Evaluation of Deep Signal Fading Effects Due to Ionospheric Scintillation on GPS Aviation Receivers

Jiwon Seo, Todd Walter, Tsung-Yu Chiou, Juan Blanch, and Per Enge

Stanford University

BIOGRAPHY

Jiwon Seo is a Ph.D. candidate in Aeronautics and Astronautics at Stanford University. He received his B.S. in Aerospace Engineering from KAIST (Korea Advanced Institute of Science and Technology) and received M.S. degrees in Aeronautics and Astronautics, Electrical Engineering from Stanford. He was a recipient of Samsung Lee Kun Hee Graduate Fellowship for five years. His current research focuses on aircraft navigation using GPS and WAAS under severe ionospheric scintillation of the equatorial region.

Todd Walter is a Senior Research Engineer in the Department of Aeronautics and Astronautics at Stanford University. Dr. Walter received his Ph.D. in 1993 from Stanford and works on developing WAAS integrity algorithms and analyzing the follow on systems to WAAS. He is a fellow of the ION.

Tsung-Yu Chiou is a Ph.D. candidate in the Aeronautics and Astronautics Department at Stanford University. He received his B.S. in Aerospace Engineering in 1998 from Tamkang University, Taiwan and his M.S. from Stanford in 2002. His research currently focuses on the performance analysis and validation of Doppler-aided GPS carrier-tracking loops. He is also looking into the solutions to the problem of GPS/WAAS performance degradation caused by ionospheric scintillation.

Juan Blanch graduated from Ecole Polytechnique, France in 1999. He holds an M.S. in Aeronautics and Astronautics (2000), an M.S. in Electrical Engineering (2003) and a Ph.D. in Aeronautics and Astronautics (2003) from Stanford University. He received the 2004 Bradford W. Parkinson Award for Graduate Student Excellence in GNSS for his doctoral dissertation. He is currently a Research Associate in the Stanford GPS laboratory, where he works on the design of integrity algorithms for the Wide Area Augmentation System. He is an active member of the WAAS Integrity Performance Panel and the GPS Evolutionary Architecture Study. His research interests include: high integrity estimation of ionospheric delays for GNSS, Receiver Autonomous Integrity Monitoring algorithms, and next generation SBAS algorithms.

Per Enge is a Professor of Aeronautics and Astronautics at Stanford University, where he is the Kleiner-Perkins, Mayfield, Sequoia Capital Professor in the School of Engineering. He is also the Director of the GPS Research Laboratory, which works with the Federal Aviation Administration, U.S. Navy and U.S. Air Force to pioneer systems that augment the Global Positioning System (GPS). Prof. Enge has received the Kepler, Thurlow and Burka Awards from the Institute of Navigation for his work. He is a Member of the National Academy of Engineering (NAE), a Fellow of the ION, and a Fellow of the IEEE.

ABSTRACT

Deep and frequent GPS signal fading due to strong ionospheric scintillation is major concern for aircraft navigation in the equatorial region during solar maximum periods. Deep signal fading can break a receiver's carrier tracking lock on a satellite channel and the satellite cannot be used for position solution until a receiver reacquires the lost channel. Frequent signal fading also causes frequent reset of the carrier smoothing filter of aviation receivers. Aviation receivers reduce code noise by as much as a factor of 10 by using carrier smoothing, but frequent loss of lock reduces the effective smoothing time and significantly increases the effect of code noise.

This paper analyzes navigation availability during a strong scintillation period based on real scintillation data from the previous solar maximum. Both effects from satellite loss due to deep fading and shortened carrier

Institute of Navigation GNSS 2008
16-19 September 2008, Savannah, GA

smoothing time due to frequent fading are considered for the availability simulation.

The strong scintillation data for this research was collected in 2001 with early IF (Intermediate Frequency) capture technology. This paper discusses possible C/No (carrier to noise density ratio) increases through improved receiver technology. C/No gain reduces a receiver's probability of loss of lock in the scintillation environment. Various probabilities of loss of lock are considered for the availability simulation in order to assess the benefit of a current receiver technology during strong scintillation.

Availability results for vertical navigation (LPV 200) and horizontal navigation (RNP 0.1) during strong scintillation are illustrated as availability contours and the clear benefit of shorter reacquisition time is emphasized. Finally, a change of reacquisition time limit of the current WAAS MOPS (Minimum Operational Performance Standards) [1] is recommended based on the availability simulation results and observed reacquisition times of a certified WAAS receiver for 36 days in Brazil.

INTRODUCTION

Ionospheric scintillation [2] due to electron density irregularities inside ionosphere causes deep transionospheric signal fading. Carrier to noise density ratio (C/No) of received GPS signal remains almost constant when scintillation is not present as in the upper plot of Figure 1. However, if strong scintillation is present, C/No fluctuates rapidly and fades of more than 25 dB can occur as in the lower plot of Figure 1. These deep signal fadings, which are commonly observed during solar maximum in the equatorial region [3, 4], can cause the receiver's carrier tracking loop to lose lock. Since aviation receivers use both code and carrier information to calculate position solutions, carrier lock loss can be effectively considered as satellite loss. Frequent 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 form a solution.

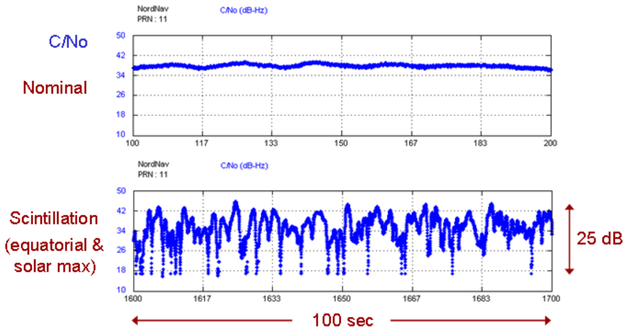

Figure 1. Example of Deep Signal Fading due to Ionospheric Scintillation [5]

According to a 36 days' campaign in Brazil, one or two satellites were affected by scintillation during solar minimum period [6]. With the given satellite geometry, one or two satellite loss for small fraction of time is not a critical problem for GPS navigation. However, previous solar maximum data shows up to seven satellites were affected by scintillation at the same time (Figure 2). This paper analyzes navigation availability during this severe scintillation period and suggests a way to mitigate the impact of scintillation on navigation.

SCINTILLATION AND NAVIGATION

This section explains the strong scintillation data used for this research and how deep and frequent signal fading affects navigation availability. Satellite loss due to deep fading adversely affects satellite geometry and navigation availability. High noise levels of pseudorange estimates due to shortened carrier smoothing time caused by frequent fading further reduces availability.

Strong Scintillation Data

The scintillation data for this paper was collected at Ascension Island in 2001 and Dr. Theodore Beach of AFRL (Air Force Research Laboratory) provided the data set. [7] has detailed information of the DSR-100 receiver used for the campaign. The raw IF data from DSR-100 was processed by a NordNav commercial software receiver [8] and 50 Hz outputs from NordNav were used for this research.

The worst 45 minutes' data, which was from 8:45 PM to 9:30 PM on March 18, 2001 (UTC, also local time), from a 9 days' campaign at Ascension Island was selected based on S4 index. During this worst 45 minutes, 7 out of 8 satellites were affected by scintillation (Figure 2). Scintillation patches covered a large portion of sky. This situation can create a low availability of GPS navigation. Although 7 satellites were fading in this example, it does not necessarily mean all 7 satellites were lost simultaneously. If a receiver quickly reacquires lost channels, it can reduce chance of simultaneous losses and scintillation impact on navigation.

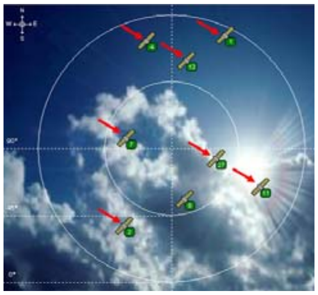

Figure 2. Satellites Affected by Scintillation during the Worst 45 Minutes [5]

Simultaneous Loss of Satellites and Reacquisition Time

For forming a GPS navigation solution, the number of simultaneous loss of satellites is more meaningful than number of fading channels. Signal fadings of different satellite channels do not usually occur at the exact same time (Figure 3 of [5]). Hence, if a receiver can reacquire lost channel before it loses other channels, it can avoid simultaneous losses and consequently reduce the impact of scintillation on navigation.

The WAAS MOPS [1] has specific requirement about reacquisition time of aviation receivers. The current WAAS MOPS says "… signal outages of 30 seconds or less … the equipment shall reacquire the satellite within 20 seconds ….", which means satellite loss after deep signal fading is allowable up to 20 seconds. This paper analyzes the effect of this requirement on navigation performance under strong scintillation in the equatorial region.

Hatch Filter Model and Carrier Smoothing Time

Aviation receivers use Hatch filters [9] to reduce the effect of the noise level of code measurements. The filter smoothes code measurements with 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 the noise is uncorrelated from one second to the next. Under nominal condition as in Figure 3, the effect of code noise exponentially decreases [10] with a 100 second time constant by Hatch filtering and converges to floor level after couple of hundred seconds. White nose can be reduced by factor of 10 by this carrier smoothing technique.

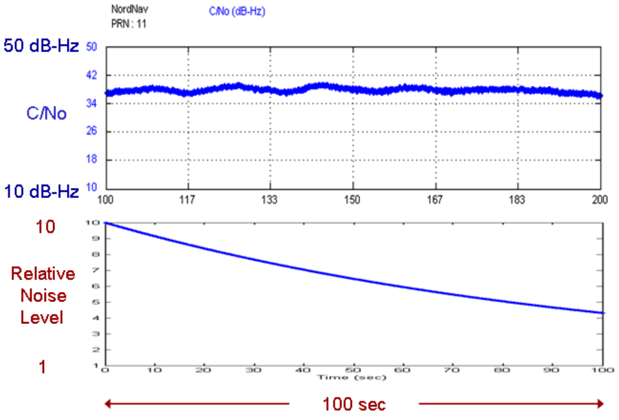

Figure 3. Decreasing Code Noise by Hatch Filtering under Nominal Condition

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 approximately 10 times higher than the floor level. For the availability simulation of this research, the relative noise level of code measurements is modeled as $9e^{-\frac{t}{100}}+1$, where t is carrier smoothing time after reacquisition. 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, t, is zero and converges to 1 if a receiver does not lose lock for couple of hundred seconds. Strong scintillation causes frequent loss of lock and prevents Hatch filter from converging (Figure 4). This higher noise level reduces navigation availability. Previous research showed that the median time between deep fades during the 45 minutes of string scintillation was only 5 seconds which is very short compared to the 100 second smoothing time constant [5].

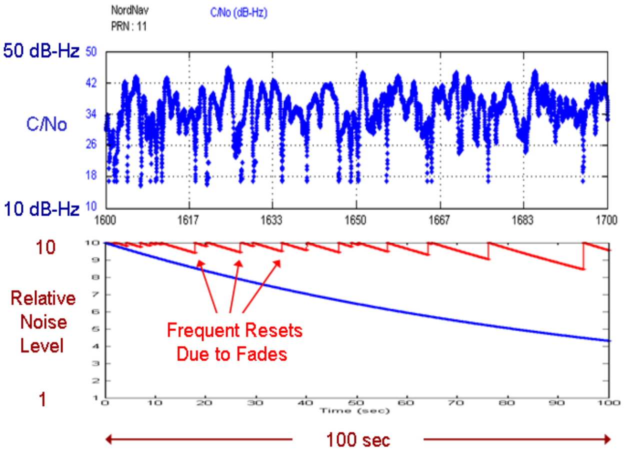

Figure 4. Frequent Reset of Hatch Filter and High Code Noise Level during Strong Scintillation

NAVIGATION AVAILABILITY DURING STRONG SCINTILLATION

This section discusses how the availability simulation was performed using the real scintillation data and shows the availability results for a single user at Ascension Island for both vertical navigation (LPV 200) and horizontal navigation (RNP 0.1) during the 45 minutes of strong scintillation. Reacquisition time and shortened carrier smoothing time discussed in the previous section were modeled in the simulation. The availability results are represented as availability contours considering different reacquisition times and probabilities of loss of lock during deep fades.

Availability Simulation Procedure

The general procedure to simulate navigation availability is shown in Figure 5. 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 navigation is available.

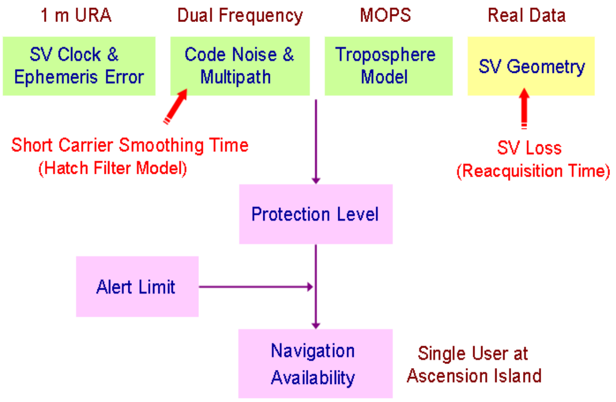

Figure 5. Availability Simulation Procedure

The simulation of this paper uses a 1 m URA (User Range Accuracy) 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 at every second for the 45 minutes of strong scintillation and availability of a single user at Ascension Island during the same period was obtained.

Strong scintillation significantly reduces availability in two ways. 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 poor navigation availability. Another impact on availability is from shortened carrier smoothing time. High noise levels caused by frequent deep fades were explained in the previous section (Figure 4).

Availability of Vertical Navigation (LPV 200)

Figure 6 shows simulated Vertical Protection Level (VPL) during the 45 minutes of strong scintillation. The VPL was obtained with the actual satellite geometry of the real scintillation data, but scintillation effects such as satellite loss and short smoothing time were not considered. This best case VPL, simulated without accounting for any scintillation effects is always below than 35 m Vertical Alert Limit (VAL) of LPV (Localizer Performance with Vertical guidance) 200 approach, so availability of LPV 200 during this period without scintillation effects would have been 100%. GPS and WAAS can guide airplanes down to 200 feet decision height in LPV 200 approach.

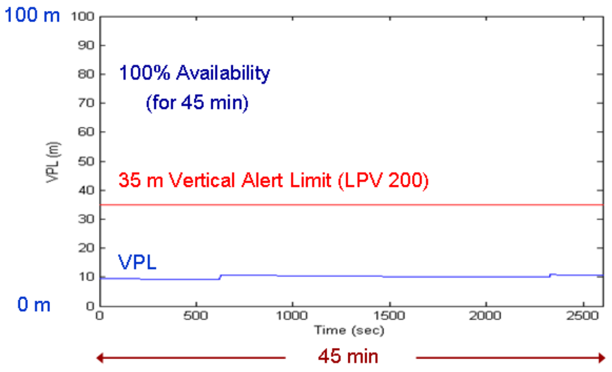

Figure 6. Vertical Protection Level without any Scintillation Effects

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

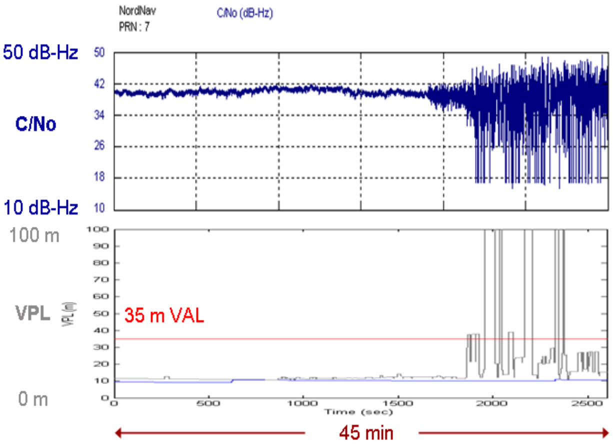

Figure 7. C/No and Vertical Protection Level during Strong Scintillation Considering only Satellite Outages

When the effect of shorter carrier smoothing times is also considered, the VPL values are further increased as shown in the green curve of Figure 8. The availability during the 45 minutes dataset is only 89.3%. The gray VPL curve of Figure 8, which is a zoomed-in plot from Figure 7, is also shown to illustrate the impact of the shortened carrier smoothing times of the Hatch filters.

Although shorter smoothing times increase the VPL further, the poor satellite geometry causes the high VPL spikes over 100 m in Figures 7 and 8. Hence, the impact of satellite geometry itself is most critical during strong scintillation. As already mentioned, the number of simultaneously lost satellites is strongly dependent on the receiver's reacquisition time. The VPL values of Figures 7 and 8 were obtained with the assumption of 20 second reacquisition time which means 20 second loss of a satellite after deep signal fading. This is an allowable but pessimistic scenario under the current WAAS MOPS.

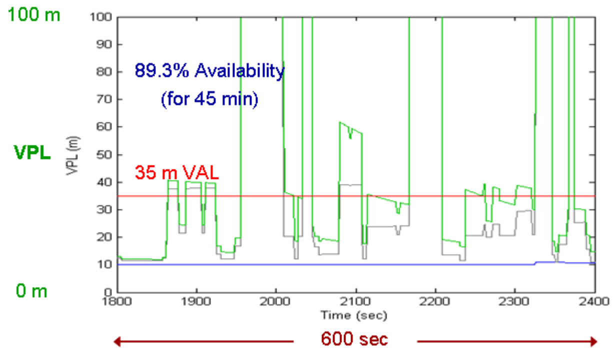

Figure 8. Impact of Short Carrier Smoothing Time Due to Frequent Fades

However, if a receiver can reacquire a lost channel within 1 second, it can achieve 99.9% availability for the same time period (Figure 9). The purple VPL curve of Figure 9 shows the case of 1 second reacquisition time. Note that this 99.9% availability was obtained after considering both effects from satellite loss and shortened carrier smoothing times based on the real scintillation data. If 150 second time window of precision approach is considered, there could be continuity breaks due to high VPL spikes for maximum of two approaches during these 45 minutes.

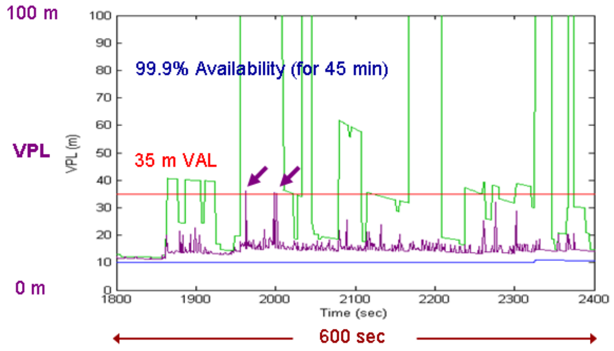

Figure 9. Availability Benefit of Shorter Reacquisition Time (20 sec vs. 1 sec)

This result demonstrates a clear availability benefit of mandating a shorter reacquisition time. Shorter reacquisition time reduces 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. Therefore, the satellite geometry effect is the dominant effect for availability during strong scintillation at least with the GPS constellation of 2001.

The future constellations of GPS and Galileo are expected to alleviate the effect of loss of multiple satellites. For example, 4 satellites loss is critical if a receiver has only 8 satellites in the sky but it can be manageable if there are 16 satellites in the sky. 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, 14 out of 16 satellites could be affected by scintillation and benefit of dual constellations may not be realized.

The dependency of availability on various reacquisition times is shown in Figure 10. According to this figure, less than 1 second reacquisition time is required to achieve more than 99.9% availability during the strong scintillation period.

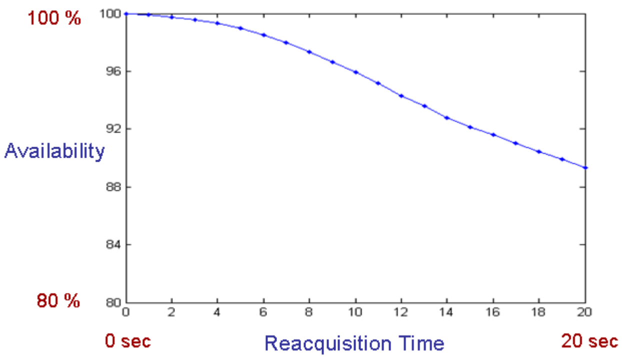

Figure 10. Availability vs. Reacquisition Time

The availability result of Figure 10 is based on the assumption that a receiver loses lock with 100% probability whenever deep signal fading occurs. Deep fading of this paper is defined as a fading with minimum C/No of 20 dB-Hz or less because the NordNav software receiver loses lock in this case. 100% probability of loss of lock at every deep fade is definitely a conservative assumption.

The scintillation data for this research was collected in 2001 by early technology that had limitations such as 1 bit sampling, narrow bandwidth, and aliasing due to low sampling frequency. However, a current receiver with multi-bit sampling, wide bandwidth, better front end, and a better frequency plan can experience higher C/No in the same scintillation environment. Through observation of the NordNav receiver, about 8 dB improvement is attainable with current receiver technology. The NordNav receiver achieves up to 50 dB-Hz when it processes normal data collected with NordNav IF recorder but it only achieves about 42 dB-Hz with the scintillation data collected with the DSR-100.

After gaining 8 dB, a receiver may not lose lock at the same fading depending on actual fading depth. It is hard to quantify fading depth from the scintillation data because a receiver cannot track carrier below a certain C/No threshold. A receiver would need to track the carrier even at the lowest C/No of a fading in order to know the actual fading depth. For example, the fading depth of Figure 11 is at least 25 dB but could be much worse. Because of the uncertainty from actual fading depth and possible C/No improvement, a probabilistic approach was favored in this paper. It is evident that probability of loss of lock at deep fades will be lower than 100% after 8 dB improvement.

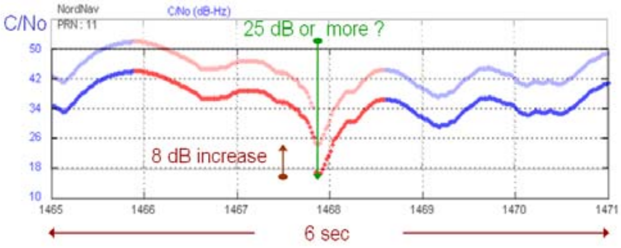

Figure 11. Possible C/No Improvement by Current Receiver Technology

The availability simulation was repeated with different probabilities of loss of lock (every 10% from 0% to 100%) and various reacquisition times (every second from 0 second to 20 seconds) and the results are shown as a contour plot (Figure 12). The plot confirms the intuitive result that shorter reacquisition times and lower probability of loss of lock at deep fades result in better availability. In addition to this qualitative expression, the plot quantitatively shows availability level during the worst 45 minutes according to different reacquisition times and probabilities of loss of lock.

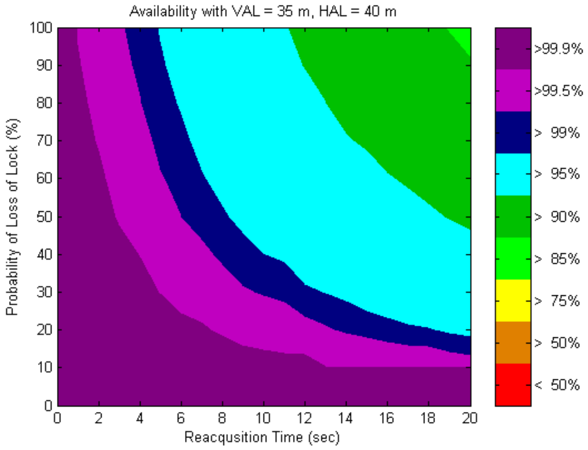

Figure 12. Availability Contour for Vertical Navigation (LPV 200) during Strong Scintillation

As already mentioned, an increased C/No by current receiver technology results in a lower probability of loss of lock at deep fades. If a receiver has 30% chance of loss of lock, a 4 second reacquisition time achieves more than 99.9% availability. Figure 13 is a VPL plot of this case versus time. Although a lower probability of loss of lock can relax reacquisition time limit, the probability depends on actual fading depth which is unknown. Hence, the result from the most conservative assumption of 100% probability of loss of lock at deep fades is still meaningful as a lower bound of availability during strong scintillation.

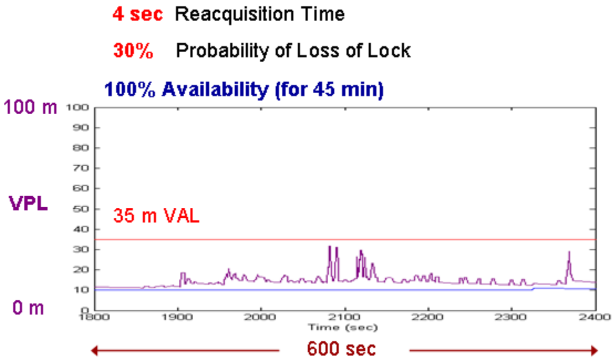

Figure 13. Vertical Protection Level with 30% Probability of Loss of Lock at Deep Fades

Availability of Horizontal Navigation (RNP 0.1)

The procedures to simulate availability and the effects of satellite loss and shortened carrier smoothing times of Hatch filters were discussed in the previous session. The availability contour for LPV 200 (Figure 12) was useful to illustrate impact of reacquisition time and probability of loss of lock at deep fades. Similarly, the availability contour for horizontal navigation (RNP 0.1) was generated as seen in Figure 14. A 185 m HAL (Horizontal Alert Limit) for RNP (Required Navigation Performance) 0.1 was used for this simulation.

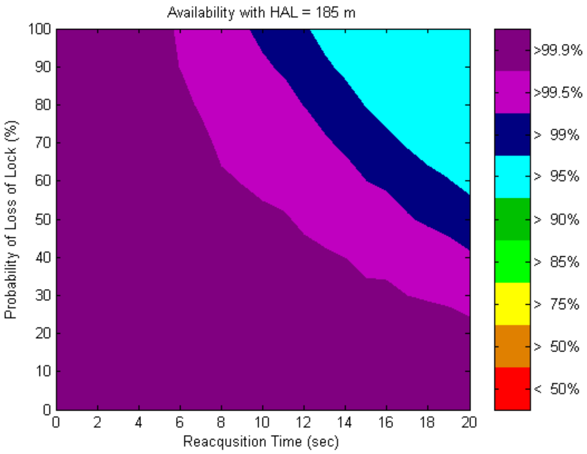

Figure 14. Availability Contour for Horizontal Navigation (RNP 0.1) during Strong Scintillation

Availability of RNP 0.1 is considerably better than 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 fades, a 97.5% availability is achieved as seen in Figure 15. The high HPL (Horizontal Protection Level) spikes exceeding HAL are due to 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 4 satellites required to form a position solution. When this occurs the HPL becomes infinite.

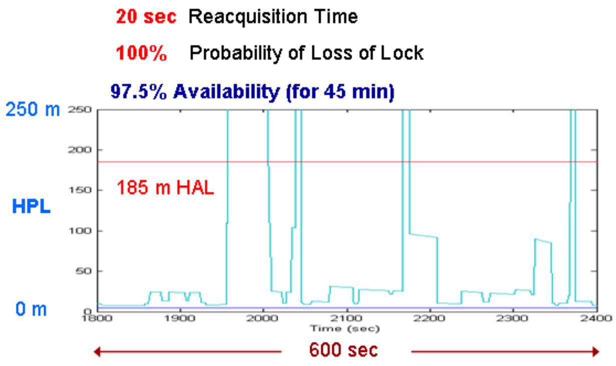

Figure 15. Horizontal Protection Level during Strong Scintillation

However, if a receiver reacquires a lost channel within 4 seconds, it always tracks more than or equal to 4 satellites and achieves 100% availability even with the most conservative assumption of 100% probability of loss of lock at every deep fade (Figure 16).

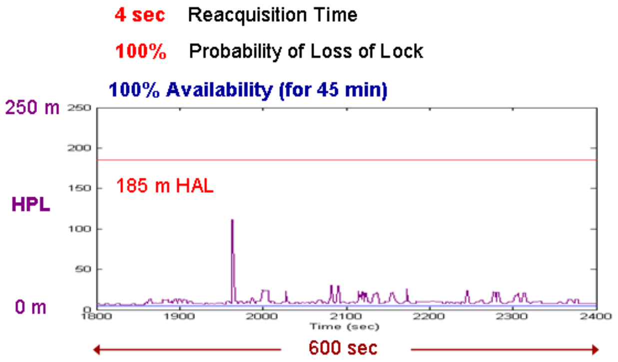

Figure 16. Horizontal Protection Level with 4 Second Reacquisition Time

Observed Reacquisition Times of a Certified WAAS Receiver

It was shown as an example that a 4 second reacquisition time gives 100% availability for RNP 0.1 during the 45 minutes of strong scintillation (Figure 16). Now it would be helpful to discuss if this 4 second reacquisition time limit is reasonable with current receiver technology.

According to a 36 days' campaign in Brazil from December 2005 to January 2006, a certified WAAS receiver always satisfied 20 second reacquisition time limit of the current 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 17). Hence, performance of a certified WAAS receiver is much better than the WAAS MOPS requirement. From this observation, it is evident that shorter reacquisition time is attainable with current technology and the 20 second limit of the WAAS MOPS can, in principle, be reduced. In fact, the previous WAAS MOPS [11] had 10 second reacquisition time limit but it was changed to 20 seconds for the most recent WAAS MOPS.

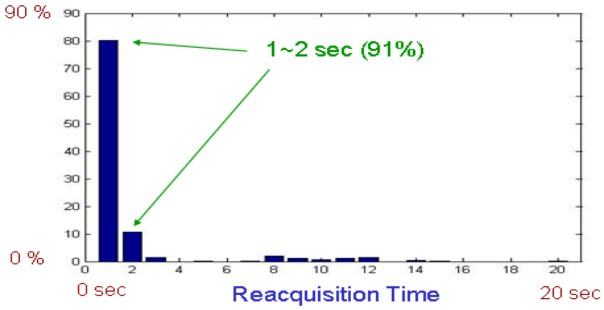

Figure 17. Observed Reacquisition Times of a Certified WAAS Receiver [6]

CONCLUSION

This paper analyzed availabilities of vertical navigation (LPV 200) and horizontal navigation (RNP 0.1) at Ascension Island during a strong scintillation period of the pervious solar maximum.

It was discussed that a generic aviation receiver just complying with the current WAAS MOPS requirement does not necessarily provide high availability during strong scintillation. In order to achieve high availability, a receiver should reacquire lost channels within reasonably short time.

This paper predicts with limited information from the previous solar maximum that RNP 0.1 navigation would not be a problem even during strong scintillation, if the reacquisition time limit is reduced, and availability of vertical navigation will be improved. This paper also predicts based on the observed performance that a certified WAAS receiver currently in use would provide enough availability for RNP 0.1 during strong scintillation because it outperforms the WAAS MOPS requirement.

ACKNOWLEDGMENTS

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

REFERENCES

[1] RTCA, Inc., *Minimum Operational Performance Standards for Global Positioning System/Wide Area Augmentation System Airborne Equipment*, RTCA DO-229D, December 13, 2006.

[2] R. Crane, *Ionospheric Scintillation*, Proceedings of the IEEE, Vol. 65, No. 2, February 1977.

[3] S. Basu and S. Basu, *Equatorial Scintillations - A Review*, Journal of Atmospheric and Terrestrial Physics, Vol. 43, No. 5, June 1981.

[4] J. Aarons, *Global Morphology of Ionospheric Scintillations*, Proceedings of the IEEE, Vol. 70, No. 4, April 1982.

[5] J. Seo, T. Walter, T-Y. Chiou, and P. Enge, *Characteristics of Deep GPS Signal Fading Due to Ionospheric Scintillation for Aviation Receiver Design*, Proceedings of the 12th International Ionospheric Effects Symposium, 13-15 May 2008, Alexandria, VA.

[6] J. Seo, T. Walter, E. Marks, T-Y. Chiou, and P. Enge, *Ionospheric Scintillation Effects on GPS Receivers during Solar Minimum and Maximum*, Proceedings of the International Beacon Satellite Symposium 2007, 11-15 June 2007, Boston, MA.

[7] M. May, A. Brown, and B. Tanju, *Applications of Digital Storage Receivers for Enhanced Signal Processing*, Proceedings of the Institute of Navigation GPS 1999, 14-17 September 1999, Nashville, TN.

[8] P. Normark, C. Stahlberg, *Hybrid GPS/Galileo Real Time Software Receiver*, Proceedings of the Institute of Navigation GNSS 2005, 13-16 September 2005, Long Beach, CA.

[9] R. Hatch, *The Synergism of GPS Code and Carrier Measurements*, Proceedings of the 3rd International Geodetic Symposium on Satellite Doppler Positioning, 8-12 February 1982, Las Cruces, NM.

[10] T. Walter, S. Datta-Barua, J. Blanch, and P. Enge, *The Effects of Large Ionospheric Gradients on Single Frequency Airborne Smoothing Filters for WAAS and LAAS*, Proceedings of the Institute of Navigation NTM 2004, 26-28 January 2004, San Diego, CA.

[11] RTCA, Inc., *Minimum Operational Performance Standards for Global Positioning System/Wide Area Augmentation System Airborne Equipment*, RTCA DO-229C, November 28, 2001.