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International Civil Aviation Organization
CAR/SAM REGIONAL PLANNING IMPLEMENTATION GROUP (GREPECAS)
Fifth Meeting of the CNS Committee of the GREPECAS ATM/CNS Subgroup (CNS/COMM/5)
Lima, Peru, 13 to 17 November 2006

Agenda Item 2: **Navigation systems developments**
2.2 Study of a SBAS/GBAS regional implementation system.

IONOSPHERE EFFECTS ON GNSS

(Presented by the Secretariat)

SUMMARY

This paper presents the first draft of the paper on ionosphere effects on GNSS written by the Ionospheric Ad Hoc Group of the ICAO Navigation Systems Panel (NSP)

References:

- NSP WG1&2/WP28, dated May 2006.

1. Introduction

1.1 The Draft NSP Paper on Ionospheric Effects on GNSS is presented in the **Appendix** to this information paper.

2. Conclusion

2.1 The draft information shown in the Appendix is presented only for information purposes.

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APPENDIX

NSP WG1&2/WP28

INTERNATIONAL CIVIL AVIATION ORGANIZATION
NAVIGATION SYSTEMS PANEL (NSP)

Working Group (WG1&2) Meeting
Brussels, Belgium
May 8-19, 2006

Agenda Items 7h: GNSS vulnerability, mitigation strategies

(Also Agenda Items 2b and 3a: impact of ionospheric effects on L1 operations)

Draft NSP Paper on Ionospheric Effects on GNSS

Ionospheric Ad hoc Group

Summary

This working paper presents the first draft of the paper on ionospheric effects on GNSS written by the ad hoc group at the request of NSP (see attachment). The decision to produce an NSP paper on ionospheric effects on GNSS was discussed and agreed by WG1 and WG2 at the last WG1&2 meeting in Montreal, Canada, October 11-21, 2005. During that same meeting, a high-level discussion of the contents of the proposed paper took place within GSSG.

The working groups are invited to review the attached document and provide comments and suggestions to the ad hoc group. The goal of the ad hoc group is to present a final draft of the paper at the next NSP WG1&2 meeting. Comments and suggested changes can be sent by email to Roland Lejeune (rlejeune@mitre.org) who will coordinate the responses of the ad hoc group.

1. Introduction

This working paper presents the first draft of the paper on ionospheric effects on GNSS NSP written by the ad hoc group at the request of NSP (see attachment).

2. Background

At the last NSP WG1&2 meeting in Montreal, Canada, October 11-21, 2005, the working groups decided that NSP should produce material discussing the state of knowledge on ionospheric effects on GNSS in order to support implementation decisions by States (Meeting report 3.4.8.1). Such a task is part of the NSP's work program; it also follows from a recommendation from the 11th Air Navigation Conference. While discussing this task in Montreal, it was agreed that the scope of the paper should not be limited to SBAS, but should cover all aspects of GNSS including basic service and GBAS. An ad hoc group was formed and charged with preparing a first draft to be reviewed at this meeting. Participation in the ad hoc group included representatives from Europe, India, Japan and the United States.

Also in Montreal, a high-level discussion of the contents of the proposed paper took place within GSSG. It was agreed that the paper should cover the following topics (Meeting Report 3.4.8.2):

- effects on navigation solutions and on ATS services, particularly when there are ionospheric disturbances;
- mitigation techniques or potential mitigation techniques in the receiver, in the system design, and through operational means; and
- planned and existing research activities, including expected products and timeframes.

It was also agreed that papers on ionospheric effects presented at previous meetings, as well as the white paper from the SBAS Ionospheric Working Group and the paper on GNSS vulnerabilities presented at the 11th AN Conference, should be used as input material.

3. Comments

The ad hoc group has developed the attached paper in accordance with the instructions from GSSG and WG1&2. Nevertheless, now that a first draft is available for review, the following basic questions should be asked: (1) does the paper generally cover the material envisioned by NSP and (2) should some of the material covered in the paper be further expanded, or further summarized? Answers to these basic questions are relatively urgent since the goal expressed at the last meeting is to have a final draft of the paper available for review at the next NSP WG meeting.

Feedback from the SBAS Ionospheric Working Group, which authored the White Paper that served as initial starting point for this paper, would be very useful. It is proposed that the draft paper be presented to this group at its forthcoming meeting in June and that comments from the group be requested.

A few comments from the ad hoc group have been left in the draft paper. They are provided between brackets and in italic for easy identification. Feedback from NSP on these comments will be appreciated, particularly if changes need to be made.

4. Recommendation

NSP WG1&2 are invited to review the attached first draft of the paper on ionospheric effects on GNSS and provide comments and suggested changes to the ad hoc group. Major comments such as comments on the structure, contents and level of detail of the paper are requested as soon as possible, preferable before the end of July. Minor comments and editorial changes can be provided at any point, up to a few weeks prior to the next meeting. Comments and suggested changes can be sent by email to Roland Lejeune (rlejeune@mitre.org) who will coordinate the responses of the ad hoc group.

May 2006

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[1]), Satellite-Based Augmentation Systems (SBAS) and Ground-Based Augmentation Systems/Ground-based Regional Augmentation Systems (GBAS/GRAS).

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 such issues as signal propagation delays and their effects on pseudorange measurements, and scintillation and its effects on signal tracking. It also covers a few more, but perhaps less well-known, ionospheric phenomena such as ionospheric storms, equatorial anomalies and depletion bubbles. The existence of these phenomena cannot be ignored when considering GNSS implementation because their effects on GNSS can be significant (SBAS Ionospheric WG, White Paper, 2003).

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 also happen to be 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 mitigation techniques. It is not intended to provide detailed technical information on system designs, nor describe the algorithms that have been developed to mitigate these effects. Detailed information on proposed designs and algorithms can be found in numerous research paper presented to the International Ionospheric Effects Symposium, the U.S. Institute of Navigation, the International Union for Radio Science, and other technical forums. The reference section lists some of these papers.

Similarly, this paper is not intended to provide a detailed discussion of the ionosphere, nor to elaborate on 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). Textbooks and papers on this subject are generally oriented to describing the morphology of the ionosphere, explaining its behavior or its effects on communications, and they typically offer only limited insights on the issues confronting developers of GNSS systems and providers of GNSS services. These issues are driven by two main concerns: (1) the ability to generate and communicate ionospheric corrections as well as integrity bounds that support the desired level of service while meeting the standards for accuracy, integrity, availability

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[1] 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 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.

and continuity, and (2) the ability of GNSS user equipment to track the code and carrier phase of GNSS signals in a manner that is sufficiently robust to support the desired level of service.

1.2 Operational Categories

For the purposes of this discussion, the range of levels of service 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 (PA).

1.3 Ionospheric Delay Corrections Methods used by GNSS

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

Dual-frequency systems use measurements at different frequencies to directly compute pseudoranges that exclude ionospheric delays (so-called ionosphere-free pseudoranges). This method cannot currently be used by airborne receivers used by civil aviation. This situation will change within the next decade or so when new and modernized GNSS core constellations will broadcast civil coded signals on two or more aeronautical frequencies. However, until that time, airborne receivers used by civil aviation are limited to using the GPS L1 signal for pseudorange measurements. Therefore, the discussion in this paper is oriented toward single-frequency users. Unless special mention to the contrary is made, it will be assumed that user receivers -- whether ABAS, SBAS or GBAS/GRAS receivers -- are single-frequency receivers.

Single-frequency receivers use one of three methods to obtain ionospheric corrections.

ABAS avionics (RTCA DO-208, 1993), and SBAS receivers outside the SBAS service area, compute ionospheric corrections using a simple model and a set of model coefficients broadcast by core constellation satellites. A simple model is also used to compute conservative standard deviations for the residual errors. This correction method is adequate for en route navigation through nonprecision approach (ER/NPA).

[*Some words should be added to include GLONASS in this description.*]

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 approach and landing operations known as Approach with Vertical Guidance (APV-I and APV-II). However, the level of service it can support will vary from one region of the world to another. This method can also provide high-availability support to ER/NPA navigation.

GBAS avionics do not compute ionospheric corrections (ICAO, 2005; RTCA, DO-253a, 2001). Instead, they correct for a combination of pseudorange errors including ionospheric delays, satellite clock and ephemeris, and tropospheric delay errors by applying the corrections broadcast by the GBAS ground system, which are specific to the satellites in view of the reference station. Information broadcast by GBAS also allows the receiver to compute integrity bounds. This correction method is adequate for Category I (and perhaps also for Category II/III[2]) approach and landing operations. It can also be used to

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[2] Standards for GBAS to support Category II/III operations are still under developments.

support NPA, APV-I and APV-II, and terminal area navigation, although providing support for these operations is only a secondary function for GBAS.

GRAS avionics use an extension of the method used by GBAS avionics to offer an ER/NPA service as well as APV-I/II and terminal area navigation. However, the latter services may not be available throughout the GRAS service area depending on the density and configuration of reference and broadcast stations.

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.

Section 3 discusses differences between ionospheric effects in equatorial, mid-latitude, and auroral regions. Brief discussions of ionospheric storm effects, scintillation and other phenomena of interest are included.

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

Section 5 discusses the impact of the ionosphere on operational service.

Section 6 discusses past and current research efforts aimed at better understanding these effects and more precisely assessing their impact on GNSS performance.

2. The Ionosphere and its Main Effects on GNSS

The ionosphere is a layer of the upper atmosphere located roughly between 50 km and 1000 to 1200 km above the Earth's surface, which has been ionized by solar extreme ultraviolet (EUV) and other emissions from the sun. While the densities of atoms at these altitudes are very small, this medium has noticeable electromagnetic properties due to the small fraction of these atoms (< 1%) that are disassociated into ions and free electrons. In particular, the presence of free electrons affects the propagation of radio signal in different ways depending on their frequencies.

The ionosphere is composed of several overlapping layers corresponding to changes in the chemical composition of atmosphere (Oxygen and Nitrogen in the lower altitudes, Hydrogen, then Helium 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 EUVs). Four layers are specifically identified, which are labeled D, E, F1 and F2 [Klobuchar, 1996]. The D, E, and F1 layers are located at the lower heights (from 50 km to about 210 km); these layers normally disappear during the local night. The F2 layer occupies the higher heights (from about 210 km to about 1000 km where it becomes indistinguishable from a region of ionized hydrogen called the protonosphere). Among the various layers, the F2 layer has the greatest concentration of electrons with a peak density at a height that varies between 250 km and 400 km. It is present during the night as well as during the day, although ion recombination causes the concentration of electrons to decrease during the night. This layer has the greatest effect on the propagation of radio signals, in particular GNSS signals. It is also the most variable and the least predictable.

The structure of the ionosphere is not constant but is continually varying in response to changes in the intensities of solar radiations. It is also affected by the solar wind (gaseous ionized material ejected from the sun's corona that carries magnetic clouds) and its effects the Earth's magnetic field. It follows that delays in the propagation of GNSS signals from satellite to receiver due to the ionosphere vary with time as well as with the locations of the receiver and the satellite. Some variations in the amount of delay that are due to the latitude of a receiver as well as to diurnal and seasonal changes in the incidence of sun rays are predictable to a limited extent. Other delay variations are totally unpredictable such as, for example, those associated with solar events (e.g. solar flares) resulting in magnetic and ionospheric storms[3].

While the ability of GNSS to provide ER/NPA services is very robust to such variations, large and sudden variations in ionospheric vertical delays of the order of 6 meters or more can seriously affect the availability of GNSS-provided APV and Precision Approach (PA) services. Even smaller delay variations, if they occur over short distance and time scales, have the potential to affect the availability of PA service.

The main causes of large scale variations in ionospheric delays are related to the 11-year solar cycle, seasonal changes, day-to-day changes, and diurnal changes. Major causes of both large and small scale irregularities in the distribution of free electrons in the ionosphere are related to magnetic and ionospheric storms as well as large plasma drifts causing the displacement of large masses of free electrons both in altitude and latitude. This transport of ionization characterizes the ionosphere over the magnetic equator and the low latitudes region giving rise to large horizontal and vertical gradients of electron density in the low latitude regions.

Figure 1 illustrate the solar cycle as indicated by the Sun Spot Number (SSN). The last solar cycle peak occurred in 2000-2001. The next peak is expected to occur in 2011-2012. Data collected near a solar cycle peak is highly desirable in order to evaluate the full effect of the ionosphere on potential GNSS implementations.

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[3] Similarly to the terminology used in meteorology, storms are essentially defined as departures from the normal. Magnetic storms correspond to atypical variations in the magnetic field of the Earth. Ionospheric storms correspond to atypical distributions of free electrons in the upper atmosphere. Magnetic and ionospheric storms are closely related and typically occur together, but the exact processes controlling their interaction are not fully understood. Magnetic and ionospheric storms may last from a few hours to several days and evolve in three phases: a usually short "initial phase" during which the electric field and the concentration of electrons increase above normal, a longer "main phase" during which they decrease below normal, and an even longer "recovery phase" during which they return to normal.

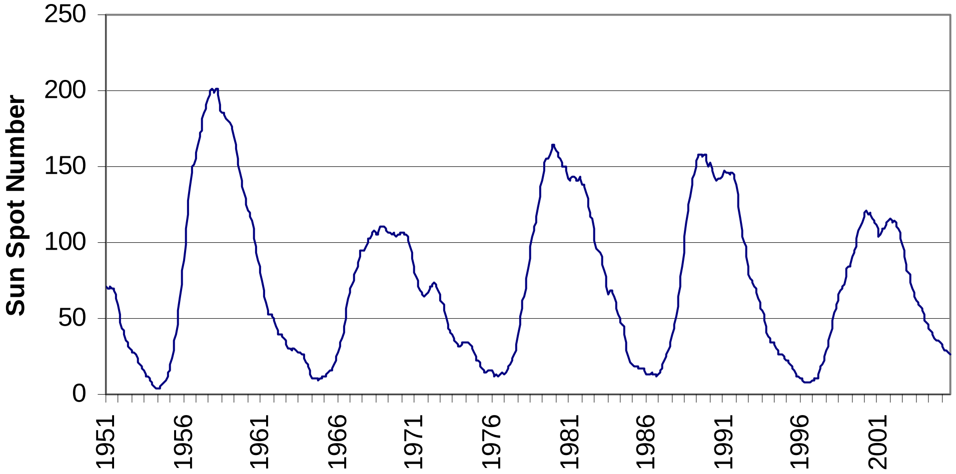

Figure 1. Solar Activity as Indicated by the Smoothed Monthly Sun Spot Number

While magnetic and ionospheric storms can occur at any point of the solar cycle, the most severe ionospheric storms tend to occur near the peak and during the first few years following the peak of the cycle (down phase). The space weather scientific community characterizes the severity of magnetic and ionospheric 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. These planetary indices are of limited utility to GNSS because they provide very little information on where and when ionospheric disturbances will affect GNSS. Furthermore, they provide insufficient information on the degree to which GNSS will be affected. However, they can be used to identify days of recorded data that would be of particular interest to evaluations of SBAS or GBAS performance.

At the frequencies used by GNSS (L-band), the ionosphere has three main effects on the propagation of signals between satellites and ground or airborne receivers: 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 the absence of the ionosphere. This phenomenon also causes an advance in the phase of the carrier with a magnitude equal (but opposite sign) to group delay. Ionospheric scintillation causes rapid variations in the amplitude and phase of a received signal. If the magnitudes of these variations are sufficiently large, the receiver may not be able to maintain lock on the signal, at least during the short periods of deep attenuation (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 topic will not be further discussed in this paper.

2.1 Group Delay

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 with a cross-sectional area of one square meter along the propagation path. There are two versions of that measure: one refers to the TEC along a vertical path[4], the other to the TEC along an oblique (or slant) path[5]. In a good, first order approximation, the amount of delay affecting a signal in the frequency range 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} el/m^2. At the GPS L_1 frequency of 1.575 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].

2.2 Scintillation

Irregularities in the distribution of free electrons along the propagation path due to small structures in the distribution of free electrons in the ionosphere can cause rapid fluctuations in the amplitude and phase of received signals, a phenomenon known as ionospheric scintillation. Scintillation typically occurs in relatively narrow patches, and therefore it affects signals with different propagation paths differently. GNSS receivers are generally able to maintain lock on signals affected by low to moderate levels of scintillation, but will often lose lock on signals affected by high levels of scintillation. Scintillation can thus cause GNSS receivers to temporarily lose lock on one or more of the satellite signals, depending on the number of signals affected by scintillation and on the intensity of the resulting amplitude and phase fluctuations.

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, $\sigma_{\phi,}$ is defined as the standard deviation of signal phase variations. These parameters can be measured with specially designed GNSS receivers sometimes called ionospheric scintillation monitors (ISMs). GNSS receiver performance is relatively insensitive to values of S4 that remain at or below 0.5 for carrier-to-noise density ratio (C/N0) above 30 dB-Hz and values of σ_ϕ that remain at or below 0.15 radians for C/N0 above 30 dB-Hz.

3. Ionospheric Effects as a Function of (Magnetic) Latitude

From the perspective of ionospheric effects on GNSS, the world can be divided into three main regions: 1) the low-latitude regions which include the equatorial and equatorial "anomaly" regions (shown as one band between 20N and 20S of magnetic latitudes in Figure 2), 2) the mid-latitude regions, and 3) the high-latitude regions which include the auroral and polar cap regions. Each of these major ionospheric regions can be further broken down into sub-regions, but, for the purpose of this paper, it is sufficient to consider these three main regions. Figure 2 illustrates the approximate geographic extent of each of these

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[4] This version corresponds to the original definition of TEC, which is commonly used by scientists of the ionosphere.

[5] This version is an adaptation of the original measure that is commonly used when GNSS signals are used to obtain TEC measurements.

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.

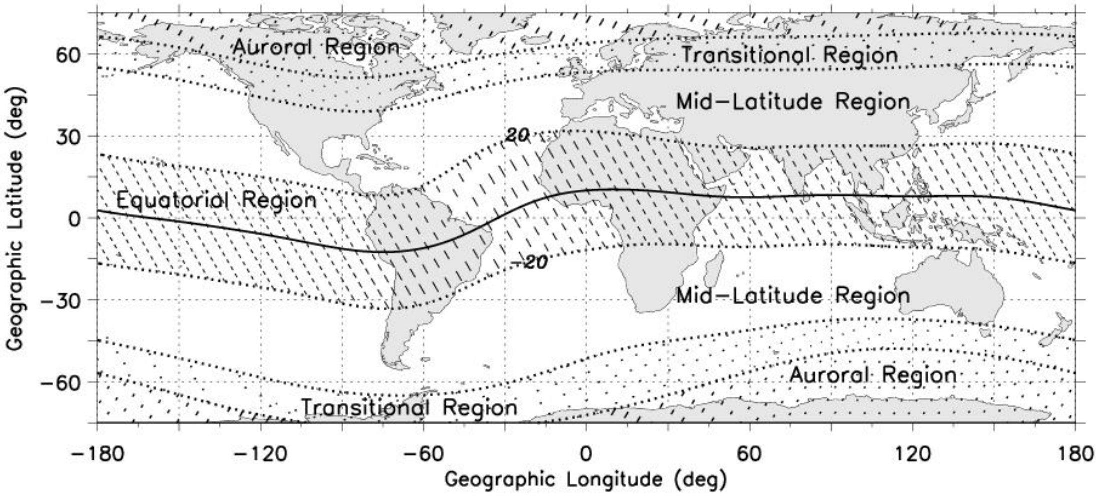


Figure 2. Ionospheric Regions

The polar regions are generally thought of as being at magnetic latitudes greater than about 75°. They are not illustrated in Figure 2 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 the equatorial region as are large portions of South Asia.

GNSS receivers located in the lower mid-latitudes can be affected by the ionosphere in the equatorial region when they track GNSS satellites at relatively low elevation angles while looking generally toward the equator from their location. As a result, the effects of the equatorial and equatorial anomaly region on GNSS can be seen beyond the boundaries of this region shown in Figure 2. Likewise, receivers in the higher mid-latitude regions can be affected by the ionosphere of the nearest auroral region. Thus, the nature of the ionospheric effects affecting a GNSS receiver is not a simple function of the location of that receiver, but of the geographic extent of the regions crossed by the lines of sight to the satellites in view.

Figure 3 is a typical map showing the magnitudes of vertical ionospheric delays across the world, in units of meters at the GPS L1 frequency, 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, with 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 (00 UT).

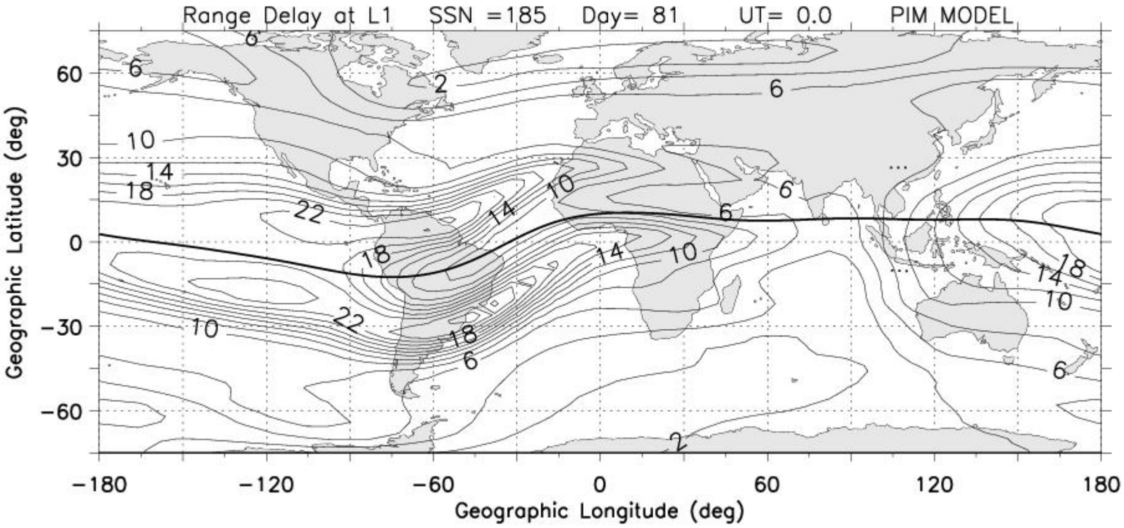


Figure 3. Contours of equal ionospheric range delay, in meters at L1, for typical solar maximum equinox conditions at 00 UT.

As the earth rotates, these range delay isocontours move approximately westwards along lines of constant magnetic latitudes at the earth's rotation rate of 15° per hour, so that the large spatial gradients over South America will be located over the middle of Pacific 5 hours later, then over Asia approximately 10 hours later, and over Africa and the southernmost part of Europe approximately 14 hours later.

The following discussion separates between the three main regions. It starts with the mid-latitude regions where ionospheric effects on GNSS are better understood than in any other part of the world and where the first few SBAS implementations operate. Ionospheric effects in mid-latitude regions are also less complex than those seen in other regions under the prevalent nominal ionospheric conditions (i.e., quiet ionosphere).

3.1 Middle Magnetic Latitude Regions

3.1.1 TEC 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, storms cause the ionosphere to be disturbed. The level of ionospheric disturbances can range from minor ionospheric storms to severe ionospheric storms. Their effect on GNSS varies depending on their intensity in the region where the GNSS user navigates and on the type of flight operation being conducted; the availability of an approach and landing service can be particularly sensitive to severe ionospheric storm effects. An example of the relatively benign behavior of ionospheric range delay over the northern mid-latitudes, as compared with that of the equatorial region, is shown in Figure 3.

3.1.2 Ionospheric Storm Effects

One of the most noticeable effects of ionospheric storms is to disrupt the typical vertical delay surface shown on Figure 3. For example, the surface representing vertical delays seen from the coterminous United States is normally sufficiently flat that it can be closely approximated by local planes over fairly wide areas of a few tens of degrees in latitude and longitude. The U.S. Wide Area Augmentation System (WAAS) takes advantage of this characteristic and estimates the ionospheric delays at each of the Ionospheric Grid Points (IGDs) in its service volume by fitting a local plane to the vertical delay measurements within a given distance of each IGP. During severe ionospheric storms, however, the planar model may not be able to adequately represent the spatial variations between observed vertical delays. Such a case is illustrated in Figure 4, which shows the distribution of vertical delays observed with a dense network of dual-frequency GPS receivers (much denser than the network of WAAS reference stations) during the severe ionospheric storm of October 29-31, 2003.

During severe ionospheric storms, temporal variations between observed vertical delays may also affect the accuracy with which ionospheric delay information can be communicated to users. Furthermore, as a result of changes in the vertical distribution of electrons, the effectiveness of the thin shell model itself -- and with it the accuracy of conversions between slant and vertical delays -- can also be reduced. It follows that maintaining the integrity of SBAS-broadcast ionospheric information in areas affected by severe ionospheric perturbations requires that the Grid Ionospheric Vertical Errors (GIVEs) at the IGPs affected by such conditions be adequately increased while such perturbations persist.

The operational impact of irregularities in ionospheric delay caused by storm activity on ER/NPA navigation is negligible. ER/NPA navigation using unaugmented GPS and RAIM is very robust against ionospheric storms because the integrity bounds computed by RAIM have sufficient margin to tolerate the larger pseudorange measurement errors caused by storms. On the other hand, the operational impact of storm activity on APV/PA navigation can be significant. These flight operations cannot tolerate large pseudorange measurement errors, and as a result, depend on accurate ionospheric corrections and require relatively small integrity bounds, i.e. small GIVEs in the case of SBAS. As noted above, it may not be possible for an SBAS to continue to broadcast small GIVEs during severe ionospheric conditions, even when the SBAS operates in a mid-latitude region. For example, since the commissioning of WAAS in July 2003, APV service was severely curtailed on a few occasions in response to severe ionospheric storms (Fee, IP5 from NSP meeting in St Petersburg, 2004).

[*A paragraph dealing with GBAS seems to be needed.*]

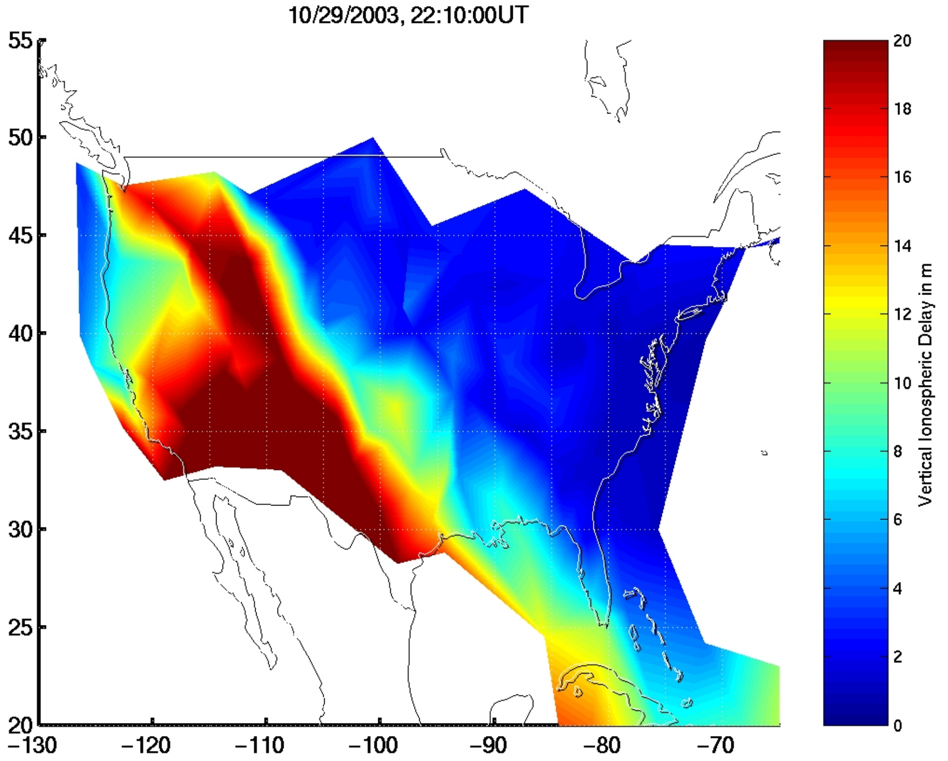


Figure 4. Vertical Ionospheric Delays in meters over a Region of North America on 10/29/2003

3.1.3 Scintillation Effects

Scintillation effects in the mid-latitude regions are in general insignificant, according to the statistical assessment based on L1 scintillation measurements made during the recent solar maximum (Pi, et al., 2002). During severe magnetic and ionospheric storms occurring near a solar maximum, strong phase scintillation may occur in the mid-latitude regions associated with the activities of storm-related electrodynamical perturbations and auroral oval expansion (Pi, et al., 2002). However, during such periods, the effects on augmentation systems due to the increased variability of ionospheric delays and the potential development of isolated ionospheric irregularities remain dominant compared to those due to scintillation.

It follows that scintillation has little operational impact in mid-latitude regions. When the ionosphere is quiet, scintillation is essentially non-existent. When scintillation does occur, the ionosphere is severely disturbed and TEC variability has a dominant impact on the availability of approach and landing services. Losses of GNSS signals due to scintillation tend to remain insufficient to significantly affect other types of GNSS-based flight operations (en route through non-precision approach), even during severe ionospheric disturbances.

3.2 Low Magnetic Latitude Region

3.2.1 TEC Effects

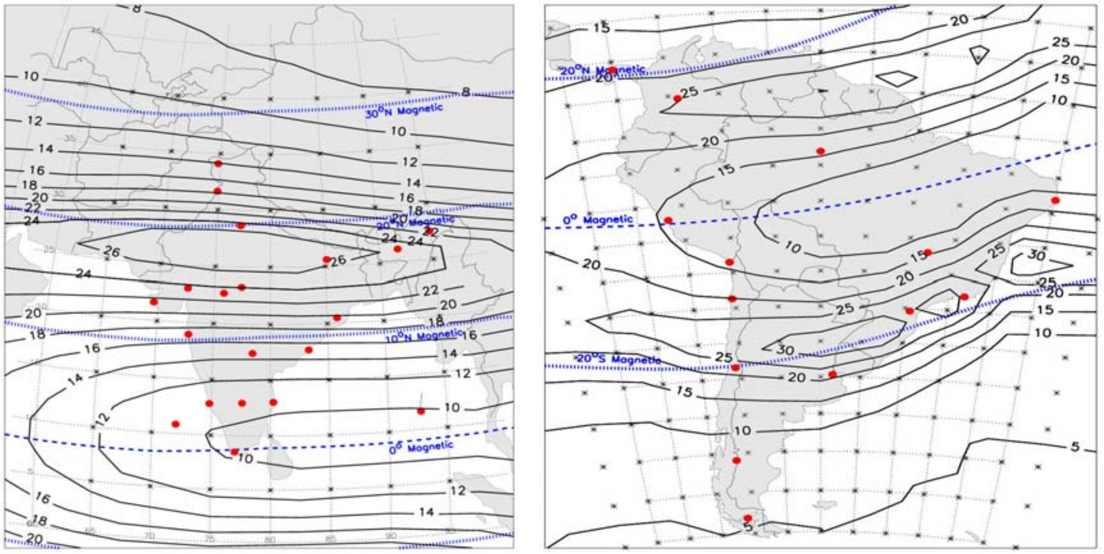
As shown in Figure 3, the equatorial region is characterized by the presence of two TEC crests located at approximately ±15° to ±20° on either side of the magnetic equator, and between them, near the magnetic equator a region of low TEC values. These crests, or "anomalies", are not formed directly as a result of solar ultraviolet (EUV) ionization, but as a result of an electrodynamic force (called "E×B drift, where E is the Electric Field, and B is the magnetic flux density of the Earth") that causes free electrons to migrate upward in altitude, then away from the magnetic equator towards higher latitudes (the so-called equatorial "fountain effect"). As a result, this region not only has the highest values of TEC in the world, but also quite often the highest TEC gradients. Day to day, as well as seasonal, variability is also typically high because the intensity of the equatorial fountain effect (and therefore also the location and height of the equatorial crests) itself varies from day to day. It also varies from one longitude sector to another.

Figures 5a and 5b were constructed using LOWLAT, a highly accurate, proprietary computer model of the equatorial ionosphere developed from the physics of the ionosphere in this region. The figures show contours of vertical ionospheric delays for a typical day during solar maximum conditions and an average E×B drift. Figure 5a illustrates the conditions over the Indian sub-continent; while Figure 5b illustrates the conditions over the South American continent. Large spatial gradients can be seen in both cases. Note that the maximum value is in excess of 30 meters of vertical range delay. The figures also shows the standard 5° by 5° grid used by SBAS.

These two figures illustrate one of the engineering challenges of implementing an SBAS in the equatorial region, which can be summarized as follows:

1. Capture the actual variations in ionospheric range delays using a reasonable number of ionospheric reference stations;
2. Communicate these variations to the users by means of vertical delays at the nodes of a 5° by 5° grid; and
3. Keep the integrity bounds on residual errors sufficiently small to support APV procedures, while ensuring that they meet their allocated integrity requirements.

Some of these challenges were highlighted in few preliminary analyses of SBAS ionospheric algorithm performance in low latitudes (Lejeune et al., 2002; Lejeune et al. 2003).



Figures 5a and 5b. Ionospheric Range Delays (in meters of range delay at L1) over the Indian sub-continent and the South American continent for solar maximum and geomagnetically quiet conditions

A study of the equatorial ionosphere in the context of GNSS compared results obtained with the WAAS ionospheric estimation algorithms using mid-latitude data from WAAS and low latitude data collected in Brazil (Komjathy et al., 2002). The results of the study confirmed that there were significant differences between the magnitudes of the slant ionospheric delays, of residuals errors from planar fits, and of spatial gradients observed from the coterminous United States and that seen from Brazil.

Another potentially major issue with ionospheric range delay in the equatorial region is the possible existence of localized areas of large depletions in TEC associated with the onset of plumes of irregularities that produce strong amplitude scintillation fading and phase scintillation effects in the post-sunset local time period. Figure 6 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 three steep drops in the range delays observed by these stations caused by depletions. The nearly identical patterns in ionospheric range delay occur later along the eastward path, which indicates that the depletions are moving eastward (Dehel, SBAS Iono Meeting No. 5, McLean, VA, May 10-11, 2002.) Such changes in slant ionospheric range delay, which are of the order of 20 meters, cannot be detected with a very high degree of confidence using a single reference station (GBAS) or a reasonably sized network of reference stations (SBAS). Communicating the sizes and locations of such depletions to SBAS users using a 5° by 5° grid would be equally problematic. Thus, the potential for large depletions in TEC could severely limit the ability of GBAS, GRAS and SBAS to provide precise ionospheric corrections during time periods when such depletions could occur because the integrity bounds will have to assume that depletions are in fact present. It should be noted, however, that neither the statistics of such depletion, nor their effects on potential GBAS, GRAS and SBAS approach services have been studied in any detail. So, while the challenges presented by such phenomena to GBAS, GRAS and SBAS implementation should be noted, more definitive statements concerning such effects will have to wait until further research has been completed.

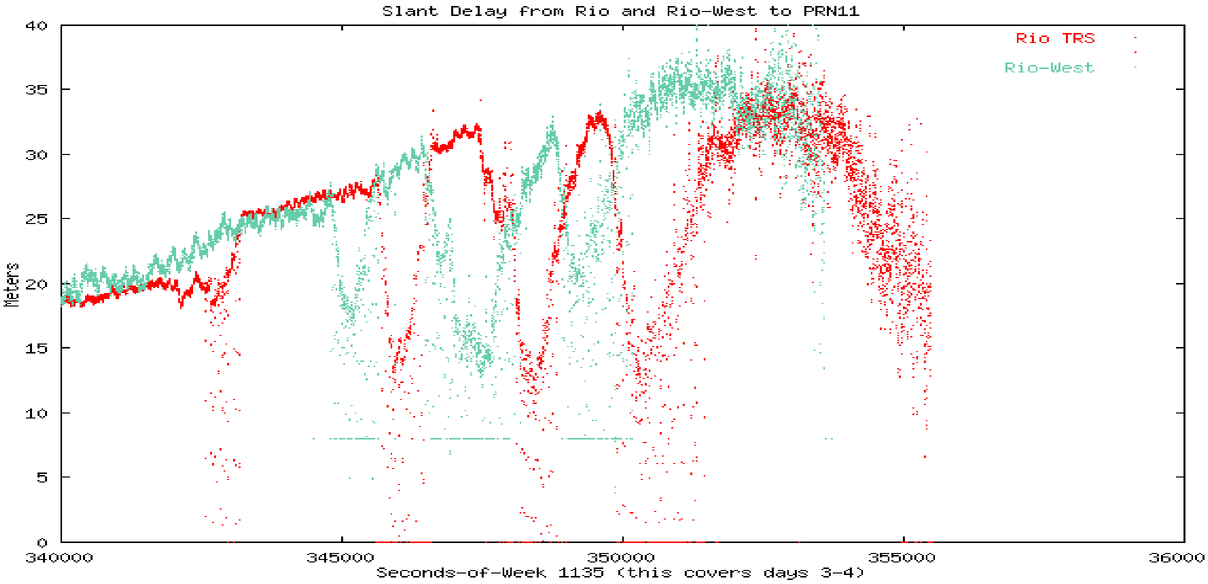


Figure 6. Slant ionospheric range delay on a night in October 2001, from two stations located near Rio de Janeiro, Brazil.

Further research by physicists of the ionosphere will also be needed to further understand the causes and behaviors of such phenomena.

An initial attempt at characterizing ionospheric depletions was performed by Conker et al. (2004) using two years of data from ten sites located in the western part of South America during the last peak of solar cycle (2000-2002). However, much further analysis is needed to fully characterize ionospheric depletions and evaluate the efficacy of potential mitigation techniques.

3.2.2 Ionospheric Storm Effects

Up to now limited data has been available from the equatorial region and few analyses of storm effects in this region have been published. However, there is a general sense that these effects may not be much worse than those 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 compared spatial gradients and planar fit residuals obtained during quiet and storm conditions in the equatorial area using GPS data collected in Brazil (Komjathy et al., 2002). The largest values obtained for these quantities using the storm data were only slightly larger that those obtained using the quiet data.

3.2.3 Scintillation Effects

In the low latitude regions, amplitude and phase scintillations can occur after the local sunset and persist for several hours until after midnight. 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. A strong correlation between amplitude scintillation and phase scintillation has been observed in the low latitude regions.

Amplitude scintillation fading on GNSS satellite signals, and on the SBAS signal transmitting the correction messages, can be a serious concern for aircraft receivers, GBAS reference stations, GRAS reference stations and SBAS reference stations (SRS). Airborne receivers must use tracking loops capable of accommodating aircraft motions, including accelerations. As a result, they tend to be more sensitive to scintillation effects on the GPS L1 signal than SRS receivers, which are static. On the other hand, SRS receivers must track the L2 signal using semi-codeless techniques that are much less robust to scintillation effects, particularly phase scintillation effects, than code-based techniques (El-Arini et al., 2003). Current implementations of GBAS do not track L2, and therefore are somewhat less sensitive to scintillation, but they could still lose lock on the L1 signal. Future GBAS implementations may use both L1 and L2.

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, the aircraft will lose the ability to perform that operation (APV or PA). In contrast, an SBAS must only receive a sufficient number of measurements to meet the requirements of the grid delay estimation function. Therefore, an SBAS can tolerate temporary losses of some of the signals and still perform its function, although some decrease in service availability and continuity may result depending on the number of signals lost. Single-frequency GBAS may lose lock on the L1 signals from some satellites; however, when it does, it is very likely that avionics using the GBAS signal have also lost lock on the L1 signals from the same satellites. In any case, the user may experience a reduced level of service as a result (Conker et al. 2002).

During a recent observation campaign in Rio de Janeiro, Brazil, the number of satellites available for an L1-only solution of an airborne experimental WAAS receiver dropped down to only two satellites for a few seconds, and the number of satellites available for a full L1-L2 solution actually went to zero, due to L2 signal loss from rapid phase scintillation (Dehel, private communication, 2001). Significant receiver loss-of-lock events have also been observed using a modified TurboRogue dual-frequency receiver at an equatorial anomaly site at Santiago (Pi, et al., 2002). However, an FAA certified (TSO C-129) GPS receiver never had less than 6 satellites in track during the data collection campaign in Rio de Janeiro, indicating that receiver design can be an important factors as far as the susceptibility of the receiver to amplitude scintillation fading effects is concerned[6].

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 to determine the statistics of simultaneous fading on more than one GNSS satellite at one time affecting airborne receivers and to characterize the position errors resulting from computing position solutions based on a changing "mix" of satellites. These points have been raised by Forte, et al., (2001) from their analysis of experimental data, and by Conker, et al. (2003), using model calculations.

An even more important scintillation-related question concerns the potential loss of real-time corrections and integrity information data from the SBAS satellites. SBAS corrections are packed in SBAS messages. Each SBAS message is only one second long, but the system specifications require a very low loss rate (Message Error Rate of 10^{-3}) for this short correction message, which may be difficult to guarantee during periods of deep, slow amplitude scintillation fading. The redundancy of having two SBAS satellites with sufficient longitudinal separation (≥ 46.3 degrees according to DasGupta, 2002) can

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[6] Further analysis revealed that the receiver computing the dual-frequency solution during that campaign was performing phase carrier smoothing and was applying a relatively long delay following a cycle slip before re-incorporating the measurements affected by the cycle slip into the position solution. This was found to be the main reason for additional satellite track losses observed with this receiver. Certified SBAS user equipment is expected to reincorporate a satellite's range measurement into the position solution quickly, although the range measurement for that satellite will be de-weighted in the position solution.

greatly improve signal availability and continuity of service, but the exact level of improvement has not yet been evaluated.

3.3 High Magnetic Latitude Regions

3.3.1 TEC 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 (e.g., 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 lower ionospheric delays than that of the mid-latitude regions; however, the variability of the auroral ionosphere tends to be greater than that of the mid-latitude regions.

3.3.2 Ionospheric Storm Effects

In the auroral regions, Skone and Cannon, (1998), have shown that, during periods of major geomagnetic storm activity, the spatial gradients in equivalent vertical ionospheric range delay are much larger than can be expected to be corrected by using an ionospheric grid size of 5° by 5°. They also showed a maximum ionospheric range delay change of almost one meter over a 30 second sampling interval, indicating that the usual SBAS update period should be smaller during those periods (Skone et al., 1998).

3.3.3 Scintillation Effects

Ionospheric scintillation is frequent in high latitude region, but is mostly limited to 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, as it is in the equatorial region. This assessment is based on statistics of GPS L1 scintillation measurements during the recent solar maximum years (Pi, et al., 2002). Phase scintillation, on the other hand, has been shown to cause loss of lock on the semi-codeless L2 reference station receivers for periods of up to tens of minutes, and on many of the available GPS satellite directions at the same time, (Dehel, et al., 1999a and b; Pi, et al., 2002) in the high latitude regions. During periods of severe geomagnetic storm activity the loss of signal on the semi-codeless L2 signals at the SRSs could be a significant limitation in specifying IGP values in the auroral regions (Pi et al., 2002).

4. Mitigation Techniques

Two types of ionospheric effects are discussed in Sections 2 and 3: (1) effects related to the accuracy with which the delay along a given line of sight can be predicted based either on a model or on delay measurements along other lines of sight with different attributes (elevations, azimuths, IPP locations, and times) and (2) effects related to the ability of a receiver to maintain lock on GNSS signals. Ionospheric conditions such as caused by an ionospheric storm or by the equatorial fountain effect, which modify the distribution of electrons between altitude layers or geographic locations, belong to the first category of effects. Ionospheric scintillation belongs to the second category of effects.

Effects in the first category affect the accuracy of the position solution computed by ABAS, GRAS and SBAS receivers operating in ER/NPA modes, but they do not normally affect their ability to provide the desired service. In contrast, SBAS and GRAS receivers operating in APV mode and GBAS receivers operating in PA mode may not be able to continue to provide the desired service when these effects occur. Mitigation techniques can be used to moderate these effects and, more importantly, to ensure that service integrity continues to meet the requirement when these effects occur. These techniques will be the main focus of this section.

4.1 Mitigation Techniques for Ionospheric Delays

GNSS receivers are designed to provide service with integrity. Independently of the method used to correct pseudorange measurements for ionospheric delays, residual errors will remain in the corrected pseudorange. These residual range errors must be accounted for when evaluating the accuracy, integrity, availability and continuity performance of GNSS navigation solutions.

4.1.1 Dual-frequency Solution

Since the amount of delay affecting a particular GNSS signal is inversely proportional to the square of the frequency of that signal, accurate estimates of TEC (or ionospheric range delay) along the line of sight between a receiver and a satellite are possible using two signals with different frequencies. The accuracy of the resulting TEC estimates can be very high (much less than one TECU, or 0.163 m at the L1 frequency); however, the accuracy obtained in practice depends on the magnitudes of residual errors associated with satellite inter-frequency biases and multipath corrections.

Dual-frequency receivers use this method to directly compute pseudoranges that exclude ionospheric delays (ionosphere-free pseudoranges). This method is not currently available to airborne receivers due to the lack of a signal at a second frequency in the aeronautical band with a coded signal accessible to civil users. Dual-frequency receivers can also compute the ionospheric delays affecting the measurements at each of the frequencies. This method is used by receivers used in SBAS reference stations. These receivers use one of several codeless or semi-codeless techniques to track the GPS L2 signal. (These techniques are not appropriate for receivers in dynamic motion.) This method is also used by authorized GPS receivers, which have the capability of tracking the P(Y) code on both the GPS L1 and L2 signals.

Note that while dual-frequency receivers can correct for ionospheric delay, they are equally or perhaps more affected by scintillation than single-frequency receivers because they normally use measurements at two frequencies, not just one. Furthermore, lower frequencies are more severely affected by scintillation, although greater signal power can compensate for signal power losses caused by scintillation to some degree.

Future GNSS core constellations will broadcast dual-frequency signals for use by civil aviation. This development 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). It will then be possible to obtain a high availability of ER/NPA navigation in most of the world using only a receiver-based Fault Detection and Exclusion function to ensure the integrity of the navigation solution[7]. This development

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[7] It is currently unclear whether APV procedures will be possible using FDE as the only source of integrity, even when dual-frequency receivers compute highly accurate position solutions. Current FDE algorithms are not able to reliably detect possible simultaneous faults on multiple satellites. Adequate mitigation for this integrity risk will be required before such operations could be approved. This is a subject of active research at this point.

will also be beneficial to SBAS-based navigation. It will likely make SBAS-based Cat I Precision Approach possible anywhere in the world, provided of course the approach is within the service area of an SBAS. However, until such GNSS core constellations are implemented and operationally available, aviation users will be limited to using single-frequency receivers, and therefore will depend on corrections provided by core constellation satellites and augmentation systems.

4.1.2 Single-frequency Solution

Single-frequency ABAS, SBAS, GRAS and GBAS receivers use different methods for correcting for ionospheric delays. These methods were briefly summarized in Section 1.3; they are further described in the following subsections.

Uncorrected ionospheric delays can cause position errors of several tens of meters. Such errors, while undesirable, are not intolerable for en route (ER) and terminal area navigation as well as for nonprecision approach (NPA) operations because of the comparatively large Horizontal Alert Limits (HAL) associated with these operations. In contrast, errors of such magnitude cannot be tolerated for approach operations during which vertical guidance is provided to the aircraft such as Approach with Vertical Guidance (APV) and Precision Approach (PA) operations. As a result, corrections for ionospheric delays are recommended, but not required, for ER through NPA operations. In contrast, they are required for APV and PA operations.

4.1.2.1 Correction Method used by ABAS Receivers

ABAS receivers can approximately correct for ionospheric delays using a 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 be used by SBAS receivers inside the SBAS service area, when conducting en route through 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, these 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. In both cases, simple equations are programmed in the avionics to compute the corrections as well as conservative standard deviations for the residual errors remaining after application of the corrections. This correction method is adequate for en route (oceanic and domestic) and terminal area navigation as well as for non-precision approach operations; a wide range of operations generally summarized as en route through non-precision approach, or ER/NPA.

[*Note the above talks about GPS and Galileo but what about GLONASS?*]

The single-frequency GPS ionospheric model (IS-GPS-200D, and Parkinson, 1996, Vol. I, Chapter 12) is a vertical TEC model that relies on the thin shell approximation[8] and uses a mapping function to convert from vertical to slant TEC. It has been shown to correct approximately 50% of the actual ionospheric delays for mid-latitude locations on the average during quite ionospheric conditions (Klobuchar, 1987; Feess et al. 1987). The equations for the model are implemented in the receiver, but they operate on a set of eight model coefficients broadcast by GPS satellites. These coefficients are regularly updated by the GPS Ground Control Segment based on observations of the state of the ionosphere during the previous few days. As shown in Figure 7, the GPS Ground Control Segment has five monitoring stations located

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[8] According to the thin shell model, the total amount of delay affecting a signal is accumulated at a particular altitude (the altitude of the thin shell) and the amount of delay is a function of the coordinates of the point where the propagation path pierces the thin shell and the angle with which it pierces the thin shell.

in Hawaii (HTS), Colorado Springs, Colorado (CSPG), Ascension Island (ASC), Diego Garcia (DG) and Kwajalein (KWAJ). This configuration is adequate for monitoring satellites but insufficient to observe, let alone characterize, local or even regional variations in ionospheric delays. The accuracy of the corrections is limited by the fact that the model is simple, and therefore can only account for first order variations in the ionosphere. In particular, the model is unable to reproduce some basic spatial variations found at low latitudes. Also, it cannot account for possible irregularities, whether small or large, that may exist at the time the corrections are applied. This model performs best when the ionosphere is in a quiet state. It tends to underestimate the magnitudes of delays during ionospheric storms.

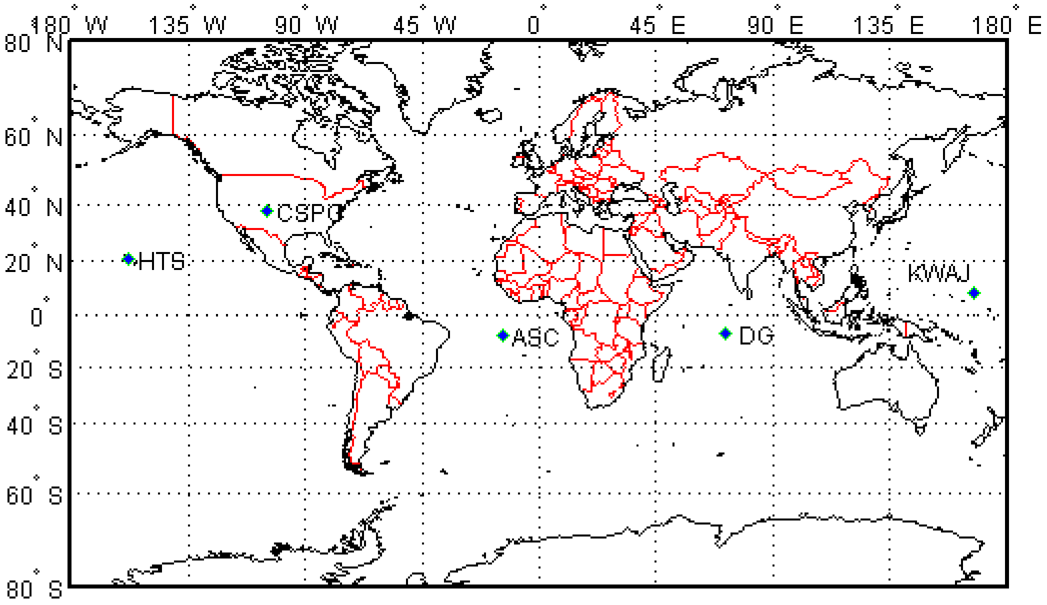

Figure 7. GPS Ground Segment and its Five Monitoring Stations

The single frequency ionospheric correction algorithm proposed for the Galileo system is based on the 3D NeQuick model (Radicella and Leitinger, 2001). It is driven by an "effective ionization level", Az, valid for the whole world and for a period of typically 24 hours. The global Az is given in terms of three coefficients, which are functions of the user's geomagnetic coordinates. These coefficients are broadcast to the user and allow Az to be calculated for any desired location. This model calculates the slant TEC by means of integration along the ray-path. Therefore no mapping function or thin layer approximation for the ionosphere is applied.

Tests carried out using both the GPS and the planned GALILEO operational models show that this model is able to correct ionospheric slant delays more effectively. These tests have been carried out using actual GPS-derived slant TEC data from a set of geographically evenly distributed observing stations. Figure 8 shows the daily 95 percentile residual error in TEC units for the two models during the year 2000, a period of high solar activity (Coïsson et al, 2004). In this figure, the blue points show the residual errors from the NeQuick model, while the green points show the residual errors from the GPS ionospheric model. Each point on the horizontal axis represents one day of the year 2000.

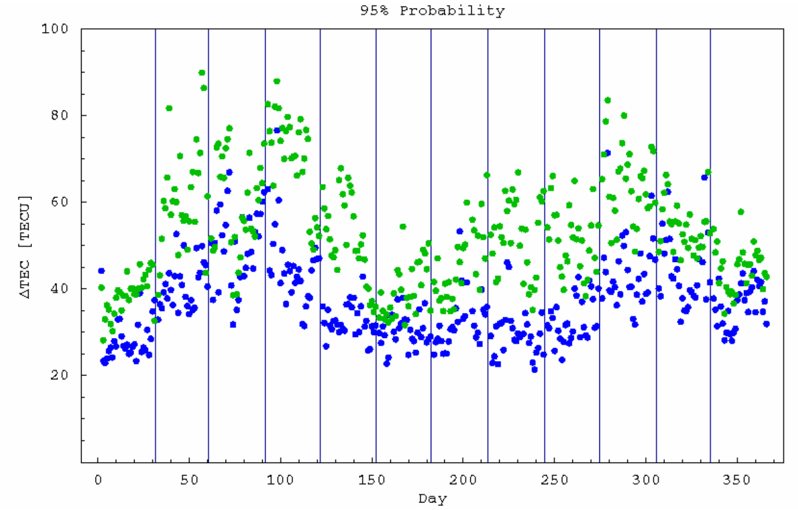

Figure 8. Comparison of 95th Percentile Residual Errors from the GPS and NeQuick models

In both the GPS and Galileo cases, the models are simple diurnal models, which cannot capture all of the variations in the ionosphere over 24 hours and over 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 ionospheric vertical delay map over periods of several days.

4.1.2.1 Correction Method used by SBAS Receivers

SBAS receivers inside the SBAS APV service area can correct for ionospheric delays more accurately than ABAS receivers because they use information derived from real-time ionospheric delay measurements. They obtain information on the estimated vertical delays and estimated standard deviations of residual errors[9] at the nodes, or grid points, of a standardized ionospheric grid directly from the SBAS broadcast data (ICAO, 2005; RTCA DO-229C, 2001). The SBAS ionospheric grid is located 350 km above the surface of the Earth and has latitude and longitude cell widths of 5 degrees for most of the inhabited world[10]. However, a given SBAS will only provide ionospheric corrections for a small portion of that worldwide grid that corresponds to its APV service volume.

The SBAS ground system obtains real-time measurements from a network of reference stations and use them to estimate the vertical delays at the nodes, or ionospheric grid points (IGP), of the standardized ionospheric grid. For each line of sight to a satellite, a user receiver interpolates between the nearest IGPs to the location of the ionospheric pierce point (IPP), then converts the interpolated vertical delay to a range (or slant) delay by applying a standardized “obliquity factor” that accounts for the angle at which the line of sight pierces the thin shell. Similar calculations are performed for the delays and for obtaining conservative estimates of the standard deviations of the residual range errors.

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[9] These standard deviations are actually communicated in the form of 3.29σ bounds called, Grid Ionospheric Vertical Errors (GIVEs). The corresponding values in the range domain obtained after interpolation and domain conversion are known as User Ionospheric Range Errors (UIREs).

[10] Cell widths are larger than 5 by 5 degrees at the higher northern and southern latitudes.

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 ionosphere model which estimates ionospheric delays from a two-dimensional model (ionospheric grid) 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, and the application of the corrections by the SBAS receiver. To illustrate the much denser sampling of the ionosphere performed by an SBAS as compared to the GPS ground segment, the network of reference stations that will be used by the U.S. WAAS once the current upgrade is completed (2008) is shown in Figure 9. Despite the denser network of reference stations, the sampling of the ionosphere performed by an SBAS is still limited, and therefore it may fail to capture certain narrow structures in the ionosphere.

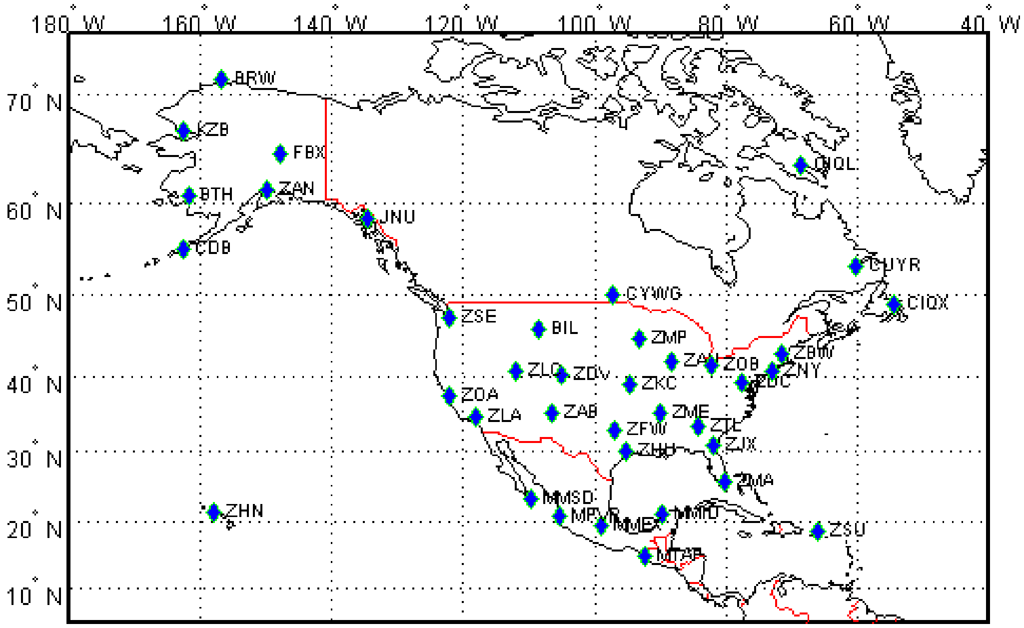

Figure 9. WAAS Reference Stations - Full LPV Performance (FLP) System

SBAS receivers correct for ionospheric delays using vertical delay estimates obtained either from a model or from an SBAS. In either case, residual errors will remain in the corrected pseudoranges. Residual errors can result for example from variations and irregularities in the distribution of free electrons in the ionosphere that may escape detection by the augmentation system. They can also result from the limitations of the ionospheric estimation model used. For example, SBAS treats the ionosphere as a “thin shell” located at 350 km above the surface of the Earth. This approach allows SBAS to broadcast vertical ionospheric delays. The user converts from vertical delay to slant delay by applying an “obliquity factor” equal to:

$$F_{pp} = \left[1 - \left(\frac{R_e \cos E}{R_e + h_I} \right)^2 \right]^{-1/2} \qquad (2)$$

where R_e is the radius of the Earth, h_I is the height of the ionospheric grid, and E is the elevation angle of the line of sight between receiver and satellite. The errors introduced by this conversion method are small when the stratification of the ionosphere is relatively uniform (e.g., in mid-latitude regions when the ionosphere is quite). However, they can reach several meters when the ionosphere is severely disturbed or when powerful transport processes cause major shifts in the stratification of the ionosphere.

4.1.2.1.1 L1/L2 Inter-frequency Bias Estimation

L1/L2 inter-frequency biases are not caused by the ionosphere but by satellite and receiver hardware. Therefore, the discussion of this topic is beyond the scope of this paper. However, it needs to be said that these biases need to be corrected (Yinger, 1999) when estimating ionospheric delays or ionosphere-free ranges using linear combinations of L1 and L2 measurements. In particular, the SBAS ground system needs to estimate and correct for these biases. These biases vary from one satellite to another and from one receiver to another. Therefore, they represent an additional source of error in the ionospheric delay measurements, which could interfere with the estimation of the ionospheric delays at the ionospheric grid points (IGPs). A number of papers discussing estimation techniques have been published (Mannucci, et al., 1993; Wilson, et al., 1993; Sardon, et al., 1994; Chao, et al., 1995).

[*This section may not be necessary as it does not really deal with a mitigation technique.*]

4.1.2.1.2 Ionospheric grid delay estimation

A number of different techniques have been investigated to characterize the spatial decorrelation of ionospheric delays and estimate ionospheric grid delay (Hansen et al., 2000). Some techniques proceed on the basis of local models that are separately estimated at each IGP. These techniques rely on low degree polynomials such as a simple constant (0^{th} degree polynomial), a planar surface (1^{st} degree polynomial) or a quadratic surface (2^{nd} degree polynomial) to represent variations in vertical ionospheric delays in the local area of each IGP. Other techniques model the ionosphere over the entire service area with a unique model such as high-degree polynomial surfaces or spherical harmonics. Finally some techniques model the 3-dimensional nature of the ionosphere using a tomographic approach (Hansen, 2002). Current SBAS implementations rely on low degree polynomial surfaces that are separately estimated at each IGP. The main reasons for this are: (1) the accuracy of these simple models is as good as that of more complicated models; (2) simple models are easy to implement (and therefore also verify and certify); (3) the availability of formal error formulas from which GIVEs that correspond to a prescribed level of confidence can be easily computed; and (4) the more parameters have to be estimated, the more error variances contribute to the variance of the estimated vertical delay at the IGP and the more measurements are needed to estimate the parameters.

The US WAAS, for example, uses a planar fit computed from the vertical delay measurements (range delay measurements converted to vertical) at selected IPPs from reference stations. The selected IPPs are captured by a search area of variable size centered at the IGP where the planar fit is being calculated. The number of IPPs captured is the result of a trade off between number of IPPs and size of search area. A very large search area will capture many IPPs but the resulting planar fit may be poor over the four grid cells connected at the IGP. A small search area will capture few IPPs and therefore generate estimates characterized by large uncertainties. The GIVEs at the IGPs are based, in part, on the Chi Squared statistic for the residuals from the planar fit (Walter, et al., 2000). Other modeling techniques can perform equally well and perhaps even better under some circumstances (Blanch, J., 2002). However, the basic notion that the design will require a trade off between using measurements with IPPs relatively far away from an IGP, on one hand, and using a sufficient number of measurements to ensure that the estimated model coefficients are characterized by acceptably small confidence bounds, on the other hand, will always exist.

4.1.2.1.3 Storm detection

During the development of the US WAAS, it was found that ionospheric delays could be accurately modeled with a local plane under typical ionospheric conditions, as described above. In other words, residual errors from the planar fit remain small and well behaved. However, it was also found that, during severe ionospheric storms the quality of the planar fit could be much poorer because vertical ionospheric delays can then vary rapidly over relatively short distances. Furthermore, the possible presence of irregularities in the ionosphere could result in relatively large errors when converting from the slant domain to the vertical domain (and, for the user, from the vertical domain to the slant domain). Under such conditions, it seemed difficult to establish that the GIVEs will bound the user errors with the required probability. For this reason, an irregularity detector was developed and implemented. This irregularity detector checks the validity of the planar fit at each IGP separately using the Chi Squared statistic already mentioned (Walter, et al., 2000). If the fit is found to be unacceptable, the GIVE is set to a high value. If the fit is found to be acceptable, the GIVE is computed on the basis of the formal estimation errors (estimated standard deviations). The result of this computation is then inflated by a factor that accounts for the fact that the state of the local ionosphere could be approaching the point where the irregularity detector would trip. The broadcast GIVE also accounts for a data derived "threat model" that accounts for the possible presence of unobserved irregularities in the local ionosphere (i.e., irregularities that escape detection because, given their sizes and locations, they affect few, if any, of the measurements used to compute the planar fit) (Altshuler, et al., 2001; Blanch et al., 2001).

In the next implementation phase of WAAS, an Extreme Storm Detector (ESD) will be added in addition to the storm detector just described. This detector is intended to trip at most twice during a solar cycle. Its design goal is to differentiate between "extreme storms" (severe storms during which the level of ionization reach particularly high levels) and more typical severe storms. Based on the definition given to "extreme storm", such storms were never observed during WAAS development, but two of them occurred since WAAS commissioning (on October 29-31, 2003, and November 20, 2003). While WAAS did provide adequate protection during these particular events, the morphology of these storms (in particular the occurrence of significant, isolated irregularities late in the recovery phase) made it possible to construct storm scenarios in which adequate protection might not be guaranteed. When the ESD trips, WAAS will broadcast GIVEs of 45 m for every IGP in the service volume for a minimum time period during and following the main phase of the storm. More detailed explanation of design considerations of this ESD can be found in Sparks et al, (2005).

[Galileo satellites are expected to broadcast an ionospheric storm flag. TBC].

4.1.2.1.4 Alert messages

Alert messages can be used to increase GIVEs when the ground system detects that a sudden change in the local ionospheric conditions invalidate GIVEs that have already been broadcast but are still active.

4.1.2.2 Correction Method used by GBAS/GRAS Receivers

[Perhaps, GRAS should have a separate subsection. GRAS is not intended to support Cat I/II/II. In terms of service, GRAS is more like SBAS than like GBAS. The same should be true with respect to ionospheric effects. However, it is not clear how many GRAS-specific analyses are available.]

GBAS and GRAS avionics do not compute ionospheric corrections per se (RTCA, DO-253, 2001). Instead, they correct for a combination of pseudorange errors including ionospheric delays, satellite clock and ephemeris, and tropospheric delay errors by applying the corrections broadcast by the GBAS ground system, which are specific to the satellites in view of the reference station. Elaborate equations are programmed in the avionics to compute conservative standard deviations for the residual errors remaining after application of the corrections. These equations use various parameters that are also broadcast by the ground system. One of them concerns the increase in the uncertainty associated with ionospheric correction that is included in the range correction as a function of distance between the receiver and the reference station.

A key limitation on the accuracy of the GBAS corrections is the spatial separation between the GBAS Ground Station and the GBAS receiver. Accuracy is not a problem for CAT I requirements under nominal ionospheric conditions. However, during disturbed ionospheric states (e.g., ionospheric storms), spatial separation (i.e., ionospheric decorrelation) can become a problem under certain scenarios. This presents significant challenges for meeting CAT I requirements and major design issues for CAT II/III, given its more stringent accuracy and integrity requirements. The main challenge is to adequately demonstrate that the system will be able to meet the integrity and availability requirements during severe ionospheric storms when ionospheric delays can potentially vary rapidly both in time and space. This requires analysis converting TEC delay data into parameters that can be used to calculate GBAS aircraft position errors. The type and amount of data that is available for such analysis dictates the level of modeling accuracy that can be attained. Achieving a high-level of accuracy is particularly difficult in the local area (~ 100 km^2 area) operational environment of CAT I/II/III. An example of this type of modeling effort was outlined in WP 15 (Burns, WP 15, Montreal 2004).

GRAS uses a similar approach to GBAS. However, unlike GBAS, its intended service area is not limited to the terminal area. Therefore, corrections may be transmitted from VHF Data Broadcast (VDB) stations located outside the perimeter of the terminal area in order to support en route navigation. The cost of this expanded coverage resides in the increased risk of unobserved ionospheric irregularities. This risk needs to be taken into accounted in the broadcast integrity information. Given the level of service supported by GRAS and the wide area over which GRAS services can be provided, the impact of the ionosphere on GRAS will similar to that on SBAS.

4.2 Mitigation Techniques for Scintillation Effects

Ionospheric scintillation typically occurs in the form of numerous narrow patches. It can cause many receivers in the region affected by it, whether user receivers or reference station receivers, to lose lock on one or several satellite signals. 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 the signal due to a deep but short lived drop in received power. It also depends on the design of the signal tracking loop.

[Mitigation techniques that can be used in receiver design are one of the topics mentioned in the last NSP report. Additional material on these techniques would be desirable. The SBAS Iono WG is working on this topic and may be able to provide such material.]

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 season to season and from region to region, and the number of satellites visible to the receiver. In the future, receiver capable of including both GPS and Galileo satellites in their position solution will be much less likely to lose service than receivers capable of using only one of the core constellations. The number of satellites in view of the receiver will then be sufficiently large to tolerate the possible loss of a few satellites that are simultaneously affected by scintillation without losing service.

4.3 Other Mitigations

The ionosphere is expected to have a limited impact on the availability and continuity of GNSS-based ER/NPA service. This impact will be seen mostly in the equatorial area where during periods of intense scintillation, some users may not be able to reliably track a sufficient number of satellites with a good geometry to maintain service. ABAS receivers that depend on FDE for integrity will be more sensitive than SBAS receivers which can provide service with a smaller number of satellites in track.

In most regions, the ionosphere will have an impact on APV service. Even in mid-latitudes where ionospheric effects are comparatively mild, losses of service availability can be caused by ionospheric disturbances. In the most extreme cases, these losses can be sufficiently severe to deny APV service over large areas for several hours. An obvious mitigation to this problem is to maintain a sufficient number of ILS installations, particularly at busy airport. In fact, the ILS approach is likely to remain the approach procedure of choice at busy airports because of both its lower decision height and its greater reliability (i.e., ILS is not affected by ionospheric storms and radio interference effects can only have a local impact).

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

5. Impact of the Ionosphere on Operational Service

This section provides a summary of the expected impact of the ionosphere on GNSS navigation services.

5.1. ER/NPA

While SBAS receivers are required to always apply ionospheric corrections (derived either from the GPS single-frequency model or from the SBAS ionospheric grid information), some ABAS receivers do not. For ER through NPA operations, the consequences of not accurately correcting for ionospheric delays will be felt mostly in the accuracy performance. The Horizontal Alert Limits (HAL) associated with these operations are large enough that residual range errors of up to 150 m can be tolerated with limited impact on service availability and continuity. Positioning accuracy depends in a large measure on the accuracy of ionospheric corrections. SBAS receivers that apply SBAS ionospheric corrections when available will statistically have better accuracy performance than ABAS and SBAS receivers that apply the ionospheric corrections from the signal-frequency GPS model. These receivers in turn will have better accuracy performance than ABAS receivers that do not apply any ionospheric corrections.

The main impact of the ionosphere on ER/NPA service is expected to be related to scintillation effects. It is expected that some loss of service availability will occur during the evening hours in low latitude regions and during disturbed ionospheric conditions in high latitude regions. ABAS service will be more sensitive to this effect than SBAS service since ABAS relies on a Fault Detection and Exclusion (FDE) function to guarantee the integrity of the position solution. An SBAS solution requires pseudorange measurements to minimum of 4 satellites. In contrast, Fault Detection requires pseudorange measurements to a minimum of 5 satellites and Fault Exclusion requires pseudorange measurements to a minimum of 6 satellites.

5.2 APV

APV performance is expected to be generally good in mid-latitudes, but uncertain in equatorial regions. In mid-latitudes, partial losses of APV service may be experienced during severe ionospheric storm conditions. In some rare cases, particularly severe ionospheric storm may even cause temporary loss of all APV service. In equatorial regions, it is expected that providing APV service will be difficult during years near the peak of the solar cycles, particularly during the local afternoon and evening hours when the equatorial anomalies are present. Scintillation will also often be a problem during the evening hours. One approach to mitigate possible severe disruptions of approach and landing capability due to loss of APV service is to maintain an adequate number of ILS installations at major airports. For airplanes not equipped with ILS receivers, there is a high likelihood that an GNSS-based NPA approach will be possible when APV service has been lost.

The application of SBAS ionospheric corrections is required for APV operations. Whenever these corrections are unable to accurately correct for ionospheric delays, the consequences are felt mostly in the availability and continuity performance. The HAL and Vertical Alert Limits (VAL) associated with APV operations cannot tolerate large residual errors. The accuracy performance will also degrade under such circumstances. However, when SBAS ionospheric corrections are applied, accuracy remains quite good under almost all conditions.

In mid-latitude regions the techniques briefly outlined above should be adequate to ensure a high availability of APV performance during time periods when the ionosphere is either quiet or mildly disturbed. However, during periods when the ionosphere is highly disturbed, the availability of APV performance may be significantly reduced. Maintaining APV performance in the presence of large variations in ionospheric delays is difficult. This is in part a consequence of the extremely high probability with which GIVEs have to "overbound[11]" the residual errors associated with the ionospheric corrections combined with the difficulty of performing an assessment of integrity performance during conditions that are rare (i.e., on the basis of limited data).

For equatorial regions, actual achievable availabilities of APV service are uncertain and currently under assessment. Of specific interest is the on-going study conducted by the European Space Agency (ESA) regarding the possible implementation of an EGNOS SBAS extension system over the African continent. Preliminary results under simulated nominal and worst ionospheric conditions are expected to be available in mid-2006.

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[11] The word "overbound" used here is convenient but inaccurately captures the requirement. The requirement actually applies to the quantity σ_{GIVE} = GIVE/3.29, which has to correspond to the standard deviation of a standard normal distribution that "overbounds" the actual distribution of residual errors in a Cumulative Distribution Function sense as defined in Bruce DeCleene, "Defining Pseudorange Integrity – Overbounding", Proceedings of the 13th National Technical Meeting of the Satellite Division of the Institute of Navigation, Salt Lake City, Utah, Sept. 19-22, 2000. An extension to that theorem was presented in T. Schempp and A. Rubin, "An Application of Gaussian Overbounding for the WAAS Fault Free Error Analysis," Proceedings of ION-GPS-2002.

Integrity performance may vary somewhat between conditions in which ionospheric delays can be accurately corrected and other conditions in which they cannot. However, the standards require that the integrity requirements continue to be met under all conditions.

To maintain integrity, therefore, SBAS system must include in the broadcast GIVE values with sufficient margins to cover possible non-observed ionospheric effects that may affect the delays observed by the users (these margins will vary depending on service area, on the observed level ionosphere activity, on the observability of ionospheric irregularities given the density of reference stations, and on the ionospheric algorithms used by the SBAS implementation).

5.3 CAT I

Present day research and acquisition efforts are focused on developing a GBAS technology aimed at supporting CAT I operations. Analysis of ionospheric storm effects on GBAS service must be conducted using local-area assumptions given the requirements for PA. Characterizing the impact on ionospheric effects on integrity has been found to present challenges. Sufficient data is not readily available to characterize the problem of local-area ionosphere decorrelation in all desired regions. The level of characterization 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 ionosphere behaviors between observation points (i.e. pierce points of lines of sight from receivers to satellites). Due to the high level of integrity needed for this operation, these assumptions must be conservative in nature.

Today's understanding of the ionosphere in the local environment indicates that GBAS can effectively support CAT I operations with an availability of approximately 99% in mid-latitudes. Further effort is required to add resolution to local area ionosphere analysis to reduce the conservatism in the current ionosphere "threat models" and thereby gain better overall availability and continuity performance.

5.4 CAT II/III

Again, this operation is local area in nature with higher required levels of accuracy and integrity. Also, a mandatory continuity requirement will add an extra level of difficulty beyond simply hardening Ground Station hardware to lower failure probabilities. In this case, understanding of ionosphere effects in the local area is even more critical.

6. Research Efforts

[Perhaps this entire section could be re-organized somewhat to include sub-sections that are dedicated to describing research performed or planned by various states (e.g, US, India, Brazil, Japan) of union of states (EU). Also, the Section could perhaps be split into two: one on Research Efforts in the SBAS Context, and one on Research Efforts in the GBAS Context. While the ionosphere is common to both SBAS and GBAS, the associated research efforts seem to have been focused on separate issues and separate models.]

6.1 Past Efforts

[The following paragraphs were extracted from the SBAS Iono WG White Paper. There are additional research papers with relevant results that should be mentioned.]

Klobuchar, et al., (2001) examined the characteristics of the equatorial anomalies and their potential effects on SBAS. They showed that the difference between the actual slant ionospheric range delay values obtained from a 3D ionospheric model and those obtained by the standard SBAS technique of interpolating vertical delays between Ionospheric Grid Points (IGPs) on a five-by-five-degree grid and then converting to equivalent slant range delay could be up to 27 meters for a GPS satellite at a low elevation. Their results confirm the work by Nava (2000), who used the 3D NeQuick ionospheric model (Hochegger, et al., 2000) to investigate a similar problem. Nava (2000) showed that even at low mid-latitudes and for low elevation angles, the combined effect of the equatorial anomaly and the large spatial gradient near sunset introduced substantial differences between the actual slant delay values and those obtained with the standard SBAS conversion technique.

The results of a more recent South American analysis (Klobuchar et al. 2002) indicate that the engineering challenge outlined in Section 2.2.1 may be difficult to meet. Even if the absence of steep depletions can be assumed, slant-to-vertical (and vertical-to-slant) conversion errors remain a major problem. Indeed, these errors can be relatively large in the equatorial region, depending on the orientation of lines of sight. This is really a problem associated with the thin shell model of the ionosphere used by SBAS, more than it is a problem related to the SBAS grid spacing or to the number of reference stations in the SBAS configuration.

Techniques that work well in mid-latitude regions such as the planar fit approach to estimating vertical grid delays (Walter, et al., 2000), and the simple obliquity factor which converts from slant to vertical delays, then back from vertical to slant delays, may not perform adequately well to ensure a high availability of APV service in the equatorial region. New techniques that are more tolerant of the large spatial and temporal variations in TEC illustrated in Figures 6a and 6b could perhaps be developed. Also, collecting ionospheric data with a high-density network of reference stations would alleviate some of these problems. However, the deep equatorial depletions will remain a problem for single-frequency SBAS, GRAS and GBAS no matter what estimation technique is used because the spatial density of measurements will, in all likelihood, remain insufficient to ensure a very low probability of misdetection of narrow depletion structures, which can as narrow as a few hundreds of kilometers but as long as one thousand kilometers or more in length.

Spatial and temporal changes in the ionosphere that cannot be adequately represented by simple models (such as the planar model mentioned above) driven by relatively dispersed measurements, combined with the possible presence of narrow ionospheric structures that may develop between those measurements, will almost certainly limit the accuracy of the ionospheric delay corrections broadcast to the users. An SBAS faced with these problems will have to generate and broadcast large ionospheric integrity bounds, or Grid Ionospheric Vertical Errors (GIVEs), which, at various times and places, may be large enough to severely limit the availability of APV service. The integrity requirements imposed on SBAS are very stringent. Designing ionospheric algorithms that can be shown to meet these integrity requirements is a difficult task. Such a task requires detailed analyses of the various integrity threats, including those that cannot be addressed by the real-time estimation algorithm, and sufficient padding has to be built into the GIVE formulation to ensure that the broadcast GIVE will protect all users against the effects of all ionospheric threats (and particularly potentially undetected threats) with the required level of confidence.

The nominal ionosphere delay environment for GBAS was characterized using a prescribed model (RTCA/MOPS) and has been updated more recently using NGS/CORS data. During finalization of requirements and the start of system acquisition in the U.S., it was found that ionosphere conditions other then nominal might exist in the local area for mid-latitude regions. Analysis began in earnest to isolate these conditions and characterize them to the extent possible. The current GBAS ionosphere threat model (finalized in January 2006) lays down the initial foundation for characterizing anomalous ionosphere

(Pullen, 2006). They are based on SBAS research, in particular post-processed WAAS data, as well as on data from others networks of dual frequency receivers from the National Oceanic and Atmospheric Administration (NOAA) in the United States.

6.2 Current and Planned Efforts

As a part of the GARMIS project supported by the Galileo Joint Undertaking (GJU), the European Ionospheric Experts Team (IET) is undertaking a number of research activities. They include the preparation of a database of GPS derived slant TEC data for ionospheric model validation, the analysis of existing ionospheric models particularly for GNSS operational use, the study of the equatorial ionosphere with particular emphasis on the electron density gradients during quiet and disturbed conditions over Africa, and equatorial and high latitudes scintillations and their impact on GNSS operation.

Through the agreement between the GJU and the Chinese National Remote Sensing Centre, special ionospheric studies for the Galileo regional augmentation services will be carried out with the participation of research groups from China and also the European IET.

Today for GBAS, there is some agreement on how to deal with these ionospheric storm threats for CAT I (IDR Report, Sept. 2005). U.S. validation and implementation is being conducted in a new prototype effort in Memphis, TN. Research is continuing to refine threats and improve system design to maximize performance.

The FAA GBAS program is also continuing to participate in a cooperative data collection and analysis campaign of equatorial ionosphere anomalies with Brazil. This effort continues to yield more information about equatorial ionosphere impact to GBAS corrections and PA operations.

6.3 SBAS Iono Working Group

In 1999, the SBAS Interoperability Working Group (IWG) established a Working Group composed of international ionospheric experts. This SBAS Iono group was charged with providing all information necessary for assessing ionospheric threats to SBAS systems. For integrity aspects, the most challenging conditions were considered storms leading to large temporal and spatial gradients as well as Traveling Ionospheric Disturbances (TIDs). For continuity and availability threats, the scintillation conditions were analyzed. The group, which has about twenty active members, has met on average twice a year (in the future this might be reduced to once per year) and has collaborated on issues such as modeling, data exchange and joint definition of experiments. In February 2003, the group produced a White Paper on key ionospheric research issues for SBAS, from which this paper has borrowed a large amount of material. The group is still active and, in recent years, has focused its primary effort on the effects of scintillation. A secondary effort aims at evaluating the integrity threat represented by depletion bubbles. In both cases, the SBAS Iono group is studying receiver-based mitigation techniques.

6.4 WAAS Integrity Performance Panel (WIPP)

In the US, the FAA established the WAAS Integrity Performance Panel (WIPP) in 2001 to review the integrity design of the Wide Area Augmentation System (WAAS) and more specifically the design of its integrity algorithms. The WIPP agreed on a 2-step methodology: (1) identify all integrity threats (i.e., circumstances or events that could lead to inadequate residual error bounds also called misleading information); and (2), for each identified threat, either mitigate its effect by use of a monitor or develop an assertion that the threat represents a negligible risk of misleading information.

Concerning the integrity threat due to variations in ionospheric delays, the WIPP decided that a dedicated monitor was necessary. Studies were conducted to characterize the spatial and temporal decorrelation of the ionosphere under both quiet and disturbed ionospheric conditions. The term decorrelation expresses the notion that some variations in the actual ionospheric delays may not be captured by the model that SBAS uses to estimate delays at the grid point, and thus, are absorbed in the residual errors. The statistics of residual errors can then be used to determine the state of the ionosphere in the vicinity of the IGP and also the magnitude of the GIVE that is needed in order to keep the probability of misleading information within the allocated integrity requirement for this monitor. Studies were conducted to elaborate the formulation of the GIVE. A clear distinction was made between "nominal state", by far the most common state in which the estimation model is considered to be valid and the magnitude of the GIVE is set according to the sizes of the residuals, and "storm state", a rare state in which the estimation model is considered to be invalid and the magnitude of the GIVE is set to a safely large numeric value.

More recently, the WIPP recommended the addition of a second storm state to protect the user during the end phase of extreme ionospheric storms. These storms are not expected to occur more than once or twice during a solar cycle. They are considered extreme because of the extremely high levels of ionization that can occur during the "initial phase" of the storm and the intense isolated irregularities that can be generated during the "recovery phase" of the storm when the regular storm detector may no longer detect significant storm activity. When such an extreme storm is detected, WAAS will deny APV service over the entire APV service area for a period of time long enough to ensure that the ionosphere has returned to its normal state before resuming service.

[Perhaps the WIPP activities should be dealt with under a US sub-section?]

6.5 LAAS Integrity Panel (LIP)

The LIP was conceived under an initial FAA acquisition program for a CAT I GBAS system. This forum was then reorganized and formalized into a more research oriented group during 2003. One of the main focuses of this group was to agree to a characterization of ionospheric storm effects on GBAS in the local area and then to derive detailed design alternative to mitigate these effects. Today, the LIP is the primary GBAS forum addressing CAT I mid-latitude ionospheric storm threats in the United States.

As outlined previously, the GBAS CAT II/III service will present additional challenges concerning the ionosphere. The analysis conducted in the LIP will need to continue in some fashion, not only for GBAS, but for any GNSS system or augmentation intended to support PA operations. A continuation of LIP activities in some new form is most likely necessary to achieve this.

[Perhaps the LIP activities should be dealt with under a US sub-section?]

6.6 Current and Planned Research in Japan

In Japan, ionospheric research related to GNSS is being performed by the Electronic Navigation Research Institute (ENRI). The research program covers ionospheric effects on both SBAS and GBAS. In the area of SBAS research, the ionospheric delay estimation and storm detection algorithms currently used in MSAS, as well as other new techniques, are being evaluated using MSAS test bed equipment and data from the GPS Earth Observation Network (GEONET). (GEONET has more than 1,000 GPS receivers located throughout Japan with a typical separation of about 20 km.) (Sakai 2005) Scintillation effects are being observed using scintillation monitors located in the southern islands (Okinawa). The objectives of the analysis are to evaluate seasonal and diurnal occurrences of scintillation and characterize the number of GPS signals simultaneously affected by scintillation (Imamura 2004). In the area of GBAS research, the distribution function of the various spatial ionospheric delay gradients and its seasonal variation from the middle geomagnetic latitude regions to the ionospheric equatorial region are evaluated using GEONET data (Imamura 2004; Yoshihara 2004, 2005). Deterioration of ionospheric delay caused by plasma bubbles (depletions) and ionospheric scintillation associated with plumes of irregularities has been observed at Okinawa (Imamura 2005). Further observations of this effect are being planned using several types of GPS receivers as well as an air glow imager (to help detecting plasma bubbles) in Okinawa Island (Imamura 2005). The purpose of this research is to characterize the plasma bubble phenomenon and analyze low latitude effects on both SBAS and GBAS.

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