of the time in mid-latitude regions).

3.7 While in mid-latitudes severe ionosphere storms may infrequently cause outages of SBAS LPV service, in equatorial regions service outages would be much more frequent due to the formation of wide bands of accumulated ionized particles located approximately 15 degrees north and south of the magnetic equator. Narrow, elongated volumes, called depletions (or bubbles), in which the density of ionized particles can drop well below that in the surrounding ionosphere, often develop in the midst of these bands just after local sunset and persist late into the local night. The combination of these phenomena results in large spatial and temporal ionosphere delay variations and therefore presents a major challenge to the integrity of SBAS ionospheric corrections. It is therefore not practical to provide single-frequency SBAS LPV service in equatorial regions with a high level of availability.

3.8 GBAS broadcasts pseudo-range corrections that account for all error sources, as well as integrity information that is effective even when the local ionosphere is severely disturbed. GBAS service would, however, be lost if severe scintillation caused avionics or the GBAS station to lose lock on enough satellite signals. The GBAS broadcast itself is not affected by ionosphere conditions. However, the ionosphere threat model used by GBAS integrity monitors must be consistent with local conditions, which may result in lower service availability or more siting constraints in equatorial regions than in mid-latitude regions. Dual frequency GBAS systems can compensate ionosphere delay effects allowing improved performance with fewer constraints.

3.9 In general, space weather can have a direct impact on GNSS. Space weather can be defined as the conditions on the sun and in the solar wind, magnetosphere, ionosphere, and thermosphere that can influence the performance and reliability of space-borne and ground-based technological systems and can endanger human life or health of aviation flight crews and passengers. Disturbances in the Sun's corona[2] can create solar radio bursts that may cause an increase in the level of radio frequency noise in the GNSS frequency band(s), thereby affecting the reception of signals from all satellites in view on the dayside of the Earth. In some rare cases, the intensity and frequency band of a solar radio burst can cause GNSS receivers to temporarily drop track on all satellites in view. Experience has shown that these events may last up to an hour, during which geodesy GNSS receivers have lost track on all satellites in view for a couple of minutes. However, the vulnerability of receivers to such events is highly dependent on their design. Aviation GNSS receivers design is different from geodesy receiver design and so far, no significant impact has been detected on aviation receivers.

4. OTHER VULNERABILITIES

4.1 Programmatic issues, including a lack of resources, launch failures or unanticipated satellite failures could result in insufficient satellites being available to support specific GNSS based services. Control segment failure or human error could also potentially cause service outages and common-mode errors on several satellites of a single constellation. The provision of reliable services from core satellite constellations requires robust system management and funding.

4.2 States must anticipate the possibility of GNSS and conventional navigation aid service interruption or degradation during a national emergency situation (Article 89 of the Chicago Convention refers). States must also have contingency plans in the event of an international conflict or if another State jams GNSS signals in such a way that service is disrupted beyond its borders. GNSS security aspects are being addressed by some States and may result in new procedures to protect the safety and efficiency of aeronautical navigation.

4.3 In some States, military authorities test the capabilities of their equipment and systems occasionally by transmitting jamming signals that deny service in a specific area. This activity is normally coordinated with State spectrum offices and ANSPs. Military and other authorities operating jamming devices should coordinate with ANSPs to enable them to determine the airspace affected, advise aircraft operators and develop any required procedures.

4.4 The security of ground navigation aids that support aeronautical navigation is the responsibility of State authorities. GNSS coverage extends over the territory of many States, so security should be addressed at a regional or global level. It is important that the GNSS elements used by civil aviation are protected against terrorism or hostile acts.

— — — — — — — —

---

[2] These disturbances, known as coronal mass ejections (CMEs), release huge quantities of matter and electromagnetic radiation into space and may travel towards Earth at speeds of up to several thousand kilometres per second.

APPENDIX B

EXPECTED EVOLUTION OF GLOBAL NAVIGATION SATELLITE SYSTEM (GNSS) BENEFITS AND CHALLENGES

1. EXPECTED EVOLUTION OF GNSS OVER THE NEXT 15 TO 20 YEARS

1.1 Core constellations

1.1.1 The United States and the Russian Federation plan to provide additional GPS and GLONASS features over the next few years. GPS plans to have a full L1-L5 dual frequency capability by 2020, based on improved signal designs in the L5 band. In the longer term, a modernized signal is also being considered in the L1 band. GLONASS plans to provide a dual frequency service in the L1 and L3 bands with a gradual build-up towards a full constellation capability before 2020. Longer-term plans call for modernized signals using a compatible signal modulation scheme in the L1 and L3 bands that should further improve interoperability with other global systems.

1.1.2 The European Galileo system will provide dual frequency services over the E1 and E5 frequency bands and use signal designs that offer improved accuracy and robustness. System deployment will be gradual with initial service capabilities in 2015 and full constellation deployment before 2020. The Chinese BeiDou system will deliver a dual frequency regional and global service over the B1 and B2 bands with initial service capabilities in 2011 and full constellation deployment before 2020.

1.2 Augmentations

1.2.1 Aircraft-based augmentation system (ABAS)

1.2.1.1 The availability of more ranging signals on two frequencies from multiple constellations offers the possibility to improve performance through an advanced receiver autonomous integrity monitoring (RAIM) concept. This would allow the provision of enhanced services on a global basis with less reliance on external augmentation (SBAS and GBAS). Integration of advanced RAIM with inertial systems would further improve service by reducing susceptibility to short term interference or ionospheric disturbance events.

1.2.2 Satellite-based augmentation system (SBAS)

1.2.2.1 The first SBAS evolution will extend the service areas of existing systems. This is expected to occur over the next few years with LPV services provided by several SBAS. The second major evolution will be based on taking advantage of dual frequency signals. This stage could also include the use of signals from multiple constellations, but this could be considered in a third stage. This is expected to occur after the 2020 time frame when sufficient core constellation satellites offer a dual frequency capability.

1.2.3 Ground-based augmentation system (GBAS)

1.2.3.1 ICAO standards for single frequency GBAS Cat II/III service are currently in an operational validation phase. A further GBAS evolution will involve using a second frequency and more than one constellation. Dual frequency, multi-constellation Cat II/III GBAS may be available in the 2020-2025 timeframe.

2. BENEFITS

2.1 Introduction

2.1.1 The use of signals from multiple constellations broadcasting on multiple frequencies improves GNSS technical performance. This provides the opportunity to realize operational benefits. These benefits include improved performance, reduced likelihood of loss of service and increased service coverage. The use of multiple constellations would address the concerns of some States about reliance on a single GNSS constellation outside of their operational control. Transition to multi-constellation GNSS could accelerate reduction of conventional aids.

2.1.2 At this stage in the development of multi-constellation and multi-frequency technology it is only possible to identify qualitative operational benefits. As development progresses, however, States, ANSPs and aircraft operators will be able to quantify these benefits.

2.1.3 The following sections identify the key characteristics of a multi-constellation, multi-frequency GNSS, explain expected improvements in technical performance and indicate how these improvements could provide operational benefits.

2.2 Availability of additional ranging sources

2.2.1 GNSS performance is particularly sensitive to the number of satellites in view. Multiple interoperable constellations will provide additional ranging sources to significantly improve availability and continuity of service that will increase operational robustness and enable advanced applications in the navigation and surveillance domains.

2.2.2 In equatorial regions and to a lesser extent in polar regions ionospheric scintillation can cause loss of lock on individual satellite signals, which can result in loss of service. Scintillation affects patches of the sky at any given time. With more satellites in view it would be much less likely that scintillation would result in loss of service.

2.2.3 Availability of more than thirty interoperable GNSS ranging sources will support an evolution of ABAS (e.g. advanced RAIM) that could provide advanced applications such as worldwide vertically guided approaches with minimal, or potentially no need for external augmentation signals in the long term.

2.3 Availability of a second GNSS frequency

2.3.1 The main source of error for single frequency GNSS is the difficulty to estimate the error due to ionosphere vertical delays. The availability of a second frequency will allow avionics to calculate the delay autonomously in real time, effectively eliminating this error source and the need for augmentation systems to provide corrections to dual frequency-equipped users. Future SBAS systems augmenting multiple constellations with multiple frequencies would be able to support nearly 100% LPV service availability at suitable airports with minima as low as 200 ft decision altitude (DA) even in equatorial regions.

3.3.2 Future SBAS expansion based on the use of multiple frequencies would require significantly fewer monitoring stations to support vertically guided approaches in the entire GEO satellite footprint.

3.3.3 Single frequency GNSS can be disrupted by unintentional interference, such as that caused by faulty transmitters. Frequency diversification over different bands is a very effective mitigation against unintentional interference, since it is highly unlikely that an out-of-band interference source could simultaneously affect more than one GNSS frequency. Signals from upgraded (GPS and GLONASS) and emerging constellations will be more resistant to interference due to higher power and improved signal designs, resulting in better interference rejection capability.

2.4 Availability of multiple independent constellations

2.4.1 Multiple GNSS constellations provide redundancy to mitigate the risk of service loss due to a major system failure within a core constellation. The availability of additional ranging sources and frequencies provided by independent constellations will improve the operational robustness, defined as the capability to maintain the required operational performance by reducing the need to revert to a less capable backup/alternative system (e.g. radars, conventional navigation aids) that in some cases would imply a loss of capacity. GNSS provides a seamless worldwide service conventional navigation systems cannot duplicate. Future planning assumptions require a continuous increase in airspace capacity that will drive higher availability and continuity standards. It would be much easier to meet these standards in a multi-constellation environment.

2.4.2 GNSS provides a precise time reference that is used to synchronize ground systems, onboard equipment, communication networks and operations. It is expected that having a system-wide time reference will become more critical in the future operational context (e.g. 4D trajectory-based operations). Multi-constellation will provide independent sources of GNSS time reference to increase the robustness of these systems and related applications.

3. CHALLENGES

3.1 Interoperability

3.1.1 The degree of interoperability between signals of different GNSS constellations will directly influence the complexity and cost of avionics, affecting the aircraft operator’s business case. Ideally, satellites from multiple constellations would be “interchangeable”, enabling a receiver to combine all satellites into a single solution, which would provide a significant improvement in performance.

3.2 Multi-constellation liability concerns

3.2.1 Each State must assure the safety of air navigation services provided within its sovereign airspace. Experience with GPS has shown that relying on GNSS services provided by other States may raise legal liability concerns. Some States have refused to approve any GNSS-based operations.

3.2.2 A solution for some States has been to use GNSS monitoring systems and/or augmentation systems to independently monitor and control the use of authorized GNSS-based services. The emergence of multi-constellation GNSS renews the need to define a specific GNSS international liability scheme.

3.3 Role of augmentation systems

3.3.1 The role of augmentation systems in the multi-constellation GNSS scenario would be significantly more complicated for users and avionics manufacturers if different augmentation systems are designed to augment different combinations of GNSS constellations.

3.3.2 Current SBAS standards address GPS and GLONASS but are not expandable to augment up to four constellations. Redesigning the SBAS message structure to accommodate multi-constellation GNSS should be accomplished in conjunction with the planned upgrade to dual frequency GPS.

3.3.3 The situation is similar for GBAS, where the currently proposed single frequency single constellation standards will have to be extended through an internationally coordinated framework for multi-frequency/multi-constellation GNSS.

3.4 Challenges for avionics development and aircraft integration

3.4.1 Challenges for avionics development and aircraft integration are associated with the complexity of integration of the capability and in the operational control of GNSS receivers.

3.4.2 Although it may be possible to design a single receiver that uses all available core constellation and augmentation signals, such a receiver could have many modes of operation, which would increase its complexity. Use of multiple frequencies also presents a challenge for the design of antennas that can support use of multiple bands. The emergence of new core constellations and new signalling waveforms on new frequencies challenges receiver designers to implement architectures that can adapt to the new more complex environment, yet are simple and certifiable. Those challenges are currently addressed by industry standardization fora (e.g. Eurocae).

3.4.3 The operational control and avionics integration would be difficult if States required or prohibited the use of specific constellations, signals or augmentation services. Today, where virtually all aircraft avionics are based on GPS alone, the determination of the system to be used in a given airspace is relatively simple: the State has either authorized the use of GPS or it has not. In a multi-constellation scenario, more alternatives exist (depending on which combinations of constellations are authorized in each State), and the avionics need to be aware of which constellation can be used where. The same concept extends to multiple frequencies and to multiple regional augmentation systems like SBAS where significant augmentation signal coverage may extend outside the service area. It would be complex to implement a means to control when a receiver uses various elements of GNSS. Involving pilots in such decisions would increase workload and complexity, so some level of automation is anticipated. Moreover, since the status of which element is permitted or precluded in which airspace will change over time, the information driving an automated function would require updating on a regular basis.

3.4.4 Another challenge for aircraft integration is airworthiness approval. An airworthiness certificate is issued by the State of Registry. The certificate denotes among other things that the aircraft was found to conform to its approved design, which is part of the type certificate that is awarded by the State of Design. The TC is awarded to designers after they have shown that the particular design conforms to the State design standard including the applicable regulations prescribed by the CAA of the State of Design. Consequently, type certification of an aircraft that includes use of GNSS elements not approved by the State of Design will be problematic. This situation exists already in that the US FAA does not have design standards or guidance material necessary to allow certification of GLONASS receivers. Such situations are likely to become more complicated in the future as GNSS core constellations mature at different rates and if different States of Design and States of Registry approve different GNSS elements at different times. This problem is exacerbated when States mandate or prohibit the use of specific GNSS elements.

3.4.5 The willingness of the aviation industry to address the challenges related to navigation equipment upgrading and certification will play the major role in realizing advantages of a multi-constellation environment.

— END —