# CHARACTERISTICS OF DEEP GPS SIGNAL FADING DUE TO IONOSPHERIC SCINTILLATION FOR AVIATION RECEIVER DESIGN

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

*Stanford University*

## ABSTRACT

Aircraft navigation based on GPS (Global Positioning System) and WAAS (Wide Area Augmentation System) requires both code and carrier measurements to calculate the position estimate [1]. A GPS receiver's carrier tracking loop is weaker than code tracking loop. Thus, carrier lock can more easily be broken under deep signal fading caused by ionospheric scintillation. If a receiver cannot track code and carrier of at least four satellite channels, the aircraft cannot navigate using GPS or WAAS.

The solar maximum data set analyzed in this research demonstrates frequent deep fades and almost all satellites in view suffered from scintillation, which could significantly reduce number of simultaneous tracked satellites. Statistics of number of tracked satellites under 45 minutes of strong scintillation are given in this paper and importance of shorter reacquisition time of a receiver is also emphasized.

In order to design an aviation receiver with shorter reacquisition time under frequent deep signal fadings, characteristics of signal fading have to be well understood. Two important characteristics of deep fading are analyzed, which are fading duration and time between deep fades. The fading duration model in this paper can provide a guideline for more robust aviation receiver design. Even if the receiver could reacquire phase lock quickly, frequent deep fades significantly increase noise level in smoothed pseudoranges, which results in lower navigation availability. Statistics of time between deep fades given in this paper shows very frequent deep fades that could be a major concern of GPS navigation under strong scintillation during solar maximum period.

## INTRODUCTION

The ionosphere has practical importance in GPS applications because it influences transionospheric radio wave propagation. Among various phenomena of ionosphere, ionospheric scintillation [2] due to electron density irregularities causes deep GPS signal fading. Signal to noise ratio or more precisely carrier to noise density ratio (C/No) of a certain satellite channel remains almost constant without scintillation as the upper plot of Figure 1. However, if strong scintillation occurs, C/No fluctuates rapidly and sometimes drops more than 25 dB as the lower plot of Figure 1. Ionospheric scintillation is not usually observed in the mid-latitude region, but it is frequently observed in the equatorial region during solar maximum [3, 4] and potentially hazardous to GPS navigation in the region.

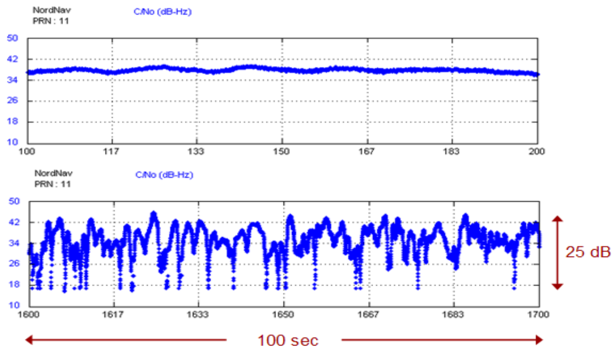

**Figure 1. Example of Deep Signal Fading due to Ionospheric Scintillation**

The data set used for this research contains frequent deep signal fadings due to strong scintillation. The signal fadings are deep

**12th International Ionospheric Effects Symposium**
**13-15 May 2008, Alexandria, VA**

enough to break a receiver's carrier lock. Since the navigation systems using GPS and WAAS utilizes both code and carrier information, loss of carrier lock can reduce navigation availability and continuity, especially when multiple satellite channels are lost simultaneously.

Previous research showed the relationship between number of simultaneous loss of satellites and a receiver's reacquisition time [5]. This paper presents similar analysis using a more severe scintillation data set. Furthermore, a fading duration model is developed to give a guideline for a more robust aviation receiver design with shorter reacquisition time. Another important parameter related to navigation availability is the time between deep fades. Statistics of time between deep fades given in this paper predicts severe impact of frequent deep fades on navigation availability.

## STRONG SCINTILLATION AND NAVIGATION

A GPS aviation receiver has to track at least 4 satellites with good geometry in order to navigate. The number of tracked satellites under scintillation has strong relationship with a receiver's carrier tracking loop performance, especially reacquisition time, which is specified by WAAS MOPS (Minimum Operational Performance Standards) [6]. Statistics of number of tracked satellites during 45 minutes of strong scintillation is discussed in this section in relation with various reacquisition times. Detailed explanation of the analyzed data set is also mentioned.

### *Severe Scintillation Data Set*

Scintillation data was collected during the previous solar maximum period at Ascension Island in the South Atlantic Ocean. The campaign was performed from March 13, 2001 to March 26, 2001 and reliable data was obtained for 9 days. Dr. Theodore Beach, AFRL (Air Force Research Laboratory), provided S4 plots and raw data for this research.

The most severe scintillation period was selected based on the S4 plots, which was from 8:45 PM to 9:30 PM on March 18, 2001 (UTC, also local time). The analysis in this paper is based on this 45 minute data set which was the worst case in the 9 days of solar maximum period.

Raw IF (Intermediate Frequency) data was collected using a NAVSYS DSR-100 receiver [7] with a Rubidium frequency standard and a NordNav commercial software receiver [8] was used to process this raw data. Carrier to noise density ratio (C/No) is the primary interest in this research. NordNav receiver can provide C/No in 50 Hz rate.

Seven out of eight satellites on sky were affected by scintillation in this data set (Figure 2), which is a quite severe case. Figure 3 shows an example of C/No fluctuations of all eight channels. Frequent deep signal fadings of almost all satellite channels are observed in Figure 3.

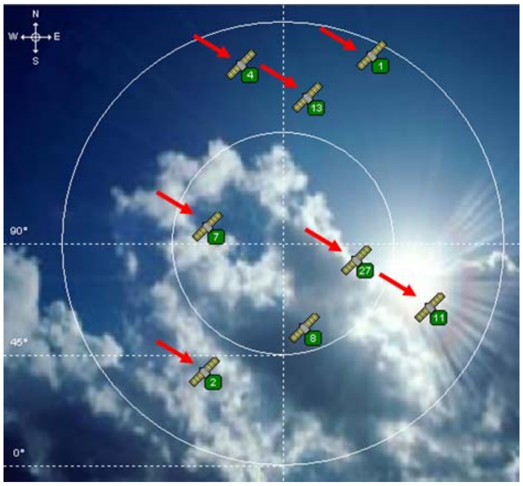

**Figure 2. Satellites Affected by Scintillation**

### *Reacquisition Time and Number of Tracked Satellites*

If strong scintillation occurs, almost all satellites in view could suffer from deep signal fadings as Figure 3. However, it does not necessarily mean that deep fadings of multiple channels happen simultaneously. Previous research showed that actual chance of simultaneous loss of multiple satellites strongly depends on reacquisition times of a receiver [5]. If a

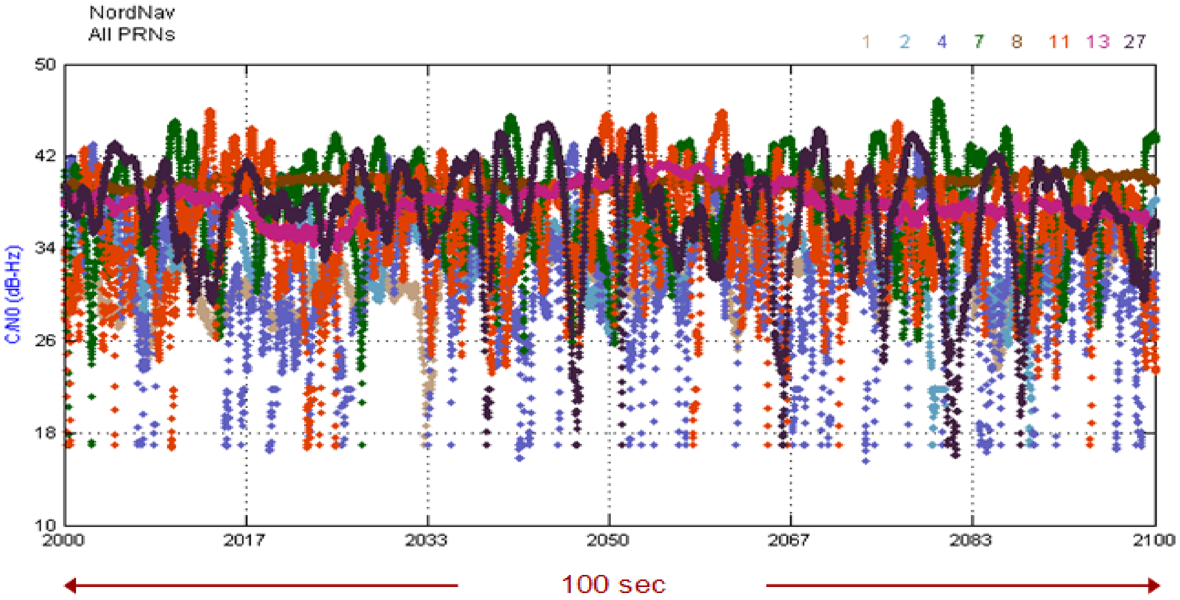

**Figure 3. C/No Fluctuations of All Eight Satellite Channels during Strong Scintillation**

receiver could reacquire a lost channel quickly, chance of simultaneous loss would be reduced and therefore scintillation impact on GPS navigation would also be reduced.

Figure 4 clearly shows the dependency of number of tracked satellites on reacquisition time. Reacquisition times of every second from 1 second up to 20 seconds were considered. Whenever a *deep fading* occurs for a certain satellite channel in the 45 minute worst case data set, a receiver is assumed to lose the channel during predefined reacquisition time in the simulation of Figure 4. (A precise definition of *deep fading* in this paper will be specified in a later section.) As reacquisition time increases, the time percentage of multiple satellite loss increases, and the number of tracked satellites decreases.

The current WAAS MOPS [6] allows up to 20 second reacquisition time. However, if 20 second reacquisition time is assumed under the worst case scintillation data with given satellite geometry, time percentage of 4 or more tracked satellites is 97.9%, 5 or more tracked satellites is 92.3% and 6 or more satellites is only 68.1% according to Figure 4. These low percentages may not provide enough navigation availability during strong scintillation. Hence, the requirement in WAAS MOPS should be changed to a shorter reacquisition time following a brief outage and aviation receivers should be designed accordingly. In order to develop strategies to design a receiver with shorter reacquisition time, it is necessary to understand signal environment first. Among various characteristics of deep signal fading due to scintillation, fading duration and time between deep fades are closely related to GPS navigation and aviation receiver design.

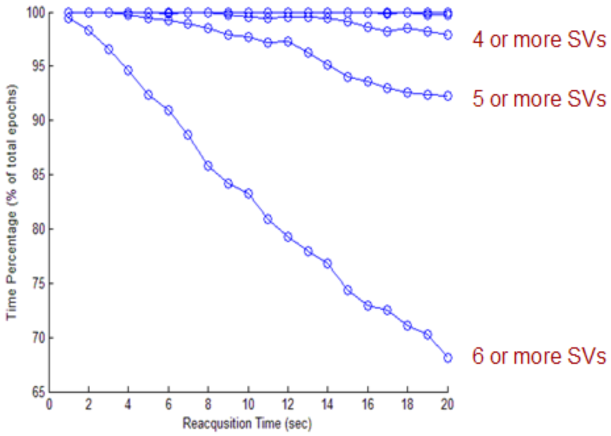

**Figure 4. Number of Tracked Satellites and Reacquisition Time**

## CHARACTERISTICS OF DEEP GPS SIGNAL FADING

This section discusses two important characteristics of deep signal fading which are closely related to GPS navigation and aviation receiver design. The characteristics investigated in this section are fading duration and time between deep fades.

If fading duration is fairly short, a receiver ideally could use a strategy of coasting during the short period of fading until the signal comes back instead of declaring loss of carrier lock immediately after signal loss. With this strategy, a receiver could reduce reacquisition time to recover carrier lock because it preserves some tracking information during coasting period. The benefit of shorter reacquisition time was clearly shown in Figure 4. Statistics of fading duration presented in this section can give a guideline of required coasting time.

The time between deep fades is also important characteristic for GPS navigation. An aviation receiver using GPS and WAAS smoothes its code measurements with less noisy carrier measurements for 100 seconds using Hatch filter [9] to reduce noise level in pseudorange. If a receiver loses carrier lock frequently within 100 second smoothing period, effective smoothing time decreases and noise level in smoothed pseudorange increases. Consequently availability of GPS navigation decreases. The result in this section shows very frequent deep fades which is a major concern of GPS navigation under strong scintillation.

### *Definition of Deep Signal Fading*

Before investigating statistics of deep GPS signal fading, it is necessary to make a proper definition of *deep fading*. If a signal fading is deep enough to break a receiver's carrier lock, the fading can be hazardous to GPS navigation. Hence, at least in navigation's point of view, it makes sense to define *deep fading* in a context of a receiver's carrier tracking loop performance.

The NordNav software receiver used in this research almost always lost carrier lock when the minimum C/No of a fading is below 20 dB·Hz, so a *deep fading* in this paper is defined as a fading that results in a minimum C/No of 20 dB·Hz or less. Among various C/No fluctuations, only deep fadings are selected and marked in red in Figure 5. A fading selection algorithm using local minimum and maximum comparison is developed to separate deep fadings from other signal fluctuations.

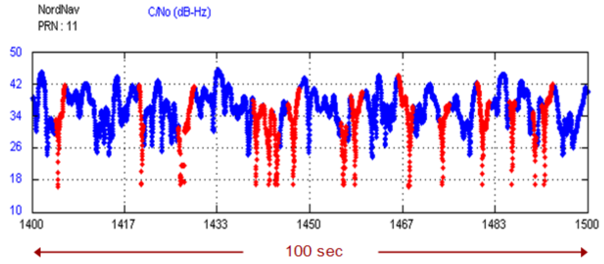

**Figure 5. Example of Deep Signal Fadings**

Since different receivers have different tracking loop performances, other definitions of deep fading could make more sense for other types of receivers. Effects of different definitions of deep fading on the results of this paper will be also discussed at the end of this section.

### *Fading Duration*

Fading duration in this paper is defined as time to recover the previous C/No when deep fading occurs. According to this definition, fading duration is not a single number for a single fading but is obtained at each 50 Hz C/No data point. With this definition, fading duration at lower absolute C/No is shorter as illustrated in Figure 6. In Figure 6, fading duration at 35 dB·Hz, which is an absolute C/No value and not a depth of fading, is about 1 second and fading duration at 25 dB·Hz is about 0.2 second.

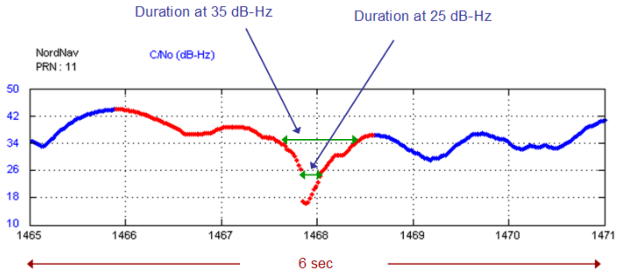

**Figure 6. Definition of Fading Duration**

Ideally, fading duration could be obtained at every 50 Hz data point, but actual response of the NordNav receiver is not ideal. For example, the NordNav receiver sometimes outputs unreliable C/No values as Figure 7. Since these unreliable data points do not describe the physics of ionosphere, they have to be separated from reliable C/No outputs to obtain meaningful statistics of fading duration.

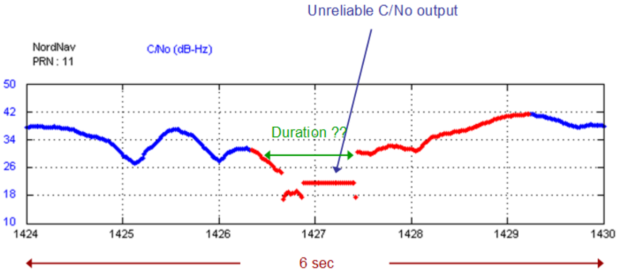

**Figure 7. Unreliable C/No Output**

Fading durations at all C/No outputs of all satellites during the 45 minutes of strong scintillation are plotted in Figure 8. Blue data points in Figure 8 represent fading durations at reliable C/No outputs and red points represent fading durations at unreliable C/No outputs. The number of reliable data points is 18,502 which is 78% of total data points.

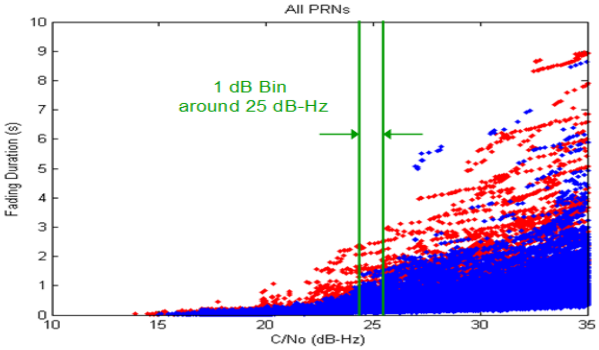

**Figure 8. Fading Durations at All C/No Outputs**

Statistics of fading duration at each C/No value can be obtained from Figure 8. For example, the upper histogram of Figure 9 is generated using reliable data points in 1 dB bin around C/No of 25 dB·Hz in Figure 8. This plot shows that the median of fading duration at 25 dB·Hz is 0.29 second and the 95th percentile is 0.88 second. If 1 dB bin around 30 dB·Hz is considered, the lower histogram of Figure 9 can be generated. In this case, the median and 95th percentile of fading duration is longer than the 25 dB·Hz case as expected in Figure 6.

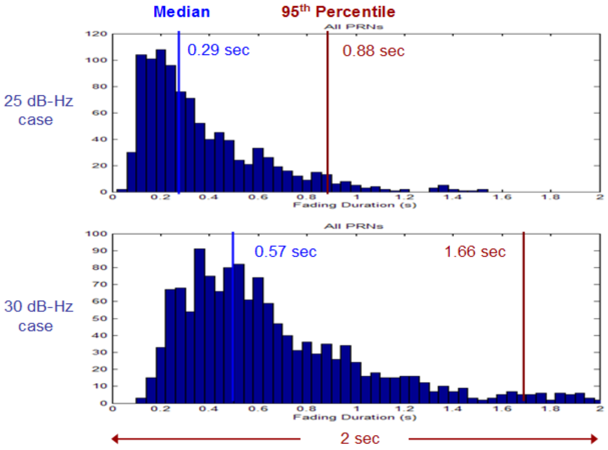

**Figure 9. Histogram of Fading Duration**

Similarly median and 95th percentile values are calculated at other C/No values from 15 dB·Hz to 30 dB·Hz to develop a fading duration model of Figure 10. Statistics of fading durations were obtained at each integer value of C/No and linearly interpolated. Note that this model has information of fading duration only at each C/No and the model does not describe actual shape of fading which is not symmetric in general. If a receiver loses phase lock at 25.4 dB·Hz for example, the receiver can expect the same level of C/No after 1 second in 95% of deep fades according to Figure 10. This model provides a guideline for how long a receiver would need to coast under deep signal fading in order to decrease reacquisition time.

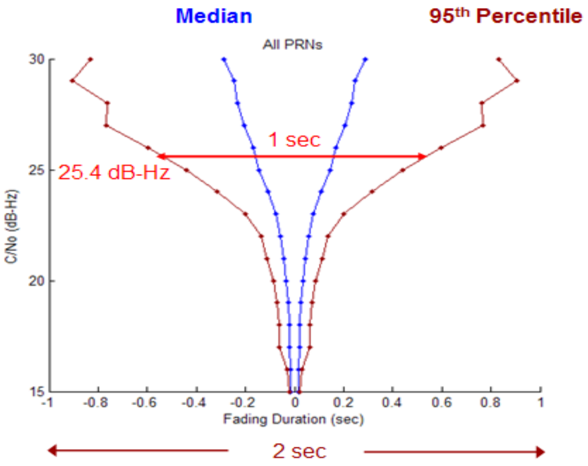

**Figure 10. Fading Duration Model**

### *Time between Deep Fades*

Another interesting characteristic of fading is time between deep fades because it is related to effective carrier smoothing time of an aviation receiver. An aviation receiver uses 100 second smoothing time and requires more than 200 seconds to converge its smoothing filter. Hence, a receiver should maintain carrier lock for more than 200 seconds to decrease noise in pseudorange to a desired level.

Time between deep fades is defined in Figure 11. Time between deep fades can also be calculated at each 50 Hz C/No point. Time between deep fades at 25 dB·Hz in Figure 11 is a little longer than time between deep fades at 35 dB·Hz.

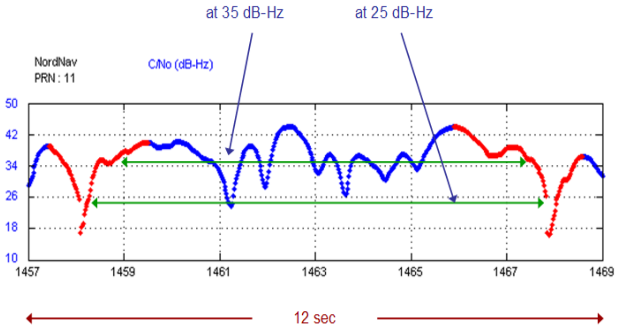

**Figure 11. Definition of Time between Deep Fades**

Time between deep fades at each C/No output is plotted in Figure 12. Red dots in Figure 12 still mean unreliable data points due to unreliable C/No outputs (Figure 7). The number of reliable data points, blue points, is 14,909 (85% of all data points) in this plot.

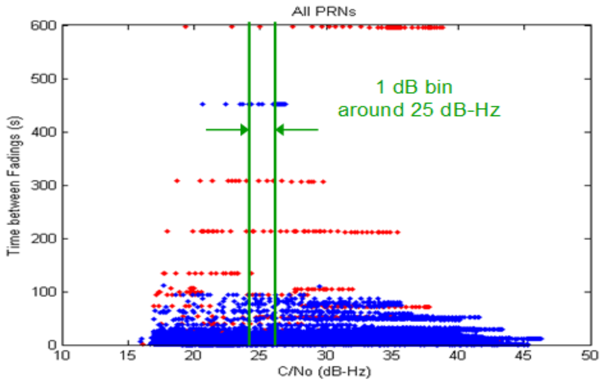

**Figure 12. Time between Deep Fades at All C/No Outputs**

If all reliable data points within 1 dB bin around 25 dB·Hz are taken, a histogram of Figure 13 can be generated. This histogram shows very short time between deep fades and median of time between fades is only 5 seconds, which is far shorter than 100 second smoothing time constant.

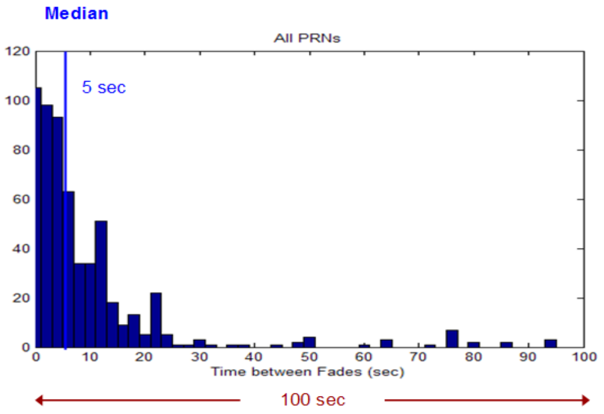

**Figure 13. Histogram of Time between Deep Fades**

Figure 14 shows an example of frequent deep fades. Three deep fades are observed within 6 second in this example.

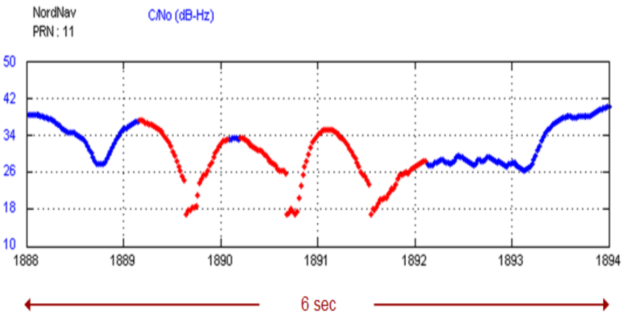

**Figure 14. Example of Frequent Deep Fades**

As already mentioned at the beginning of this section, frequent deep fades cause increased noise level in smoothed pseudorange and consequently decreased navigation availability. Under the frequent deep fades shown in this paper, the navigation system using GPS and WAAS may not be able to provide vertical guidance during strong scintillation although they may still be able to provide horizontal guidance.

*Effects of Different Definitions of Deep Fading*

Deep fading in this paper so far meant a signal fading of which minimum C/No is less than 20 dB·Hz. This definition is well suited with the NordNav software receiver because the NordNav loses carrier lock in this situation. However, other receivers could lose carrier lock at higher C/No and signal fadings not as deep as previously defined deep fading could also be hazardous to those receivers.

Figure 15 illustrates deep fadings in red according to three different definitions. The top plot in Figure 15 is the same as the previously defined deep fading case which has minimum C/No of 20 dB·Hz or less (Figure 5). The middle plot shows deep fading which is defined as fading has minimum C/No of 25 dB·Hz or less, so this plot marks more fadings in red representing deep fading. The bottom plot contains even more fadings as deep fading because deep fading in this plot is defined as minimum C/No of 30 dB·Hz or less. Note that C/No values here are all absolute values because a receiver's tracking loop performance is related to absolute C/No, not relative C/No drop. Hence, lower absolute C/No value here means deeper signal fading.

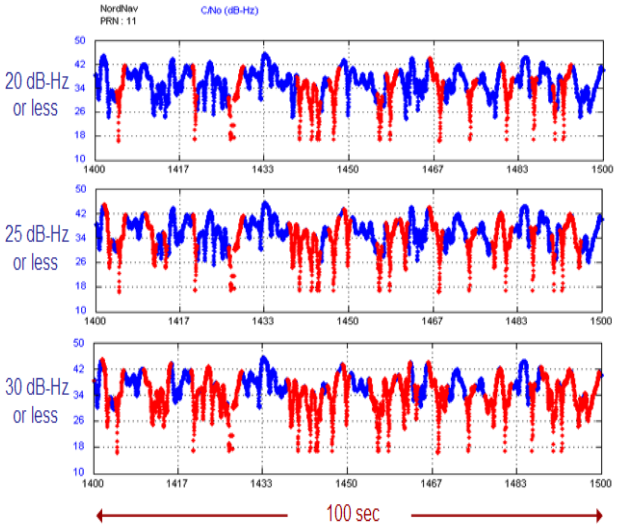

**Figure 15. Different Definitions of Deep Fading**

If minimum C/No of 25 dB·Hz or less is defined as deep fading as the middle plot of Figure 15, the left fading of Figure 16 is now considered as deep fading but it was not included in the statistics of the fading model (Figure 10) because Figure 10 only considered fadings with minimum C/No of 20 dB·Hz or less. Including shallower fadings as the left fading of Figure 16 into the analysis actually provides less conservative statistics of fading duration. Shallower fading usually has shorter fading duration at the same C/No as Figure 16. Hence, the fading duration model of Figure 10 would become sharper which certainly provides less conservative guideline for receiver design.

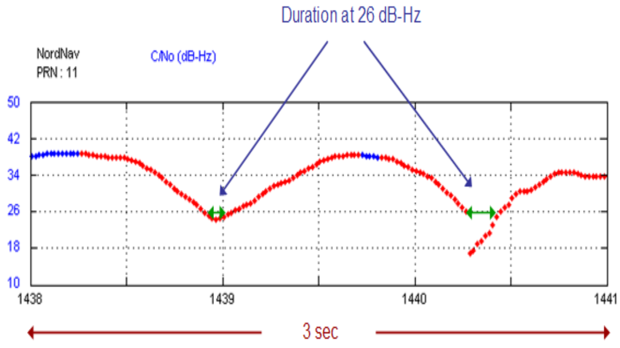

**Figure 16. Effect of Different Definitions of Deep Fading**

However, time between deep fades becomes even shorter after including shallower fading into statistics. Median value of time between deep fades is 4.7 seconds when minimum C/No of 25 dB·Hz or less is considered as deep fading, which is slightly shorter than 5.0 second of 20 dB·Hz or less case. If minimum of 30 dB·Hz or less is considered as deep fading as the bottom plot of Figure 15, median of time between deep fades is only 3.3 seconds.

Consequently, the fading duration model of Figure 10 still remains valid and has conservatism in it for any receivers losing carrier lock above 20 dB·Hz. The statistics of time between deep fades also does not change much if a receiver can maintain carrier lock down to 25 dB·Hz, but if a receiver loses carrier lock above 25 dB·Hz, time between deep fades becomes even shorter and it will be more hazardous for GPS navigation.

Note that average C/No values of Figure 3 are lower than what we normally expect, which implies implementation loss due to the data collection setup. The conservative statistics given in this paper are suggested to be updated using more data sets from better collection setups.

## CONCLUSION

The importance of shorter reacquisition time under deep signal fading was discussed using the 45 minutes of strong scintillation data. The requirement of reacquisition time in WAAS MOPS should be changed to a smaller number and aviation receivers should be designed accordingly.

A fading duration model was developed based on the real scintillation data to give a guideline for receiver design. This fading duration model (Figure 10) is conservatively valid for any receiver which loses carrier lock above 20 dB·Hz.

Frequent deep signal fades are another concern of GPS navigation. If a receiver can track carrier down to 25 dB·Hz, it would expect another deep fading every about 5 seconds, which is far less than 100 second carrier smoothing time. This result predicts poor availability of vertical navigation under strong scintillation, but horizontal navigation may still be possible.

## ACKNOWLEDGMENTS

The authors gratefully acknowledge the Federal Aviation Administration (FAA) WAAS Program Office for supporting this research and Dr. Theodore Beach, AFRL, 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.

## REFERENCES

[1] P. Enge, T. Walter, S. Pullen, C. Kee, Y. Chao, and Y. Tsai, *Wide Area Augmentation of the Global Positioning System*, Proceedings of the IEEE, Vol. 84, No. 8, August 1996.

[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, E. Marks, T. 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.

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

[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.