Ionospheric Scintillation Effects on GPS Receivers during Solar Minimum and Maximum

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ABSTRACT

The ionosphere has practical importance in GPS (Global Positioning System) applications because it influences transionospheric radio wave propagation. Among various phenomena in the ionosphere, ionospheric scintillation is characterized by rapid fluctuation and fading of the received signal intensity due to electron density irregularity inside the ionosphere.

Deep signal fading caused by scintillation can lead to loss of lock of the carrier tracking loop in GPS receivers. The aircraft navigation system based on GPS and WAAS (Wide Area Augmentation System) uses code and carrier phase data to create the position estimate. If a significant number of carrier tracking channels lose lock simultaneously, the system cannot provide service until reacquiring a sufficient number of channels. Although scintillation is not frequent in the mid-latitude region, it is a potential hazard in terms of availability and continuity of the service in the equatorial region [1].

This paper investigates scintillation effects on GPS receivers during solar minimum in the equatorial region. Among four different receivers used for data collection in Brazil, this paper primarily focuses on the scintillation effects on a certified WAAS receiver because it is currently used for aircraft navigation. A maximum of two simultaneous loss of phase locks was observed in 0.05% of epochs. With the given satellite geometry, two satellites loss in a small fraction of time was not a critical problem for navigation.

This paper also analyzes solar maximum data collected at Ascension Island during the previous solar maximum period. More satellite channels were affected by scintillation compared to solar minimum, but the maximum number of simultaneous loss of lock in a software receiver was the same as the solar minimum case. One of the most important results of this paper is that instances of simultaneous loss of satellite data can be reduced by minimizing reacquisition time of GPS receivers. Although 20 seconds reacquisition time is allowed by WAAS MOPS (Minimum Operational Performance Standards) [2], this number should be reduced to guarantee enough availability during strong scintillation.

INTRODUCTION

A simple scintillation patch model in Figure 1 is useful for understanding scintillation effects on aircraft navigation. Once patches of electron density irregularities are developed inside the ionosphere, radio waves, including GPS signals, passing through the patches fluctuate rapidly. This phenomenon is known as ionospheric scintillation [3] and deep signal fading frequently occurs with scintillation.

GPS and WAAS currently provide aircraft navigation service in the United States. GPS avionics on aircraft calculate the position estimate using code and carrier phase information. Further, integrity of the estimate is guaranteed by WAAS [4]. In order to navigate using GPS and WAAS, GPS receivers have to track at least four satellites with good geometry. Lock of carrier tracking loop, also called phase lock, is more vulnerable to signal outages than lock of code tracking loop. Under strong ionospheric scintillation, GPS signal intensity fades deeply and phase lock of a receiver can be lost. Although code lock could be maintained under strong scintillation, the channel without phase lock cannot be used for navigation solution, so a GPS receiver effectively loses the satellite until reestablishing the lock. If scintillation patches cover a large portion of sky as Figure 1, a GPS receiver has chance to lose more than one satellite simultaneously. Simultaneous loss of significant number of satellites discontinues GPS navigation. Therefore, strong ionospheric scintillation could be hazardous in terms of continuity and availability of the aircraft navigation service based on GPS and WAAS.

Statistics of simultaneous loss of satellites under strong scintillation are essential to assess scintillation effects on GPS navigation. Performance statistics of a currently used WAAS receiver under strong scintillation are shown

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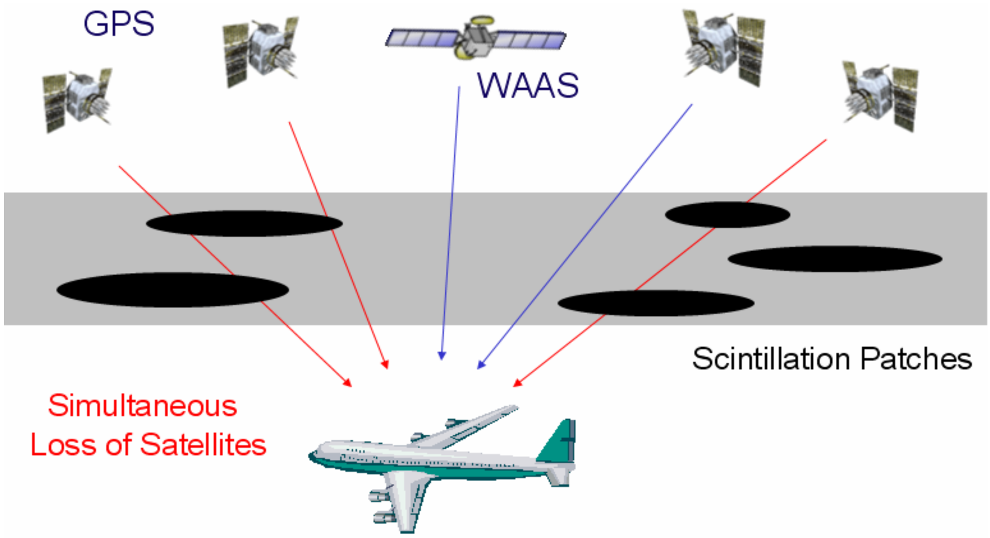

Figure 1. Potential Hazard to Aircraft Navigation due to Ionospheric Scintillation

in this paper. Relationship between reacquisition time of a receiver and simultaneous loss of satellites is also discussed. Finally, a suggestion for revising the current requirement of reacquisition time of a WAAS receiver is proposed.

SCINTILLATION DURING SOLAR MINIMUM

Performance of a currently available WAAS receiver under strong scintillation is evaluated in this section. The data in this section was collected during solar minimum period, because solar maximum data cannot be collected with a WAAS receiver until the next solar maximum. Although the data was collected during solar minimum, strong scintillation with S4 index around 1.0 was sometimes observed. Performance statistics based only on these strong scintillation cases can provide useful insight about the receiver performance under solar maximum.

Data Collection

The data collection campaign was performed by Dr. Eurico de Paula, INPE (Instituto Nacional de Pesquisas Espaciais), Brazil [5]. Scintillation data was collected at Sao Jose dos Campos in Brazil from December 2005 to January 2006 which was solar minimum period. Four different GPS receivers were used for the campaign which were a Garmin certified WAAS receiver, a Cornell Scintillation Monitor receiver [6], an Ashtech dual frequency receiver, and a Novatel receiver.

The primary interest of this paper is on performance of the Garmin WAAS receiver. Since the Garmin receiver is currently the only certified WAAS receiver for aircraft navigation with vertical guidance, its performance evaluation during scintillation is essential to assess impact of scintillation on GPS navigation. 36 days of data collected with the Garmin receiver were used for this analysis. Note that *GPS navigation* in this paper precisely means aircraft navigation based on GPS and WAAS.

Simultaneous Loss of Phase Lock

Figure 2 shows carrier to noise density ratio (C/No) of PRN 29 recorded by a WAAS receiver during strong scintillation. C/No fluctuation was as high as 20dB and S4 index calculated by Ashtech and Cornell receivers were between 0.5 and 1.3 during this period.

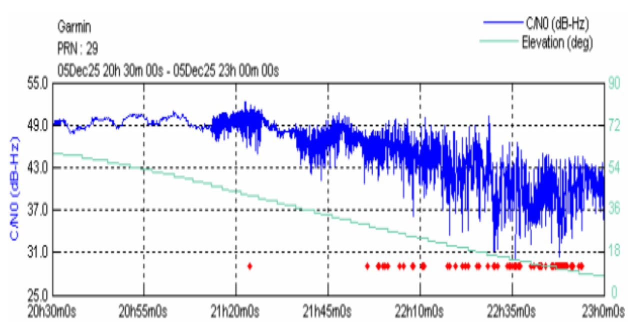

Figure 2. C/No of PRN 29 during Strong Scintillation

Red points on Figure 2 indicate that phase lock of this satellite channel was lost at corresponding epochs. Note that the receiver also lost high elevation satellites under strong scintillation in addition to low elevation satellites. Loss of low elevation satellites is normal and not a problem for GPS navigation, but loss of high elevation satellites due to scintillation is a concern.

Figure 3 provides more insights about scintillation effects on GPS navigation. A WAAS receiver is located at the center of Figure 3 and the outer circle represents 6 degree elevation. Red dots mean the receiver lost satellites at corresponding locations, which are the tracking results for 12 hours during the most severe scintillation day in the given solar minimum data set. Blue dots are the last 10 minute trajectories of each satellite of the 12 hours data. Scintillation patches were developed on the northern part of sky and the receiver suffered from tracking two satellites for about two hours. As previously mentioned, loss of low elevation satellites around the 6 degree elevation circle is not a problem for GPS navigation.

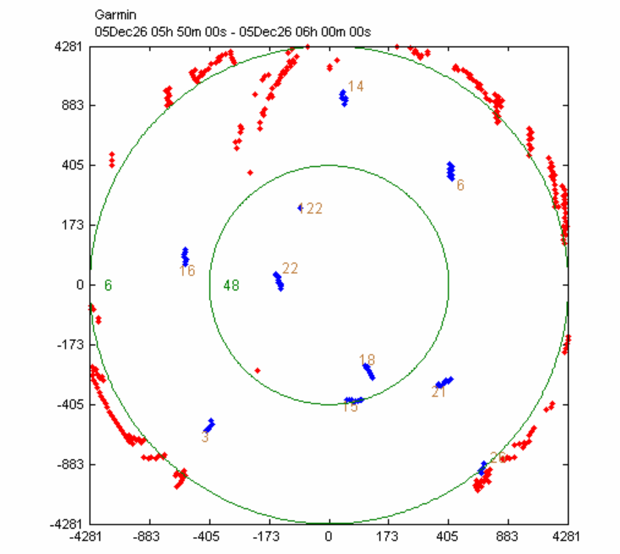

Figure 3. Loss of Phase Lock during Strong Scintillation (6 PM ~ 6 AM Local Time)

GPS avionics on aircraft use both code and carrier information to calculate the position estimate and at least four satellites with good geometry are required for navigation solution. Hence, loss of carrier information due to scintillation could be hazardous to GPS navigation if significant number of satellite channels was lost simultaneously. On the other hand, although many satellite channels would experience scintillation, it is not necessarily critical if phase lock loss of different channels does not happen at the same time.

After analyzing the 36 days of data collected with a WAAS receiver, one satellite loss was observed in 2.15% of total epochs and simultaneous loss of two satellites was occurred in 0.05% of epochs. Three or more satellites loss was not observed at all. Note that the data only from 6 PM to 6 AM at each day was used for this analysis because scintillation is more frequently observed during nighttime [7]. If daytime data were also included, the percentage loss would be half of the previous numbers.

With given satellite geometry, two satellites loss in a small percent of time is not a critical problem for GPS navigation. Therefore, based on the 36 days of data collected with a certified WAAS receiver, ionospheric scintillation during solar minimum is not hazardous for GPS navigation in Brazil with a currently available WAAS receiver. This conclusion still holds even after assuming development of scintillation patches in similar size could be ten times more frequent. Under this extreme assumption, percentage of two satellite loss would be 0.5% which is still not critical. However, if scintillation patches cover larger portion of sky at the same time as Figure 1, simultaneous loss of three or more satellites could occur. This situation was not observed during solar minimum but may be happened during solar maximum.

Reacquisition Time

Reacquisition time after losing phase lock is also an important parameter because reacquisition time is related to number of simultaneous loss of satellites which is related to availability of GPS navigation. Assuming a receiver reacquires each satellite very quickly after losing its phase lock, chance of simultaneous loss of satellites can be largely reduced. Statistics of reacquisition time of a WAAS receiver during strong scintillation are shown in Figure 4. Strong scintillation in this paper means that S4 index recorded by Ashtech and Cornell receiver is close to 1.0. These statistics are also based on the 36 days' observation during solar minimum.

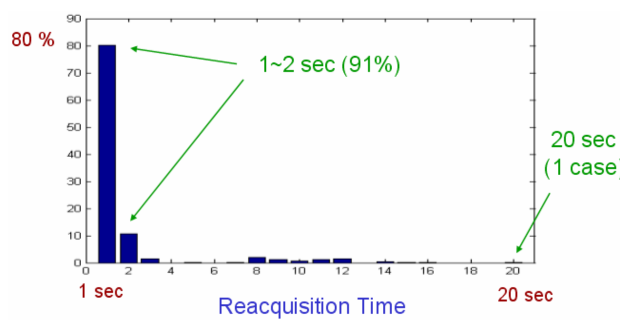

Figure 4. Reacquisition Time of a Certified WAAS Receiver during Strong Scintillation

The WAAS receiver reacquired satellites within 2 seconds in 91% of strong scintillation time. The maximum reacquisition time was 20 seconds which was observed only one time. According to WAAS MOPS [2], "… signal outages of 30 seconds or less … the equipment shall reacquire the satellite within 20 seconds …." Hence, 20 seconds reacquisition time is marginally acceptable. Statistics of the observed reacquisition time will be revisited in the later section.

SCINTILLATION DURING SOLAR MAXIMUM

As discussed in the previous section, scintillation effect on GPS navigation in the equatorial region, especially in Brazil, was not severe during solar minimum. However, the situation could be very different during solar maximum. Under strong solar activity, scintillation is more frequent and scintillation patches can cover much larger fraction of sky. Hence, a receiver may frequently lose more than two satellites simultaneously and a GPS navigation system may not provide enough availability during strong scintillation. Potential challenges during solar maximum and a suggestion to guarantee enough availability are discussed in this section.

Data Collection

Solar maximum data was collected at Ascension Island in the South Atlantic Ocean. The data set was provided by Dr. Theodore Beach, AFRL (Air Force Research Laboratory). 36 minutes of IF (Intermediate Frequency) sampled data was used for this analysis. The data was collected with a NAVSYS DSR-100 receiver from 8:50 PM on March 21, 2001 (UTC, also local time) which was a solar maximum period. A NordNav software receiver was used for analyzing the raw IF data. The output rate of the NordNav receiver was set to 20 Hz and 20 ms code and carrier coherent integration time was used. Code loop bandwidth was 0.5 Hz and carrier loop bandwidth was 5 Hz which are narrower than usual receivers but better for noise rejection. These narrow bandwidths are acceptable because the NAVSYS DSR-100 receiver was stationary and a Rubidium frequency standard was used for data collection.

Simultaneous Loss of Phase Lock

Four out of seven satellites were affected by scintillation in the 36 minutes of data set. Figure 5 clearly shows that larger portion of sky was influenced by scintillation compared with Figure 3.

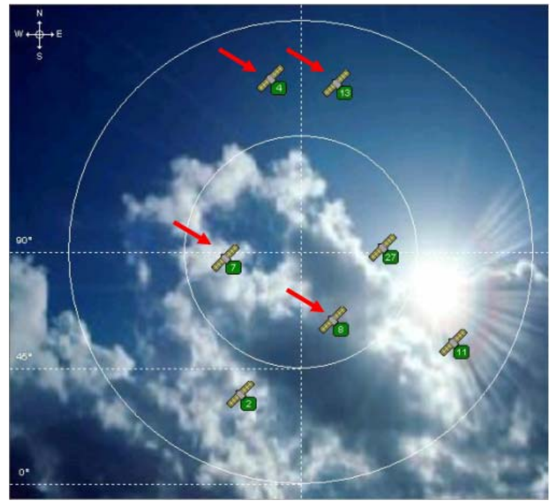

Figure 5. Four Satellites Affected by Scintillation

Although four satellites were affected by scintillation, this fact does not imply that four satellites lost lock simultaneously. In fact, deep signal fading due to scintillation of each satellite channel does not usually coincide. For example, there are thirteen cases of deep signal fading in the 160 second period shown in Figure 6, but only three pairs of them happened close to each other. Only in these three cases, the NordNav software receiver

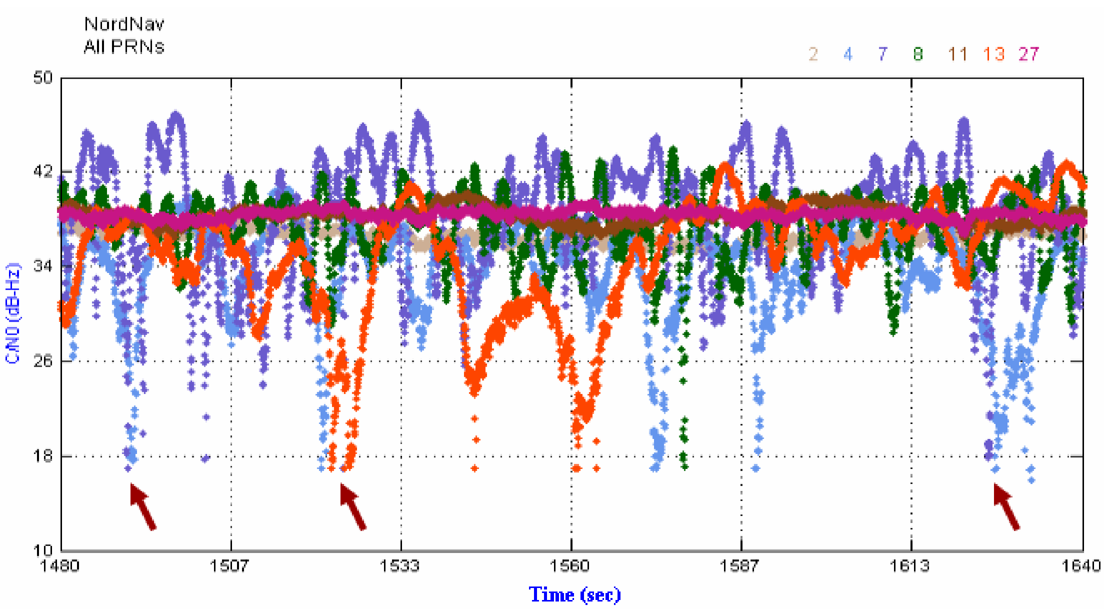

Figure 6. C/No of All Seven Satellites during Solar Maximum

lost two satellites simultaneously and in other cases only one satellite was lost. Therefore, if a receiver reacquires a lost satellite very quickly before another satellite is lost, simultaneous loss of lock can be avoided and GPS navigation is not discontinued. Actually, the maximum number of simultaneous loss of phase locks in the NordNav receiver during the 36 minutes of solar maximum data was just two which is the same as solar minimum case. The NordNav software receiver usually reacquired phase lock within 1.5 seconds. If a different receiver has longer reacquisition time, occurrence of simultaneous loss could be more frequent. Relationship between reacquisition time and simultaneous loss of satellites will be discussed in detail in the following section.

Parametric Simulation

Ideally, scintillation effects on a WAAS receiver during solar maximum would be well-known. However, scintillation data collected with a WAAS receiver during solar maximum will not be available until the next solar maximum around 2011. Performance of a WAAS receiver in terms of reacquisition time during solar minimum was already shown in Figure 4. This information could be used to obtain some insights about expected performance of a WAAS receiver during solar maximum.

The WAAS receiver usually reacquired phase lock within 2 seconds during strong scintillation in solar minimum, but it spent longer than 2 seconds in 9% of epochs (Figure 4). The maximum observed reacquisition time was 20 seconds which is acceptable by the current WAAS MOPS [2].

Figure 7 shows time percentage of simultaneous loss of satellites corresponding to simulated reacquisition times. Reacquisition times are simulated on top of solar maximum outputs from the NordNav receiver. Whenever the NordNav receiver lost phase lock of a certain satellite channel, the lock is assumed to be lost until predefined reacquisition time. With this straightforward approach, number of simultaneous loss of phase locks can be counted at every epoch as a function of predefined reacquisition time. The time percentage of simultaneous loss according to reacquisition times up to 20 seconds in Figure 7 is obtained using this approach. Two cases could be focused on in Figure 7. One is a 2 seconds reacquisition time and the other is 20 seconds. The WAAS receiver usually reacquired phase lock within 2 seconds, and 20 seconds is the maximum observed and allowable reacquisition time.

If every channel is reacquired in 2 seconds after losing its phase lock, there would be no case of three satellites loss according to the simulation (Figure 7). However, when 20 seconds reacquisition time is assumed, the time percentage of three satellites loss would be 3.3%. (Four or more satellites loss was not observed in any cases.) Although a rigorous WAAS availability study has not been performed yet, this high percentage of three satellites loss may not provide enough availability of GPS navigation during solar maximum. The requirement of reacquisition time of the previous WAAS MOPS (DO-229C) [8] was 10 seconds, but it has been changed to 20 seconds in the current WAAS MOPS (DO-229D) [2]. In the same simulation, 10 seconds reacquisition time demonstrates three satellites loss would be 0.87% of time (Figure 7). As is evident in Figure 7 either a 10 or a 20 second reacquisition time results in a significant increase in the loss of one or more satellites making it harder to achieve desired levels of availability or continuity.

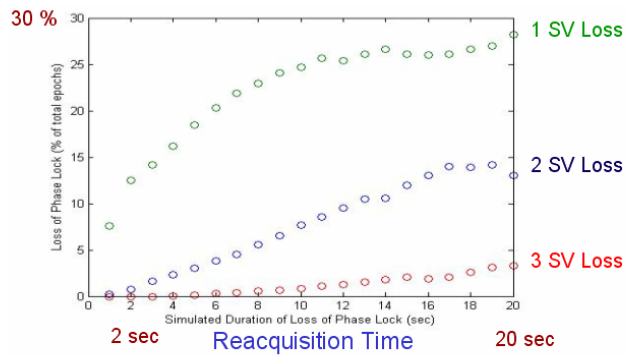

Figure 7. Simulated Reacquisition Time and Time Percentage of Simultaneous Loss of Satellites

Note that the simulation in Figure 7 takes a conservative approach. The simulation does not consider probability distribution of reacquisition time of Figure 4. Every reacquisition time in the simulation is deterministic and each lost channel is assumed to be reacquired only after predefined reacquisition time. Hence, the result in Figure 7 is generic and not related to the performance of the Garmin WAAS receiver. The important point of Figure 7 is that a generic receiver, not restricted to the Garmin receiver, perfectly complying with the current WAAS MOPS [2] could lose three satellites simultaneously in 3.3% of time during strong scintillation in solar maximum.

CONCLUSION

The requirement to reacquire satellites within 20 seconds appears to be too conservative when applied to the brief deep fades caused by scintillation. We have shown that there is a significant improvement in numbers of satellites tracked if this requirement can be shortened. This will prove especially significant during severe periods of scintillation.

Based on the observation during 36 days of solar minimum data in Brazil, ionospheric scintillation would not be a critical problem with an available certified WAAS receiver during solar minimum. With the given satellite geometry, development of scintillation patches in a small portion of sky does not significantly limit GPS navigation. However, if scintillation patches cover a larger portion of sky, more than two satellites could be influenced by scintillation, but this case was not observed during the solar minimum campaign. Although more than two satellites could be affected by scintillation during solar maximum, deep signal fading does not usually occur simultaneously. Therefore, a receiver that reacquires lost satellites within short amount of time may not observe too many simultaneous losses.

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