International Civil Aviation Organization

FIRST MEETING OF IONOSPHERIC STUDIES TASK FORCE (ISTF/1)

27 – 29 February 2012, Tokyo, Japan

国土交通省

Agenda Item 2: **Review of relevant meetings/conferences**

IONOSPHERIC EFFECT ON GNSS AVIATION OPERATIONS

(Presented by the Secretariat)

SUMMARY

ICAO NSP developed the document "Ionospheric Effect on GNSS Aviation Operations" in 2006 for guidance in the implementation of GNSS. NSP Working Group of the Whole felt that this document should be reviewed and revised to reflect the developments that had taken place since the time the document was first developed. An Expert Group was appointed to review and update the document. This paper presents the draft revised/updated document for review by the Meeting.

This paper relates to -

Strategic Objective:
A: Safety – Enhance global civil aviation safety
C: Environmental Protection and Sustainable Development of Air Transport – Foster harmonized and economically viable development of international civil aviation that does not unduly harm the environment

Global Plan Initiatives:
GPI – 21 Navigation systems

1. INTRODUCTION

1.1 ICAO Navigation Systems Panel (NSP) appointed a group of experts in the NSP Working Group Meeting held from 11 to 21 October, 2005 to develop a document on Ionospheric Effect on GNSS Aviation Operations. NSP reviewed the draft document in the Group meeting held in Brussels, Belgium from 8 to 19 May, 2006. The draft was approved in the meeting held from 10 to 20 October, 2006 and was subsequently circulated by ICAO.

1.2 During Ninth NSP Working Group of the Whole meeting held in Montreal from 9 to 18 November, 2010 it was informed that concerns had been raised by some States regarding the vulnerability of aviation to the increased solar activity expected to occur in next few years, when the solar cycle reaches its next peak. It was therefore agreed that the 2006 paper should be updated to reflect current state of knowledge as well as the evolution of mitigation techniques over the last five years. Meeting appointed an Ad hoc group of experts to review NSP document on ionospheric effects (adopted in 2006) and report on its progress at the next meeting.

1.3 Pursuant to the above Action Item, the updated and revised document was presented to the Eleventh NSP Working Group of the Whole meeting held in Montreal from 6 to 14 December, 2011.

2. DISCUSSION

2.1 Draft updated/revised "Ionospheric Effects on GNSS Aviation Operations" paper presented to the NSP Working Group of the Whole meeting in December 2011 briefly explains how solar activity affects the upper atmosphere and how regions of ionized gas in the ionosphere affects GNSS signals. This draft document revises/updates the document which was adopted by ICAO NSP in 2006. The draft paper presented to the meeting is placed as an attachment.

2.2 NSP Working Group of the Whole was invited to review the draft and provide comments. It was proposed that the final version of the paper will be provided to the Secretariat by the end of February, 2012.

2.3 It was informed to NSP Working of the Whole meeting that several sections were partially or completely re-written. The main changes, are briefly summarized below:

The summary (abstract) on the front page was completely re-written

a) The executive summary was revised in order to put a greater emphasis on operational impacts;

b) Paragraph discussing GRAS were removed and replaced with a simple footnote mentioning that GRAS is defined in Annex 10;

c) A Table of Contents and a List of Figures were added;

d) The material on data collection was moved to Section 7 on ionospheric research, and that section was completely re-written (and much of the old material was eliminated);

e) The material on Space Weather was revised and integrated into Section 2, which introduces the ionosphere (and the list of historical examples of space weather manifestation was shortened and moved to footnote);

f) A short Section 8 on solar radio busts was added;

g) A short Section 9 summarizing the main points of the paper was added;

h) The material in Section 3.2 on the low magnetic latitude region was revised;

i) Section 4 on mitigation techniques was shortened and several paragraphs were revised;

j) Section 5 on the impact on operational service was largely rewritten; and

k) The list of references was revised and shortened

2.4 The meeting is invited to review the paper and forward comments to Mr. Roland Lejeune at the address rlejeune@mitre.org

3. ACTION BY THE MEETING

3.1 The meeting is invited to review the attached document "Ionospheric Effects on GNSS Aviation Operations" and provide its comments to Mr. Lejeune.

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DRAFT – 8 November 2011

INTERNATIONAL CIVIL AVIATION ORGANIZATION NAVIGATION SYSTEMS PANEL (NSP)

Ionospheric Effects on GNSS Aviation Operations

December 2011

Summary

This paper was developed by the ICAO Navigation Systems Panel to present a broad discussion of ionospheric effects on GNSS. The information in the paper is similar to that provided in the 2006 paper with the same title, which was circulated to ICAO Regional Offices. However, major portions of the paper have been updated to account for progress in research and experience acquired in the provision of GNSS services since 2006.

The paper briefly explains how solar activity affects the upper atmosphere of the earth and how regions of ionized gas in the upper atmosphere (ionosphere) affect GNSS signals. GNSS signals received on the ground, as well as in flight, are delayed by their propagation through the ionosphere, and in some circumstances fluctuations in the amplitude and phase of the received signals (scintillation) can affect the ability of a receiver to track them. The paper explains how these ionospheric effects vary during the eleven-year solar cycle as well as from one region of the world to another. The paper then provides a high level discussion of techniques used by ABAS, SBAS and GBAS to mitigate these effects in order to meet the accuracy, availability, continuity and integrity requirements in Annex 10 for GNSS-based navigation. Finally, the paper discusses the operational impact of the ionosphere during nominal and perturbed ionospheric conditions on the different navigation services from en route navigation to Category II/III precision approach.

GNSS implementation programs need to take into account potential limitations and disruptions to GNSS service due to ionospheric effects. Unique phenomena of the ionosphere of the equatorial region may severely limit the availability of SBAS-based approach with vertical guidance (APV) service in that region. Severe ionospheric storms will disrupt SBAS-based APV service in mid-latitude regions about 1% of the time. Some limitations to the availability of GBAS landing services may result from the need to adapt a GBAS installation to the local ionospheric environment, and thus the availability of GBAS Category I/II/III services may vary from one region to another. En route and terminal area navigation services are very robust to ionospheric effects. However, severe ionospheric scintillation may sometime cause temporary losses of these services in low latitude and high latitude regions. Some increase in the frequency of SBAS-based APV service disruptions should be expected in 2013 when the solar cycle is predicted to reach it next peak as well as during a few years after 2013 when ionospheric storms tend to occur a little more frequently. This being said, experience acquired during the past fifteen years of GNSS implementation, including the 2000-2001 solar cycle peak, indicates that the vulnerability GNSS service to ionospheric effects is sufficiently well understood and limited to not compromise the ultimate goal of transition to GNSS as a global source of navigation for all phases of flight.

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Executive summary

Elements of the Global Navigation Satellite Systems (GNSS) are standardized in ICAO Annex 10 and various industry standards such as those published by RTCA Inc. in the United States and the European Organisation for Civil Aviation Equipment (EUROCAE). GNSS includes three different types of systems: Airborne-Based Augmentation Systems (ABAS), Satellite-Based Augmentation Systems (SBAS) and Ground-Based Augmentation Systems (GBAS). The services provided by all of these systems are affected by the ionosphere to various degrees.

The ionosphere is a region of the upper atmosphere ionized by solar radiations and therefore containing ions and free electrons. The free electrons affect the propagation of radio signals. In the frequency band used by GNSS (L band), the two main effects are: a delay in the propagation of the modulation (i.e., the code carried by the signal from which pseudorange measurements are made) and, in some regions, rapid fluctuations in the power and phase of the received signal. The first effect is known as "group delay"; it causes errors in pseudorange measurements. The second effect is called "scintillation"; it can cause a receiver to lose lock on one or more satellite signals. While the errors in pseudorange measurements caused by group delay are typically of the order a few tenths of meter, they can exceed 100 m on rare occasions.

The behavior of the ionosphere, as far as its observable effects on radio signals are concerned, varies with time and location. Since the ionization of the upper atmosphere (i.e., the ionosphere) is caused by radiations from the sun, the density and altitude distribution of free electrons vary with both solar activity and solar exposure. In particular, they vary with the 11-year solar cycle, the season of the year, and time of day. They also vary as a function of geomagnetic latitude. Finally, they can be severely perturbed by rare magnetic (ionospheric) storms caused by powerful energetic emissions from the sun, as well as massive spatial re-distributions of free electrons in the ionosphere that occur in the equatorial area.

In general ionospheric effects in mid-latitude regions are mild: variations in ionospheric delays are gradual and scintillation is virtually inexistent. However, severe ionospheric (magnetic) storms will occasionally disrupt the ionosphere resulting in an increased spatial and temporal variability of ionospheric delays and sometime in moderate to severe levels of scintillation. In low-latitude regions, ionospheric effects are more severe. Large variations in ionospheric delays and localized irregularities caused by the physics of the ionosphere near the geomagnetic equator occur in the local evening hours almost on a daily basis. In addition, they are often accompanied by severe amplitude and phase scintillation. The intensity of these phenomena increases near the peak of the solar cycle. In high-latitude regions, ionospheric effects are more severe than in mid-latitude regions, but less severe than in low-latitude regions. While ionospheric delays in high-latitude regions tend to be fairly variable, the delays themselves are generally much smaller than in low-latitude regions, and therefore their variations have smaller amplitudes. Scintillation can also occur in high-latitude regions, particularly during periods of increased ionospheric activity, and occurs mainly in the form of phase scintillation.

Current GNSS avionics systems relying on the Global Positioning System (GPS) make pseudorange and phase measurements at a single frequency (GPS L1 frequency). These systems are unable to compensate directly for ionospheric delays and thus need to apply corrections in order to reduce the measurement errors they would otherwise induce. ABAS, SBAS and GBAS use different approaches to correcting for these delays.

Current ABAS avionics systems use simple models and associated sets of parameters broadcast by core constellation satellites. These models provide an adequate representation of ionospheric delay variations on the average, but are unable to account for localized effects such as might be caused by ionospheric storms, or by the formation of crests in ionospheric delays known as "anomalies" in equatorial regions, for example. This approach to correcting for ionospheric delays is adequate for phases of flight from en route navigation to non-precision approach, but it is not adequate for any form of approach operation during which vertical guidance is provided.

Single-frequency SBAS avionics systems use ionospheric corrections updated in real-time by the SBAS ground system and broadcast by the SBAS satellites. The SBAS ground system derives ionospheric delay information from pseudorange and phase measurements made at both the GPS L1 and L2 frequencies. (It is able to track the GPS L2 signal using a semi-codeless tracking technique, which is not appropriate for receivers in dynamic motion.) The approach to correcting for ionospheric delays used by single-frequency SBAS is adequate for Approaches with Vertical Guidance (APV) as well as for phases of flight from en route navigation to non-precision approach.

Single-frequency GBAS avionics systems correct for the combined effects of multiple sources of range measurement errors simultaneously, including satellite clock and ephemeris errors, ionospheric delay errors, and tropospheric delay errors, using the differential corrections broadcast by a GBAS ground station. This approach is used for all categories of precision approach operations; however, additional requirements must be met both by the ground station and the avionics in order to support Category II/III (CAT II/III) precision approach and landing operations. The integrity architecture used for GBAS CAT II/III service is different than the integrity architecture used for GBAS CAT I service: for CAT II/III service, integrity monitoring responsibilities are allocated to both the ground station and the user equipment, while for CAT I service all integrity monitoring is done in the ground station. The availability of CAT I service is expected to be very high in mid-latitude regions. Studies being performed in the context of GBAS system development programs will determine the achievable level of CAT I service availability in low latitude regions. The levels of CAT II/III service availability achievable in the various regions of the world are yet to be determined.

GNSS-based navigation is vulnerable to temporary losses of service caused by ionospheric events. It is difficult to precisely characterize the risk, duration and geographic extent of such service outages; however, experience acquired thus far confirms that navigation services for en route, terminal area and non-precision approach operations are very robust to ionospheric events. This is true whether these services are based on ABAS or SBAS. In some cases, particularly in the equatorial area, ionospheric scintillation in the local evening hours may cause repeated, short outages of a few minutes due to the loss of one or more critical satellites. Similar infrequent losses of service due to scintillation may also occur in high latitude regions. SBAS-based navigation is more robust to scintillation than ABAS-based navigation because an ABAS receiver depends on Receiver Autonomous Integrity Monitoring (RAIM) for integrity, and thus requires more satellites in view and a better satellite geometry than an SBAS receiver within the service area of an SBAS. SBAS-based APV service is more sensitive to ionospheric effects. Severe ionospheric storms have caused occasional outages of APV service over wide areas lasting several hours. Such occasional outages are expected to occur again, particularly during a period of about three to four years following a peak of the solar cycle. However, such conditions are not expected to occur more than two or three times per year, on average, during this approximately three-to-four year period, and they are not expected to occur more than once a year, on average, during the remaining approximately eight-to-nine years of the solar cycle. SBAS-based en route through non-precision approach is not affected by similar outages. GBAS service does not suffer outages during severe ionospheric storms, but a GBAS installation must be adapted to the local ionospheric environment, and therefore the overall availability of GBAS service may be lower in regions where the ionosphere is more highly variable than in mid-latitude regions where the initial studies in support of GBAS were performed.

By 2020, new and modernized core constellations will broadcast civil signals on two or more aeronautical frequencies. GNSS avionics systems capable of tracking multiple frequencies will then become commercially available, and they will likely become predominant as time passes. Using dual-frequency measurements, these avionics systems will be able to compute pseudorange measurements that are free of ionospheric delay. This will be a welcome development that will essentially reduce the ionosphere from a major to a minor contributing source of navigation error for GNSS-based navigation services.

Receiver capable of tracking the GPS L5 and/or Galileo E5 coded signals will be much more robust to scintillation effects than existing SBAS ground system receivers tracking the GPS L2 signal using semi-codeless techniques[1]. Nevertheless, in some regions during periods of intense scintillation, the possibility of losing track on signals from a few low elevation satellites that are affected by scintillation will continue to exist. However, the risk of losing navigation due to scintillation will likely be significantly reduced, and perhaps eliminated, when the receiver is capable of tracking the signals from multiple core constellations simultaneously.

[1] Support for semi-codeless tracking of the L2 signal will no longer be supported after 31 December 2020 (see IP15 from the October 2008 WGW meeting). Efforts are being put in place to modify existing SBAS implementations by 2020 in order to track the GPS L5 signal instead of the GPS L2 signal.

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December 2011

Ionospheric Effects on GNSS Aviation Operations

1. Introduction

This paper provides a high-level discussion of ionospheric effects on Global Navigation Satellite Systems (GNSS) standardized in ICAO Annex 10 and various industrial standards [ICAO, 2005; RTCA 1993, 2000, 2001a, 2001b]. It is intended to provide initial insight into the issues raised by the ionosphere to aviation decision makers and navigation engineers working on GNSS implementation programs. The various forms of GNSS implementation are covered, including Airborne-Based Augmentation Systems (ABAS[2]), Satellite-Based Augmentation Systems (SBAS) and Ground-Based Augmentation Systems (GBAS)[3].

The material in this paper reflects the experience acquired over several years of research and development activities in support of GNSS implementation. The discussion covers signal propagation delays and their effects on pseudorange measurements, and scintillation and its effects on signal tracking. It also covers ionospheric phenomena such as ionospheric (magnetic) storms, equatorial anomalies and depletions. These phenomena should be taken into consideration when planning the implementation of an augmentation system because their effects on certain navigation services can be significant [SBAS Ionospheric WG, 2003, 2010].

The discussion covers the various parts of the world. However, it does not do so to a uniform extent and depth because much understanding is yet to be gained in some regions of the world, particularly those regions where ionospheric effects on GNSS are more complex and more severe. These regions are also those where GNSS implementation efforts are still in their early stages.

1.1 Scope

This paper is intended to highlight ionospheric effects that are relevant to GNSS, and outline correction and mitigation techniques. It provides a high-level discussion of the ionosphere and is not intended to explore the physics of the ionosphere. Material on these topics can be found in a few specialized textbooks as well as in numerous research papers [Davies, 1990; Hargreaves, 1995; Kelley, 1989].

This paper discusses augmentation systems but does not provide detailed technical information on system designs, nor describe the algorithms that have been developed to correct or mitigate ionospheric effects. Some information on such topics can be found in numerous research papers presented to the International Ionospheric Effects Symposium, the Institute of Navigation (www.ion.org), the Royal Institute of Navigation (http://www.rin.org.uk), the International Union for

[2] As defined in Annex 10, Section 3.7.1, ABAS includes a variety of designs depending on the degree to which other information available on board the aircraft (e.g., from and Inertial Navigation System) is integrated into the position solution. In this paper, the terminology ABAS is used to refer to a receiver that relies exclusively on GNSS signals to calculate position and has a Fault Detection and Exclusion function to ensure the integrity of the solution.

[3] Ground-based Regional Augmentation System (GRAS) is also standardized in Annex 10, but it is not covered in this paper since there are currently no plans to implement GRAS.

Radio Science (URSI) (http://www.ursi.org), and other technical forums. The reference section lists some of these papers.

1.2 Operational categories

For the purposes of this discussion, the range of navigation services can be divided into three major categories: en route through non-precision approach (ER/NPA), approach with vertical guidance (APV); and (Category I/II/III) precision approach and landing (PA).

Note 1: This paper uses the terminology APV for approach services during which SBAS user equipment provides vertical guidance. The terminology used in the operational context for these services is Localizer Performance with Vertical guidance (LPV). There are slight differences between the notions captured by these two terminologies. In particular under appropriate circumstances, LPV can be used for operations associated with a 200 ft Decision Height (LPV-200). However, these differences have no impact on the high-level discussion in this paper.

Note 2: Annex 15 defines two types of APV operations: one during which vertical guidance is provided by an approved barometric altimeter (APV/Baro-VNAV) and one during which vertical guidance is provided by SBAS (SBAS-based APV). During APV/Baro-VNAV approaches, GNSS generally provides horizontal guidance, and so from the point of view of ionospheric effects, these approaches have the same vulnerability as NPA operations (also known as Lateral Navigation, or LNAV operations). Therefore, in the context of this paper, the term APV is used exclusively in reference to SBAS-based APV.

1.3 Primary focus

For reasons to be discussed later, the current airborne receiver technology is limited to single-frequency equipment. Therefore, while the future of the satellite navigation technology resides in dual-frequency, multi-constellation receiver designs, the discussion in this paper will be primarily, although not exclusively, oriented toward single-frequency users of GPS signals and GPS augmentations.

1.4 Organization

This paper covers the various topics briefly outlined above in the following order.

Section 2 discusses the ionosphere and its main effects on GNSS including propagation delays and scintillation. It also presents introductory material on solar activity and space weather.

Section 3 discusses differences between ionospheric effects in equatorial, mid-latitude, and auroral regions. It includes brief discussions of ionospheric (magnetic) storm effects, scintillation, as well as unique phenomena of the equatorial ionosphere.

Section 4 discusses correction and mitigation techniques for the effects described in Sections 2 and 3. The discussion includes mitigation techniques that are used in existing GNSS implementations as well as other potential mitigation techniques.

Section 5 discusses the impact of the ionosphere on operational service. The discussion is based on the experience gained during the last fifteen years of GNSS implementation. This experience was primarily acquired in mid- and, to a lesser extent, high-latitude regions, and therefore this section may need to be updated once GNSS implementation in low-latitude regions has further progressed.

Section 6 discusses GNSS evolution and the performance improvements that will become possible when dual-frequency signals will give user receivers the ability to essentially remove ionospheric delays from range measurements.

Section 7 discusses the need for data collection and analysis in the context of a GNSS implementation program.

Section 8 briefly discusses solar radio bursts.

Section 9 contains a brief summary of the main points discussed in the paper.

2 The ionosphere and its main effects on GNSS

The ionosphere is a region of the upper atmosphere that has been ionized by solar extreme ultraviolet (EUV) and other emissions from the sun. It is located roughly between 50 km and 1000 to 1200 km above the Earth's surface. The densities of atoms at these altitudes are very small, but the fact that a small fraction of these atoms are disassociated into ions and free electrons confer to this medium (plasma) noticeable electromagnetic properties. In particular, the presence of free electrons in the upper atmosphere affects the propagation of radio signals.

The ionosphere is composed of several overlapping regions corresponding to changes in the chemical composition of the atmosphere (Oxygen and Nitrogen in the lower altitudes, Helium, then Hydrogen in the higher altitudes) and the depth of penetration of the solar radiations responsible for the ionization (hard x-rays, Lyman α radiation, soft x-rays or extreme ultraviolet radiation, EUV). Four regions are specifically identified, which are labeled D, E, F1 and F2 [Klobuchar, 1996]. The D, E, and F1 regions are located at the lower heights (from 50 km to about 210 km); these regions normally disappear during the local night. In the E region heights, a thin but very dense layer mainly consisting of metallic ions often appears. The layer is called "sporadic E layer" or "Es layer", because it appears and disappears sporadically. The F2 region occupies the higher heights (from about 210 km to about 1000 km). Among the four regions, the F2 region has the greatest concentration of free electrons with a peak density at a height that varies between 250 km and 400 km. The F2 region is present during the night as well as during the day, although ion recombination causes the concentration of free electrons to decrease during the night. This region has the greatest effect on the propagation of radio signals, in particular GNSS signals (L-band). It is also the most variable and the least predictable.

2.1 Solar activity and space weather

The structure of the ionosphere is continually varying in response to changes in the intensities of solar radiations. As solar radiation increases, the electron density in the ionosphere also increases. The increase in solar radiation changes the structure of the background neutral atmosphere and changes the electrodynamics of the ionosphere. The ionosphere is also affected by changes in the magnetic field of the earth resulting from its interaction with the *solar wind*, a stream of ionized material ejected by the sun into space and carrying a magnetic field. Infrequent high-energy particles ejected into space during powerful solar eruptions such as coronal mass ejections and solar flares can cause large disturbances, called *magnetic storms*, to the magnetic field of the earth. These powerful eruptions can also cause perturbations to the structure of the ionosphere, called *ionospheric storms*. Finally, these powerful eruptions are sometimes accompanied by bursts of energy in a wide band of radio frequencies, called *solar radio bursts*, which can interfere with radio transmissions on the earth. Geomagnetic and ionospheric phenomena affect communications, GNSS, and other systems (such as the electric power grid for example[4]) on which our technological society depend. They are generically referred to as *space weather*[5] and are the subject of active scientific research.

Solar activity generally varies according to an 11-year cycle. This cycle consists of a period of increased activity culminating in a peak, or maximum, followed by a period of low activity during which the intensity of radiations deceases to a low level and the severity and probability of occurrence of eruptions are much lower (but not equal to zero). This cycle is generally characterized by the Sun Spot Number (SSN)[6], which is the arithmetic sum of visible dark spots on the solar surface. As this parameter is quite easy to determine, it has been recorded since 1749. Figure 1 shows solar activity as indicated by the SSN. The figure highlights the fact that some solar cycles have higher peaks than others. However, the intensity of the solar cycle is not directly linked to the severity of solar eruptions. As an example, one of the most severe solar storms has been recorded in 1859 during a moderate solar cycle.

[4] Geomagnetic storms can induce electrical currents into the power grid, which can lead to electrical failures. On March 13th, 1989, for example, the entire power grid in Quebec, Canada, collapsed and 6 million people were affected.

[5] A visible manifestation of space weather occurs when high energetic particles from the sun penetrate the earth's atmosphere and follow the earth's magnetic field lines toward the magnetic poles creating a display of natural light in the sky called aurora. Such displays usually happen in the northern latitudes, but they can sometimes also be seen at lower latitudes during severe geomagnetic storm events.

[6] Another measure frequently used is the solar flux at a wavelength of 10.7 cm (F10.7), which varies from about 80 solar flux units (SFUs) at the minimum of the solar cycle to about 200 SFUs at the maximum of the solar cycle. This measure is referred to in Figures 15 and 16.

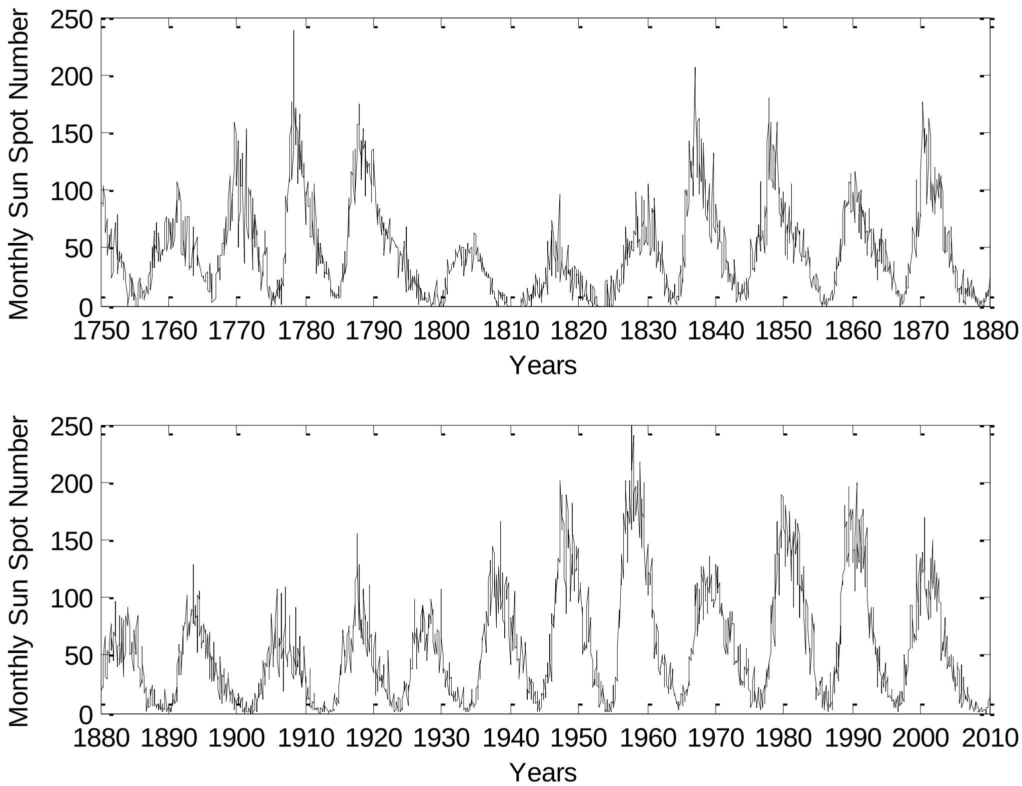

Figure 1: Sun Spot Number evolution

Once the period of minimum solar activity of the previous solar cycle has been reached, observations of solar behavior as the new cycle begins allow the space weather scientific community to make predictions regarding the next solar cycle. Figure 2 shows the latest prediction (updated in February 2011) of the next solar cycle. The intensity of the next solar cycle is expected to be moderate with the SSN peaking at about 90 in mid-2013. Since strong solar eruptions are most likely to occur during the period of maximum solar activity, and also during the period of solar activity decrease that follows, the probability of occurrence and severity of solar eruptions is expected to be the highest from 2012 to 2017. Figure 2 also shows the evolution of the SSN since January 2000.

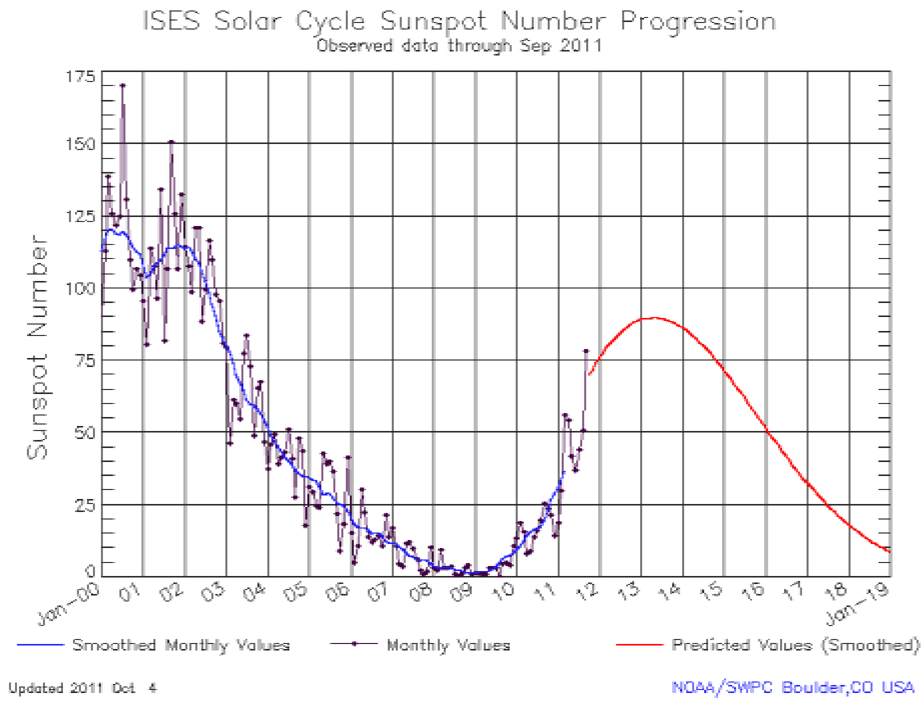

Figure 2: Sun Spot Number progression as recorded by the U.S. National Oceanic and Atmospheric Administration (NOAA)

2.2 Main effects of the ionosphere on GNSS

The main causes of large scale (and somewhat repeatable) variations in the distribution and density of free electrons in the ionosphere are related to the 11-year solar cycle, seasonal changes, and diurnal changes. Plasma densities are greater near the peak of the solar cycle than near its minimum; they are greater toward the middle of the day (local time) than at night; and they tend to be greater around the equinoxes. Major causes of both large and small scale irregularities in the distribution of free electrons in the ionosphere are related to ionospheric storms, as well as plasma drifts causing the displacement of large masses of free electrons both in altitude and latitude. Such a large plasma drift characterizes the ionosphere over the magnetic equator and the low latitude regions. It is responsible for the development of crests of electron content known as Appleton anomalies, and therefore also for the existence of large horizontal and vertical gradients of electron content in these regions.

At the frequencies used by GNSS (L-band), the ionosphere has three main effects on the propagation of signals between satellites and receivers near the surface of the earth (whether on the ground or airborne): group delay, scintillation, and Faraday rotation. Group delay is a consequence of the dispersive nature of the medium, which causes sinusoidal waves with different frequencies to travel at slightly different velocities. This in turn causes complex signals that can be represented in terms of groups of waves (e.g., modulation) to travel at a slower velocity, called group velocity, than the so-called phase velocity of the carrier wave. As a result, the time of arrival of a modulated satellite signal at the receiver is delayed compared to what it would be in neutral free space. This phenomenon also causes an advance in the phase of the carrier with a magnitude equal (but with opposite sign) to group delay. Ionospheric scintillation causes rapid variations in the amplitude and phase of a received signal. If the amplitudes of these variations are sufficiently large, a receiver may not be able to maintain lock on the signal, at least during the short periods of deep fades (typically of the order of a second or less). Faraday rotation affects the polarization of linearly polarized signals. Since GNSS signals are circularly polarized, GNSS is insensitive to Faraday rotation, and therefore this effect will not be further discussed in this paper.

2.2.1 Propagation delay effects

The amount of delay affecting a particular signal is proportional to the total number of free electrons along the propagation path between satellite and receiver. A frequently used measure of that number is called the Total Electron Content (TEC). TEC represents the number of free electrons in an imaginary column along the propagation path with a cross-sectional area of one square meter. There are two versions of that measure: one refers to the TEC along a vertical path[7], the other to the TEC along an oblique (or slant) path[8]. In a good, first order approximation, the amount of delay affecting a signal in the band of frequencies used by GNSS is inversely proportional to the square of its carrier frequency but proportional to TEC (i.e., the integral of the electron density) along the ray path. The following formula expresses this delay as a distance corresponding to the apparent increase in path length:

$$d_I = \frac{K}{f^2}\int_S^R n_e\,ds = \frac{K}{f^2}TEC \qquad (1)$$

where d_I is in meters, K is a constant equal to 40.3 m^3s^{-2}, f is the carrier frequency of the signal (Hz), n_e is the electron density (el/m^3), and the integration is from the satellite (S) to the receiver (R).

TEC is frequently measured in terms of TEC units (TECUs). One TECU corresponds to 1×10^{16} e^-/m^2. At the GPS L_1 frequency of 1.57542 GHz, 1.0 TECU is equivalent to a delay of 0.542 nanoseconds (ns), or an apparent increase in the path length of 0.163 m [Klobuchar, 1996].

The TEC between a satellite and a receiver is referred to as "slant" TEC. The slant TEC for a satellite with a low elevation angle is larger than that for a satellite with high elevation angle because the propagation path through the ionosphere is longer for a low elevation satellite. The amplification factor due to the obliquity of the propagation path ranges from 1 to about 3 and is called "slant factor".

2.2.2 Scintillation effects

Irregularities in the distribution of free electrons along the propagation path due to small structures in the ionosphere can scatter radio waves and cause rapid fluctuations in the amplitude and phase of received signals, a phenomenon known as ionospheric scintillation. Amplitude scintillation, or signal fading, causes fluctuations in the signal-to-noise ratio or the received signal and can lead to short-term losses of signal tracking. Phase scintillation affects the ability of a receiver's tracking loop to maintain lock on the carrier signal and can cause cycle slips and even a complete temporary loss of signal tracking.

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[7] This version corresponds to the original definition of TEC, which is commonly used by scientists of the ionosphere.
[8] This version is an adaptation of the original measure that is commonly used when GNSS signals are used to obtain TEC measurements.

The amplitude and phase fluctuations are characterized by two parameters known as S4 and σ_ϕ. The amplitude scintillation parameter, S4, is defined as the ratio of the standard deviation of the signal intensity (or power) to its mean value. The phase parameter, σ_ϕ, is defined as the standard deviation of signal phase variations. GNSS receiver performance is relatively insensitive to values of S4 that remain at or below 0.5 for carrier-to-noise density ratio (C/N_0) above 30 dB-Hz and values of σ_ϕ that remain at or below 0.15 radians for C/N_0 above 30 dB-Hz. It should be noted that S4 is proportional to $1/f^{1.5}$ and σ_ϕ is proportional to $1/f$, where f is the carrier frequency of the signal so that scintillation effects are stronger on lower frequencies (i.e., GPS L5 and Galileo E5 as compared to GPS L1).

3. Ionospheric effects as a function of (magnetic) latitude

In order to further characterize ionospheric effects on GNSS, it is convenient to divide the world into three main regions:

1. the low-latitude regions including the equatorial and equatorial "anomaly" regions (shown as one band between 20º N and 20º S of magnetic latitudes in Figure 3),
2. the mid-latitude regions (extending from 20º to about 65º), and
3. the high-latitude regions (above 65º) which include the auroral and polar cap regions.

Figure 3 illustrates the approximate geographic extent of each of these main regions. During typical geomagnetic conditions, the mid-latitude regions include the transitional regions. During disturbed geomagnetic conditions, the auroral regions can expand toward equator to include all or part the transitional regions, thus reducing the width of the mid-latitude regions [SBAS Iono WG, 2003].

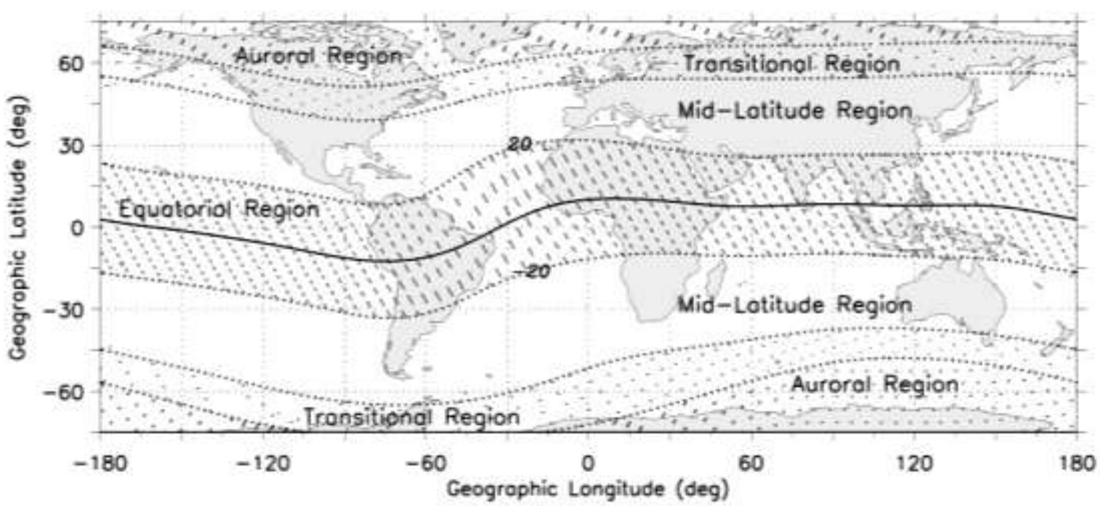


Figure 3: Ionospheric regions [SBAS Iono WG, 2003]

The polar regions are generally thought of as being at magnetic latitudes greater than about 75°. They are not illustrated in Figure 4 due to the distortion of the Mercator map projection, which overemphasizes the extent of the high latitude regions. The largest region is the equatorial and equatorial anomaly region, which covers a band of latitudes of about 20° on each side of the magnetic equator. Most of the continents of South America and Africa are located in this region as are large portions of South Asia.

It is important to note that GNSS receivers acquire and track satellites down to an elevation angle of 5 degrees (and in some cases down to 2 degrees) above the horizon, and therefore, GNSS receivers located in the northern (southern) lower mid-latitudes can be affected by the ionosphere in the equatorial region when they track GNSS satellites at relatively low elevation angles to the south (north) of their locations. Receivers in Southern Japan for example can see portions of the equatorial ionosphere. Likewise, receivers in the higher mid-latitude regions can be affected by the ionosphere of the nearest auroral region. This effect is further magnified by the slant factor. As a result, the ionosphere of the low and high-latitude regions can affect GNSS beyond the boundaries of these regions shown in Figure 3.

Figure 4 is a typical map showing the magnitudes of vertical ionospheric delays across the world, in units of meters at the GPS L1 frequency (1575.42 MHz), for typical conditions (i.e., quiet ionosphere) near an equinox during a year near a solar maximum at 00 Universal Time (UT). The map was constructed using the Parameterized Ionospheric Model (PIM), a well-established computer model developed from a large database of ionospheric TEC measurement data [Daniell et al., 1995]. Note that the vertical delay contours over the North America and Europe are fairly far apart (i.e., the spatial gradients are small) and indicate a maximum range delay of approximately 10 meters. In contrast, large range delay values of up to 22 meters and large spatial gradients can be seen over the South American continent at the time of the map.

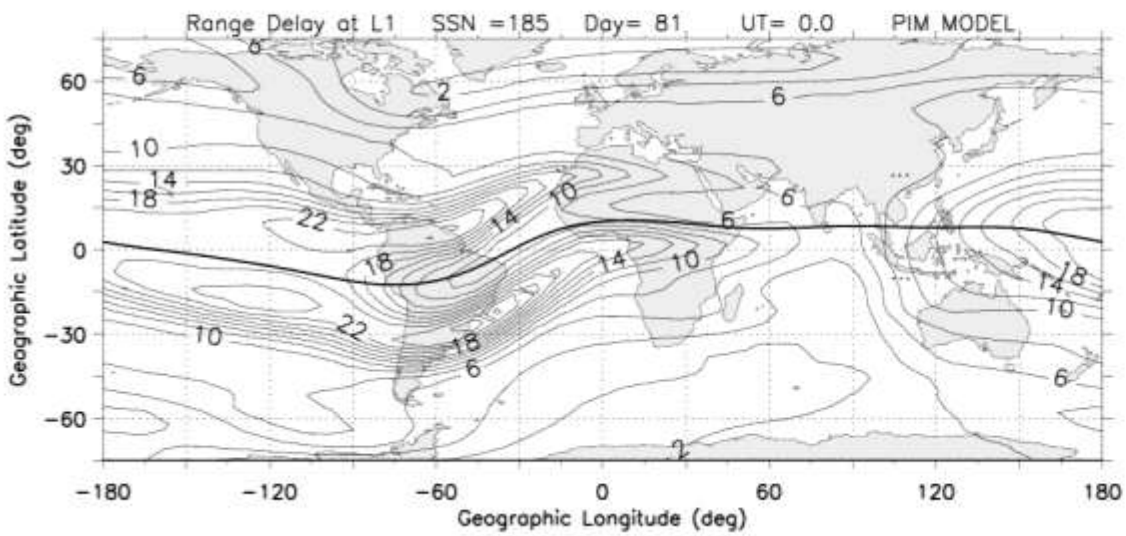


Figure 4: Contours of equal vertical ionospheric range delay, in meters at L1, for typical solar maximum equinox conditions at 00 UT [SBAS Iono WG, 2003]

As the earth rotates, its exposure to the sun changes and the range delay contours shown on the figure move approximately westwards along lines of constant magnetic latitudes at the earth's rotation rate of 15° per hour. So, the large spatial gradients over the eastern portion of South America at 00 UT will be located over the middle of Pacific approximately 8 hours later, then over Asia approximately 13 hours later, and over Africa and the southernmost part of Europe approximately 20 hours later.

The following discussion separates between the three main regions. It starts with the mid-latitude regions where ionospheric effects are less complex than those seen in other two regions under the prevalent nominal ionospheric conditions (i.e., quiet ionosphere).

3.1 Middle magnetic latitude regions

3.1.1 Propagation delay effects

The ionosphere of the mid-latitude regions is characterized by relatively small and slowly varying spatial gradients under normal conditions. Normal conditions exist when the ionosphere is quiet (i.e., not disturbed), which is the case approximately 98% of the time. During the remaining approximately 2% of the time, geomagnetic storms cause the ionosphere to be disturbed. There are several levels of ionospheric storms ranging from *minor storms* to *severe storms*. The effect of an ionospheric storm on a GNSS aviation user varies depending on the intensity of the disturbances it causes in the region where the user navigates, and also on the type of flight operation being conducted.

Severe ionospheric storms are relatively rare (less than 1% of the time), but they can have a noticeable effect on the typical spatial vertical delay distribution (map), which is normally relatively flat in mid-latitudes as shown on Figure 4. For example, Figure 5 shows the distribution of vertical delays observed with a dense network of dual-frequency GPS receivers in the United States at 22:10 UT during the severe ionospheric storm of October 29-31, 2003.

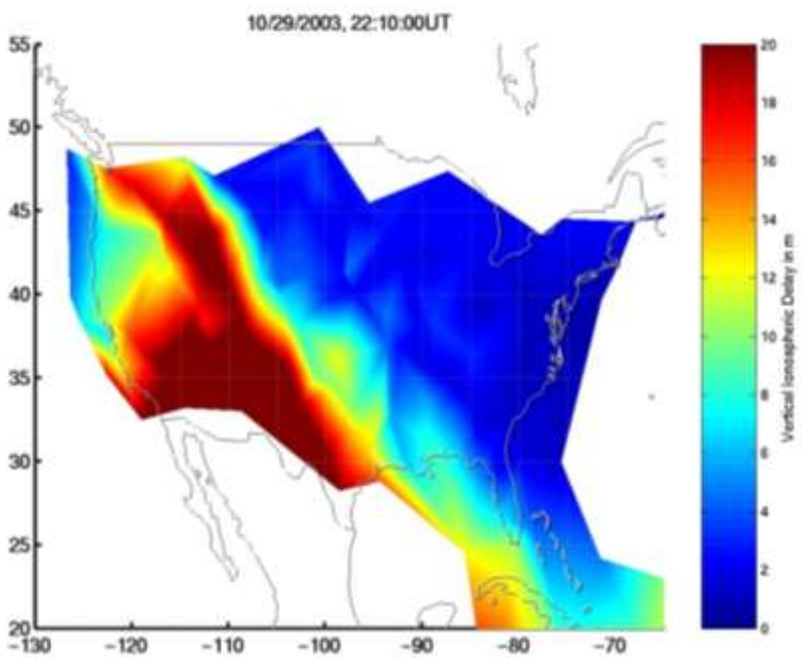


Figure 5: Vertical ionospheric delays in meters over a region of North America on 10/29/2003

During the same storm, a much smaller effect was observed in the European sector where an increase in vertical delay was only observed in high latitudes [Azpilicueta et al., 2004].

In general, storm effects depend strongly on season and time (UT) of storm onset, producing different local ionospheric responses [Buonsanto, 1999; Hibberd, 2004; Fedrizzi et al., 2004; Immel et al., 2005]. The extremely intense effects observed in the American sector have not been recorded over Europe, even during very severe storms. This is not to suggest, however, that magnetic storms do not affect the behavior of the ionosphere in Europe, nor that their effects are always milder in the European sector than in the American sector.

3.1.2 Scintillation effects

Scintillation effects in the mid-latitude regions are in general insignificant [Pi, et al., 2002]. During severe ionospheric storms occurring near a peak of the solar cycle, the possible expansion of an auroral region toward the equator can cause strong phase scintillation in parts of the mid-latitude region [Pi, et al., 2002]. However, such circumstances are very rare.

3.2 Low magnetic latitude region

The behavior of the low latitude ionosphere is different from that in the mid and high latitudes because it is mainly governed by the electrodynamic coupling between the ionized and neutral atmosphere. As described below, most of the low latitude ionosphere disturbances are not caused by magnetic storms. Hence, the space weather associated with solar magnetic storms and ionospheric storms does not adequately describe the low latitude region. This is not to suggest that magnetic storms do not disturb the low latitude ionosphere also.

3.2.1 Propagation delay effects

As shown in Figure 4, the equatorial region is characterized by the development, during the local evening hours, of two crests of enhanced ionization (TEC) several degrees wide and located at approximately ±15° to ±20° on each side of the magnetic equator, and between them, a region of low ionization (TEC) near the magnetic equator. These crests, or “anomalies”, are not caused by a local increase of solar ultraviolet (EUV) ionization; they are the result of a unique phenomenon called “equatorial fountain effect” that causes free electrons from the low latitudes to migrate upward in altitude, then away from the magnetic equator towards higher latitudes[9] [Anderson et al, 2001]. As a result, this region not only sees the highest values of vertical delay (TEC) in the world, but also quite often the highest vertical delay (TEC) gradients. Furthermore, the variability of the vertical delay distribution (map) is typically high as a result of day-to-day and seasonal variations in the location and height of the equatorial crests. The coupling effects from the lower atmosphere are believed to play an important role in this variability.

Figure 6 shows a longitudinal cross-section of vertical delay (TEC) at 25° E at the same local time on four consecutive days during a period of high solar activity. These cross-sections are derived from global vertical delay (TEC) maps constructed using data from GPS stations distributed all over the globe. They illustrate the day-to-day variations in vertical delay (TEC) that can be observed in the equatorial anomaly regions [GARMIS report D-2431].

[9] This phenomenon is driven by an electrodynamic force, referred to as “E×B drift” where E and B stand for the electric field and the magnetic flux density of the Earth. The uplifting force is caused by the motion of the neutral atmosphere driving the plasma in the magnetic field and causing an electric current in the ionosphere along the magnetic equator. The migration of the plasma to higher latitudes is due to diffusion along the Earth’s magnetic field.

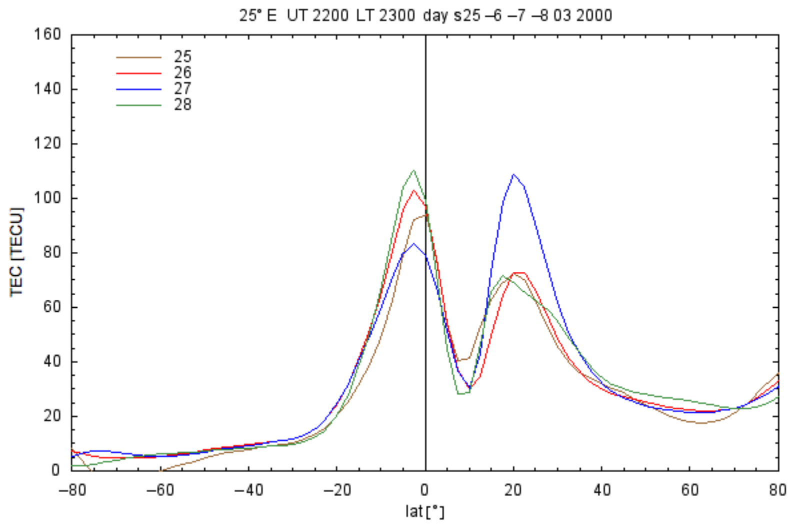
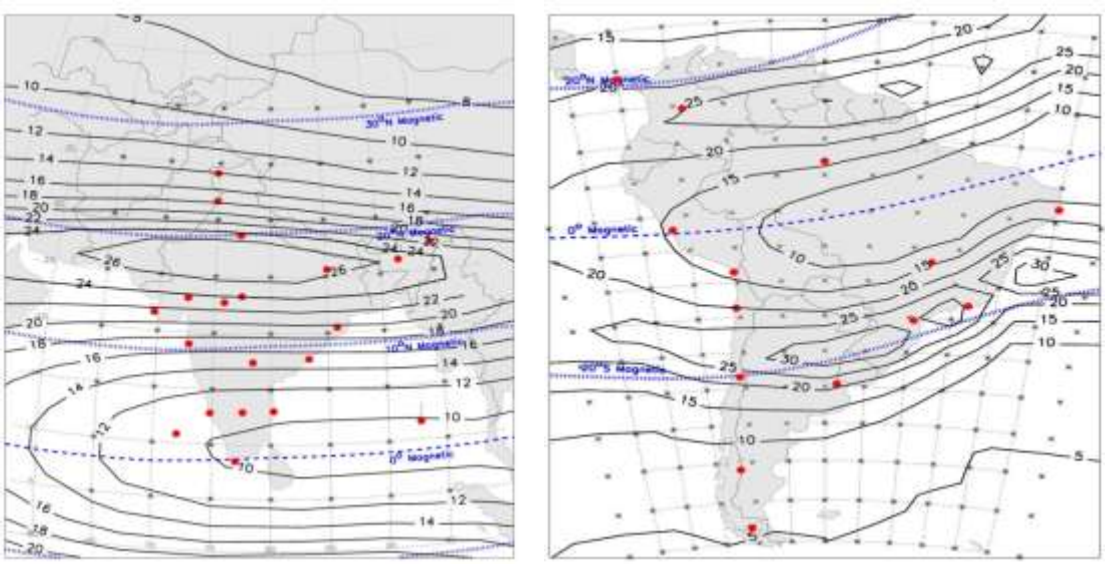


Figure 6: Longitudinal cross sections of vertical TEC at 25ºE and 23:00 LT on four consecutive days from global vertical TEC maps [GARMIS report D-2431]

Figures 7a and 7b were constructed using LOWLAT, a proprietary computer model of the equatorial ionosphere developed from the physics of the ionosphere in this region that is able to model the 3-dimentional distribution of the ionization effects over wide areas very accurately. The figures show contours of vertical ionospheric delays for a typical day during solar maximum conditions and an average fountain effect. Figure 7a illustrates the conditions over the Indian sub-continent; while Figure 7b illustrates the conditions over the South American continent. Large spatial gradients can be seen in both cases. Note that the maximum vertical delay value is in excess of 30 meters. The figures also show the standard 5° by 5° grid used by SBAS for comparison.



Figures 7a and 7b: Ionospheric vertical delays (in meters of delay at L1) over the Indian sub-continent and the South American continent for solar maximum and quiet ionospheric conditions [SBAS Iono WG, 2003]

Another potentially major issue with ionospheric range delay in the equatorial region arises from the possible existence of localized structures containing much lower densities of free electron than the surrounding ionosphere. These structures are referred to as “depletions” or “plasma bubbles”. They develop in the post-sunset local time period and cause abrupt changes in the propagation delay at their edges. They are also associated with the onset of plumes of irregularities that produce strong amplitude and phase scintillation effects.

Figure 8 shows data collected in 2002 by two stations located a few tens of kilometers apart in an East-West direction near Rio de Janeiro, Brazil. The data shows the effect of depletions on range delay measurements in the form of three steep drops of about 10 to 20 m. A nearly identical pattern in ionospheric range delay occurs later along the eastward path, which indicates that the depletions were moving eastward [Dehel, SBAS Iono Meeting No. 5, McLean, VA, May 10-11, 2002.]

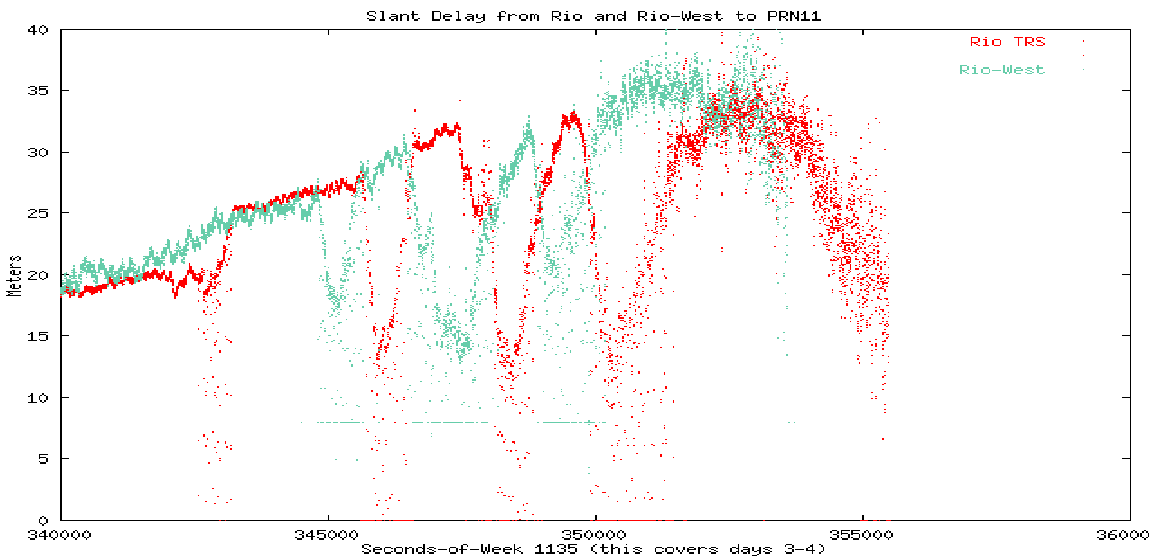


Figure 8: Slant ionospheric range delay on a night in October 2001, from two stations located near Rio de Janeiro, Brazil [Dehel, 2002]

The causes, behaviors and characteristics of ionospheric depletions are topics of active scientific research. An analysis of depletions in Brazil based on wide-angle imaging data collected from 1987 to 1999 observed a strong seasonal variation in the occurrence of plasma bubbles with a maximum during the southern summer (October-March) and a minimum during the southern winter (May-August). The study also found a strong dependence on solar activity. Plasma bubbles were found to occur on almost every night during October-March in a year of high solar activity [Sahai at al., 2000, Pimenta et al., 2001]. Another study performed using two years of GPS ionospheric delay data from ten sites located in the western part of South America recorded during the last peak of solar cycle (2000-2002) estimated the 95th percentile depletion depth to be about 9.1 m of vertical delay [Conker et al., 2004]. It is important to note that most of plasma bubbles occur during magnetically quiet periods. Their rate of occurrence decreases when the magnetic activity increases to moderate level ($Kp \leq 4$), but it increases again during severely disturbed magnetic conditions ($Kp \geq 5$) [Huang et al., 2001].

A study of equatorial plasma bubble occurrence was conducted using data from 75,000 passes of Defense Meteorological Satellite Program (DMSP) satellites across the evening, low-latitude ionosphere. The data was accumulated over a full solar cycle (from 1989 to 2000). One or more plasma bubble was found in over 8300 of these satellite passes. The study observed that, while the rate of plasma bubble occurrence decreases by an order of magnitude between solar maximum and solar minimum, the seasonal variations remain similar within given longitude sectors. Figure 9 shows the seasonal-longitudinal distribution of the rate of equatorial plasma bubble occurrence.

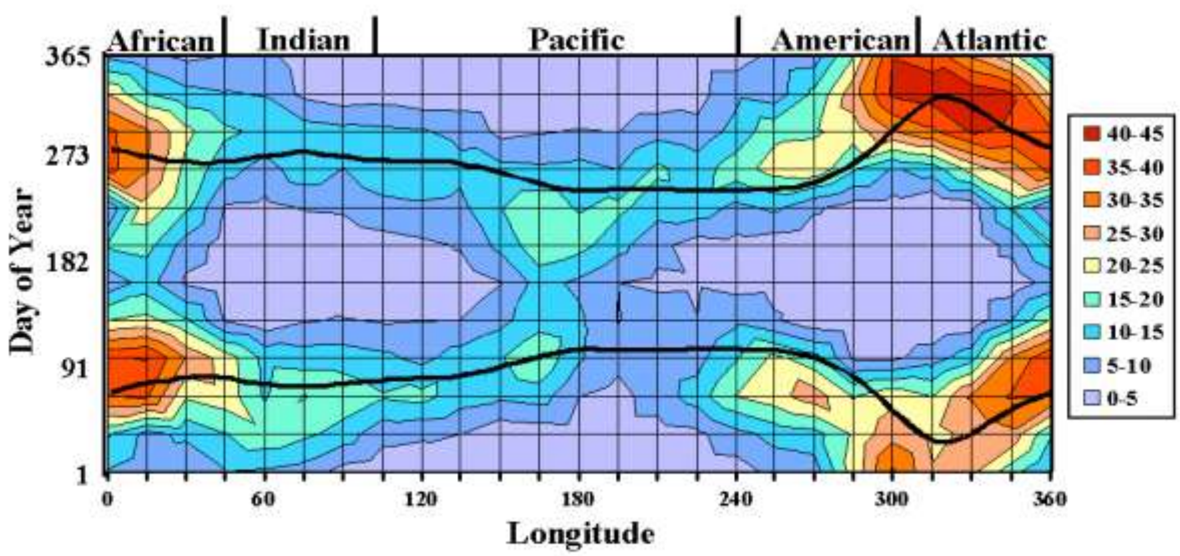


Figure 9: Contour plot representing the rate of equatorial plasma bubble occurrence on a month-versus-longitude grid in increments of 5% [Burke et al., 2001]

Up to now limited data has been available from the equatorial region to analyze storm effects in this region. However, many experts believe that storm effects may not be worse in this region than in mid-latitudes. This view still needs to be verified through analysis of data collected during a time period when the solar cycle is at or near a peak. One analysis has compared the residuals obtained from modeling ionospheric vertical delays at SBAS grid points using planar fits to vertical delay measurements during quiet and storm conditions using GPS data collected in Brazil [Komjathy et al., 2002]. It concluded that the residuals obtained in the equatorial area using the storm data were only slightly larger than those obtained using the quiet data. However, the resolution of the study may not have been sufficient to capture the effects of steep delay gradients over short distances such as those that occur at the edges of plasma bubbles, and a recent study has shown that the spatial delay gradients associated with plasma bubbles are as steep as those observed during severe magnetic storms in the mid latitude region.

3.2.2 Scintillation effects

In the low latitude regions, amplitude and phase scintillations can occur after the local sunset and persist for several hours until midnight, but can continue past midnight in some cases. This phenomenon frequently occurs during years near the peak of the solar cycle. It can occur on days during which the ionosphere remains quiet as well as on days during which it is affected by storm activity. The intensity of signal fading varies with the season. Severe fading is typically observed in March and October in the region between 110º and 130º East longitude, with lower values during the summer and the winter months. Severe fading tends to occur between September and May in the region between 0º and 30 º West longitude [J. Aaron, ION GPS 94].

Scintillation also varies with solar activity and gain in intensity near the peak of the solar cycle. A strong correlation between amplitude scintillation and phase scintillation has been observed in low latitude regions. A high degree of correlation also appears to exist between the existence of scintillation and the development of depletions.

Figure 10 shows the S4 and σ_ϕ values measured at two locations in Japan over a two-year period (2000-2001) [Matsunaga et al, 2002, El-Arini et al, 2003]. It uses color to represent percentage of time that S4 > 0.4 and σ_ϕ > 0.15 radians. A first ionospheric scintillation monitor (ISM)[10] was located in Naha in southern Japan, i.e., inside the northern anomaly region, and a second ISM was located in Chofu near Tokyo, i.e., a mid-latitude location. As the figure shows very high amounts of amplitude and phase scintillation were observed in Naha during the equinox seasons after the local sunset. In contrast, low levels of scintillation were observed in Chofu[11].

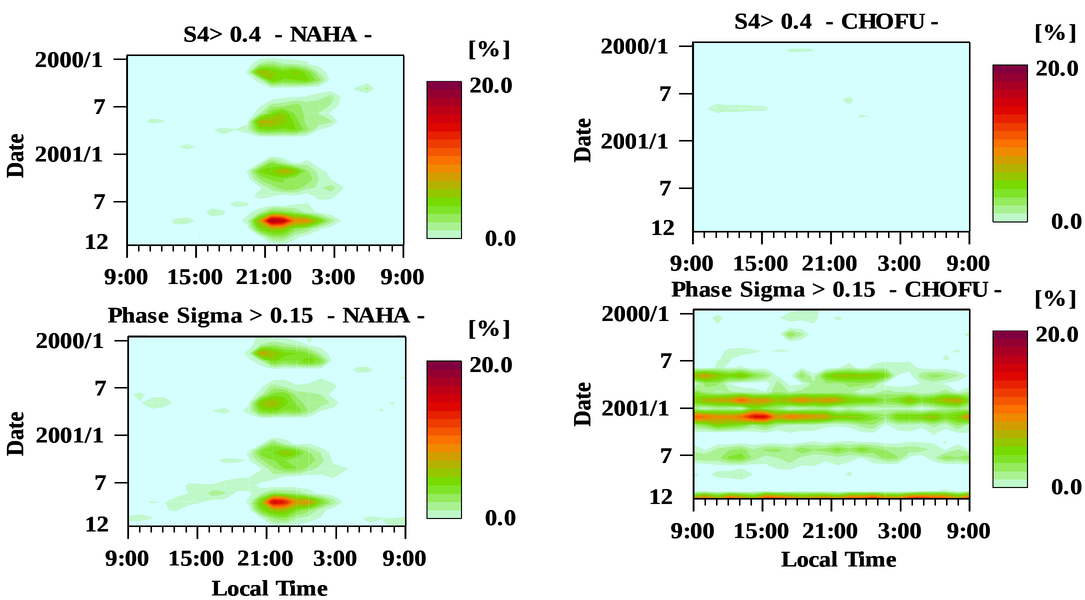


Figure 10: Amplitude and phase scintillation in Naha and Chofu, Japan, daily (2000–2001) [Matsunaga et al, 2002, El-Arini et al, 2003]

Figure 11 shows the percentage of occurrence of amplitude scintillations (> 3dB) at Waltair, India (an equatorial location) at the GPS L1 frequency during a 6-month period near the peak of the solar cycle (upper left panel – October 1998-March 1999), and also during a 6-month period near the minimum of the solar cycle (lower left panel – October 2004-March 2005). The figure also shows the diurnal variation of amplitude scintillation occurrence at the same location during a month near the peak of the solar cycle (upper right panel – March 1999), and also during a month near the minimum of the solar cycle (lower right panel – March 2005) [Rama Rao et al, 2006]. The scales are in dB of the fade depth.

[10] Specially modified GPS receivers with a very stable internal clock and a high output data rate,

[11] The lowest panel shows some activity. However, this activity is related to phase noise caused by the receiver rather than phase scintillation.

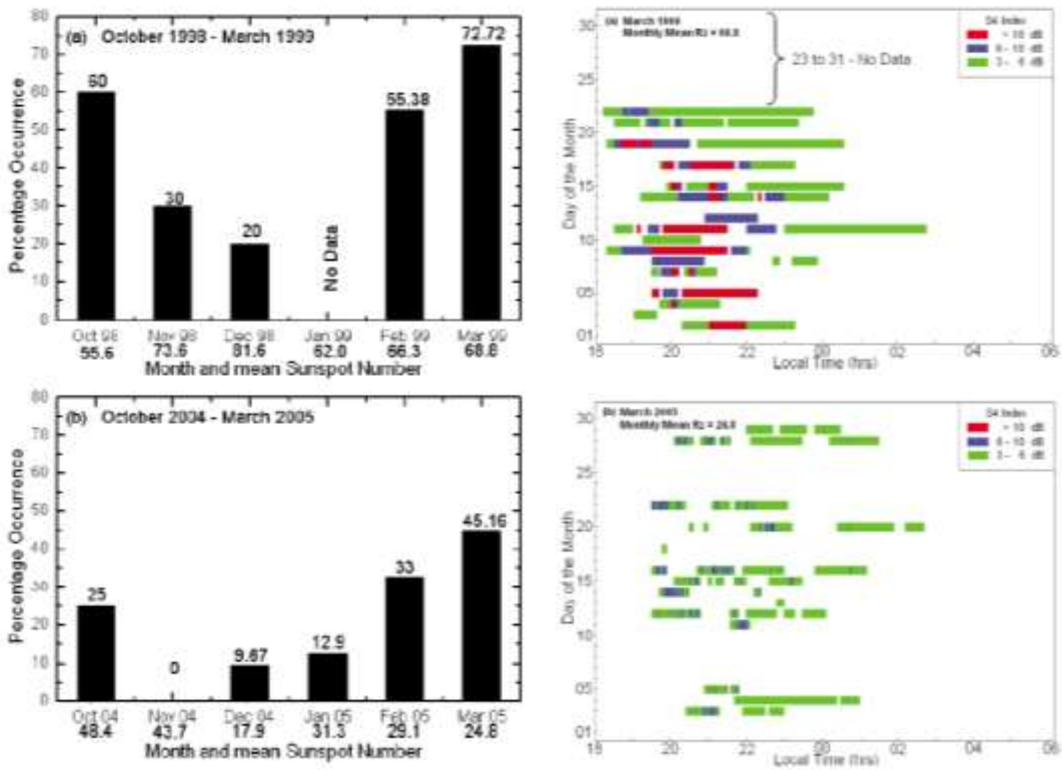


Figure 11: Percentage occurrence of amplitude scintillations (> 3dB) at Waltair India at various points of the solar cycle [Rama Rao et al, 2006]

It should be noted that scintillation activity is known to have a seasonal anomaly versus longitude. In the American, African and Indian Longitude regions, scintillation is most likely to occur between the months of October and March. In the Pacific sector (at least at Kwajalein and Hawaii), scintillation is most likely to occur in the northern summer months of May-August. The reasons for this anomaly are not fully understood. However, analysis has shown that this seasonal/longitude dependence is consistent with magnetic declination in various longitude sectors [Wernik et al., 2003; Fejer et al, 1999; Kil et al, 1998; Basu et al, 1996; Wanniger, 1993].

3.3 High magnetic latitude regions

3.3.1 Propagation delay effects

The Polar Cap regions can at times exhibit ionospheric delays considerably in excess of what would be typically seen in the mid-latitude regions [Klobuchar, et al., 1985]. However, since the polar cap regions represent comparatively small areas, and there is little need for a civilian precision approach service in these regions, they will not be discussed further.

The ionosphere of the auroral regions normally causes smaller ionospheric delays than the ionosphere of the mid-latitude regions; however, the variability of the auroral ionosphere tends to be greater than that of the mid-latitude regions.

An analysis of data collected in the auroral region of Canada, for example, showed a noticeable increase in the vertical delay spatial gradients during periods of major ionospheric storm activity [Skone et al., 1998].l

3.3.2 Scintillation effects

Ionospheric scintillation occurs frequently in high latitude regions near the peak of the solar cycle. It occurs mostly in the form of phase scintillation, which can be intense during ionospheric storms.

Amplitude scintillation on the L-band GPS L1 signals is not a significant concern in the disturbed auroral ionosphere. This assessment is based on statistics of GPS L1 scintillation measurements during the 2000-2001 solar maximum years [Pi, et al., 2002]. Phase scintillation, on the other hand, has sometimes caused WAAS reference stations in Alaska, which track the GPS L2 signal using a semi-codeless technique, to loose lock on several GPS satellites simultaneously for periods of up to tens of minutes [Dehel, et al., 1999a and b; Pi, et al., 2002]. During periods of severe ionospheric storm activity, losses of lock on the L2 signals by SBAS reference stations could affect the estimation accuracy of ionospheric grid delays in the auroral regions [Pi et al., 2002].

Figure 12 shows the percent occurrence of S4 and 1-minute phase scintillation (σ_ϕ) (in radians) derived from data recorded in Fairbanks, Alaska, during the time period between November 1999 and July 2000 [Doherty et al, 2000]. The figure shows that there is fairly little amplitude scintillation at this high latitude location (e.g., S4 $\leq$ 0.2), but there is frequent phase scintillation (σ_ϕ), which can reach 1 radian on rare instances.

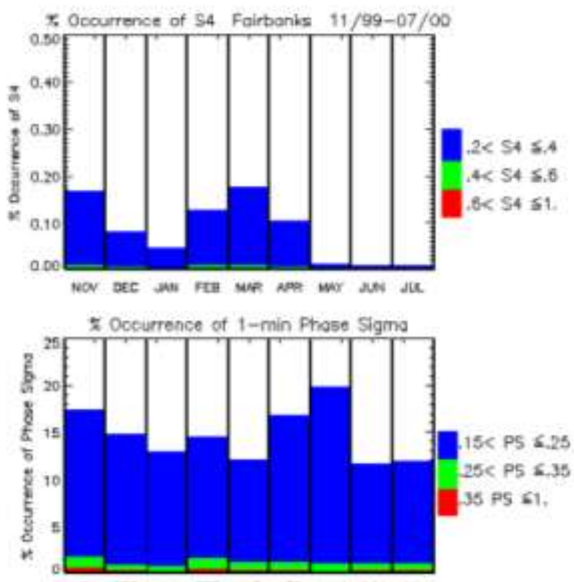


Figure 12: Occurrence of S4 and 1-minute phase scintillation (σ_ϕ) (in radians) in Fairbanks, Alaska [Doherty et al, 2000]

4. Current (single-frequency) GNSS mitigation techniques

Two types of ionospheric effects are discussed in Sections 2 and 3: (1) ionospheric conditions (e.g., mid-latitude storms or equatorial anomalies) resulting in a reduction in the accuracy with which the delay along a given line of sight can be predicted and therefore corrected, and (2) amplitude and phase scintillation effects affecting the ability of a receiver to maintain lock on GNSS signals.

Mitigation techniques are used to moderate these effects and, more importantly, to ensure that service integrity continues to meet the requirement when these effects occur. The main techniques are briefly discussed in this section.

4.1 Mitigation techniques for propagation delays

Accurate pseudorange measurements require the application of corrections for the increase in signal travel time from satellite to receiver, or propagation delay, caused by the ionosphere. ABAS, SBAS, GBAS use different methods for generating, transmitting and applying these corrections.

Independently of the method used by GNSS to correct pseudorange measurements for ionospheric delays, some corresponding residual errors will remain in the corrected pseudoranges. These residual range errors, which will vary in magnitude depending on the ionospheric conditions, must be accounted for when evaluating the accuracy, integrity, availability and continuity performance of GNSS navigation solutions.

Current civil GNSS airborne receivers were designed to track the Coarse Acquisition (C/A) code broadcast by GPS satellites on the L1 frequency. They do not track the GPS signal broadcast on the L2 frequency, which only carries an encrypted code. Single-frequency GNSS airborne receivers need to correct for ionospheric delays on the L1 signals in order to compute accurate position solutions. They use one of the following three methods to obtain the necessary ionospheric corrections.

ABAS avionics [RTCA DO-208, 1993], and SBAS receivers outside an SBAS service area, compute ionospheric corrections using a simple delay model implemented in the receiver and a set of model coefficients broadcast by core constellation satellites. A related model is used to compute integrity bounds (or more precisely conservative standard deviations for the residual errors). This correction method is adequate for ER/NPA, but it does not yield integrity bounds that meet the requirements for APV or PA. Further details on this method are provided in 4.1.1.

SBAS avionics inside the SBAS service area [ICAO, 2005; RTCA DO-229C, 2001] compute ionospheric range delays and integrity bounds using real-time information broadcast by SBAS. This correction method is designed to support APV service. However, the level of service that can be supported in practice will depend on the ionospheric environment in which the SBAS operates. SBAS ionospheric corrections can also be used to provide high-availability of ER/NPA navigation, when and where they are available. Further details on this method are provided in 4.1.2.

GBAS avionics apply corrections broadcast from a single ground station located at the arrival airport. These corrections are intended to eliminate, or at least greatly reduce, common pseudorange errors between the aircraft and the reference station, including ionospheric and tropospheric delays. They are specific to the satellites in view of the reference station [ICAO, 2005; RTCA, DO-253a, 2001]. Information broadcast by GBAS also allows the receiver to compute integrity bounds. In some cases where integrity bounding is not assured, an alternative integrity method may be used to deny service to the aircraft under constellation conditions that could be potentially hazardous [NSP WP30, May 2010]. This correction method is adequate for Category I approach and landing operations. It is also used for Category II/III; however, additional requirements are imposed on both the ground station and the avionics in this case. This method is further explained in 4.1.4.

The potential for spatial and temporal variations of ionospheric delays and delay gradients needs to be taken into account when planning and designing an augmentation system. In some cases, the position solution computed by a user will be relying on range measurements affected by different ionospheric delays than those affecting the measurements available to the augmentation system to generate the broadcast corrections. The design of the augmentation system must mitigate such potential differences in order to ensure that the integrity requirements are met for all users under all foreseeable conditions. Different strategies are adopted by SBAS and GBAS as briefly discussed in 4.1.3 and 4.1.4.

4.1.1 Correction method used by ABAS

ABAS receivers can approximately correct for ionospheric delays using a delay model and a few coefficients broadcast by core constellation satellites [RTCA DO-208, 1993]. This method is also used by SBAS receivers outside the SBAS service area. It can also be used by SBAS receivers inside the SBAS service area when conducting ER/NPA operations. Currently, these receivers use GPS as a source of ranging signals, and thus, they compute ionospheric corrections using the GPS single-frequency ionospheric delay model. In the future, user receivers will also be able to use Galileo as source of ranging signals, and in that case, they will compute ionospheric corrections using the Galileo ionospheric delay model (when tracking a single frequency only). These models include simple mathematical algorithms programmed in the receivers to compute both corrections and integrity bounds. This correction method is adequate for en route (oceanic and domestic) and terminal area navigation as well as for non-precision approach operations (ER/NPA).

In both the GPS and Galileo cases, the models are simple diurnal models [IS-GPS-200D, RTCA DO-208, 1993, Parkinson, 1996, Vol. I, Chapter 12, Radicella and Leitinger, 2001], which are unable to capture all of the variations in the ionosphere both over time (24 hours) and space (the entire world), particularly when atypical conditions exist such as during an ionospheric storm, for example. They use sets of coefficients derived from historical data. However, the set of coefficients that is actually broadcast is regularly updated to ensure that the model will approximately follow slow changes in the ionosphere over periods of several days.

The GPS navigation message does not include an error bound for the single-frequency ionospheric correction model. However, the SBAS SARPs and MOPS provide a simple formula to calculate an error bound as a function of the latitude of an ionospheric pierce point (IPP). This model was validated using data recorded at more than six hundred worldwide sites during six severe ionospheric storm days in 2003 and 2004 [El-Arini, RTCA SC159, March 2005]. The error bound model was found to be valid for all flight operations with a Horizontal Alert Limit (HAL) of at least 186 m (corresponding to RNP 0.1 for many aircraft types).

4.1.2 Correction method used by SBAS

SBAS receivers inside the SBAS service area can correct for ionospheric delays more accurately than ABAS receivers because they can use the SBAS ionospheric corrections, which are derived from real-time ionospheric delay measurements. The SBAS ground system obtains these measurements from a network of reference stations and uses them to estimate the vertical delays and associated integrity bounds[12] at the nodes, or ionospheric grid points (IGPs), of a standardized ionospheric grid located 350 km above the surface of the Earth [ICAO, 2005; RTCA DO-229D, 2006]. The user equipment uses the SBAS grid information to compute a vertical delay and vertical integrity bound for each line of sight to a satellite, then applies a standardized "obliquity factor" to account for the angle at which the line of sight pierces the ionospheric thin shell (grid).

With this type of augmentation, the accuracy of the corrections is limited by (1) the relatively sparse sampling of the ionosphere available to the SBAS ionospheric delay estimation process, (2) the SBAS ionospheric delay model which uses a two-dimensional grid to communicate ionospheric delay information and a fixed one-to-one mapping between vertical delays and range (slant) delays; and (3) time delays between the collection of ionospheric delay measurements by the SBAS ground infrastructure, the broadcast of ionospheric grid information by the SBAS satellites, and the application of the corrections by the SBAS receiver.

The challenge of engineering an SBAS intended to support APV operations varies from one region to another. This challenge is greater in equatorial regions than in mid-latitude regions for reasons explained in Section 3. Any SBAS implementation intended to support APV procedures needs to account for the limited sampling of the ionosphere that will result from the proposed network of reference stations as well as the limited resolution of the 5° by 5° SBAS ionospheric grid.

Analysis is needed to show that SBAS ionospheric corrections and integrity bounds meet the integrity requirement over the full range of conditions that could occur in the geographic area served by the SBAS. Such an analysis requires a sound statistical approach, engineering judgment, and a fair amount of actual ionospheric delay measurements providing a good sampling of the range of ionospheric conditions (including representative "worst case" conditions) that the SBAS may encounter during its lifetime. It is important that such a data set include representative data collected near the peak of the solar cycle during both nominal and disturbed conditions.

The ionospheric delay estimation algorithms of WAAS, for example, rely on simple estimation algorithms developed on the basis of a threat model analysis. The threat model analysis led to the implementation of two storm, or irregularity, detectors, which will raise the integrity bounds (GIVEs) so as to deny APV service when and where the ionospheric conditions are inconsistent with the assumptions of the estimation process. In addition, a threat model analysis was performed to ensure that the integrity bounds generated by the algorithm will adequately bound[13] the residual errors when ionospheric disturbances are present that are not large enough to trip one of the storm detectors. This analysis relied on over 30 days of ionospheric delay data recorded during days near the peak of the solar cycle when the ionosphere was severely disturbed. It used a variety of processing techniques to simulate the possibilities that (1) some reference station(s) or satellite(s) may be off line and (2) localized irregularities in the ionosphere may not be directly visible to WAAS because of its limited sampling of the ionosphere. The ionospheric estimation approaches used by WAAS were found satisfactory in mid- and high-latitude regions because severe ionospheric disturbances causing APV service to be denied are relatively rare (less than 1% of the time), and a high availability of APV service is provided under nominal ionospheric conditions.

[12] The integrity bounds broadcast by SBAS are called Grid Ionospheric Vertical Delays (GIVEs).
[13] The term "adequately bound" is used to mean "bound with the required probability as specified in the derived requirements for this processing function."

Preliminary results from two analyses of a potential SBAS implementation in South America, one using simulated ionospheric data and the other actual data collected at 12 South American sites, suggest that the ionospheric estimation techniques used in mid-latitude SBAS implementations may not deliver an acceptable level of performance in equatorial regions [Lejeune et al., 2002; Lejeune et al. 2003].

4.1.3 Correction method used by GBAS

The correction method used by GBAS is different than the one used by SBAS in that the GBAS ground station does not broadcast ionospheric delay corrections. Instead, it provides the aircraft with differential corrections for all satellites in view. The corrections are applied by the receiver and eliminate, or at least greatly reduce, the majority of common range measurement errors (including ionospheric delay errors) between the ground station and the aircraft. The corrections are sent to the aircraft via a VHF Data Broadcast function. The broadcast messages also provide the values of parameters characterizing the uncertainties in these corrections (integrity data) as well as information on the approach path to be flown. Equations implemented in the avionics use these parameters to calculate protection levels. These protection levels are then compared to the maximum alert limits for that station and the desired flight operation.

A key limitation on the GBAS corrections is the spatial separation between the GBAS ground station and the GBAS aircraft user, since the corrections broadcast to the aircraft can only correct common errors. However, local ionospheric delay gradient can sometimes cause differences between the ionospheric delays affecting the aircraft and those affecting the ground station. This difference tends to be small over small distances typical of the local area under nominal ionospheric conditions in the mid-latitudes. (This is not necessarily the case, however, in the equatorial area where variations can be large even in a local area). Conditions associated with severe mid-latitude ionospheric storms present a different case. In this case, delay magnitudes can vary quite rapidly over short distances and thus may not be adequately mitigated even after the corrections from the GBAS ground station are applied.

In the CAT I architecture, the ground system is fully responsible for the integrity of the navigation solution. Several mitigating techniques are implemented in the ground system to ensure that ionospheric delay spatial variations will not result in intolerable position errors. These techniques depend on the individual ground system design. They may include the implementation of a geometry screening and an ionosphere threat model [NSP WP39, May 2010]. In this design, the ground station evaluates the impact in the position domain of an ionospheric delay gradient within the limits of the ionosphere threat model. It does this for all useable satellite geometries. It then inflates the integrity parameters as needed to ensure that service will be unavailable for satellite geometries that would result in an intolerable position error. This mitigation technique reduces residual errors in the position domain, but it also reduces service availability. Other solutions may include the use of external information on the state of the ionosphere, for instance by networking and/or dynamic adjustment of related integrity parameters. For example, the GBAS installation could include an ionospheric field monitor consisting of the GBAS reference station and additional monitoring stations near the landing decision point of the runways served. Such a mitigation approach has been implemented in the prototype GBAS CAT-I station developed in Japan.

In the CAT II/III architecture, the ground station and the avionics share the responsibility for the integrity of the navigation solution. The integrity design requires additional processing in the ground station, additional broadcast data, and an ionospheric delay monitoring function in the airborne receivers. In addition, the ground station monitors temporal and spatial ionospheric delay gradients. The airborne equipment uses the additional broadcast data to perform a temporal ionospheric gradient monitoring. Airborne equipment will assume a global threat model specified in the SARPs guidance material for ionospheric error mitigation. This model will be designed to protect against residual ranging errors resulting from ionospheric gradients, whether they are caused by mid-latitude ionospheric storms or by equatorial phenomena such as depletions ("bubbles"). The ground subsystem will be responsible for maintaining its correction data within the bounds required by this global threat model [GBAS GAST-D Baseline Development Standard as referenced in ICAO EB2010/41, attachment D, section 7.5.6.1.1].

4.2 Mitigation techniques for scintillation effects

Both amplitude scintillation and phase scintillation can cause a receiver to lose lock on the affected signal, particularly when they occur simultaneously. GNSS receivers are generally able to maintain lock on signals affected by low to moderate levels of scintillation when they can track the signals using a code-based tracking technique. However, any receiver, whether airborne or on the ground (e.g., a reference station receiver), is likely to lose lock on the GPS L1 signal of satellites for which the received C/N_0 drops below 30 dB-Hz during periods of intense amplitude scintillation.

The probability of loss of lock has been calculated for various levels of C/N_0 and compared to that obtained from measurements as illustrated in Figure 13 [Béniguel, 2002].

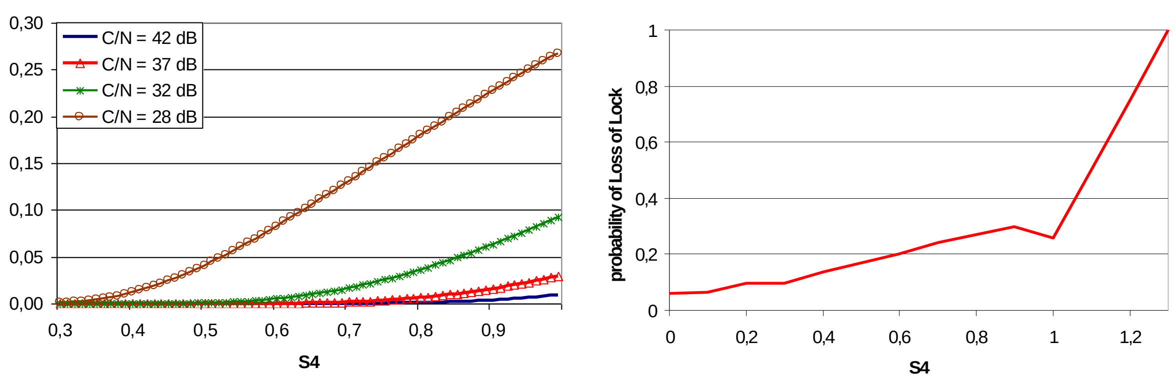


Figure 13: Probability of loss of lock (Left panel: calculated with GISM model; Right panel: measured) [Béniguel, 2002]

The durations of fades due to amplitude scintillation being usually quite large compared to the pre-integration time of the receiver, the net effect on the receiver is a decrease of C/N_0. Phase scintillation has to be considered in addition to amplitude scintillation in order to fully assess the capability of the receiver to maintain lock on the signal.

A study of scintillation effects in Japan was conducted using GPS data recorded by scintillation monitors in Naha, Okinawa, (an equatorial site) and Chofu (a mid-latitude site near Tokyo) from August 15, 2001 to November 30, 2001 (108 days) [El-Arini et al, 2003]. Figure 14 shows the normalized frequency of loss of lock of on the L2 signal versus S4 (L1).

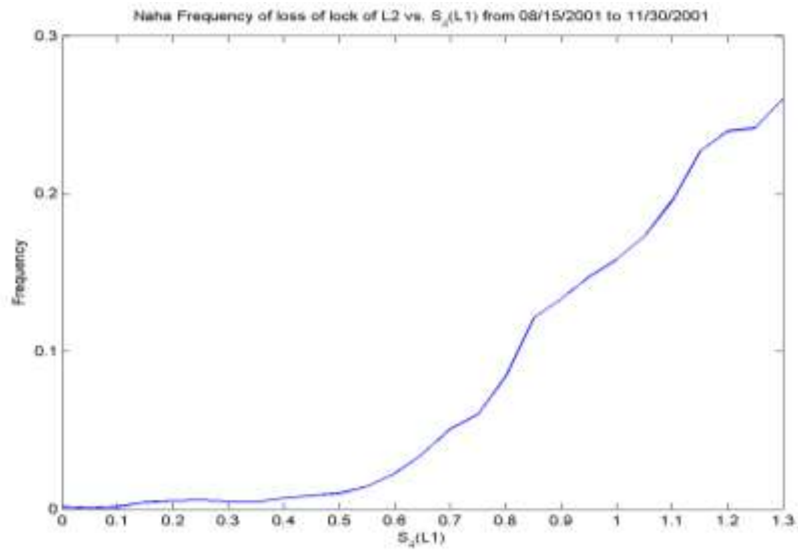


Figure 14: Normalized frequency of loss of lock of L2 at Naha (August 15, 2001– November 30, 2001) [El-Arini et al, 2003]

Airborne receivers and reference station receivers are not equally sensitive to scintillation on the GPS L1 signal. Current airborne receivers track the GPS L1 Coarse Acquisition (C/A) signal using a wide signal tracking loop in order to maintain track during aircraft accelerations. Reference station receivers in SBAS implementations, on the other hand, track the C/A code of the GPS L1 signal using a narrow signal tracking loop in order to reduce multipath errors. As a result, reference station receivers are more robust to scintillation on the L1 signal than airborne receivers. However, current SBAS reference station receivers track the GPS L2 signal using a semi-codeless technique, which makes them much more sensitive to scintillation on the L2 signal, particularly phase scintillation [El-Arini et al., 2003]. This sensitivity is further heightened by the fact that scintillation on the L2 frequency is stronger than on the L1 frequency (See Section 2.2.2). Losses of lock on the GPS L2 signal have occurred at WAAS receivers in Alaska, for example.

Current GBAS reference stations only track the GPS L1 signal and are therefore fairly robust to scintillation.

Ionospheric scintillation typically occurs in the form of numerous patches. It does not therefore equally affect all satellite signals received at one particular location simultaneously. Nevertheless, it can cause a receiver, whether a user receiver or a reference station receiver, to lose lock on one or several satellite signals simultaneously at various times during periods of intense scintillation.

The consequences of losing lock on a few satellites are not the same for airborne receivers and reference station receivers. If an airborne receiver loses track on the signals of a few satellites that are critical to maintaining the protection levels below the alert limits for the intended operation (critical satellites), particularly for APV or PA, the aircraft will lose the ability to initiate or continue the operation. In contrast, an SBAS ground system must only receive a sufficient number of measurements to meet the requirements of the ionospheric delay estimation function. Therefore, SBAS ground systems can tolerate temporary losses of some signals and still perform their function, although with perhaps some reduction in service availability and continuity performance. A single-frequency GBAS station may also lose lock on the L1 signals from some satellites; however, when it does, it is likely that airborne receivers using the GBAS signal have also lost lock on the L1 signals from the same satellites. However, due to filter and monitor stabilization effects, the effect of a lost satellite track lasts typically much longer for a GBAS ground station than for an airborne receiver. When losses of lock on some satellite signals happen, the user may experience a reduced level of service [Conker et al., 2000, Arbesser-Rastburg et al., 2005].

A key question concerning the effects of equatorial scintillation relates to the densities and sizes of scintillation patches and their effect on the ability of GNSS receivers to maintain track on a sufficient number of satellites to support service. Measurements should be made, from an airborne receiver perspective, to determine the statistics of simultaneous fading on more than one GNSS satellite and to characterize the effect of a changing mix of useable satellite signals on navigation performance [Forte, et al., 2001, Béniguel et al., 2004, Conker, et al., 2003].

Figure 15 shows the probability of simultaneous fading on different numbers of satellites affected by amplitude scintillation given the value of S4. These plots were derived from measurements made in Douala, Cameroon, in 2004 and in São Jose dos Campos, Brazil, in 2001 [Beniguel, 2007]. The solar flux value was equal to 100 (moderate) in Douala and 190 (high) in São Jose dos Campos. The probability drops quickly with the number of satellites affected but increases with the flux number. All satellites in view of the ground stations were used for this analysis.

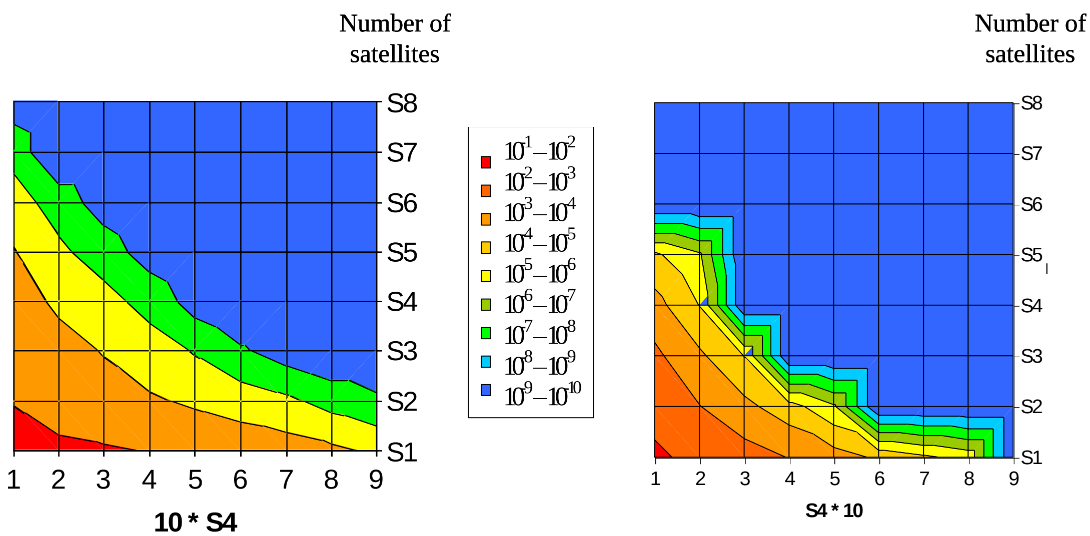


Figure 15: Probability of simultaneous fading (The left plot corresponds to a solar flux of 100; the right plot to a solar flux of 190) [Beniguel, 2007]

Another scintillation-related question concerns the potential loss of real-time corrections and integrity information data from an SBAS satellite. One of the SBAS requirements is a message error rate of 10^{-3} or less at the user receiver. The level of performance that can actually be achieved in this regard during periods of severe scintillation has not been established. However, redundant system designs relying on two or more SBAS satellites with sufficient longitudinal separation (≥ 46.3 degrees according to DasGupta, 2002; ≥ 40° according to Béniguel, 2003) should greatly improve signal availability and continuity of service in regions affected by scintillation.

An analysis confirmed that the message error rate is directly related to the amplitude scintillation intensity as measured by S4. This analysis was based on measurements obtained for two different solar flux values [Beniguel, 2007]. The curves shown in Figure 16 were obtained with a limited set of data, but in both cases it appears that the message error probability approximately follows a Log normal distribution model.

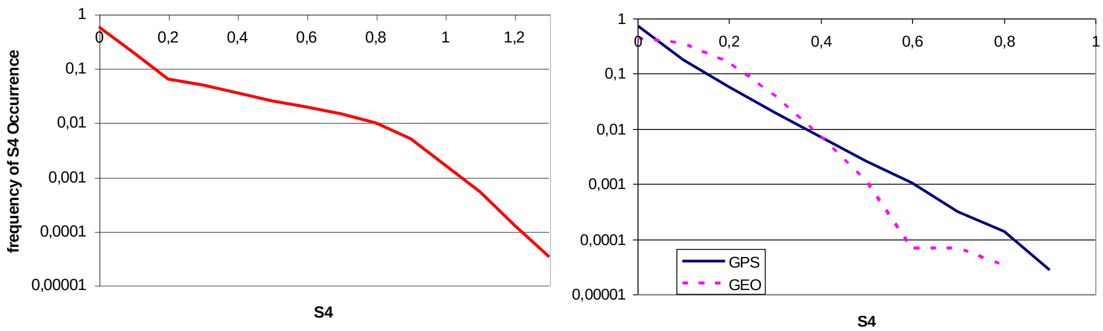


Figure 16: Message error rate from measurements (Left panel: São Jose dos Campos, flux = 190. Right panel: Douala, flux = 100) [Beniguel, 2007]

Receiver design is the primary source of mitigation against scintillation effects. The robustness of receiver to scintillation effects depends on the bandwidth of the signal tracking loop inside the receiver and on the ability of the receiver to quickly re-acquire the signal after it has lost lock on it due to a deep but short-lived drop in received power. It also depends on the design of the signal tracking loop.

Based on the nature of scintillation, which develops in patches (dispersed areas) of a few hundreds of km in widths, as well as on observations of GNSS signal receptions, it appears that, even in the worst case, scintillation will affect no more than 3 or 4 satellites in view of a user simultaneously. In many cases, GNSS receivers will be able to provide continuous service during periods of scintillation, even severe scintillation, because a temporary loss of tracking on one or two satellites does not necessarily result in a loss of service. However, a loss of 3 or 4 satellites can result in a significant increase in Dilution of Precision (DOP) and consequently in an increase in the positioning error, as well as in a loss of service. Errors in the tens of meters from the loss of satellites due to scintillation have been observed [DasGupta, 2002; Béniguel, 2003].

The probability of a loss of navigation service due to scintillation is function of several factors besides receiver design. These include the intensity of ionospheric scintillation, which varies from region to region, from season to season, and from day to day. As noted above, it also depends on the number of satellites visible to the receiver. In the future, as already mentioned, receivers capable of including both GPS and Galileo satellites in their position solutions will be much less likely to lose service than receivers capable of using only one of the core constellations.

5. Impact of the ionosphere on operational service

Position solutions relying on pseudorange measurements with uncorrected ionospheric delays can have position errors of several tens of meters, even during quiet ionospheric conditions. Such errors, while undesirable, are not intolerable for en route (ER) and terminal area navigation, or even for non-precision approach (NPA) operations, because of the comparatively large alert limits associated with these operations. In contrast, errors of such magnitudes cannot be tolerated for approach operations during which vertical guidance is provided to the aircraft (APV and PA). As a result, avionics standards recommend the application of corrections for ionospheric delays for ER/NPA operations, but they require their application for APV and PA operations.

For ER/NPA operations, ionospheric delay corrections and associated integrity bounds can be obtained from algorithmic models such as briefly described in 4.1.1. These models are sufficiently accurate to ensure a very high availability of navigation service with integrity provided by RAIM (even when the navigation solution is derived from a single core constellation, as long as that constellation is not significantly degraded, i.e., does not have several orbital slots without healthy satellites).

For APV operations, ionospheric delay corrections and associated integrity bounds must be obtained from an SBAS. SBAS is capable of broadcasting ionospheric integrity bounds that are sufficiently small to ensure a high availability of APV service in mid- and high-latitude regions. However, the availability of APV service may be reduced or even severely limited in relatively rare occasions (roughly 1% of the time) due to disturbances caused by a severe ionospheric storm. APV service is also conceptually possible in low-latitude regions; however, the variability and unique phenomena of the equatorial ionosphere present a very difficult challenge to ensuring the integrity of the ionospheric corrections without causing frequent interruptions of APV service (i.e., frequent, and perhaps even daily, interruptions of service in the local evening hours during years near the peak of the solar cycle).

For GBAS Landing System (GLS) operations, ranging corrections and associated integrity bounds must be obtained from a GBAS. GBAS is capable of broadcasting differential integrity bounds that are sufficiently small to ensure a high availability of PA everywhere in the world. However, interruptions to PA service are likely to be more frequent in equatorial regions than in mid- and high-latitude regions because system implementations will need to include more conservative provisions in order to constrain the risk of a loss of integrity due to sharp ionospheric gradients.

The loss of a few critical satellites due to scintillation can also cause disruption to APV and PA services. This effect will be mostly felt in the equatorial area during the evening hours, especially during the spring and fall seasons of years near the peak of the solar cycle.

5.1 En Route through non-precision approach (ER/NPA)

GNSS provides ER/NPA navigation either by using unaugmented GNSS and RAIM or FDE for integrity, or by using SBAS corrections and integrity information. The availability and continuity of GNSS-based ER/NPA services provided by both of these technical approaches are very robust against ionospheric delay effects such as caused by severe ionospheric storms or by unique equatorial phenomena. This robustness is due mostly to the relatively large alert limits associated with these flight operations.

Temporary losses of ER/NPA service during periods of severe scintillation may occur in equatorial regions (particularly during the evening hours near the peak of the solar cycle) and to a lesser extent in high-latitude regions (particularly during severe ionospheric storms). This effect has been observed during data collection campaigns, but the severity of the service degradation as a function of solar activity, geographical region and number of core constellation satellites has not been characterized in detail. While the statistics of such losses of service are not well established, the potential for such losses of service should not be viewed as a major concern because ER/NPA service can often tolerate a loss of track on one or two satellites in view due to the redundancy of ranging sources. Of course the sensitivity of the navigation solution to such losses could increase if the constellation being used is degraded, and as a result the number and geometry of satellites in view are barely supporting service without any satellite loss. ABAS receivers are more prone to such losses of ER/NPA service than SBAS receivers because a larger number of tracked satellites is generally needed to maintain service when integrity is provided by RAIM/FDE than when integrity is provided by SBAS.

It is not clear that a non-GNSS form of mitigation is needed to reduce the risk of loss of navigation due to potential losses of GNSS-based ER/NPA service caused by ionospheric effects. However, many states may decide to maintain a certain number of ground-based radio-navigation systems in order to mitigate the risk of loss of GNSS service due to radio-frequency interference or to a potential degradation of the core constellation used for navigation, and that same approach would also be adequate to mitigate the potential risk of loss of GNSS-based ER/NPA service due to ionospheric scintillation effects.

High-end users equipped with avionics using integrated GPS and Inertial Navigation System (INS) solutions will likely be much less sensitive to such effects than low-end users equipped with simple GNSS receivers.

5.2 Approach with vertical guidance (APV)

SBAS augmentation makes APV service possible by performing a real-time monitoring of core constellation satellites and ionospheric delays. APV operations require accurate ionospheric corrections as well as relatively small integrity bounds, and these bounds may need to be raised during periods when the ionosphere is severely disturbed in order to account for the increased variability of ionospheric delays while ensuring the integrity of the position solutions of all users. For example, APV service provided by WAAS was severely curtailed on a few occasions in response to severe ionospheric storms such as those of October 29-31, 2003 and November 20-21, 2003 [Fee, IP5 from NSP meeting in St Petersburg, 2004].

APV service is very robust in mid- and high-latitude regions, and losses of service due to ionospheric effects are expected to occur less than 1% of the time. Interruptions of APV service may occur during severe ionospheric storm conditions and affect portions of the service area for a few hours. In some rare cases, extremely severe ionospheric storms may even cause temporary loss of APV service over large portions of the SBAS APV service area for several hours. Such extremely severe storms may occur a few times during the 11-year solar cycle. Figure 17 illustrates that during non-storm days, WAAS (Initial Operating Capability) generally maintained 95% availability over 95% of the Conterminous United States (CONUS) region between 1 July 2003 and 1 March 2004[14]. However, APV availability was severely impacted during the extremely disturbed days of October 29-30 and November 20, 2003, and APV service was unavailable over the entire CONUS region for periods of approximately 15 and 10 hours respectively.

[14] The current APV (LPV) availability requirements for WAAS, which is now in its third phase of implementation, are: 99% availability over 100% CONUS and 95% availability over 75% of Alaska.

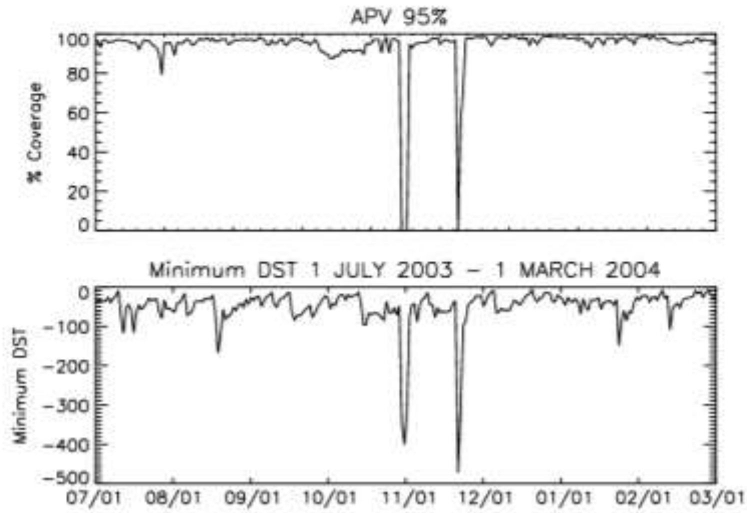


Figure 17: Example response of the WAAS APV service to geomagnetic activity

In equatorial regions, providing APV service with high integrity, availability and continuity, particularly during the local afternoon and evening hours of years near the peak of the solar cycle when the equatorial anomalies create large spatial variations in ionospheric delays, will likely present a very difficult engineering problem. The potential for high ionospheric delay gradients due to depletions that may not be adequately sampled by the SBAS network of reference stations adds further difficulty to resolving this problem. Scintillation further compounds the difficulty by raising the risk of potential simultaneous losses of track on multiple satellites.

An obvious mitigation to the risk of loss of APV service during periods when the ionosphere is severely disturbed is to maintain a sufficient number of Instrument Landing System (ILS) installations, particularly at busy airports. In fact, the ILS approach is likely to remain the approach procedure of choice at busy airports in the near future because of its lower decision height, its greater reliability (ILS is not affected by the ionosphere and radio interference effects can only have a local impact) and legacy avionics in high-end aircraft. For airplanes not equipped with ILS receivers, there is a high likelihood that a GNSS-based NPA approach will be possible when APV service is not available.

Mitigation against losses of APV service due to unusual ionospheric conditions can also be provided through the rules concerning the use of SBAS navigation equipment. For example, the U.S. rules require that pilots who plan to conduct an LPV approach (an approach corresponding to APV performance) at their destination airport file an alternate airport with an LNAV (non-precision) approach and verify that the weather conditions at that alternate airport will allow an LNAV approach, if landing at the alternate airport is needed.

For Precision Approach operations, the presence of ILS constitutes a strong mitigation and according to several navigation infrastructure plans, reduction in ILS can only be started once multi-frequency GNSS systems provide the necessary robustness.

5.3 Precision Approach Category I (CAT I)

Research and acquisition efforts aimed at the implementation of GBAS for CAT I operations are continuing in various states. Analysis of ionospheric storm effects on GBAS service requires data and modeling assumptions that are specific to the ionospheric environment in which the service is to be provided. Characterizing the impact of ionospheric effects on integrity has been found to present challenges, in part because severely disturbed ionospheric conditions are relatively rare, and in part because the lack of sufficient data available to characterize the local ionospheric environment in some regions. The level of characterization of ionospheric delay variations needed for GBAS requires a high degree of measurement resolution, i.e., a locally dense network of GPS receivers. Without direct observations, educated assumptions must be made about atypical ionospheric behaviors. However, such assumptions must be conservative in order to ensure the high level of integrity needed for CAT I operation, and therefore they may limit the achievable level of service availability.

Using data recorded in the U.S. during a number of ionospheric events, simulations have been conducted to assess the impact of mid-latitude ionospheric events on GBAS CAT I [Pullen, 2008]. These simulations showed that a severe ionospheric storm may cause an error of 41 m in the vertical position domain. When geometry screening is performed by the ground station, the error is limited to 28.8 m. Since the Vertical Alert Limit for CAT I operations is 10m, an error larger than 10 m that is also larger than the computed protection level corresponds to an integrity failure if its probability of occurrence is higher than 10^{-7}. The probability of occurrence of such errors is quite difficult to assess as it depends on:

- the probability that an ionosphere storm occurs;
- the satellite geometry available during that event; and
- the orientation and motion of an ionospheric gradient relative to the aircraft position and runway orientation.

Further work is needed to fully assess the probabilities of these conditions and provide clear guidance on the selection of certain system parameters that control the behavior of GBAS ground stations. However, in order to ensure the safety of all users under all foreseeable conditions, a GBAS architecture that does not have a means to detect ionospheric disturbances has to assume that such disturbances are always present.

5.4 Precision Approach Category II/III (CAT II/III)

The development of GBAS for CAT II/III has reached a major milestone in 2010 with the approval of “baseline” SARPs material. The development effort has now migrated to the aircraft integration arena, where major airframe manufacturers will develop and fly test aircraft with GBAS CAT II/III capability, and through this effort provide an operational validation of the SARPs material.

As described in Section 4.1.3, the CAT II/III integrity architecture is different from the CAT I integrity architecture. The CAT II/III concept requires additional monitoring both in the ground station and in the airborne equipment. Simulations have shown that the additional monitoring successfully constrains the size of residual errors in the vertical domain to about 10 m. This error size is still quite significant and the ability of autopilots to perform satisfactorily in the presence of such errors needs to be investigated.

6. Future (multi-frequency/multi-constellation) GNSS mitigation techniques

6.1 GNSS evolution

By 2020, multiple GNSS core constellations, including new and modernized constellations, will broadcast civil signals on two or more aeronautical frequencies. GNSS receivers capable of tracking multiple frequencies and multiple core constellations will then become available, and will likely become predominant as time passes. So far, four constellations are foreseen to be operational by 2020:

- GPS III with civil signals on the L1/L5 frequencies
- Galileo with civil signals on the E1/E5 frequencies
- COMPASS with dual frequency signals
- GLONASS K (with new signals interoperable with GPS and Galileo)

Figure 18 illustrates the expected evolution of these constellations. The figure also shows a prediction concerning the percentage of the worldwide aircraft fleet expected to equip with multi-constellation/multi-frequency receivers as well as the current prediction concerning the Sun Spot Number. In 2010, only 65% of the aircraft fleet was equipped with GPS L1 avionics. It appears therefore highly probable that, even if multi-frequency/multi-constellation user equipment is available in 2020, the majority of aircraft may not be equipped with these receivers, and navigation during Solar Cycle 25 may still mostly rely on single frequency/constellation user equipment.

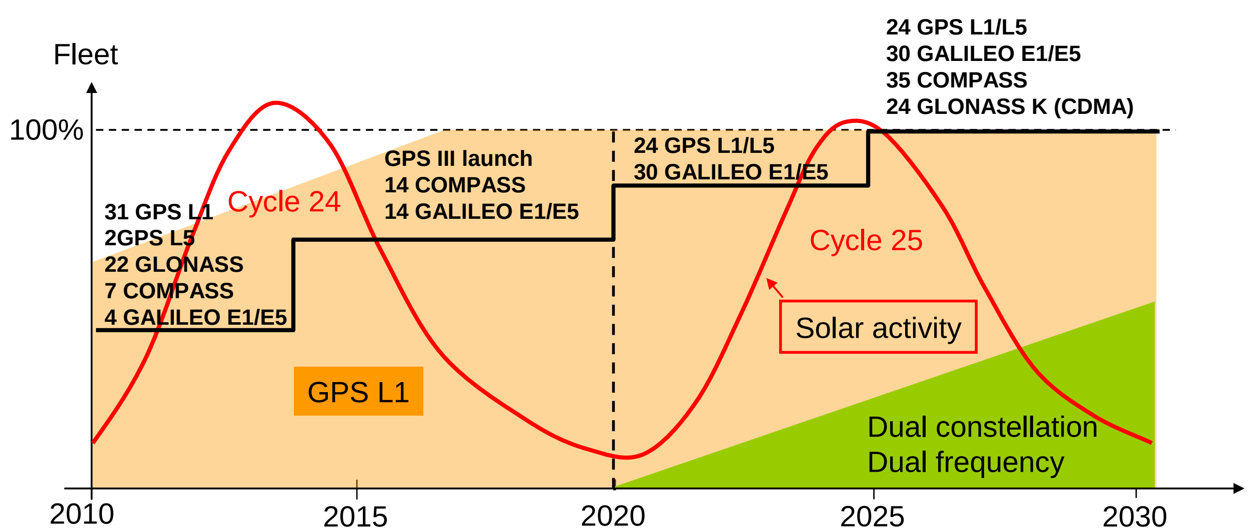


Figure 18: Evolution of GNSS Core Constellations

6.2 Mitigation techniques for propagation delays

The amount of ionospheric delay affecting an L-band signal is inversely proportional to the square of the frequency of that signal. Therefore, accurate estimates of ionospheric delay at a given L-band frequency along the line of sight between a receiver and a satellite are possible by combining pseudorange (and/or carrier phase) measurements derived from two GNSS signals with different L-band frequencies. It is also possible to directly obtain pseudorange measurements from which the ionospheric delays have been removed (ionosphere-free pseudoranges).

The theoretical accuracy of the resulting ionospheric delay estimates can be very high (of the order of 0.163 m at the L1 frequency or about one TEC Unit or TECU). However, the accuracy that will be obtained in practice will depend on the magnitudes of residual errors associated with satellite inter-frequency biases and multipath corrections.

This method of removing ionospheric delay effects is currently used by authorized GPS receivers, which have the capability of tracking the encrypted, or P(Y), code transmitted on both the GPS L1 and L2 signals.

This method is also used by receivers used in reference stations of current SBAS implementations. In this case, however, the receivers must rely on one of several codeless or semi-codeless techniques in order to track the GPS L2 signal. These techniques result in a loss of signal-to-noise density ratio of at least 10 dB-Hz [Woo, 2000]. They are very sensitive to dynamic motion, multipath errors and scintillation effects, and as a result, are not appropriate for airborne receivers.

The future implementation of GNSS core constellations that broadcast dual-frequency signals for use by civil aviation will be a welcomed development, which will essentially reduce the ionosphere from a major to a minor contributing source of navigation errors (as long as the signals from both frequencies are available and tracked). Following this development, dual-frequency receivers will be able to provide a high availability of ER/NPA navigation in most of the world using only a receiver-based FDE function to ensure the integrity of the navigation solution. Dual-frequency, multi-constellation receivers using an advanced RAIM technique for integrity may also be capable of supporting APV approach procedures without augmentation. However, this is a topic of active research, and it is currently too early to tell whether it will be possible to meet the integrity requirement under scenarios of multiple satellite faults using receiver-based techniques exclusively.

Dual-frequency, multi-constellation signals will also be beneficial to SBAS-based navigation. They may make SBAS-based CAT I Precision Approach possible anywhere in the world, provided of course that the approach is within the service area of an SBAS. Furthermore, as the need to provide ionospheric correction deceases, it will become possible to consider SBAS implementations with reduced ground infrastructures since the main role of SBAS will then be to monitor the satellites and provide satellite integrity information. (However, the SBAS ionospheric function may still be of value to continue to provide service to users equipped with legacy single-frequency receivers, and also as a fallback solution to maintain APV service when users equipped with dual-frequency receivers are unable to receive one of the frequencies due to interference or severe scintillation on only one frequency.)

Finally, this development will also be beneficial to GBAS-based navigation since it will eliminate the additional monitoring currently needed to detect and mitigate potential sharp differences in the ionospheric delays seen by the aircraft and by the GBAS station. Therefore, it will be possible to further improve GBAS service availability and continuity performance in all regions.

6.3 Mitigation techniques for scintillation

Future and modernized core constellation will broadcast multiple signals for civil use. The optional use of receivers tracking two civil signals will greatly reduce the sensitivity of SBAS reference station receivers to phase scintillation by eliminating the need for semi-codeless tracking.

Dual-frequency airborne receivers tracking two civil signals may be slightly more sensitive to phase scintillation by virtue of the fact that either one of the two frequencies could be affected by scintillation. However, the increased sensitivity is expected to be relatively minor because there is a high probability that both signals will be affected simultaneously. The higher intensity of scintillation at the GPS L5 and Galileo E5 frequencies will not results in a greatly increased sensitivity of these signals to scintillation, as compared to the GPS L1 signal, because of the greater signal power of the L5 and E5 signals as compared to the GPS L1 signal.

Studies of scintillation effects based on scintillation models have indicated that there is a high correlation between scintillation events on signals at frequencies near one another such as GPS L1 and L5 or Galileo E1 and E5 at least for low S4 values [Béniguel, 2002, 2003, 2006]. However, a subsequent study of this correlation as a function of the S4 value suggests that this correlation is much weaker for S4 values above 0.3, which corresponds to a moderate level of amplitude scintillation [Béniguel, 2006].

A study based on available literature was conducted as part of the GALILEI Task G project sponsored by the European Commission to evaluate the robustness of receivers able to make a combined use of multiple GNSS signals to amplitude scintillation effects [Butsch, 2003]. The analysis considered the GPS L1, L2 (for semi-codeless tracking) and L5 signals and the Galileo L1, E5a and E5b signals. The study concluded that lock on the semi-codeless tracking of the GPS L2 signal can be lost under low to moderate amplitude scintillation conditions (S4 values between 0.2 and 0.7). In contrast, losing lock a GNSS signal from which the code is tracked requires more intense scintillation (S4 values between 0.8 and 1.2 for GNSS signals received at elevations of 12° or less and S4 values above 1.2 for signals received at elevations above 12°).

7. Ionospheric research in the context of GNSS implementation

A program of ionospheric research is not considered indispensable in order to approve GNSS for ER/NPA operations. These operations can be flown using a basic GNSS receiver or an SBAS receiver using ionospheric corrections derived from mathematical models as briefly described in 4.1.1. These models were validated for worldwide use as part of the development of avionics standards, and so they do not require further validation for the area concerned by the approval.

However, GNSS navigation is clearly a major building block of the future development of civil aviation, and therefore, GNSS-oriented research programs aimed at characterizing the ionospheric environment of an area where GNSS navigation is approved, or considered for future approval, would provide valuable information to support the future extension of such approvals to SBAS-based or GBAS-based navigation.

A program of ionospheric research is an essential component of the development and implementation of an augmentation system. In fact, a good understanding of the challenges posed by the ionosphere in the area where such implementations are under consideration could provide important insights to the development of a program plan.

Much relevant research has already been performed by various States participating in the work of the Navigation System Panel, and in many cases useful information in the form of report, papers, and expert advice can be provided by these States. It is generally desirable to tailor an envisioned research program to the GNSS implementation program the research is intended to support.

Data collection and analysis should be an important component of a research program. Research in an SBAS implementation context, for example, would be concerned with characterizing ionospheric effects over a wide area, and therefore would need data collected from dual-frequency GNSS receivers at widely dispersed locations over the intended service area. In contrast, research in a GBAS implementation context would be concerned with characterizing ionospheric effects over one or several local areas, and therefore would need data collected by closely spaced clusters of dual-frequency receivers in areas where GBAS implementations are being considered.

The importance of ionospheric data collected with high-quality dual-frequency GNSS receivers during the year of a solar cycle peak and for two to three years after the peak should not be underestimated. Augmentation systems are intended to provide service for many years well into the future, and therefore their design need to provide adequate guarantees that they will continue to meet the requirements (in particular the integrity requirements) during periods of high solar activity. Data recorded when the ionosphere is severely disturbed is particularly important to properly assess the achievable level of performance of a proposed augmentation system design.

While magnetic storms can occur at any point of the solar cycle, the most severe magnetic storms tend to occur near the peak and during the first few years following the peak (down phase). The space weather scientific community characterizes the severity of geomagnetic storms using indicators such as the geomagnetic Kp, Ap and D_{st} indices. These planetary indices actually characterize variations in the magnetic field of the earth as measured by 13 measuring stations distributed across the globe. As a result, these planetary indices are not of direct use to GNSS because of the limited degree of correlation between their magnitudes and the severity of GNSS effects in a given geographic location. However, these indices are very useful to identify days of recorded data that might be of interest to evaluations of SBAS or GBAS performance.

7.1 Propagation delay

Dual-frequency GNSS ground receivers can be used to measure the propagation delay from pseudorange (and carrier phase) measurements made at two separate frequencies. Using a network of GNSS ground stations, propagation delays caused by the ionosphere can be mapped over large areas. Several providers already offer real-time maps of worldwide or regional ionospheric propagation delay computed from data provided by networks of GNSS ground stations such as the International GNSS Service (IGS), the Continuously Operating Reference Station (CORS) network, or the EUREF GNSS Permanent Network (GPN). An example of such products is shown on Figure 19.

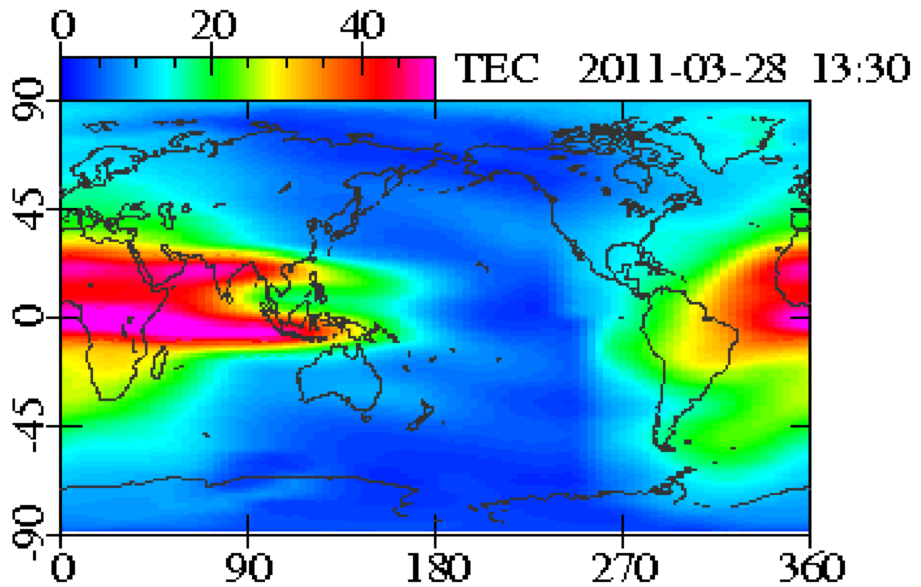


Figure 19: Real time ionosphere propagation delay from spaceweather.usu.edu

However, the density of these measurements is usually not sufficient to compute localized ionosphere spatial gradients or to evaluate the effects of plasma bubbles.

7.2 Scintillation

Scintillation measurements require dedicated GNSS receivers. Typical GNSS receivers do not output data with a sufficiently high rate to capture the high temporal variations induced in a received signal by scintillation. These dedicated GNSS receivers are usually called Ionospheric Scintillation Monitors (ISM). Scintillation data collections are recommended in areas known to be regularly affected by intense scintillation.

8. Solar radio bursts

Solar radio bursts are not ionospheric phenomena, but they are produced by the sun and they can affect the operation of GNSS receivers. They will therefore be briefly discussed in this section.

Solar radio bursts are bursts of energy emitted by the sun in the radio frequency spectrum. They usually occur in conjunction with solar flares. Like flares solar radio bursts tend to be more frequent near the peak of the solar cycle as shown in Figure 20. They can last from a few tens of seconds to a few hours, and they can have different intensities, polarizations and bandwidths. They typically occur in the frequency range from a few tens of megahertz up to 3 gigahertz [Bastian et al., 1998]. From a GNSS receiver's perspective, a solar radio burst acts as a source of interference by raising the noise environment of the received signal. Its impact on the operation of the receiver depends on its intensity, polarization and amount of overlap with the GNSS signal bandwidth [Cerruti, 2008].

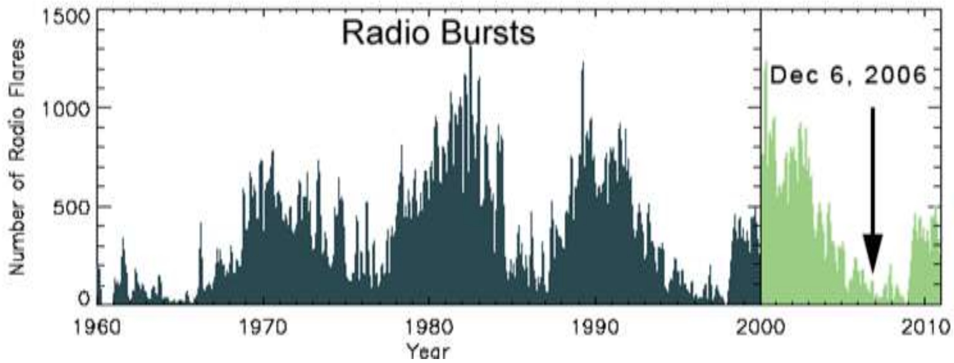


Figure 20. Occurrences of Solar Radio Burst since 1960
(Courtesy New Jersey's Science and Technology University)

Solar radio bursts are relatively frequent but have typically no noticeable effect on GNSS receivers. In fact, up to late 2006, it was generally thought that they simply had no impact at all on GNSS. However, on December 6, 2006, a solar radio burst of record-setting intensity occurred in the GNSS signal band and caused many receivers from the International GNSS Service (IGS) and Continuously Operating Reference Station (CORS) networks in North America to lose service for several minutes (a drop in signal-to-noise ratio of 35 dB on L1 was recorded at Cornell University in Ithaca, New York). Its impact on WAAS reference station receivers was however much more limited (a drop in signal-to-noise ratio of 10 dB on L1 and 13 dB on L2 was recorded at the WAAS reference station in Islip, New York): WAAS ER/NPA service remained unaffected and WAAS LPV service continued over most of the United States, but a short temporary loss of service occurred in the Northwest [Pat Doherty, 2007].

9. Conclusions

This paper contains a discussion of the ionosphere and its effects on GNSS. It is intended for civil aviation decision makers and GNSS implementation engineers. The main points covered in the paper are as follows:

1. The ionosphere is a region of the upper atmosphere that has been ionized by solar radiation. As a result of this ionization, it contains free electrons, which affect the propagation of radio frequency signals. At the GNSS receiver antenna the two main effects of the signal propagation through this medium (plasma) are: (1) a delay in the propagation of the code used for pseudorange measurement (and a corresponding advance in the carrier phase), and (2) a possible fluctuation in the signal power and phase known as scintillation.

2. The magnitudes of these effects vary depending on various factors including the portion of the 11-year solar cycle when measurements are made, the time of day when they are made, the latitude where they are made, and even the season when they are made. In general, these effects are mild in mid-latitude regions, except during severe ionospheric storms, which can occur about 1% of the time. These effects are somewhat more significant in high-latitude regions. They are much more significant in low-latitude regions where a large plasma drift away from the equator takes place in the local evening hours and causes large crests of electron contents and other phenomena (e.g., plasma bubbles or depletions) resulting in large ionospheric delay gradients as well as intense scintillation.

3. ABAS, SBAS and GBAS use different techniques to correct for ionospheric delays. ABAS uses simple models implemented in the receiver software that are adequate for navigation in the en route through non-precision approach phases of flight, but are not adequate for any type of approach during which vertical guidance is provided. SBAS provides ionospheric delay corrections derived from ionospheric delay measurements at a set of reference stations distributed over a wide area. GBAS provided differential corrections correcting for the combined effects of various sources of ranging measurement errors, including ionospheric delays. The corrections provided by SBAS and GBAS are much more accurate that those calculated by ABAS because they are derived in real-time from actual measurements and are therefore adequate for approach with vertical guidance (APV) and Category I precision approach. However, many experts question the feasibility of an operationally meaningful APV service from single-frequency SBAS in the equatorial region as a direct consequence of the great variability of the ionosphere in that region. Further evolution of the GBAS technology will soon allow GBAS to be used for Category II/III precision approach.
4. Scintillation, if sufficiently intense, can cause a receiver to temporarily lose lock on the signal from one or multiple satellites in view. Signal losses due to scintillation are typically very short in duration (1 second or less). However a loss of navigation can result if the signals from several satellites are lost simultaneously. Scintillation can affect service for several hours. The main mitigation against this effect resides in the receiver design, and in particular the ability of a receiver to rapidly re-acquire a satellite signal temporarily lost to scintillation.
5. The residual ranging errors from ionospheric delay corrections are currently the largest among the various ranging errors affecting the accuracy of GNSS position and timing solutions. Ranging errors due to the ionosphere will be greatly reduced when GNSS receivers are able to process dual-frequency signals and therefore able to derive ranging information that excludes ionospheric delay effects (iono-free ranges). However, the new technology may not become available much before 2020.
6. Ionospheric effects on GNSS are well understood and mitigated and do not put at risk the ultimate goal of transition to GNSS as a global system for all phases of flight.

10. References

Anderson, D., A. Anghel, K. Yumoto, M. Ishitsuka, and E. Kudeki, “Estimating Daytime, Vertical ExB Drift Velocities in the Equatorial F-region using Ground-Based Magnetometer Observations,” presented at the International Beacon Satellite Symposium (BSS), Boston College, Boston, June 2001.

Arbesser-Rastburg, B., Y. Beniguel, “The Effects of Scintillations in the Equatorial Regions on the Positioning Errors,” IES, 3-5 May 2005.

Azpilicueta, F. , Radicella S.M. and Brunini C., "VTEC behavior based on GPS observations in the North Pole region during 2003 magnetic storms", proceedings of the International Beacon Satellite Symposium 2004, Trieste 18-22 October 2004.

Bastian, T. S., A. O. Benz, D. E. Gary, “Radio emissions from solar flares,” Annual Review of Astronomy and Astrophysics, No. 36, 1998, pp. 131-188.

Beniguel, Y., "Statistical properties of signals affected by ionospheric scintillation," presented to the 6th SBAS Iono. Working Group meeting, Maastricht, the Netherlands, August 2002.

Beniguel, Y., Adam J.-P., "Ionospheric Scintillation and System Availability and Accuracy in the African Zone," presented to the 7th SBAS Iono. Working Group meeting, Graz, Austria, April 2003.

Béniguel, Y., J.-P Adam, J. Geiswiller, "Characterization of ionosphere scintillations, PLL and DLL errors at receiver level," Proceedings of the Atmospheric Remote Sensing Conference, Matera, Italy, 2003.

Béniguel, Y., J.-P. Adam, B. Arbesser-Rastburg, J. Pita, "Analysis of scintillation data recorded in Africa at low latitudes," Beacon Symposium, Trieste, Italy, October 2004.

Beniguel, Y., J.-P.Adam, "Scintillation Parameters Obtained from Measurement Data," SBAS-Iono Meeting # 12, Boston, June 1-2, 2006.

Beniguel, Y., J.-P. Adam, "Effects of Scintillations in GNSS Operation", Chapter 3.5 in the book by J. Lilensten, *Space Weather - Research towards Applications in Europe*, Springer, 2007.
Buonsanto, M.J., "Ionospheric storms - A review", Space Science Reviews 88, 563-601, 1999.

Burke, W. J., C. Y. Juang, L. C. Gentile, L. Bauer, "Seasonal-longitudinal variability of equatorial plasma bubbles", Annales Geophysicae, No. 22, European Geosciences Union, 2004, pp. 3089-3098.

Cerruti, A. P., "Solar Radio Burst Effects on Global Positioning System Receivers," PhD Dissertation, Cornell University, New York, 2008.

Chatre E., F. Salabert, A. Lipp., O. Glaser, B. Vauvy, "Extensibility of GAST-D SARPs to multiple constellations and frequencies," WP30, NSP WGW, May 2010.

Conker, R., M. B. El-Arini, C. H. Hegarty, T. Hsiao, "Modeling the Effects of Ionospheric Scintillation on GPS/SBAS Availability," Proceedings of the Institute of Navigation 56th Annual Meeting, San Diego, 26-28 June 2000.

Conker, R. S., M. B. El-Arini, R. Lejeune, P. Doherty, and C. Valladares, "Description of a Real-Time Algorithm for Detecting Ionospheric Depletions for SBAS and the Statistics of Depletions in South America During the Peak of the Current Solar Cycle," Beacon Satellite Symposium (BSS), Trieste, Italy, October 2004.

Daniell, R. E., L. D. Brown, D. N. Anderson, M. W., Fox, P. H. Doherty, D. T. Decker, J. J. Sojka, and R. W. Schunk, "Parameterized Ionospheric Model: A Global Ionospheric Parameterization based on First Principles Models," pp. 1499-1510, Volume 30, Number 5, Radio Science, September-October 1995.

DasGupta, A., S. Ray,, A. Paul, "Estimation of Minimum Separation of Geostationary Satellites for Satellite-Based Augmentation System (SBAS) from Equatorial Ionospheric Scintillation Observations," Ionospheric Effects Symposium, Alexandria, Virginia, 2002.

Davies, Kenneth, *Ionospheric Radio*, Peter Peregrinus LTD, London, United Kingdom, 1990.

Dehel, T., "Ionospheric Scintillation Effects on SBAS at the Geomagnetic Equator," briefing to the 5th SBAS Ionospheric Working Group meeting, McLean, VA, May 10-11, 2002.

Dehel, T., K. Pham, J. Sheftic, D. Nelthropp, "National Satellite Test Bed (NSTB) Recent Observations of the Effects of Ionospheric Storms on a Prototype Wide Area Augmentation System," pp. 239-246, Proceedings of the 1999 Ionospheric Effects Symposium, 4-6 May 1999, available from JMG Associates, Alexandria, VA 22308, 1999.

Doherty, P. H., S. H. Delay, C. E. Valladares and J. A. Klobuchar, "Ionospheric Scintillation Effects in the Equatorial and Auroral Regions," pp. 662-671, proceedings of the Institute of Navigation conference ION-GPS-2000, Salt Lake City, UT, September 19-22, 2000.

Doherty, P. H., "Solar Effects on WAAS", briefing to the 13th SBAS Iono. Working Group meeting, June 2007.

El-Arini, M. B., R. S. Conker, S. D. Ericson, K. W. Bean, F. Niles, K. Matsunaga, and K. Hoshinoo, "Analysis of the Effects of Ionospheric Scintillation on GPS L2 in Japan," proceedings of the Institute of Navigation conference ION-GPS-2003, Portland, OR, September 2003.

El-Arini, M. B., R. S. Conker, R. Lejeune, J. P. Fernow, T. Hsiao, "Validation of the En Route Through NPA GPS Ionospheric Delay Model in the WAAS MOPS (DO-229C)," briefing to RTCA Special Committee 159, Working Group 2, 8 March 2005.

Eldredge, L., J. Burns, B. Clark, "Anomalous Ionosphere Change Proposal for Geometry Screening," WP 39, NSP WGW, May 2010.

Fedrizzi, M., E. R. de Paula, I.J. Kantor, R.B. Langley, A. Komjathy, Eduardo A. Araujo-Pradere, T.J. Fuller-Rowell, ""Investigation of Ionospheric Response to Severe Magnetic Storms Using GPS Total Electron Content Measurements," proceedings of the International Beacon Satellite Symposium 2004, Trieste 18-22 October 2004.

Fee, J., "Ionospheric activity and its effects on WAAS," IP5, meeting of the NSP Working Group of the Whole in St Petersburg, 25 May to 4 June 2004.

Forte, B., S. M. Radicella, R. G. Ezquer, "A Different Approach to the Analysis of GPS Scintillations Data," Adbus Salam ICTP, IC/2001/29, 2001

GARMIS Report D-2431, Ionospheric conditions in the equatorial region, 2006.

Hargreaves, J. K., *The Solar-Terrestrial Environment: An Introduction to Geospace – the Science of the Terrestrial Upper Atmosphere, Ionosphere and Magnetosphere*, Cambridge Atmospheric and Space Science Series, 1995.

Hibberd, F.H., "Positive and Negative Ionosphere Storms," proceedings of the International Beacon Satellite Symposium 2004, Trieste 18-22 October 2004.

Huang, C. Y, W. J. Burke, J. S. Machuzak, L. C. Gentile, "DMSP observations of equatorial plasma bubbles in the topside ionosphere near solar maximum," Journal of Geophysical Research, Vol. 106, No. A5, pages 8131-8142, May 1, 2001.

ICAO, International Standards and Recommended Practices (SARPs), Aeronautical Communications, Annex 10, Vol. I, Appendix B, Montreal, Canada, 5th Edition, July 1996, Amendment 80, 2005.

Immel, T. J., J. C. Foster, A. J. Coster, S. B. Mende, H. U. Frey , "Global storm time plasma redistribution imaged from the ground and space," Geophysical Research Letters, 32, L03107, doi:10.1029/2004GL021120, 2005.

Kelley, M. C., *The Earth's Ionosphere Plasma Physics and Electrodynamics*, Vol. 43 in the International Geophysics Series, Academic Press, Inc. New York, N. Y., 1989.

Klobuchar, J. A., G. J. Bishop and P. H. Doherty, "Total Electron Content and L-Band Amplitude and Phase Scintillation Measurements in the Polar Cap Ionosphere," AGARD-CPP-382, May 1985.

Klobuchar, J. A., "Ionospheric Effects on GPS," Chapter 12, Volume I, Global Positioning System: Theory and Applications, Edited by B. W. Parkinson, and J. J. Spilker, Volume 163, Progress in Astronautics and Aeronautics, AIAA, Inc., Washington, D.C., 1996.

Komjathy, A., L. Sparks, A. J. Mannucci, X. Pi, "An Assessment of the Current WAAS Ionospheric Correction Algorithm in the South American Region," Institute of Navigation International Technical Meeting, ION-GPS-2002, Portland, OR, September 24-27, 2002.

Lejeune R., M. B. El-Arini, J.A. Klobuchar, P. H. Doherty, "Adequacy of the SBAS Ionospheric Grid Concept for Precision Approach in the Equatorial Region," ION-GPS-2002.

Lejeune R., M. B. El-Arini, P. Doherty, J. Klobuchar, E. De Paula, F. Rodrigues, A. Canavitsas, "Performance of SBAS Ionospheric Estimation in the Equatorial Region," Institute of Navigation GPS Meeting, ION-GPS-2003, Portland, OR, September 2003.

Matsunaga, K., K. Hoshinoo, "Observation of Ionospheric Scintillation on GPS Signals in Japan," Proceedings of the Institute of Navigation conference ION-NTM-2002, San Diego, CA, January 28-30, 2002.

Parkinson, B. W., and J. J. Spilker (Editors), *Global Positioning System: Theory and Applications*, Volume I, American Institute of Aeronautics and Astronautics, 1996.

Pi, X., S. Nandi, B. M. Boulat, D. A. Stowers, and A. J. Mannucci, "Development of Ionospheric Scintillation Monitoring System Using IGS GPS Receivers and Analysis of Effects of Scintillation on GPS Signals," JPL Technical Report to the FAA, Pasadena, CA, April 2002.

Pimenta, A. A., P. R. Fagundes, J. A. Bittencourt, Y. Sahai, "Relevant Aspects of Equatorial Plasma Bubbles under Different Solar Activity Conditions," Advances in Space Research, Vol. 27, No 6-7, pp. 1213-1218, Published by Elsevier Science Ltd., 2001.

Pullen, S., M. Luo, J. Lee, G. Zhang, and P. Enge, "Update on Mitigation of Ionosphere Spatial Anomaly threat to GBAS," presentation to RTCA SC-159, WG4, 22-23 March 2006.

Radicella, S.M., and R. Leitinger, "The Evolution of the DGR Approach to Model Electron Density Profiles," Advanced Space Research, Vol. 27, No. 1, 35-40, 2001.

Rama Rao, P. V. S., S. Tulasi Ram, S. Gopi Krishna, K. Niranjan, and D. S. V. V. D. Prasad, "Morphological and Spectral Charactersitics of L-Band and VHF Scintillations and their Impact on Trans-Ionospheric Communications," Earth Planets Space, Vol. 58, pp. 895-904, 2006.

RTCA, Inc., "Minimum Operational Performance Standards for Airborne Supplemental Navigation Equipment Using Global Positioning System", DO-208 July 12, 1991 and DO-208 Change 1, September 21, 1993.

RTCA, Inc., "Minimum Operational Performance Standards for GPS Local Area Augmentation System Airborne Equipment," DO-253C, Washington, D.C., December 16, 2008.

RTCA, Inc., "Minimum Operational Performance Standards for Global Positioning System/Wide Area Augmentation System Airborne Equipment," DO-229D, Washington, D.C., December 13, 2006.

Sahai, Y., P. R. Fagundes, J. A. Bittencourt, "Transequatorial F-region ionospheric plasma bubbles: solar cycle effects," Journal of Atmospheric and Solar-Terrestrial Physics, No 62, pp. 1377-1383, Published by Elsevier Science Ltd., 2001.

SBAS Ionospheric Working Group, "Ionospheric Research Issues for SBAS – A White Paper", 2003, (available as NSP IP39, Joint WG1/WG2 meeting in Montreal, 11-21 October 2005).

SBAS Ionospheric Working Group, "Effect of Ionospheric Scintillation on GNSS Issues – A White Paper", 2010, (available as NSP Flimsy14, WGW meeting in Montreal, 9-20 May 2011).

Skone, S., and M. E. Cannon, "Auroral Zone Ionospheric Considerations for WADGPS," pp. 117-127, *NAVIGATION*, Journal of The Institute of Navigation, Vol. 45, No., 2, Summer 1998.

Woo, K. T., "Optimum Semi-codeless Carrier-Phase Tracking of L2," Navigation, Journal of the Institute of Navigation, Vol. 47, No. 2, Summer 2000.

11. Acronym List

ABAS	Airborne-Based Augmentation System
APV	Approach with Vertical guidance
CAT I/II/III	Category I/II/III
CONUS	Conterminous United States
CORS	Continuously Operating Reference Station
C/A	Coarse Acquisition
C/N_0	Carrier-to-noise density ratio
EGNOS	European Geostationary Navigation Overlay Service
ER	En Route
ER/NPA	En Route through Non-precision Approach
EUROCAE	European Organization for Civil Aviation Equipment
EUV	Extreme Ultraviolet
FDE	Fault Detection and Exclusion
GBAS	Ground-Based Augmentation System
GLONASS	Global Navigation Satellite System
GNP	GNSS Permanent Network
GNSS	Global Navigation Satellite System
GPS	Global Satellite System

HAL	Horizontal Alert Limit
HF	High Frequency
ICAO	International Civil Aviation Organization
IGS	International GNSS Service
LPV	Localizer Performance with Vertical guidance
NPA	Non-precision Approach
NSP	Navigation System Panel
PA	Precision Approach
RAIM	Receiver Autonomous Integrity Monitoring
RNP	Required Navigation Performance
PIM	Parameterized Ionospheric Model
SARPs	Standards and Recommended Practices
SBAS	Satellite-Based Augmentation System
SSN	Sun Spot Number
TEC	Total Electron Content
TECU	Total Electron Content Unit
URSI	International Union for Radio Science
US	United States
UT	Universal Time
WAAS	Wide-Area Augmentation System
WG	Working Group