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WORKING PAPER

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

APPROACH TO GLOBALLY HARMONIZED GNSS IMPLEMENTATION – IONOSPHERE THREAT AND SPACE WEATHER PERSPECTIVES

(Presented by Japan)

SUMMARY

The *Global Air Navigation Capacity and Efficiency Plan* (GANP, Doc 9750) has defined global navigation satellite system(GNSS) as one of core technologies, which will enable performance-based navigation (PBN) operation, trajectory-based operation (TBO) and other advanced ATM improvement through the evolution of GNSS technology.

Understanding the significance of proper assessment of and measures against ionospheric issues and other space weather matters, globally harmonized GNSS implementation need to be undertaken in a cost-effective manner through close collaboration among States, or between States and industry.

This paper addresses ionospheric and space weather issues affecting GNSS implementation and operation over the envisaged timeframe of aviation system block upgrades (ASBUs) of the GANP, and suggests actions to complement those relating to GNSS vulnerability proposed in WP/21"*GNSS Implementation Issues*".

Action: The Conference is invited to agree to the recommendation in paragraph 3.

1. INTRODUCTION

1.1 Global navigation satellite system (GNSS) has been regarded as a core navigation infrastructure to support performance-based navigation (PBN) and trajectory-based operation (TBO) and other advanced air traffic management (ATM) improvement, which contribute to the enhancement of capacity and efficiency of air transportation.

1.2 WP/21 explains the technical details of GNSS vulnerability attributable to space weather phenomenon, especially ionospheric anomaly, followed by suggestion on actions to be taken by ICAO and States for the effective implementation of GNSS. In order to realize a future GNSS environment for PBN and other GNSS-based ATM enhancement at such large scale as sub-regional or regional, the vulnerability issues accrued from ionospheric anomaly must be effectively resolved as long as they remain to be impedance to GNSS implementation and operation.

1.3 Of another interest to GNSS developers is that space weather, as briefed on in WP/21, can cause CNS systems degrading, and radiation hazards to human beings and avionics. Research has been underway in several States to further study the mechanism of different phenomena and the operational impact in aviation. Under ICAO framework, space weather issues have been under discussion by some technical expert bodies or on regional basis.

1.4 In light of the expectation for steady GNSS implementation over the 2013-2028 ASBUs timeframe, States, air navigation service providers (ANSPs) and industry need to further study ionospheric threat and other space weather issues as a far-term issue, which influence the harmonized GNSS-based navigation service at a scale beyond a State or a region.

2. DISCUSSION

2.1 Ionospheric effects on GNSS

2.1.1 When implementing and operating GNSS properly in a given airspace for its individual operational needs, ANSPs and regulators are required not only to have adequate expertise but also to take appropriate measures against the ionospheric effects on GNSS. As the ionospheric behaviour and characteristic which affect GNSS performance vary by region, to be more specific, by the magnetic latitude, ionospheric characteristics should be assessed taking the regional difference into consideration. (Ref. Appendix A and WP/21).

2.1.2 To assist those who need GNSS platform, ionospheric effects on GNSS have been studied by ICAO and documented in ICAO documents, among other things, *Global Navigation Satellite System (GNSS) Manual (Doc 9849)* and *Report on Ionospheric Effects on GNSS Aviation Applications by Navigation Systems Panel (hereafter referred to as "NSP Iono Paper")*. Further studies are being conducted for exploration of the subjects.

2.2 Consideration on Ionospheric effects to GNSS in ASBUs

2.2.1 According to the technology roadmaps in GANP and major GNSS projects outlook in WP/21, multi-frequency and multi-constellation (MF-MC) GNSS are envisioned for their debut from the last half of Block 1 (2018-22) to the first half of Block 2(2023-27). Theoretically speaking, the MF-MC GNSS can help mitigating the vulnerabilities associated with ionospheric anomaly (Ref. paragraph 2 and Appendix B, WP/21).

2.2.2 However, the moderate development of MF-MC-adapted GNSS including avionics and uncertainty in the availability of technical solution for the envisaged period cast some doubt about the on-schedule deployment of MF-MC GNSS. GNSS operation on the current single-frequency and single-constellation (SF-SC) GNSS avionics, which have now worldwide prevalence, are anticipated to continue to be in service and need to be supported until such time when MF-MC GNSS environment has been adequately laid out at a global context.

2.2.3 As long as SF-SC GNSS-based services are required, it is essential to characterize how the ionosphere behaves and to what extent the ionosphere may affect GNSS in designing and developing GNSS. Even when MF-MC GNSS-based systems are available, ionospheric characterization should remain an important basis to ensure that those systems properly mitigate the ionospheric impacts.

2.3 Regional and global approaches for mitigation of ionospheric impacts

2.3.1 WP/21 recommends that both ICAO and States take measures to reduce the likelihood that ionospheric effects will disrupt GNSS signals. Ionospheric characterization is a requisite for designing a technical solution of mitigating GNSS vulnerability associated with the ionosphere.

2.3.2 For ionospheric characterization with more reliability, the key is to secure enough amounts of observed data in appropriate forms in the region where the GNSS services are to be implemented. To characterize the ionosphere in an efficient and effective manner and to make it consistent and reliable across the States/FIRs, data collection and sharing should be conducted in a coordinated manner by States belonging to the same magnetic latitude zone. Regional initiatives, when appropriately combined, will contribute to a coordinated global ionospheric characterization, which in turn will support the harmonized implementation of GNSS and GNSS-based navigation.

2.3.3 Japan, with the focus on collaborative approach to tackle such a regional GNSS challenge, has been working on characterization of ionospheric anomaly for GNSS applications to air navigation and taking a leadership in relevant regional activities. ENRI (Electronic Navigation Research Institute), a CNS/ATM dedicated research organization in Japan has long been working on the ionospheric threat and making a contribution to international fora as well as to national one in this subject matter.

2.3.4 In the Asia and Pacific Region, Ionospheric Studies Task Force (ISTF) has been established under the communications, navigation, and surveillance and meteorology subgroup (CNS/MET SG) of Asia/Pacific Air Navigation Planning and Implementation Group (APANPIRG) with a final goal of ionospheric characterization by 2014, which is commonly applicable to the region (Ref. Appendix B). Thus, States concerned, can avoid the duplication of work as well as contribute to seamless GNSS services across the States/FIRs. This should be a common benefit to States, ANSPs, airspace users and GNSS manufacturers.

2.3.5 Ionospheric issues are of great interest to International GBAS Working Group (IGWG), which is a voluntary group to study various aspects of GBAS, consisting of regulators, ANSPs, industries, and research institutes. A subgroup of IGWG is working on coordinated ionospheric studies for GBAS. Japan is involved in the activity and acting as a liaison between IGWG and ICAO NSP.

2.3.6 Ionosphere data collected under disturbed conditions are particularly important when ANSPs operate and provide GNSS service for all the period in a given airspace. Ionosphere is disturbed more often and severely during a high solar activity period, which is expected to peak in the next couple of years and then in eleven years onward. In light of the observation in paragraph 2.2, it is recommended that GNSS be developed and deployed, with adequate assessment of the solar disturbance to the ionosphere without missing the once-in-ten year chance.

2.3.7 Involvement of States in such ionospheric characterization activity can enrich their expertise and hands-on experiences, which States concerned should acquire to certify or/and approve design and operation of GNSS including avionics, GNSS-based procedures and aircraft operations in their own jurisdiction.

2.4 **Space weather information for GNSS**

2.4.1 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*" (Ref. paragraph 3.9 and Appendix A of WP/21).

2.4.2 Utilization of space weather information has recently been noteworthy in terms of its application into safe and efficient aircraft operations. *Concept of Operations for International Space Weather Information in Support of Aviation* (hereafter referred to as Space Weather ConOps), which are under review by an ICAO meteorology expert group, suggests that space weather information can be exploited to mitigate HF communication disruption, GNSS failure, radiation dose by high-energy particles and so forth.

2.4.3 Ionospheric irregularity that impacts on GNSS signals is one of the space weather phenomena. Monitoring and predicting the ionospheric conditions, which falls in the category of space weather information, will enhance the effectiveness and efficiency of SC-SF GNSS-based services by properly applying such information. Space weather information can provide for useful data for early warning, availability prediction, or situational awareness of system failure in future MC-MF GNSS-based navigation, thus it can enhance the effectiveness and efficiency of GNSS operation.

2.4.4 Space Weather ConOps of the latest version describes the space weather effects on GNSS primarily in mid and high magnetic latitudes. In the low magnetic latitude region, effects of the thermosphere, which is a background neutral atmosphere, on the ionosphere are more influential to GNSS than in other regions (Ref. paragraph 2.1 of NSP Iono paper. To make it more practical and applicable to worldwide, thermospheric effects on the ionosphere, which is more influential in the low magnetic latitude region, should be reviewed with regional difference into account and properly incorporated into the ConOps.

3. CONCLUSION

3.1 Paragraph 2 of this paper highlights the efficacy and efficiency for collaborative approach against ionospheric threat, and optimum utilization of space weather information to augment GNSS integrity and availability by effectively mitigating ionospheric impacts. In this context, and with cognizance of the relevant recommendations in WP/21, the Conference is invited to agree on the following recommendations:

Recommendation 6/x – Ionosphere and space weather information for future global navigation satellite system implementation

That the Conference requests ICAO:

a) to coordinate regional and global activities in the ionospheric characterization for globally harmonized global navigation satellite system implementation;

b) to continue its effort to address the global navigation satellite system (GNSS) vulnerability to space weather to assist States in GNSS implementation taking into account of long-term GNSS evolution as well as projected space weather phenomena; and

c) to study the optimum use of space weather information that is globally applicable from low to high magnetic latitude regions for enhanced global navigation satellite system performance at a global context.

That the Conference requests States:

a) where the global navigation satellite system (GNSS)-based air traffic management operation is required or planned, to consider a collaborative approach by States or regions to resolve ionospheric issues including ionospheric characterization for cost-effective, harmonized and regionally suitable GNSS implementation.

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APPENDIX A

A NEED FOR IONOSPHERIC THREAT MODEL IN GNSS IMPLEMENTATON

1. Importance of properly addressing ionospheric threat in GNSS implementation

The ionosphere is one of the vulnerabilities, which need to be properly treated when implementing GNSS. *(Ref. ANConf/12-WP/21)*. To achieve safe and available services, the range of variability in the ionospheric effects (or threats) in the airspace where the GNSS-based air navigation service is provided must be clearly defined.

The ionospheric effects depend primarily on the region with respect to the earth's magnetic field and on solar activity. Thus, the ionospheric effects need to be evaluated in a manner suitable for the region where GNSS-based navigation service is given with data covering high solar activity periods.

2. Distribution of ionosphere

Distribution of the ionosphere is subject to the magnetic latitudes determined by the earth's magnetic field rather than the geographic latitude. The magnetic equator where the magnetic latitude is zero and the magnetic field is horizontal deviate from the geographic equator by about ±10º (Figure A.1).

The ionosphere can be divided into three regions by the magnetic latitude, namely, Low-latitude (±20º), Mid-latitude (20 to about 65º), and High-latitude (above 65º) regions (Figure A.1). Ionospheric dynamics are strongly affected by the magnetic field, and this dynamism makes the ionospheric phenomena vary by region. For example, the aurora-related phenomena is critical in the auroral region, the mid-latitude region is rather moderate except for the period of severe magnetic storms, and the equatorial region is more disturbed due to so called "equatorial anomaly", which translates into the enhancement of ionospheric density around ±15º magnetic latitude due to a local sharp depletion of the ionosphere dubbed "depletions" or "bubbles".

It should be noted that when GNSS signals pass the ionosphere region, the GNSS signals received at a particular site is affected. The locations where signals from a particular satellite passes the ionosphere (Ionospheric Pierce Point: IPP) distribute around the receiving sites with a radius of more than 1600 km (assuming the ionospheric altitute at 350 km), when satellites with elevation angles greater than 5º are used. Providers and regulators of GNSS-based air navigation services should consider the ionospheric effects which influence GNSS performance within the said circular area.

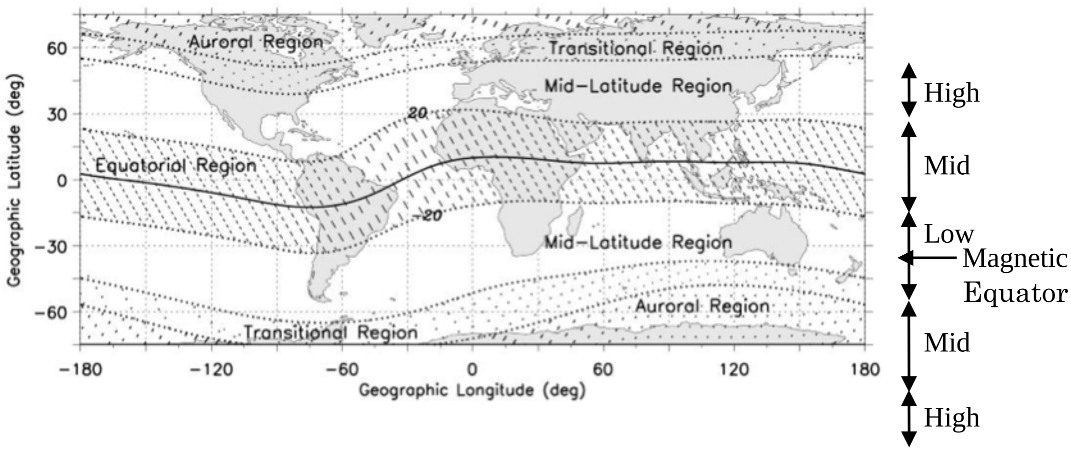

Figure 1. Ionospheric regions (adapted from Figure 3, NSP Iono paper)

3. Solar cycle consideration

The ionospheric activity (density and disturbance) strongly depends on the solar activity in various ways (increase in ionization, increase in the frequency and severity in solar disturbances, increase in thermospheric density and dynamics, etc.). The solar activity has periodicity and repeats the cycle with high and low solar activity periods almost every eleven years. The previous solar cycle reached its bottom in 2009. The current solar cycle is in its increasing phase and is expected to reach its summit around 2013-2014 (Figure A.2). To support GNSS-based services in the long-term, it is obtain to collect ionospheric data during the high solar activity period. Otherwise, it would take another eleven years to obtain data in challenging conditions, which are necessary for GNSS design and engineering to ensure the safety of GNSS-based services as well as the required performance of GNSS.

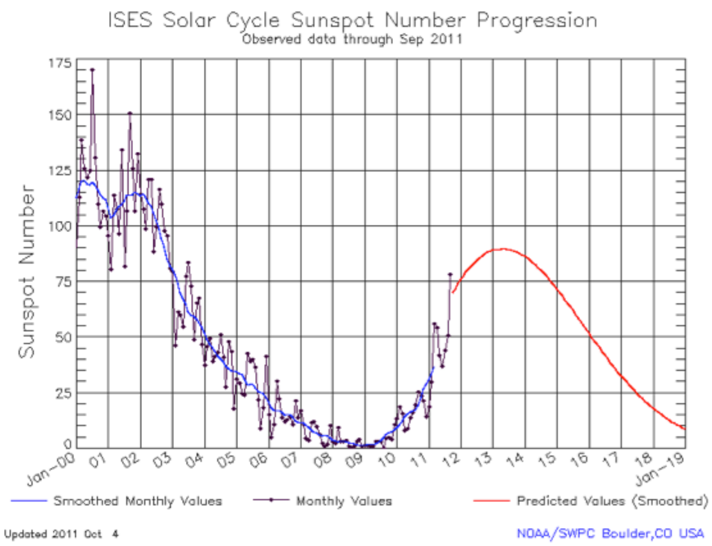

Figure 2. Sun spot number progression as recorded by the U.S. National Oceanic and Atmospheric Administration (NOAA) (Figure 2, NSP Iono paper)

4. Role of providers and regulators of GNSS-based air navigation services

Defining the range and degree of ionospheric variation which affect GNSS performance in their FIRs (ionospheric threat model) is the role of regulators of GNSS-based air navigation services, whether the model is developed by their own or modeled after other data sources. GNSS-based services must be proved to be compliant with international standards by employing the ionospheric characteristics the regulators define. Thus, it is important for regulators and service providers to correctly understand the ionospheric conditions and to build threat models applicable in their FIRs.

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APPENDIX B

IONOSPHERIC STUDY TASK FORCE ACTIVITIY IN ASIA/PACIFIC REGION

1. Background

1.1 In the Asia/Pacific Region, it has been widely recognized that ionosphere data collection is indispensable to characterize the low latitude ionosphere more appropriately for implementing GNSS infrastructure in the region. Such awareness was shared not only by air navigation domain, but also by regional multi-national fora such as Asia Pacific Economic Cooperation (APEC).

1.2 In the ICAO framework, the question on how to properly address ionospheric effects on GNSS was table on the 20th Asia/Pacific Air Navigation Planning and Implementing Regional Group meeting (APANPIRG/20) in September 2009. The meeting resolved that the member States cooperate with each other to collect ionosphere data and urged the member States to provide a focal point of contact in their Administration to ICAO for coordinated collection and exchange of the ionosphere data (Ref. APANPIRG/20 Report).

1.3 As a follow-up to the APANPIRG Resolution, its CNS/MET Subgroup meeting in 2010 agreed on conducting a coordinated ionospheric review and measurement campaign in the Asia Pacific region. Recognizing its dedication to R & D on ionospheric threat modeling as well as GNSS, Japan was invited to assume the technical leadership in that regional missions. (Ref. APANPIRG CNS/MET-SG/14 Report and APANPIRG 21 Report).

1.4 Inception of the mission of convening a workshop on the ionosphere data collection, analysis, and sharing in May 2011, which was followed by establishment of a dedicated Task Force, named “Ionospheric Studies Task Force (ISTF)”, of which outlines are explained in the following sections. The 1st meeting of the ISTF (ISTF/1) was held in Tokyo, Japan, in February 2012 resulting in a good kick-off for driving the regional initiative.

2. Purpose and Terms of Reference

2.1 The objectives of ISTF are to facilitate ionospheric data collection and sharing, to study the need for development of Regional Ionospheric Threat Models for GBAS and SBAS, and to develop them if the need is identified.

2.2 The current TOR of ISTF is as follows: Take the responsibility for identification of the available GNSS data source:

a) make recommendation on sharing scenario for Ionospheric data collected;

b) make recommendations on selecting ionospheric data sources and sharing scenario for the collected data;

c) steer process for evaluation of the data analysis;

d) study the need for development of regional Ionospheric threat models for GBAS and SBAS;

e) provide guidance on the development of regional Ionospheric threat models for GBAS and SBAS if the need is identified; and

f) establish rules for use of shared data and the result of study for non-commercial purpose.

3. Membership

3.1 The membership of ISTF is open to all the member States of APANPIRG.

3.2 The ISTF/1 meeting was attended by 9 States/Administaions including Australia, Hong Kong China, India, Japan, The Philipines, Republic of Korea, Singapore, Thailand, and United States of America.

3.3 The States which are not participating in the Ionospheric Studies Task Force are expected to share ionospheric data from their national sources with the Task Force to support development of regional ionospheric models for GBAS and SBAS.

4. Work plan

4.1 Five specific tasks were identified by ISTF/1 with sequence and corresponding task leads as follows:

a) identification of data source, GNSS data collection, sharing, distribution and archiving. Identification of data sharing format. (Sequence 1);

b) identification of analysis methodology and GNSS ionospheric data analysis (Sequence 1);

c) GNSS total electron content (TEC) gradient data generation (Sequence 2);

d) GNSS ionospheric scintillation data generation (Sequence 2); and

e) assessment of need to Regional GBAS and SBAS ionospheric models and development of these models if it is needed (Sequence 3).

4.2 The ISTF plans to have meetings twice in the first year and once from the second year, with a target of delivery of its final product by 2014.

5. Financial implication

5.1 The ISTF activities are supported by the voluntary contributions by the participating States, who have already been engaged with great interest in their domestic activities in this subject.

5.2 The cost incurred from data collection and ionospheric threat modeling can be minimized by making the best use of the GNSS networks which have already been operated by national organizations for such purposes of geodetic reference, reference for intelligent transportation system, GNSS augmentation or scientific research. In light of the regional or global nature of GNSS and the entire implementation cost of relatively large-scale projects, team work by those of the common interest can reduce the total cost and time by avoiding duplication of similar work as well as system harmonization in an efficient way. ICAO, being as facilitator or usher, assists them in building inter-regional or global ionospheric threat models, which allow States and ANSPs to enhance PBN as well as GNSS in a globally harmonized fashion.

5.3 The ISTF adopted a sample MOU for assisting States in entering into a data sharing agreement with their national organizations concerned.

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