Availability Impact on GPS Aviation due to Strong Ionospheric Scintillation

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Abstract

Strong ionospheric scintillation due to electron density irregularities inside the ionosphere is commonly observed in the equatorial region during solar maxima. Strong amplitude scintillation causes deep and frequent Global Positioning System (GPS) signal fading. Since GPS receivers lose carrier tracking lock at deep signal fading and the lost channel cannot be used for the position solution until reacquired, ionospheric scintillation is a major concern for GPS aviation in the equatorial area. Frequent signal fading also causes frequent reset of the carrier smoothing filter in aviation receivers. This leads to higher noise levels on the pseudorange measurements. This paper analyzes aviation availability during a severe scintillation period observed using data from the previous solar maximum. The effects from satellite loss due to deep fading and shortened carrier smoothing time are considered. Availability results for both vertical and horizontal navigation during the severe scintillation are illustrated. Finally, a modification to the upper bound of the allowed reacquisition time for the current Wide Area Augmentation System (WAAS) Minimum Operational Performance Standards (MOPS) is recommended based on the availability analysis results and observed performance of a certified WAAS receiver.

Keywords: Ionospheric Scintillation, Global Positioning System (GPS), Wide Area Augmentation System (WAAS), Aviation, Availability, Continuity

Running Title: Strong Ionospheric Scintillation Effects on GPS Aviation

I. Introduction

The ionosphere is the largest error source for Global Positioning System (GPS) [1] aviation. Although ionospheric delay can be directly measured by future dual frequency GPS avionics, signal outages caused by ionospheric scintillation [2, 3] still remains a concern. Characteristics of ionospheric scintillation and its effects on GPS applications are well summarized in [4, 5], but the impact of scintillation on GPS aviation availability is not yet well understood. This is mainly due to lack of high rate scintillation data collected by GPS receivers during the past solar maximum. Strong scintillation is frequently observed during solar maxima which follow an 11-year average solar cycle [6]. Although this paper focuses on equatorial scintillation [7], scintillation is also important in the auroral regions and the poles [8, 9].

A previous effort [10] to analyze GPS and Satellite-Based Augmentation System (SBAS) availability under scintillation used the Wideband scintillation model (WBMOD) [11] for simulating scintillation parameters. WBMOD provides the level of intensity and phase scintillation based on a power law phase-screen propagation model and globally collected data. This approach is useful to illustrate the global trend of GPS/SBAS availability under scintillation. As [10] also pointed out, the probability of simultaneous loss of satellites during scintillation is very small. However, WBMOD does not provide this probability and consequently this previous study showed very conservative results.

This paper analyzes the operational availability of dual frequency GPS aviation under a severe scintillation period rather than investigating the global trend of aviation availability. Section II explains the way scintillation reduces aviation availability. In order to demonstrate realistic operational availability, our analysis relies on a worst-case scintillation data set collected during a campaign at Ascension Island during the past solar maximum (Section III). Our analysis does not use a physics-based global scintillation model. Operational availabilities of two different operational procedures (vertical and horizontal navigation) are illustrated in Section IV.

Furthermore, reacquisition performance of a certified Wide Area Augmentation System (WAAS) [12] receiver during scintillation was observed for a 36-day campaign in Brazil (Section III). The current WAAS Minimum Operational Performance Standards (MOPS) [13] does not have a specific performance requirement for an aviation receiver under scintillation. Possible modification of the upper limit for reacquisition time in the WAAS MOPS is recommended in Section V based on the availability study and the observed performance of the WAAS receiver.

II. Ionospheric Scintillation and GPS Aviation

Ionospheric scintillation due to electron density irregularities in the ionosphere can cause deep and frequent transionospheric signal fading. The carrier to noise density ratio (C/N_0) of a received GPS signal remains nearly constant over 100 seconds when scintillation is not present. However, if strong scintillation is present, C/N_0 fluctuates rapidly and fades of more than 25 dB can occur (Figure 1). These deep signal fadings, which are commonly observed during solar maxima in the equatorial region [14, 15], can cause the receiver's carrier tracking loop to lose lock. Since GPS aviation receivers should not really trust the code measurement if the carrier loop is not locked, carrier lock loss can be effectively considered as satellite loss until lock is reestablished. Simultaneous loss of many satellites has a significant impact on GPS navigation because a receiver has to track at least four satellites with good geometry in order to form a position solution [16, 17].

This section explains the way deep and frequent signal fading affects aviation availability. Satellite loss due to deep fading adversely affects satellite geometry and significantly decreases aviation availability. High noise levels affecting pseudorange estimates due to shortened carrier smoothing time caused by these frequent fades further reduces availability. The effects from satellite loss and shortened carrier smoothing lengths are considered in the availability analysis of Section IV.

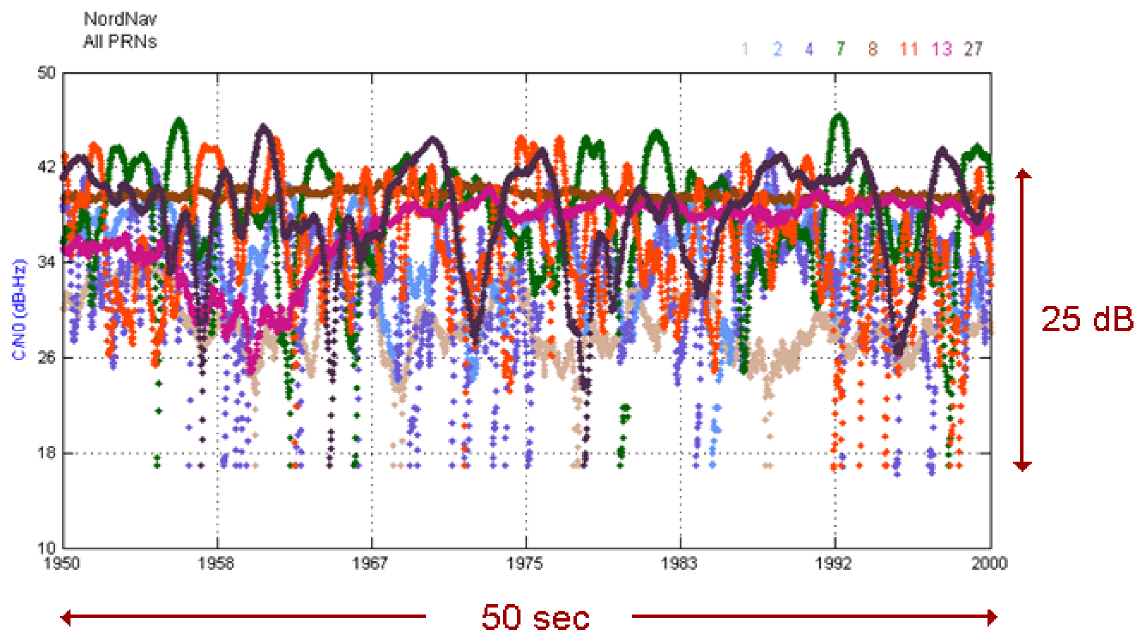

Fig. 1. Example of C/N_0 outputs of all satellites in view during strong scintillation. Different colors represent different satellites. This data was collected at Ascension Island in 2001 and processed using a NordNav commercial software receiver. Detailed information of the data set is given in Section III.

A. Simultaneous Loss of Satellites and Reacquisition Time

As shown in Figure 1, almost all satellites in view could suffer from deep signal fadings during a severe scintillation period. In forming a GPS navigation solution, the number of simultaneously lost satellites is more meaningful than the number experiencing fading. Although almost all channels are fading in Figure 1, signal fadings of different satellite channels do not usually occur at the exact same time. Hence, if a receiver can reacquire a lost channel before it loses other channels, it can avoid simultaneous outage and can still navigate provided that the receiver tracks at least four satellites with good geometry. Therefore, fast reacquisition capability of a receiver after losing lock reduces the chance of simultaneous losses and provides better aviation availability.

The WAAS MOPS contains a specific requirement for the reacquisition time of aviation receivers. The current WAAS MOPS says, "For satellite signal outages of 30 seconds or less when the remaining satellites provide a GDOP of 6 or less, the equipment shall reacquire the satellite within 20 seconds from the time the signal is reintroduced. This requirement applies to a satellite with the minimum signal power in the presence of interfering signals as described in Appendix C [13]." This means that a satellite lost after deep signal fading could have its reintroduction into the position solution delayed for up to 20 seconds. Section IV analyzes the effect of this requirement on operational availability during a severe scintillation period and demonstrates the potential availability benefit of shorter reacquisition times.

B. Frequent Signal Fading and Shortened Carrier Smoothing Time

Aviation receivers use Hatch filters [18] to reduce the effect of the noise level of code measurements. The filter smoothes code measurements with the less noisy carrier measurements. The WAAS MOPS specifies a smoothing time constant of 100 seconds. The WAAS MOPS specifies noise performance for a fully converged filter, but does not specify a noise model for shorter smoothing times. We have conservatively assumed that the noise is uncorrelated from one second to the next. Under nominal condition as in Figure 2, the effect of code noise exponentially decreases [19] with a 100 second time constant by Hatch filtering and converges to floor level after couple of hundred seconds.

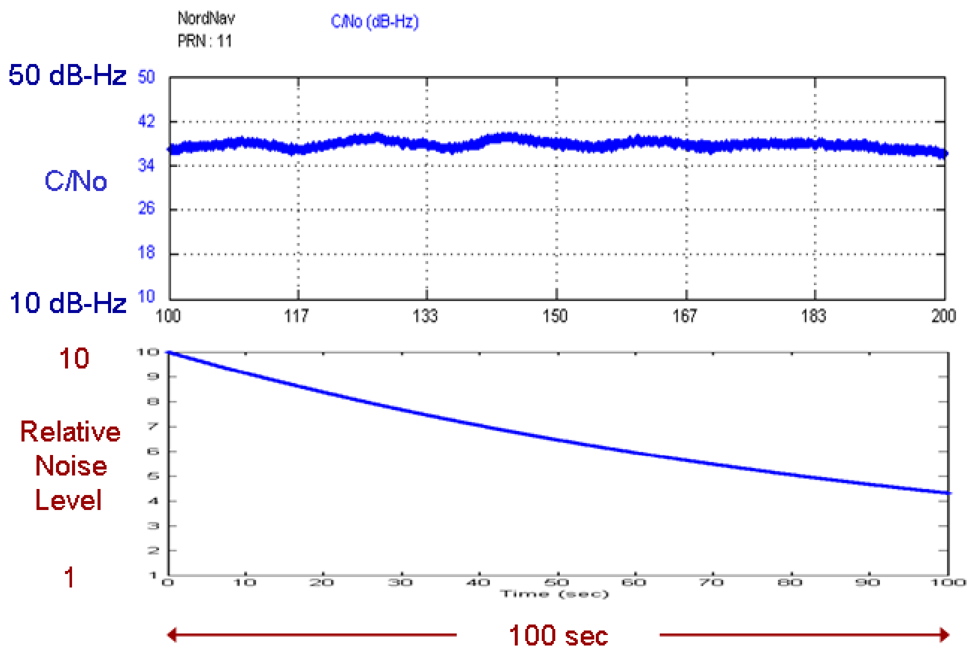

Fig. 2. Decreasing code noise by Hatch filtering under nominal conditions without scintillation. Carrier tracking lock is assumed to be established at 0 seconds. C/N_0 remains nearly constant over 100 seconds.

The relative noise level of code measurements with respect to the fully converged value is modeled as $9e^{-\frac{\Delta t}{100}}+1$, where Δt is the carrier smoothing time after establishing carrier lock. This model implies that the noise level is reduced by a factor of 10 after filter converging. However, the Hatch filter has been shown to actually reduce noise level by a factor of about 2--5 depending on satellite elevations (based on empirical data) [20]. Hence, our Hatch filter model is conservative because after reestablishing carrier lock, the relative noise level is assumed to be 10 times larger than the floor value rather than 2--5 times larger. Once the filter is converged, the relative noise remains at the floor level until the receiver loses carrier lock again.

However, if strong scintillation is present, a receiver frequently loses carrier lock and tries to reacquire the lost channel. After reacquiring the channel, the Hatch filter is reset and starts to smooth code measurements from the beginning. When the Hatch filter is reset, the effect of the noise level on the code measurements is modeled as 10 times higher than the floor level as in Figure 3.

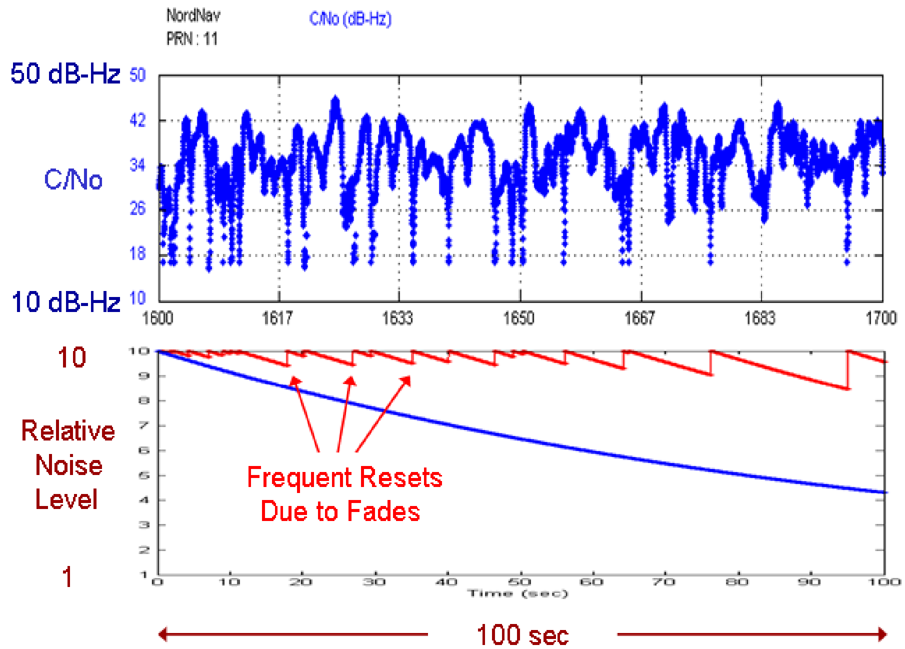

Fig. 3. Frequent reset of Hatch filter and high code noise level during severe scintillation. For illustration purposes, a receiver is assumed to reestablish carrier lock promptly after loss of lock. More than 25 dB fading can occur during severe scintillation.

As previously explained, for the availability analysis of Section IV, the relative noise level of code measurements is modeled as $9e^{-\frac{\Delta t}{100}}+1$, where Δt is time since the filter reset. The code noise and multipath model for the availability simulation is multiplied by this relative noise level factor. This multiplication factor starts from 10 when smoothing time, Δt, is zero and converges to 1 if a receiver does not lose lock for a couple of hundred seconds. However, strong scintillation causes frequent loss of lock and prevents the Hatch filter from converging (Figure 3). This higher noise level due to frequent loss of lock reduces aviation availability. Previous research showed that the median time between deep fades during the 45 minutes of severe scintillation was only about 5 seconds which is very short compared to the 100 second smoothing time constant [21]. El-Arini observed about 9 second median time between fades at 25 dB fading in Naha, Japan on 20 March 2002 (8:30 PM -- 11:00 PM, local time) [22]. To the authors' knowledge, a GPS/SBAS availability study with consideration of the Hatch filter model under severe scintillation has not been previously performed.

III. Scintillation Data Collection

There are two sets of scintillation data used for this research. The solar maximum data set was collected at Ascension Island in March 2001 and the solar minimum data set was collected at Sao Jose Dos Campos, Brazil from December 2005 to January 2006.

A. Severe Scintillation Data from the Previous Solar Maximum

The severe scintillation data was collected at Ascension Island in 2001 and Theodore Beach of the U. S. Air Force Research Laboratory (AFRL) provided the data set. This data set has been used for other studies [21, 23] and detailed information of the DSR-100 receiver used for the campaign is found in [24]. The raw Intermediate Frequency (IF) data from DSR-100 was processed by a NordNav commercial software receiver [25] and 50 Hz outputs from NordNav were used for this research.

The most severe 45 minute scintillation data, which was from 8:45 PM to 9:30 PM on 18 March 2001 (UTC, also local time), from a 9 day campaign at Ascension Island was selected based on the amplitude scintillation index (S_4 index). During this worst 45 minutes, seven out of eight satellites were affected by scintillation (Figure 2 of [21]). Note that although seven satellites were fading for this period, it does not necessarily mean all seven satellites were lost simultaneously. If a receiver quickly reacquires lost channels, it can reduce chance of simultaneous losses and alleviate scintillation impact on navigation.

B. Scintillation Data Collected by a Certified Aviation Receiver during Solar Minimum

It is informative to observe performance of a currently-used certified aviation receiver during scintillation. Unfortunately, there was no certified SBAS aviation receiver available during the past solar maximum, so solar maximum scintillation data has not been collected by a certified receiver. As an alternative, a data collection campaign was performed during a solar minimum period with the help of Eurico de Paula at the Instituto

Nacional de Pesquisas Espaciais (INPE), Brazil [26]. Although it was a solar minimum period, strong scintillation with S_4 index of about 1.0 were sometimes observed during the 36-day campaign.

The solar minimum data were collected at Sao Jose dos Campos, Brazil from December 2005 to January 2006 (36 days). Four different GPS receivers were deployed for the campaign, which were a certified WAAS receiver, a Cornell Scintillation Monitor receiver [27], an Ashtech dual frequency receiver, and a NovAtel receiver. The primary interest of this paper is on the performance of the certified WAAS receiver. Since the certified WAAS receiver used for this study was the only certified WAAS receiver for aircraft navigation with vertical guidance, its performance evaluation during scintillation is essential to assess scintillation impact on GPS aviation.

IV. Operational Availability during a Severe Scintillation Period

This section discusses how the availability analysis was performed based on the real scintillation data. It provides hypothetical availability results of the Localizer Performance with Vertical Guidance (LPV)-200 [28], which is a form of vertical navigation, and the Required Navigation Performance (RNP)-0.1 [29], which is a form of horizontal navigation, for a single user at Ascension Island during the 45 minutes of severe scintillation. Reacquisition time and shortened carrier smoothing time (discussed in Section II) were modeled in the simulation. The availability results are represented as availability contours considering different reacquisition times and probabilities of loss of lock at deep fade.

A. Availability Simulation Procedure

The general procedure to simulate aviation availability is shown in Figure 4. In order to calculate the protection level which is a confidence bound on the position solution, satellite clock and ephemeris error, code noise and multipath, troposphere model, and satellite geometry need to be specified. Then the protection level is compared to the alert limit which is specified by the desired operation. If the protection level is smaller than the alert limit, GPS aviation is available. The simulation of this section uses a 1 m User Range Accuracy (URA) value, the iono-free dual frequency code noise and multipath model based on the WAAS MOPS, the troposphere model from the WAAS MOPS, and the real satellite constellation from the scintillation data. The protection level was calculated every second for the 45 minutes of severe scintillation. Operational availability of a single user at Ascension Island during the same period was obtained.

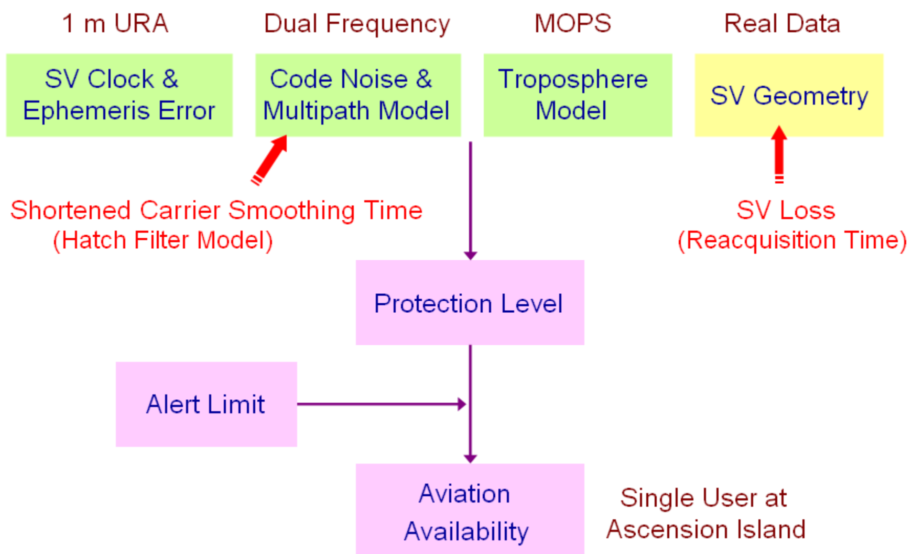

Fig. 4. Availability simulation procedure. 1 m user range accuracy, iono-free dual frequency code noise and multipath model, troposphere model from the WAAS MOPS, and real satellite constellation were used for the availability analysis. Satellite loss due to deep signal fading changes satellite geometry. Shortened carrier smoothing time due to frequent fadings increase code noise and multipath.

Since the simulation utilizes 1 m URA and the iono-free dual frequency model, the availability result of this section is valid under a future GPS Evolutionary Architecture Study (GEAS) configuration which can provide aviation integrity worldwide. Among the three architectures discussed in [30], Relative Receiver Autonomous Integrity Monitoring (RRAIM) may not be fully appreciated during severe scintillation periods of the equatorial region because RRAIM relies on continuous carrier phase measurements without cycle slips, which is not guaranteed under severe scintillation. The Global Navigation Satellite System (GNSS) Integrity Channel (GIC) architecture is assumed in our simulation, which means the integrity is assumed to be provided by separate WAAS-like channels.

Strong scintillation significantly reduces availability in two ways. First, satellite loss caused by deep fading changes satellite geometry. This effect is critical especially when multiple satellites are lost simultaneously. The duration of each satellite loss determines the probability of simultaneous losses. The outage duration depends on the receiver's reacquisition time. Longer reacquisition time results in worse satellite geometry and lower aviation availability. Another impact on availability is from shortened carrier smoothing time which leads to high code noise level. High code noise level caused by shortened carrier smoothing time was already explained in Section II (Figure 3). The Matlab Algorithm Availability Simulation Tools (MAAST) [31] was modified for this study to incorporate these scintillation effects.

B. Availability of Vertical Navigation (LPV-200)

Figure 5 shows the simulated Vertical Protection Level (VPL) during the 45 minutes of severe scintillation. The VPL of Figure 5 was obtained with the actual satellite geometry of the severe scintillation period, but scintillation effects such as satellite loss and shortened carrier smoothing time are not yet considered. This best case VPL, simulated without accounting for any scintillation effects, is always below the 35 m Vertical Alert Limit (VAL) of LPV-200 approach, so availability of LPV-200 during this period without scintillation effects would have been 100%. GPS and GIC can guide airplanes down to a 200-foot decision height in LPV-200.

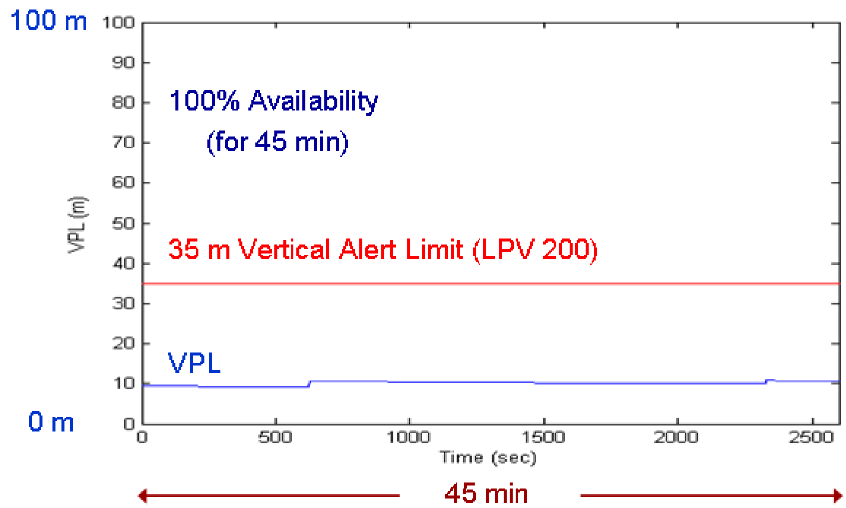

Fig. 5. Simulated vertical protection level without considering scintillation effects. The actual satellite geometry during the 45 minutes of severe scintillation at Ascension Island on 18 March 2001 was used for the VPL calculation.

However, if strong scintillation occurs, the VPL increases significantly as the lower plot of Figure 6 demonstrates. Deep and frequent signal fades of PRN 7 (the upper plot of Figure 6) are compared to high VPL values as an example. Only the effect of satellite loss is considered to calculate the VPL of Figure 6. The effect of shortened carrier smoothing time due to frequent fades is not yet considered.

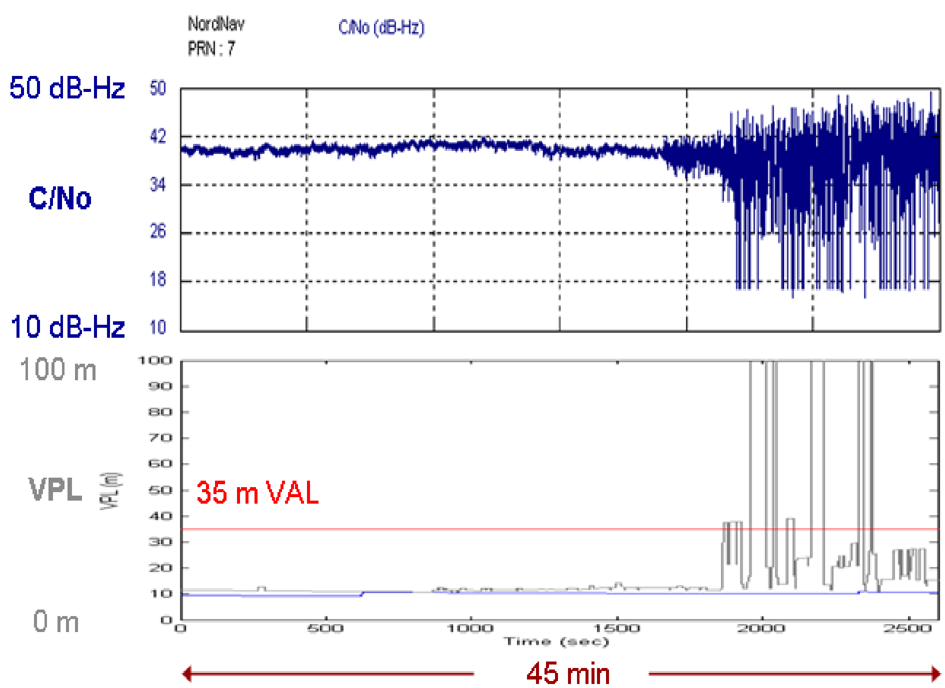

Fig. 6. C/N_0 and vertical protection level during the severe scintillation period considering satellite outages only. The longest allowable reacquisition time limit under the WAAS MOPS (20 seconds) was always assumed for VPL calculation. The effect of shortened carrier smoothing time is not yet considered.

When the effect of shortened carrier smoothing times due to frequent fades is also considered, the VPL values are further increased as shown in the green curve of Figure 7. Availability during the 45 minutes is only 89.3% in this case. The gray VPL curve of Figure 7, which is a zoomed-in plot from Figure 6, is also shown to illustrate the impact of the shortened carrier smoothing times of the Hatch filters on top of the impact of satellite outages in Figure 6.

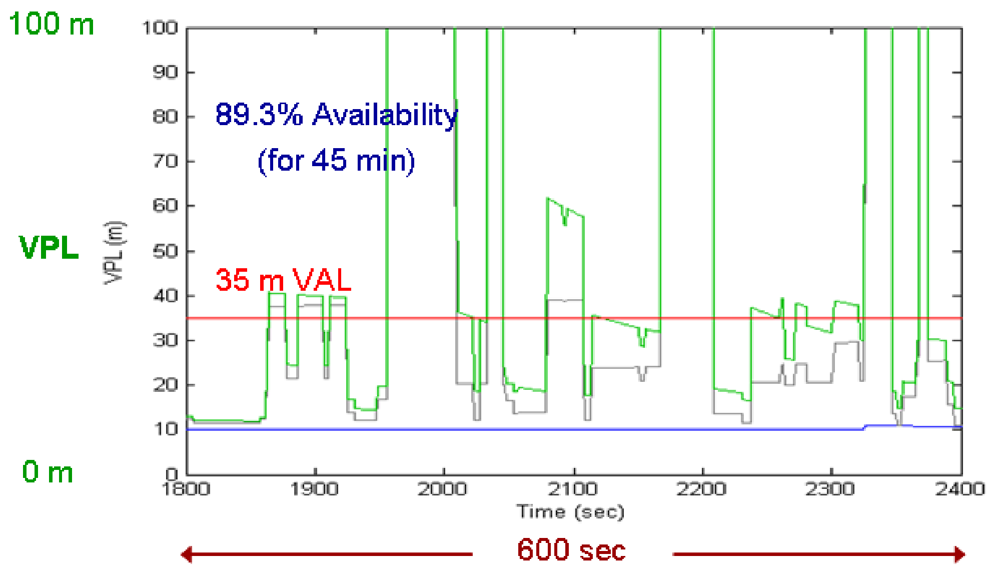

Fig. 7. Impact of shortened carrier smoothing times due to frequent fades (600 second example from the 45 minute data). The gray VPL curve was obtained after considering satellite outages only, but the green VPL curve considers effects from both satellite outages and shortened carrier smoothing times. A 20 second reacquisition time was assumed as in Figure 6.

Although shortened smoothing times increase the VPL further, the poor satellite geometry causes the high VPL spikes over 100 m in Figures 6 and 7. Hence, the impact of satellite geometry itself is most critical during strong scintillation. As already mentioned in Section II, the number of simultaneously lost satellites is strongly dependent on the receiver's reacquisition time. The VPL values of Figures 6 and 7 were obtained with the most conservative assumption of a 20 second reacquisition time which allows 20 second loss of a satellite after deep fading. A 20 second loss of lock after a deep fading is an allowable but pessimistic scenario under the current WAAS MOPS.

However, if a receiver can reacquire a lost channel quickly, for example within 1 second, it can achieve 99.9% availability for the same time period (Figure 8). The purple VPL curve of Figure 8 shows the case of 1 second reacquisition time. Note that this 99.9% availability was obtained after considering the effects from both satellite loss and shortened smoothing times based on the real scintillation data. If a 150 second time window of precision approach is considered, there could be continuity breaks due to high VPL spikes for a maximum of two approaches during these 45 minutes.

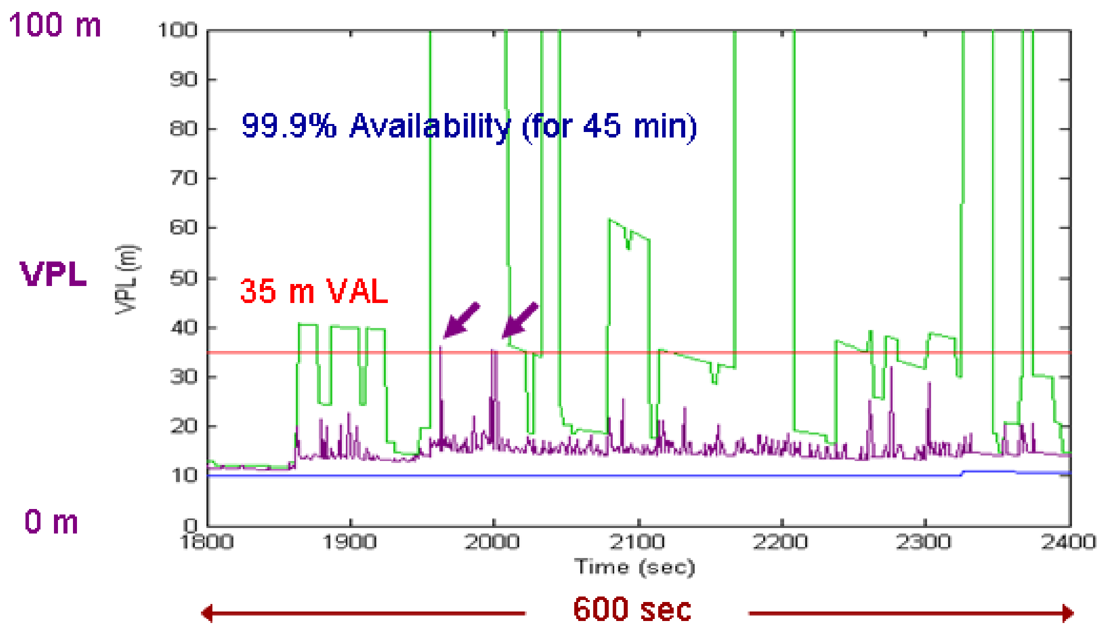

Fig. 8. Availability benefit of a shorter reacquisition time (1 second vs. 20 seconds). The green VPL curve assumes 20 second reacquisition time (the WAAS MOPS limit) and the purple VPL curve assumes 1 second reacquisition time. The figure shows the clear availability benefit of shorter reacquisition time for a receiver (600 second example from the 45 minute data).

This result demonstrates a clear availability benefit from mandating a shorter reacquisition time. The satellite geometry effect is the dominant effect for availability during strong scintillation at least with the GPS constellation of 2001. Shorter reacquisition time reduces the chance of simultaneous loss of satellites. Better satellite geometry results in higher availability even with the effect of the shortened carrier smoothing time of the Hatch filters.

The future constellations of GPS and Galileo (European satellite navigation system under development) are expected to alleviate the effect of loss of multiple satellites. For example, four satellites lost is critical if a receiver has only eight satellites in the sky, but it can be manageable if there are 16 satellites in the sky. However, the geometry of the scintillation patches should also be considered in this case. If the scintillation patches cover almost all of the sky as in Figure 2 of [21], 14 out of 16 satellites could be affected by scintillation and the benefit of dual constellations may not be fully realized.

Figures 7 and 8 showed VPLs and availabilities of LPV-200 with reacquisition times of 20 seconds and 1 second, respectively. The NordNav commercial software receiver was set up to maximize its tracking performance for processing the raw IF data collected at Ascension Island. With narrow tracking loop bandwidth and postprocessing, the receiver demonstrated very fast reacquisition after loss of lock due to deep fading, which may not be realized for a real-time receiver. Using the C/N_0 outputs from the NordNav receiver, a 20 second reacquisition time for Figure 7 was simulated by assuming that a generic aviation receiver does not retrack a lost satellite channel for 20 seconds after deep fading although the NordNav receiver does. A 1 second reacquisition time for Figure 8 was simulated in the same way. Similarly, VPLs and availabilities with other reacquisition times can also be obtained. The dependency of availability on a receiver's reacquisition time is shown in Figure 9. According to this figure, less than 1 second reacquisition time is required to achieve more than 99.9% availability during the severe scintillation period. The availability result of Figure 9 is based on a conservative assumption that a receiver loses lock with 100% probability whenever deep signal fading occurs.

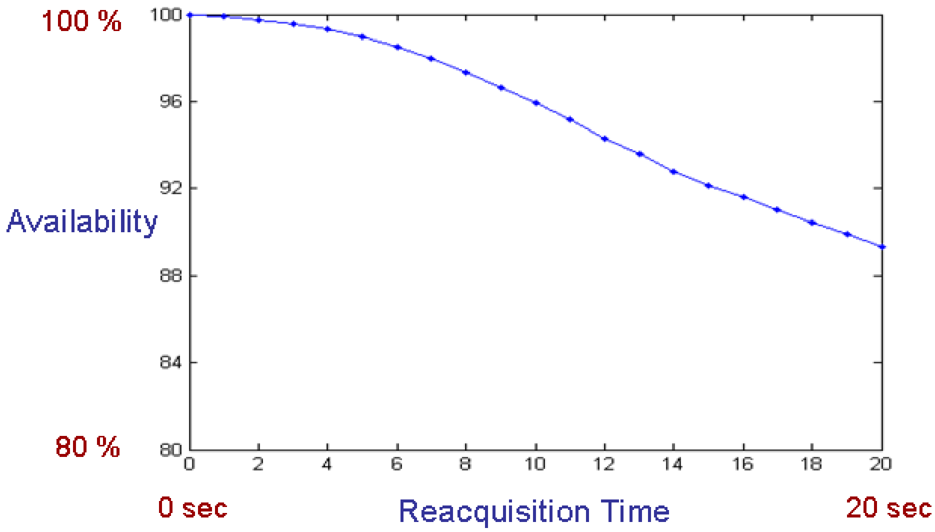

Fig. 9. Availability vs. reacquisition time. Operational availability for vertical navigation (LPV-200) during the 45 minutes is shown as a function of reacquisition time. Less than 1 second reacquisition time is required to have more than 99.9% availability. A receiver was assumed to lose lock with 100% probability at every deep fade.

Tracking loop performances of various receivers are very different depending on their designs and dynamic environments. The NordNav software receiver with narrow tracking loop bandwidth for this research loses lock at around 17--19 dB-Hz but typical receivers require 26--30 dB-Hz to maintain tracking lock [4]. The certified aviation receiver used for the Brazil campaign (explained in Section III) also tracked signal down to around 28--30 dB-Hz. Since an aviation receiver must track high vehicle dynamics, it cannot use a very narrow tracking loop bandwidth as a terrestrial software receiver can when it tracks stationary data.

As discussed in [21], the scintillation data for this research was collected in 2001 by an early IF capture technology. If current receiver technology with multi-bit sampling, wide bandwidth, better front end, and a better frequency plan is considered, about 8--10 dB improvement would be attainable (This is a rough estimate based on our observations). This means that a current aviation receiver would experience about 8--10 dB higher C/N_0 than what is shown here. C/N_0 of the upper plot of Figure 6 before scintillation is about 40 dB-Hz in the collected scintillation data, but after gaining 8--10 dB more, the C/N_0 value would be similar to the normally expected C/N_0 level (46.5 dB-Hz and can be 6 dB higher in reality [4]) for L1 signal given a typical noise floor. Note that several dB difference in C/N_0 can be caused by satellite elevations and transmitting power of a particular satellite.

Remember that there is no available scintillation data from the past solar maximum collected with a certified aviation receiver. In order to deduce performance of a certified aviation receiver during next solar maximum from the raw IF data from the past solar maximum, a deep fading causing loss of lock in this paper is defined as a fading that results in minimum C/N_0 of 20 dB-Hz or less. If 8--10 dB possible improvement from the current technology is considered, the fadings with a minimum of 20 dB-Hz or less from the data collected in 2001 would be comparable to fadings with a minimum of 28--30 dB-Hz or less in 2009, where the certified aviation receiver lost tracking. Although this definition of deep fading can make a connection between previously collected data and expected performance of an aviation receiver for next solar maximum, another data collection campaign with a certified aviation receiver should be performed during the next solar maximum to provide higher confidence.

Because of the uncertainties from receiver sensitivity, C/N_0 improvement from current technology, and actual fading depth, the exact probability of loss of lock of an aviation receiver at deep fade is not obtainable from the given data. Alternatively, we assumed the most conservative scenario first (100% probability of loss of lock at deep fade) for Figures 6 through 9. We repeated simulations with different probabilities of loss of lock (every 10%, from 0% to 100%). Another dimension of the simulation space is the reacquisition times (every second, from 0 second to 20 seconds). The results are shown as a contour plot in Figure 10. The plot confirms the intuitive result that shorter reacquisition time and lower probability of loss of lock at deep fade result in better availability. In addition to this qualitative expression, the plot quantitatively shows availability levels during the worst 45 minutes according to different reacquisition times and probabilities of loss of lock. The result from the most conservative assumption of 100% probability of loss of lock at deep fade (Figure 9) is still meaningful as a lower bound of availability during the severe scintillation.

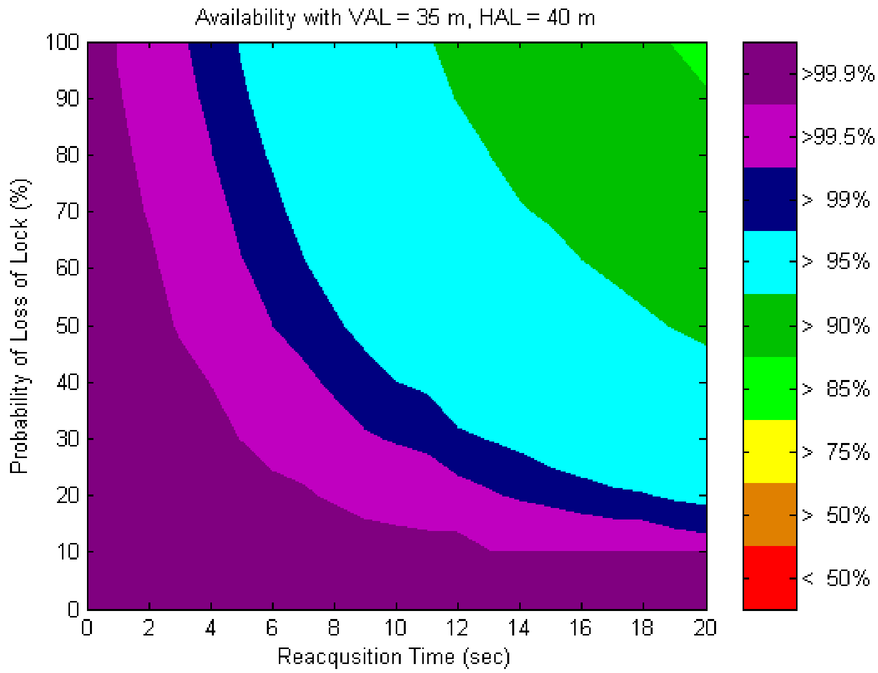

Fig. 10. Availability contour for vertical navigation (LPV-200) during the 45 minutes of severe scintillation. The color represents operational availability at every combination of probability of loss of lock and reacquisition time. 35 m vertical alert limit and 40 m horizontal alert limit for LPV-200 are used for the simulation.

C. Availability of Horizontal Navigation (RNP-0.1)

The procedures to simulate availability under scintillation and the effects of satellite loss and shortened smoothing times of Hatch filters on availability were already discussed. The availability contour for LPV-200 (Figure 10) is useful to illustrate operational availabilities during the severe scintillation period according to two parameters which are probability of loss of lock at deep fade and reacquisition time of a receiver after loss of lock. Similarly, the availability contour for horizontal navigation (RNP-0.1) was generated as seen in Figure 11. A 185 m Horizontal Alert Limit (HAL) for RNP-0.1 was used for this analysis.

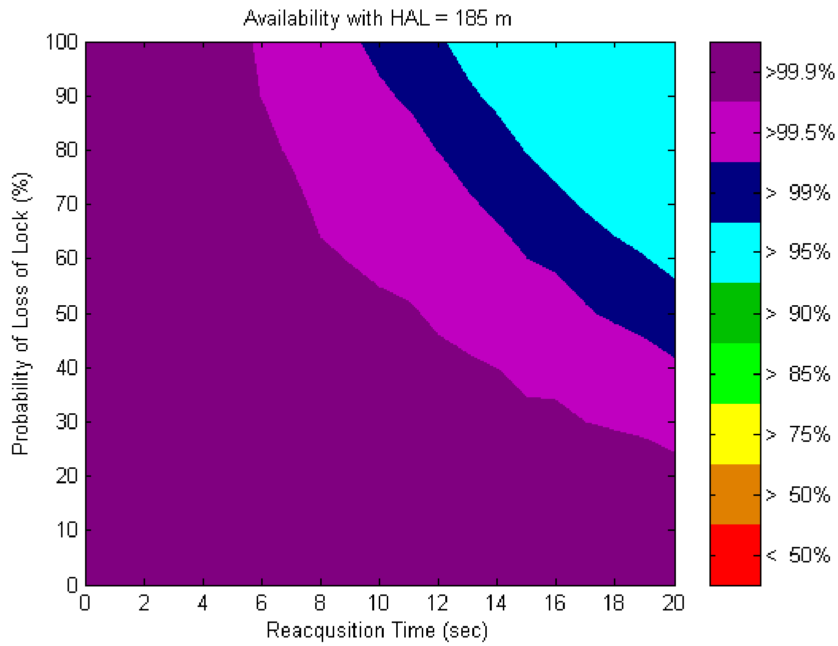

Fig. 11. Availability contour for horizontal navigation (RNP-0.1) during the 45 minutes of severe scintillation. The color represents operational availability at every combination of probability of loss of lock and reacquisition time. 185 m horizontal alert limit for RNP-0.1 is used for the simulation.

Availability of RNP-0.1 is considerably better than the availability of LPV-200 as expected. Even with the worst-case assumption of 20 second reacquisition time and 100% probability of loss of lock at deep fade, a 97.5% availability is achieved as seen in Figure 12. The high Horizontal Protection Level (HPL) spikes exceeding HAL are due to very poor satellite geometry. Many satellites are lost simultaneously if a receiver takes 20 seconds to reacquire each lost channel. As a result, the receiver cannot always track the minimum of four satellites required to form a position solution. When this occurs the HPL becomes infinite. However, if a receiver reacquires a lost channel within 4 seconds, it always tracks more than or equal to four satellites and achieves 100% availability even with the most conservative assumption of 100% probability of loss of lock. Note that increased noise level due to shortened carrier smoothing time is not critical for horizontal navigation, but satellite geometry is paramount. Therefore, fast reacquisition capability to guarantee a good geometry is highly desired to provide high availability during severe scintillation.

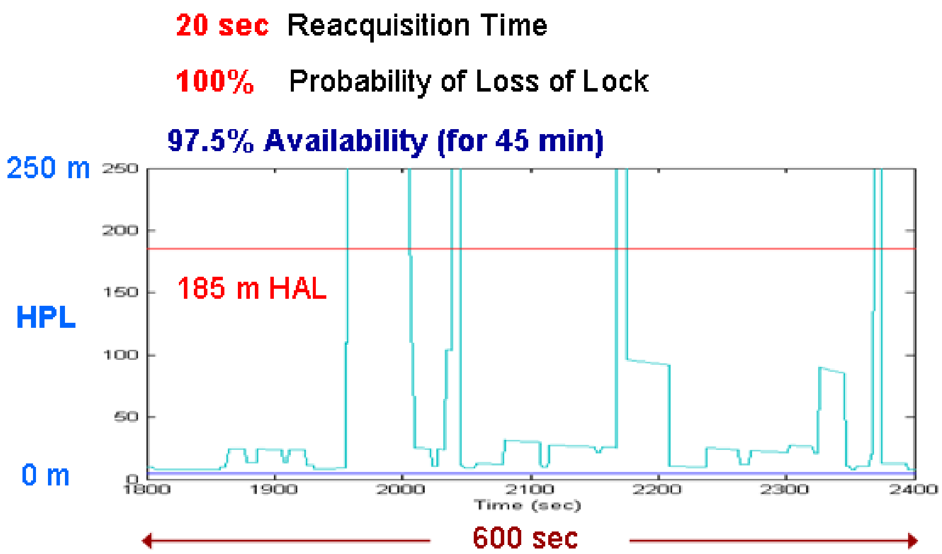

Fig. 12. Horizontal protection level during the severe scintillation (600 second example from the 45 minute data). Even with the most conservative assumptions about reacquisition time and probability of loss of lock, operational availability for RNP-0.1 during the 45 minutes is 97.5%.

V. Suggestion for the WAAS MOPS

Figure 11 shows that a 5 second reacquisition time gives more than 99.9% availability for RNP-0.1 during the severe scintillation, but Figure 10 shows that less than 1 second reacquisition time is required for 99.9% availability for LPV-200. As mentioned in Section II, the WAAS MOPS mandates that aviation receivers reacquire a lost channel within 20 seconds after signal comes back. It is evident that shorter reacquisition time is better, but it cannot be arbitrarily short. A reasonable suggestion for the reacquisition time limit under current receiver technology could be obtained by observing performance of a certified aviation receiver during scintillation.

As mentioned in Section III, a certified WAAS receiver was deployed during the Brazil campaign. Although the campaign was performed during a solar minimum period, strong scintillation was sometimes observed. During the 36-day campaign, the certified WAAS receiver always satisfied the 20 second reacquisition time limit of the WAAS MOPS. There was one case of 20 second loss of a satellite but the certified receiver reacquired the lost channels within 1--2 seconds for 91% of the cases (Figure 13). From this observation, we know that a certified aviation receiver is capable of performing much better than the WAAS MOPS requirement. The 20 second limit of the WAAS MOPS can, in principle, be reduced under current technology.

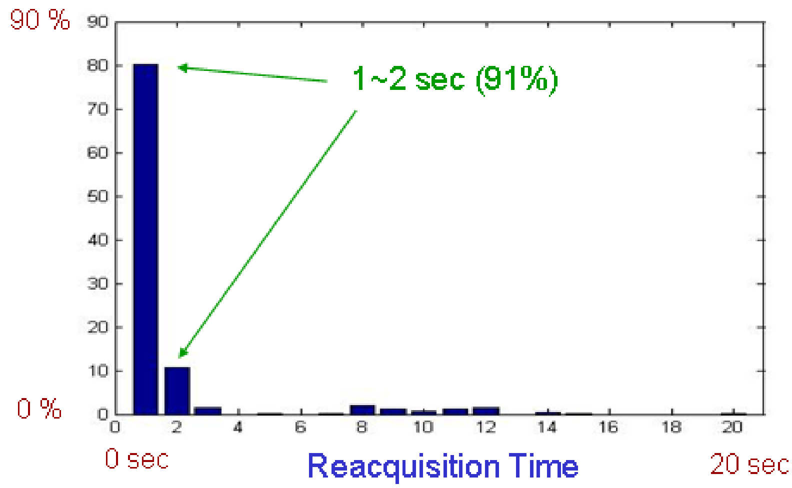

Fig. 13. Observed reacquisition times of a certified WAAS receiver during the 36-day campaign in Brazil. The performance was much better than the WAAS MOPS requirement (20 second limit).

In fact, the current WAAS MOPS addresses scintillation in the following statement, "There is insufficient information to characterize scintillation and define appropriate requirements and tests for inclusion in this MOPS. … New requirements may be defined when ionospheric effects can be adequately characterized [13]." Based on the study of this paper, we suggest mandating a shorter reacquisition time in the next version of the WAAS MOPS.

Using a moderate reacquisition time limit of 5 seconds, which is already almost satisfied by the certified receiver, RNP-0.1 navigation would be possible even during severe scintillation. A more aggressive limit of 1 second, which may be realized by a traditional receiver design or a novel design such as Doppler aiding [32] or vector phase lock loops [33], could provide LPV-200 with enough availability during severe scintillation. Note that the observation of Figure 13 was from a solar minimum period. Although 1 second reacquisition time limit is not far from the performance of Figure 13, there is no real performance data from an aviation receiver under the frequent fadings of solar maximum. The solar maximum data of this study demonstrates 5 second median time between fades.

Under this stressing case, the aviation receiver may take a longer time than Figure 13 to reacquire lost channels, which should be validated in the next solar maximum.

VI. Conclusion

This paper analyzed operational availabilities of vertical navigation (LPV-200) and horizontal navigation (RNP-0.1) at Ascension Island during a severe scintillation period of the past solar maximum. Seven out of eight satellites were affected by scintillation during the worst 45 minutes, which represents severe scintillation. The achievable availability level was illustrated as a function of reacquisition time of a receiver and probability of loss of lock at deep fade.

A generic aviation receiver just complying with the WAAS MOPS requirement does not necessarily provide high availability during severe scintillation. In order to achieve high availability, a receiver should reacquire lost channels within 1--2 seconds. Since the certified WAAS receiver used in the campaign outperforms the WAAS MOPS requirement, the receiver is expected to provide high availability for RNP-0.1 during the next solar maximum. However, LPV-200 would be still challenging under severe scintillation.

The current WAAS MOPS does not have a specific performance requirement for an aviation receiver under scintillation. Based on limited information from the past solar maximum and observed performance of a certified receiver during solar minimum, the authors recommend a shorter reacquisition time limit for the next version of the WAAS MOPS. With this modification, a generic aviation receiver complying with the WAAS MOPS should provide enough availability for horizontal navigation even during severe scintillation. With a reacquisition time of 2 seconds or less, LPV-200 should also have good availability during severe scintillation. Novel receiver technologies such as Doppler aiding or vector phase lock loops, which prevent loss of lock or promptly reacquire lost channels, will better guarantee LPV-200 under severe scintillation with high availability.

Acknowledgement

The authors gratefully acknowledge the Federal Aviation Administration (FAA) CRDA 08-G-007 for supporting this research and Theodore Beach, AFRL, and Eurico de Paula, INPE, for providing the data sets. The opinions discussed here are those of the authors and do not necessarily represent those of the FAA or other affiliated agencies.

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