Space Weather: Its Effect on GNSS, DGNSS, SBAS, and Flight Inspection

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Abstract

Space weather, primarily the ionosphere, produces the largest GNSS errors. This paper reviews the ionosphere's effect on satellite ranging measurements and discusses how the effect is accounted for in receivers. In addition, the variations in the ionospheric delay will be discussed along with historical ionosphere delay data on normal days as well as some of the solar storm days with the highest variations. Scintillation, a highly random anomaly of the ionosphere, will also be discussed and data presented that demonstrates the effect of this phenomenon. These two ionospheric effects will then be examined in terms of their effect on differential GNSS, a common system used by many flight inspection agencies worldwide. The performance of the FAA's WAAS during normal and anomalous ionospheric periods will also be presented. Finally, the 11-year ionosphere cycle will be discussed along with the implications on GNSS. Widespread use of GNSS for aviation has largely occurred during a relatively quiet time in solar activity; however, we are now emerging from that quiet period and the time of maximum solar activity is expected to occur around 2013 with likely increased ionospheric effects. Flight inspection activity may be affected; therefore, it will be prudent for flight inspectors to monitor ionospheric activity to ensure the integrity of their data.

Introduction

Space Weather has been in the news because of the possibility of intense solar activity damaging power grids and communications, thus causing trillions of US$ worth of damage. Efforts are being undertaken to improve our ability to predict these events [1]. Likewise, the phenomenon can also have an effect on GNSS accuracy. Most of the GNSS transmissions are through the vacuum of space where they are not affected by solar activity; however, they are affected as they pass through the ionosphere during approximately the last 1000 km before reaching the earth. The signals travel at the speed of light (299,792,458 m/sec) through space, but are slowed slightly by varying degrees as they pass through the ionosphere. Both normal and unusual solar activities produce variations in the effect of the ionosphere on GNSS signals. Ionospheric models are used to remove as much of the variability as possible, but there are random components that create errors in the position fixes. We use the term *Space Weather* here to describe the GNSS navigation error sources that occur due to the ionosphere. There is also some signal delay in the troposphere; however it is small and not significantly affected by solar activity so it will not be addressed in the paper.

The paper will first discuss the magnitude of ionospheric delays and its variation over time, both over short time frames and over the centuries. This will be followed by an explanation of how the various types of GNSS receivers deal with ionospheric issues. Finally, the impacts on flight inspection activities will be assessed.

Characteristics of the Ionosphere

The ionosphere's effect on GNSS range measurements is highly variable. During a low solar activity period it would typically cause vertical (zenith) range measurement delays between 1 m at night to 5 – 10 m during the day. During peak periods of solar activity, the delay can vary between 1 m at night to 100 m during the early afternoon [2]. Perhaps even more important from a navigation or flight inspection perspective is that there can be large spatial gradients in the ionosphere's effect on range measurements. Depending on the type of receiver used, the gradient could cause significant position errors. In addition to range measurement errors, there can also be *scintillation*, which can cause power fades of 30 dB-Hz that typically last a few tenths of a second [3, 4]. Figure 1 illustrates the solar cycle history for the last 250 years. It is a plot of the *sunspot number*, which has been observed by astronomers over the centuries. It has been determined in more recent history that the variability of the ionospheric delay is highly correlated with the sunspot number.

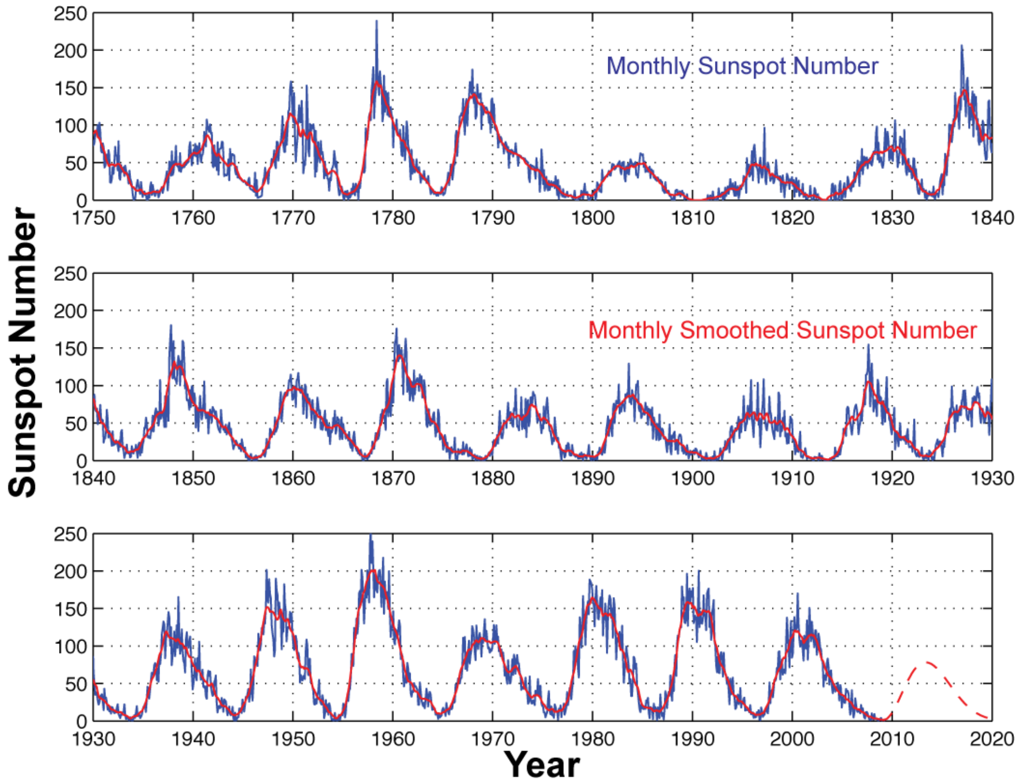

Figure 1. Sunspot Observations [5]. Current data and projections can be obtained from www.swpc.noaa.gov/SolarCycle

There are a number of observations to be made from Fig. 1: 1) "Solar maximums", on average, occur every 11 years, but the period has varied by as much as 4 years. 2) The average sunspot number at the peak of the solar cycle has varied by a factor of 2. 3) We are now (2010) very near the low point in solar activity and the next solar maximum is predicted to be one of the lower ones and arrive around 2013 – 2014. However, there is not universal agreement on these predictions nor have prior predictions always been accurate. 4) Even when the average (red line in Fig. 1) sunspot number is relatively low, there can still be monthly peaks (blue) and daily bursts that greatly exceed the average. Those monthly and daily variations are reduced during the solar minimum periods.

During solar maximum periods, the increased solar activity causes the sun to send out bursts of high energy x-rays and protons that increase the density and thickness of the ionosphere. This activity also increases the electron content of the ionosphere which directly contributes to changes in the range measurements from GNSS satellites.

Figure 2 shows the effect of the ionosphere on *zenith* range measurements (i.e., those from satellites directly overhead) through the daily cycle during the solar maximum period in 1981. Note the pronounced daily effect that is highest slightly after noon local time. Also note the large variations from month to month during this solar maximum year and, for some months, the large variations from day to day (e.g., April, May, and October).

Scintillation acts in a very different way and at different times of the day. Its effect is worse at or near solar maximum years due to increased high energy emissions from the sun, just like the range error measurements discussed above. However, with scintillation, the effect is to reduce the received power and phase coherence of the GNSS signals which can cause a loss of lock on the signal for short periods. The loss of lock results in no GNSS measurement, as opposed to the range measurement errors previously discussed. The frequency of these disturbances varies greatly based on the distance from the geomagnetic equator as shown in Fig. 3.

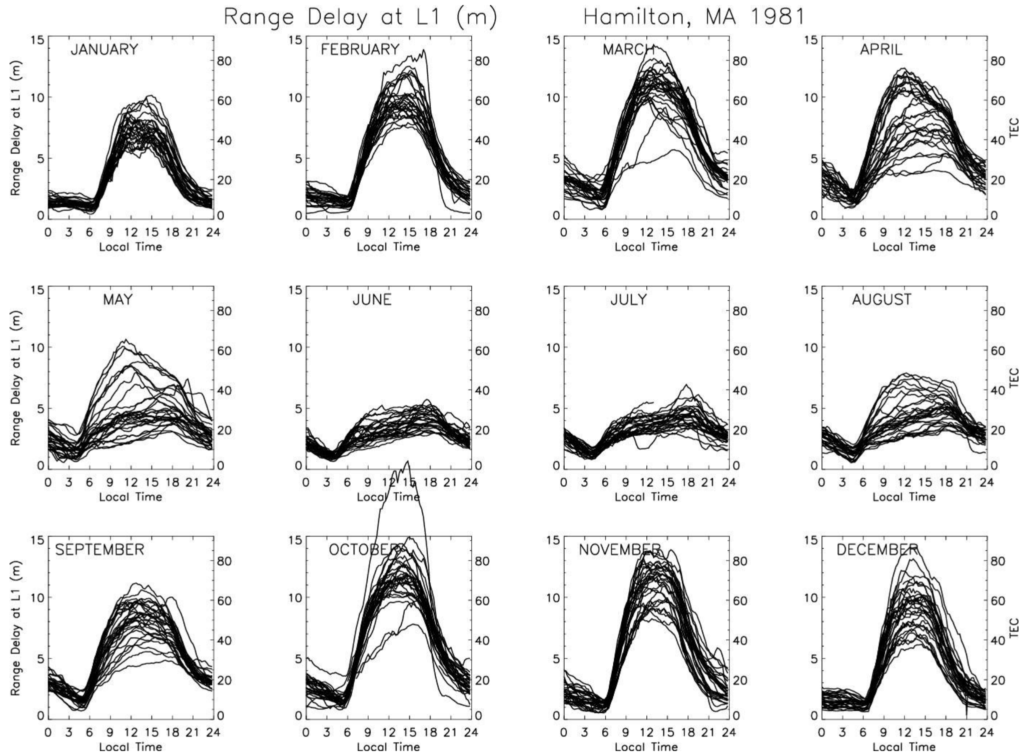

Figure 2. Measured ionospheric zenith delays during the 1981solar max period in Massachusetts [8]

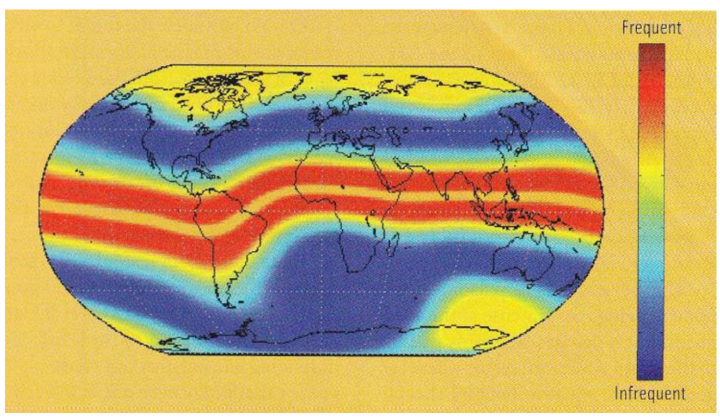

Figure 3. Scintillation map showing the frequency of disturbances [3]

Fortunately, the effect of scintillation is minimal throughout much of North America, Europe, Northern Asia, Australia, and New Zealand; however, much of South America and the equatorial regions in Africa and Asia will be affected much more severely than other parts of the world. During periods near solar maximum years, the red areas in Fig. 3 will experience intense scintillation on the order of 100 days per year while the dark blue areas less then 10 days per year [3]. Unlike the range errors that occur during the daylight hours, scintillation mostly occurs during a time shortly after sunset, which is illustrated in Fig. 4 for a specific time of day.

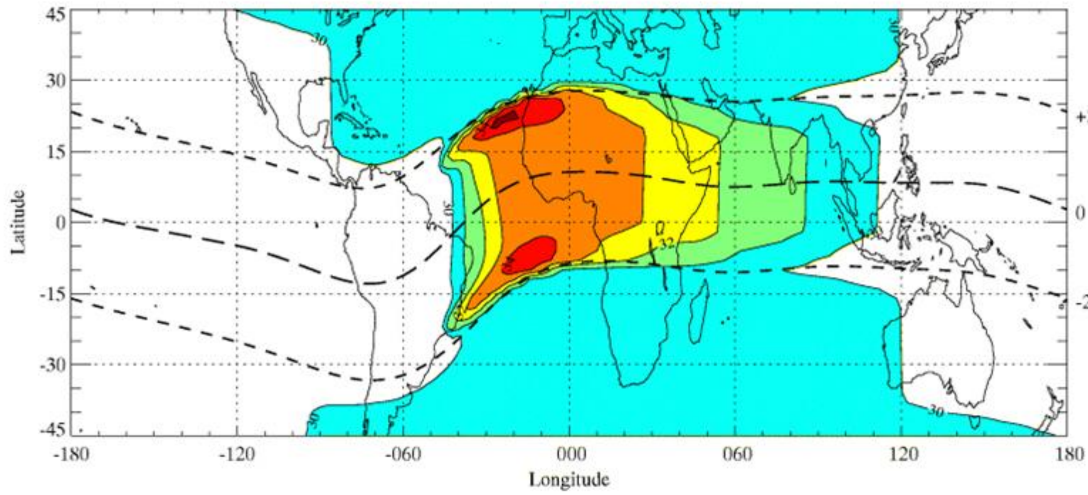

Figure 4. Scintillation map showing intensity for a specific time of day. [6]

Figure 5 illustrates the significant difference between normal, healthy GNSS signals and those that are affected by scintillation. It demonstrates why receivers are susceptible to loss of lock during severe scintillation periods.

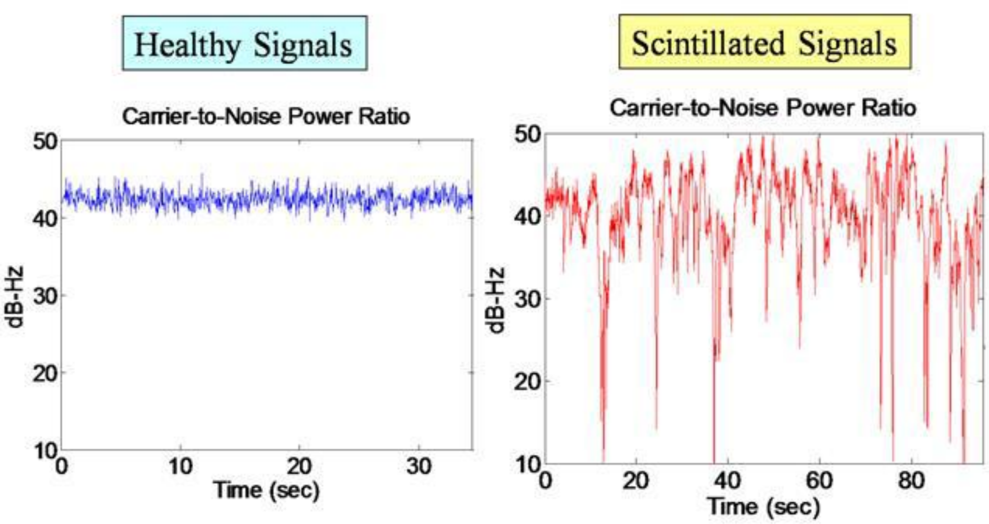

Figure 5. GPS Signal-to-noise power ratio for healthy and scintillated signals [4,7]

Mitigation of Ionospheric Ranging Errors

Current aviation GPS receivers use a model of the ionospheric effect on range errors in order to reduce the navigation error as much as possible. The model used is shown in Fig. 6 (a). It was developed by Klobuchar [8] and is essentially a fit to the data such as that shown in Fig. 2. The parameters A_2 and A_4 are adjusted by the GPS master control station for the best fit to ionospheric conditions. Information is broadcast to the users daily so those parameters can be determined based on the expected ionospheric activity and the user's latitude. The function in Fig. 6(a) represents the zenith delay for a satellite that is directly overhead the user. However, most range measurements are not from satellites directly overhead; therefore, the zenith delay is adjusted by a *obliquity factor* to account for the longer propagation path through the ionosphere.   Figure 7 depicts the geometry and shows why the obliquity factor in Fig. 6(b) increases for low elevation angles.

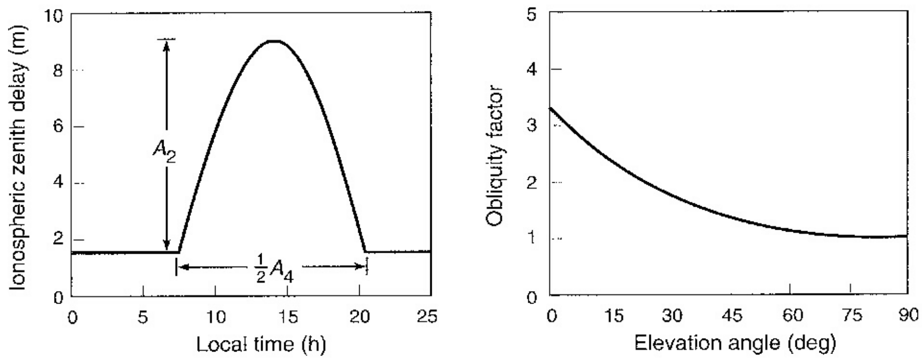

Figure 6. (a) Klobuchar ionosphere zenith delay model, (b) Obliquity factor [2]

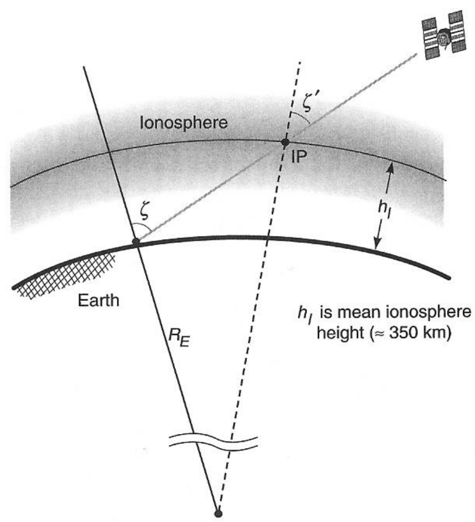

Figure 7. Ionosphere geometry effect on the obliquity factor [2]

This model has been estimated to reduce the uncompensated ionospheric zenith delay by about 50% [2]. However, as can be seen by the delay variations shown in Fig. 2, there can be significant error remaining in spite of the use of the Klobuchar model. At mid latitudes, the remaining zenith error can be up to 7 m during the day during nominal solar maximum periods, and as high as 30 m during severe solar disturbances.   For actual range measurements from the satellites, these errors could be a factor of 3 higher if derived from low elevation satellites, as can be seen from Fig. 6(b).

Aviation receivers manufactured to date rely solely on the L1 frequency (1575.42 MHz) being broadcast from the GPS satellites. The satellites also broadcast an L2 frequency (1227.60 MHz) which is primarily designed for use by the military. This second frequency is utilized by many non-military receivers in order to provide further mitigation of the ionospheric errors. However, the L2 frequency is not part of the internationally accepted spectrum for civil aviation nor is the signal designed for civilian use; therefore, it cannot be used for civilian navigation purposes. Many of the GPS receivers used in flight inspection do make use of this second frequency, so it is instructive to review the benefits of using a *dual-frequency* (L1 & L2) receiver.

When the GNSS signals reach the ionosphere, they are changed slightly from the speed of light in a vacuum due to the presence of charged particles. The amount of speed change depends on the frequency of the wave. Therefore, a receiver that can receive both signals is able to deduce the effect of the ionosphere by comparing the two simultaneous range determinations and attributing the difference to ionospheric effects. Thus, the ionosphere delay can be essentially removed with an error less than a meter with no modeling required.

Furthermore, the GPS signals are made up of a carrier (at 1575.42 MHz) and a superimposed code (at 1 MHz). The code is said to *spread* the bandwidth of the GPS signal. In fact, the overall signal occupies the radio spectrum from approximately (1575.42 –1.00) MHz to (1575.42 + 1.0) MHz. The speed change is different for the signal components near (1575.42 –1.00) MHz than the signal components near (1575.42 +1.00) MHz. The net effect is to change the relationship between the code and carrier in the combined signal. This is commonly referred to as *code-carrier divergence.* It is so named, because the code goes more slowly than the speed of light and the carrier phase is advanced relative to the speed of light. (Since the carrier phase does not carry any signal power, this does not mean that any signal power is going faster than the speed of light.) However, code-carrier divergence can be a factor when using carrier smoothed code algorithms in single frequency receivers. Furthermore, code-carrier divergence can be used to estimate the ionospheric delay [9] in single frequency receivers and is being utilized in some DGPS reference receivers as will be described in the next paragraph. No commercial aviation receivers currently use this process to reduce errors due to the ionosphere.

Another method of mitigating the errors due to ionospheric variations is to use Differential GPS (DGPS). These systems are used widely throughout the world for many applications because they remove many of the errors in the system, not just those due to the ionosphere. For DGPS systems, no error from the ionosphere will result if the user is located at the same site as the reference receiver. However, if the user has a single-frequency receiver and is some distance from the reference site, any spatial gradient in the ionospheric delay will create an error that grows with the distance from the reference site. An ionospheric gradient on the order of 1ppm (or 1mm/km) is typical for a quiet solar period in the mid latitudes such as that shown in Fig. 8. Therefore, the error due to the ionosphere would be 10 cm at 100 km from the reference under these quiet conditions. However, under the solar storm condition on 20 November 2003, gradients of the zenith delay on the order of 300 ppm were observed [10] in the mid latitudes which would result in a zenith ionospheric error of 6 m at 20 km from the reference site. In addition, it has been estimated [11] that the worst worldwide ionospheric gradient that might occur is around 500 ppm, most likely during a solar maximum period. However insufficient data exists for the equatorial regions to be sure that this is a reasonable upper bound worldwide. Given this estimate, for a user with a single-frequency DGPS receiver, the worst possible range error would be approximately 10 m at 20 km from the reference site. Note that these maximum error estimates are based on receivers using "raw" or unfiltered range measurements. In the Ground Based Augmentation System (GBAS) discussed below, reference and airborne receivers apply 100 seconds of carrier smoothing to range measurements and thus incur additional error due to the impact of code-carrier divergence on the smoothing filter. Since code and carrier-phase measurements are affected by equal but opposite amounts, the range error due to divergence can be approximated as twice the smoothing time constant times the user velocity times the ionospheric spatial gradient. For an aircraft moving at 70 m/sec and a maximum gradient of 500 mm/km, this divergence effect can add as much as 2×100 s $\times$ 0.07 km/s $\times$ 0.5 m/km = 7 additional meters of ranging error to the error created by reference-to-user separation. The possibility of such large errors is partially responsible for the slow adoption of the GBAS for CAT III use. GBAS is being implemented now for CAT I use and is susceptible to ionospheric delay errors at several kilometers from the reference receiver antenna under extreme solar storm conditions. The ground reference receivers for GBAS are single-frequency receivers; therefore, they are not able to directly measure the ionospheric delay. However, they are able to utilize the code-carrier divergence phenomenon described above to monitor the ionosphere's behavior and to provide warnings when the observed temporal gradients are excessive.

On the other hand, many other DGPS systems consist of dual-frequency user and reference receivers, many of which are Real-Time Kinematic (RTK) Systems [2]. Use of a dual-frequency receiver essentially eliminates any significant ionospheric error no matter what the gradient is. The RTK systems primarily use the carrier phase measurements; therefore, their errors are typically at the cm level providing they have determined the correct integer number of carrier wavelengths between satellite and receiver. The process of determining the correct integers is referred to as Ambiguity Resolution (AR) and can typically be accomplished with a very high probability of success. However, during severe ionospheric storms, the probability of a successful AR determination has been shown to drop to 78% [12].

Satellite-Based Augmentation Systems (SBAS) are also differential GNSS systems. The FAA's Wide Area Augmentation System (WAAS) is now in operation in North America, the Japanese Multifunction-transport Satellite Augmentation System (MSAS) is in operation around Japan, and the European Geostationary Navigation Overlay Service (EGNOS) will become operational by 2011. SBAS for other parts of the world are in the planning phase. These systems have dual-frequency reference stations spread over the coverage area. The continental U.S. has 25 reference stations that are roughly 600 km apart. Figure 8 shows the measured ionosphere delay information depicted by the colored bands. The reference station measurements of the ionospheric delay are used to map the information into a grid with points that are 5 deg apart in latitude and longitude over the continental U.S., which are then transmitted to users via Geostationary satellites along with corrections for satellite ephemeris and clock errors. Real time values of these ionosphere grid points are updated every few minutes and can be viewed at the FAA's website [13]. This scheme has been shown to yield total system errors smaller than 1 m in horizontal and 2 m vertical 95% of the time [14].

WAAS protects integrity by guaranteeing that the vertical position error will not exceed a Vertical Protection Level (VPL). VPL is calculated by users based on the user's satellite geometry and error bounds transmitted by WAAS. A real time display of VPL can also be seen from the FAA's website [15] and typically shows a VPL of 20 to 30 m for Canada, U.S., and Mexico. This VPL level is sufficient to support a "LPV200" approach, which provides precision landings with a 200 ft Decision Height (DH). However, during high solar activity the ionosphere has large gradients that cannot be represented well by the coarse grid representation [16]. WAAS transmits this fact to the users, thus some types of flight operations become unavailable during very high solar activity periods over portions of the coverage area. An example of the ionospheric delay measurements during a severe solar storm are shown in Fig. 9. It shows the substantially larger ionospheric delays and gradients in the southeast portion of the U.S., which would have prevented acceptable VPLs for precision approaches. Note that the zenith ionospheric delay varied from about 1 to 25 m over short distances in Fig. 9 vs. 1 to 8 m over much longer distances for the normal solar day in Fig. 8.

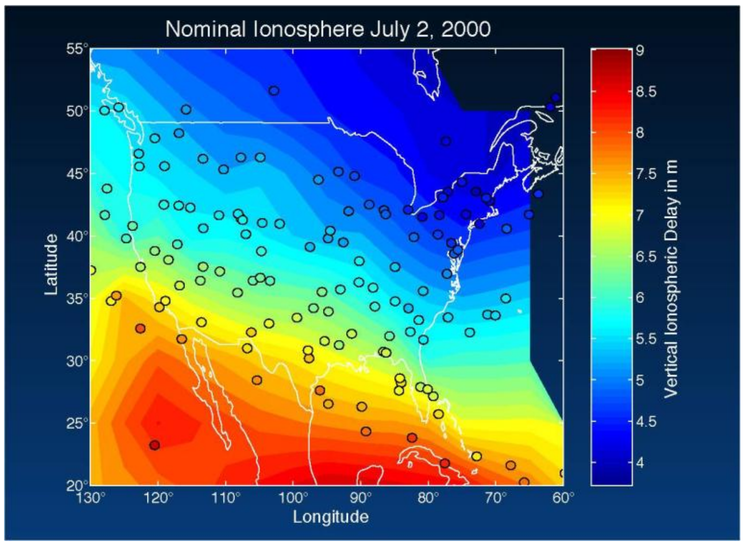

Figure 8. Mid latitude zenith ionosphere delay during quiet solar activity [17].

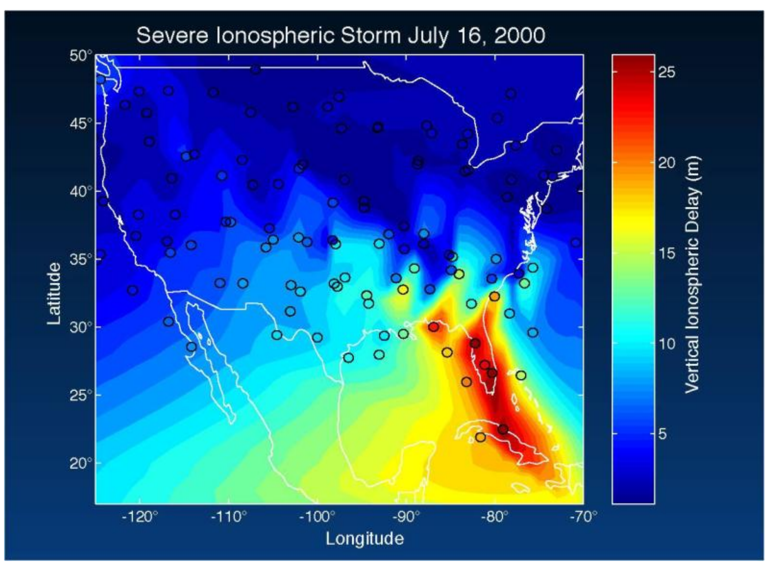

Figure 9. Mid latitude zenith ionosphere delay during severe solar activity [16,17].

Scintillation effects are less easily mitigated. None of the systems described in this section were designed to improve the ability of receivers to maintain lock through severe scintillation. The phase-lock loops in receivers have filtering time constants designed for normal ionospheric conditions. These time constants are selected to balance the need to maintain lock through vehicle accelerations with the need to smooth out range measurement noise. Scintillation severe enough to cause loss of lock occurs primarily in the equatorial and arctic regions (red and yellow bands in Fig. 3) and only for a few hours after sunset; therefore, receivers have been primarily optimized to operate in scintillation-free environments. However, as GNSS adoption becomes more widespread, more effort is being placed on how to also optimize performance during severe scintillation. It is possible to couple inertial navigation information to the receiver tracking loops to enhance the ability to perform precision landing operations in equatorial regions during severe scintillation [7].

There are improvements to GNSS on the horizon that will also mitigate the effects of ionospheric variations. The European GNSS (Galileo) is nearing deployment. Galileo will have two civil frequencies at L1 and L5 (1176.45 MHz), which will encourage the development of aviation GNSS receivers that rely on two frequencies. These receivers can essentially eliminate ionospheric variations as a source of error. Contracts have been awarded to deploy the Galileo satellites with a scheduled completion by 2014 [18]. Also, GPS launched its first satellite with L5 in March 2009 and will continue deploying satellites with both L1 and L5 as current on-orbit satellites are replaced. The current plan is for a sufficient number of GPS satellites to be on orbit in 2018 [19] to enable a user to have enough satellites in view with both L1 and L5 for a reliable, dual-frequency navigation solution. Given that manufacturers develop and certify dual-frequency receivers and that users replace their existing single-frequency GPS receivers, errors due to the ionosphere will essentially be eliminated for both GPS and Galileo users. The most likely scenario is that receiver manufacturers will produce multi-constellation receivers designed to receive dual-frequency (L1/L5) signals from both Galileo and GPS with an availability timed to coincide with the advent of the first operational dual-frequency constellation. Russia and China also have GNSS constellations being deployed; however, their plans to transmit civil dual-frequency positioning signals worldwide for aviation users are less clear.

Ionospheric Effects on Flight Inspection (FI)

Ionospheric delay errors potentially affect flight inspection in two ways: 1) errors in the system used to determine the true position of the FI aircraft, and 2) errors in the aviation receiver used to determine the navigation signal while performing FI of a GNSS approach procedure.

First considering the truth systems, four different systems are used: (a) dual frequency RTK systems with a reference site installed at the airport, (b) DGPS code-based systems with dual-frequency receivers, (c) DGPS systems using single-frequency airborne receivers, and (d) INS-based systems with biases removed via single-frequency un-augmented aviation GPS receivers, radar or laser altimeters, and runway threshold cameras.

(a) RTK systems have essentially no errors from the ionosphere due to their dual-frequency receivers, providing that they have converged to a correct set of phase ambiguities. As pointed out on page 6, there can be a 22% chance of Ambiguity Resolution (AR) failure during severe solar storm days. On days when convergence failures are encountered, the FI aircraft would have to return to the inspection site on another day with less solar storm activity or use another method to obtain the true position. The AR determination procedure will report a failure to determine the ambiguities in most cases. If flight inspection is carried out in the early evening hours during severe solar storms, and especially near equatorial or polar regions (the red and yellow areas in Fig. 3), scintillation may cause a loss of lock in the RTK receivers, thus necessitating a repeat, perhaps at a different time of day. In fact, this phenomenon could pose difficulties for any of the GPS-based truth systems. The severe storm days can be determined in advance to some degree by monitoring the sun's activity which is reported almost daily by SpaceWeather.com [20]. SpaceWeather.com will also issue email alerts of space weather anomalies upon request. Longer term measurements and predictions are offered by the U.S.'s National Oceanic and Atmospheric Administration (NOAA) [21]. It is interesting to note from the NOAA data that the average sunspot number for July 2000, the month during which the severe storm shown in Fig. 9 occurred, was 170 whereas from Fig. 2 we see that the average monthly sunspot numbers from 2004 to the present have remained below 100. On the other hand, the average sunspot number for October 2003 was 65, whereas the sunspot number for a severe storm on 30 October 2003 was 330! However, the sunspot number for 20 November 2003 was 114, the same day that produced the extreme ionospheric gradients discussed above. The predictions from 2010 to 2020 are that the monthly average sunspot numbers will remain below 100. Nevertheless, severe storms can still occur even with low sunspot numbers as evidenced by the 30 October 2003 and 20 November 2003 examples. So it would be prudent for flight inspectors to monitor the solar activity on a daily or weekly basis, not just during the predicted solar max years from 2013 to 2014. The website: www.spaceweather.com provides a range of measurements reporting on the sun's activity, including the probability of severe activity of the earth's magnetic field. The reported probability of a severe storm on 20 November 2003 was 20% while the probability reported for 30 October 2003 was 70%. During quiet solar periods, the reported probability of a severe solar storm is typically below 5%. Another measure of ionospheric disturbances is the *Kp Index* [22]. It is also correlated with magnetic disturbances due to solar activity and current data is available from NOAA [23].

(b) DGPS with dual-frequency airborne receivers and a reference site at the airport are not susceptible to range errors due to ionospheric variations, severe storm or not. Code-based receivers do not require AR; therefore, they do not experience the higher chance of initiation failure during severe storm periods that RTK systems do. As mentioned in the paragraph above, DGPS systems would be exposed to a loss of lock possibility due to scintillation for a few hours after sunset, especially in equatorial and polar regions.

(c) DGPS with single-frequency airborne receivers could experience ionospheric delay errors due to the gradient as described on page 6. We saw that zenith gradients of 300 ppm have been observed and that such a gradient could result in range measurement errors of 6 m at 20 km from the reference site. Larger gradients are possible, especially in equatorial and polar regions during severe solar storm conditions, which would result in larger range errors. Here again, it would be prudent for flight inspectors to monitor the actual solar activity on a daily or weekly basis as discussed in (a) to alert them to possible severe ionospheric delay variations.

(d) INS-based systems, when aided by non-GPS measurements only, would not be affected by any ionospheric effects. However, when aided by a single-frequency, aviation GPS receiver without SBAS capability, the receiver would not be able to correct for ionospheric delay variations and could exhibit large ranging errors (10 m or more) during a severe solar storm. A certified aviation Receiver's Autonomous Integrity Monitoring (RAIM) algorithm would most likely detect the errors and display that information to the flight inspector, but the flight inspection would need to be repeated.

The second area of FI that could be affected by space weather is the flight check of a GNSS-based approach. These flight checks are done to assure the flyability of the approach design, the accuracy of the database for the approach, and the quality of the VHF data link for GBAS installations. Here the flight inspector needs to be aware that the aviation receiver may be experiencing larger errors than typical during severe solar storms. The pilot would be given an alert if the protection levels were exceeded, whether it be a RAIM, SBAS, or GBAS-based approach. However, that does not preclude abnormal GNSS errors that are within the protection levels required for the approach being flight checked. Again, it would be prudent for the flight inspector to monitor solar activity on a routine basis.

Once the dual-frequency GNSS constellations are operational, probably by 2020, and flight inspectors are equipped with dual-frequency airborne equipment, ranging errors due to severe solar activity will no longer be an issue. Due to the frequency diversity, loss of lock due to scintillation in the equatorial regions may also be reduced. However, the correlation of scintillation across L1 and L5 is not yet known but is believed to be high; thus relatively little improvement can be expected at present.

Conclusions

Space weather can potentially have a significant effect on the accuracy and usability of GNSS flight inspection on rare occasions. Variability in the signal delay through the ionosphere has been shown to be correlated with the sunspot number which has exhibited an 11 year cycle over the last 250 years. We are currently (2010) in a quiet period of solar activity; however, a more active solar period is expected in 2013-2014. Severe solar disruptions that materially affect the ionospheric delay, and thus GNSS accuracy, are more likely to occur during the approaching solar maximum, but they could occur during any part of the solar cycle. Flight inspection systems mitigate the ionospheric errors in varying degrees, with a code-based, dual-frequency DGPS system being the most robust. RTK systems are generally the most accurate, but they may have difficulty determining the correct carrier phase integer ambiguities during severe solar activity. The least accurate are systems depending on single-frequency airborne receivers with no augmentation from reference receivers located near the facility being inspected. Flight inspectors are encouraged to routinely monitor the current solar activity on www.spaceweather.com and/or www.swpc.noaa.gov in order to be alert to the possibility of severe ionospheric activity during the days and times at which flight inspections are conducted.

Acknowledgements

The authors gratefully acknowledge the FAA AVN for their support of this effort. Special thanks go to Per Enge and Sam Pullen for their contributions as well as to other colleagues at Stanford University and members of the ICASC.

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[23] http://www.swpc.noaa.gov/rt_plots/kp_3d.html