Statistical Characterization of GNSS Signal Carrier Doppler Frequency Deviations During Ionospheric Scintillation

Ian Collett[1], Brian Breitsch[1], Dongyang Xu[1], and Jade Morton[1]

[1]GPS Lab
Colorado State University
Fort Collins, CO

ABSTRACT

Ionospheric scintillation is the phenomenon when a radio signal propagating through electron density irregularities in the ionosphere undergoes random amplitude and phase fluctuations. Of particular interest is the negative effect that ionospheric scintillation has on Global Navigation Satellite Systems (GNSS) signals, which are primarily used to provide users on or near the surface of the Earth with precise navigation and timing information. These effects are the most pronounced in the equatorial and high latitude regions. Although scintillation is difficult to model, its effects can be statistically characterized using different metrics. The two most commonly used metrics are the amplitude scintillation indicator S_4, defined as the normalized standard deviation of the detrended signal intensity, and the phase scintillation indicator σ_ϕ, the standard deviation of the detrended carrier phase. The effect of scintillation on the Doppler frequency of the signal, on the other hand, is less commonly studied. Characterizing the fluctuations in the Doppler frequency of a GNSS signal is important because it directly impacts receiver carrier tracking operation.

This study utilizes data collected from two different locations at low and high latitudes (Ascension Island and Poker Flat, Alaska) to characterize Doppler frequency deviations under various conditions. Distributions of the Doppler are produced for two different regimes: low ($0.3 \leq S_4 < 0.6$) and high ($S_4 \geq 0.6$) scintillation. At high latitudes, there are relatively low levels of S_4. In this region, a similar procedure is followed to characterize the Doppler frequency deviations, except that the phase scintillation indicator σ_ϕ is used instead to define the low and high scintillation regimes.

1. INTRODUCTION

Ionospheric scintillation refers to the random amplitude and phase fluctuation of radio waves traversing the ionosphere. It is caused by small-scale electron density irregularities generated by complex interactions of solar activity, local magnetic and electric fields, convection, and other factors [1]. Because of the large number of complex influences, scintillation proves to be difficult phenomenon to model. In the context of GNSS, the random amplitude fading and phase fluctuations caused by scintillation negatively impact navigation solutions and can cause the receiver to lose lock on signals [2]. These issues are especially pronounced in low and high latitude regions, where ionospheric scintillation is most prevalent [3]. At low latitudes, scintillation is characterized by deep amplitude fading and large phase fluctuations; at high frequencies, phase fluctuations dominate [4]. The degree of amplitude fading and phase fluctuations associated with a scintillation event are quantified by, respectively, the amplitude scintillation indicator S_4 and the phase scintillation indicator σ_ϕ.

In the past several decades, numerous studies have been performed to quantify the effect of scintillation on the amplitude and phase of navigation signals, and how these effects vary spatially and temporally. However, less is known about how scintillation affects the signal carrier Doppler frequency. An increased understanding of these effects is helpful for choosing a bandwidth to use for carrier tracking. This paper presents a preliminary study that statistically characterizes the effects of scintillation on the carrier Doppler frequency of Global Positioning System (GPS) signals. Statistical distributions are generated and analyzed using GPS L1 (1575.42 MHz) data from low and high latitude locations.

2. DATA COLLECTION AND PROCESSING

To provide a comparison of how scintillation affects Doppler frequency at low and high latitudes, data from two contrasting locations are used in this study. The low latitude data comes from Ascension Island (7.93˚S, 14.37˚W), an isolated island located in the South Atlantic Ocean approximately halfway between the continents of South America and Africa. A GNSS collection system collected data in March 2013, and consisted of a single wideband antenna connected to a commercial ionospheric scintillation monitor (Septentrio PolaRxS receiver) and five USRP N210 RF front ends designed to collect raw intermediate frequency (IF) GNSS data [5]. For the results given in this paper, four separate datasets of IF data and Septentrio data totaling about 5 hours each were used; each dataset was collected at some point between 20:00 and 1:00 local time from 03/08-03/10. The high latitude data comes from the Poker Flat Research Range (65.14˚N, 148.01˚W), approximately 30 km north of Fairbanks, Alaska. The results presented here consist of an entire day of data collected on 12/20/2015 by a Septentrio PolaRxS receiver. Some preliminary processing of the datasets is performed using preexisting code libraries designed by the GPS Lab, resulting in high-rate (100 Hz) data for the carrier phase and the in-phase and quadrature samples.

An example of the data processing procedure for Ascension Island is depicted in Figure 1. First, the high-rate carrier Doppler frequency is calculated by differentiating the carrier phase using a first-order numerical derivative approximation. (The Septentrio receiver also provides a measurement of Doppler frequency, but only at a lower rate of 1 Hz.) Next, the Doppler frequency is detrended to remove the large-scale variations caused by the relative dynamics of the GPS satellite and the receiver. The smaller variations that remain are typically on the scale of a few Hertz and are caused by receiver clock error, ionospheric and tropospheric effects, and noise. The detrending is performed using a sixth-order high-pass Butterworth filter with a 0.1 Hz cutoff frequency [6]. Because the direction of the frequency fluctuations is unimportant in the context of signal tracking, the absolute value of the detrended Doppler frequency is taken, yielding the detrended Doppler frequency deviations.

Next, the scintillation indicator is calculated. At low latitudes, scintillation effects exhibit deep amplitude fading. For this reason, S_4 is an appropriate choice to quantify the severity of scintillation at a given moment. In contrast, high latitude scintillation events exhibit phase fluctuations with little amplitude fading. In this scenario, σ_ϕ is a better choice. To calculate S_4, the signal intensity (SI) at 50 Hz is first computed from the in-phase and quadrature samples. The SI is then detrended using a sixth-order low-pass Butterworth filter with a 0.1 Hz cutoff frequency and S_4 is calculated as the normalized standard deviation [6]:

$$S_4 = \sqrt{\frac{\langle SI^2\rangle - \langle SI\rangle^2}{\langle SI\rangle^2}}\,.$$

To calculate σ_ϕ, the carrier phase is first detrended using a sixth-order high-pass Butterworth filter with a 0.1 Hz cutoff frequency. Taking the standard deviation gives the result

$$\sigma_\phi = \langle \phi^2 \rangle - \langle \phi \rangle^2 .$$

In both cases, the scintillation indicators are calculated every 10 seconds (0.1 Hz rate). To calculate the standard deviations, 10 seconds of data are used (500 samples of detrended SI at 50 Hz are used to calculate each sample of S_4, and 1,000 samples of detrended carrier phase at 100 Hz are used to calculate each sample of σ_ϕ).

To characterize the statistical effect of the level of scintillation on the Doppler frequency, two different regimes are defined: low scintillation ($0.3 \leq S_4 < 0.6$ or 0.2 rad $\leq \sigma_\phi < 0.5$ rad) and high scintillation ($S_4 \geq 0.6$ or $\sigma_\phi \geq 0.5$ rad). Sections of data with scintillation indicators that fall below the lower threshold of the low scintillation regime are thrown out before generating the statistical distributions. There are 1,000 samples of detrended Doppler frequency deviations for each sample of the scintillation indicator. The maximum of the 1,000 samples is found and then added to the low or high scintillation distribution data per the corresponding level of scintillation.

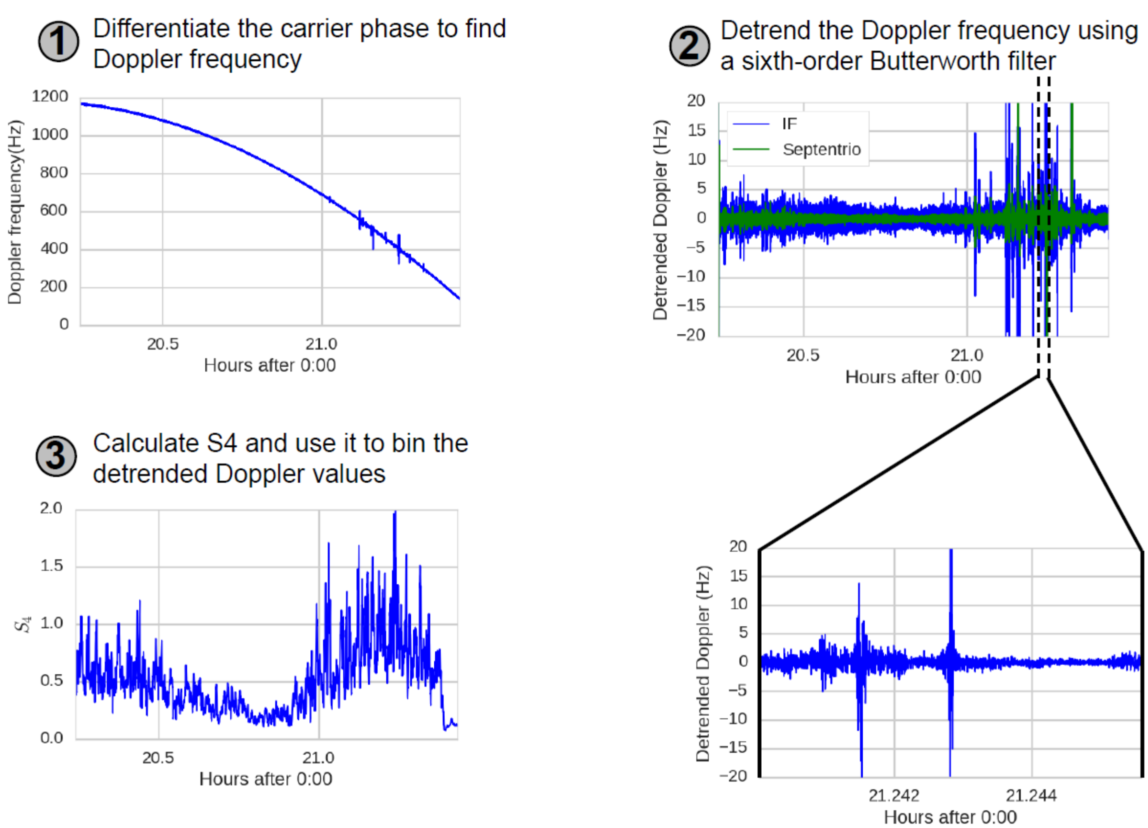

Figure 1. The data processing procedure is illustrated using the L1CA signal from GPS PRN 24 passing over Ascension Island on 03/10/2013. After detrending the Doppler frequency, it appears that large variations in excess of 10 Hz are common during high levels of S_4. However, zooming in on 20 seconds of the data reveals that the detrended Doppler frequency is dominated by lower-magnitude variations on the order of several Hertz. For this reason, the Doppler frequency values are binned according to the *maximum* deviation corresponding to each sample of S_4.

The result is an array of maximum Doppler deviations for both the low and high scintillation regimes. At this point, the statistical distributions are generated. For both the high and low latitude datasets, a probability density function (PDF) is created. The bin size, typically on the order of a fraction of 1 Hz, is chosen to best illustrate the statistical behaviour of the dataset. The low latitude data is further processed to generate a complementary continuous distribution function (CCDF). The CCDF plots the probability that the maximum detrended Doppler frequency deviation is above a given threshold.

3. RESULTS AND DISCUSSION

First, the low latitude data from Ascension Island are processed and analyzed. The IF dataset consists of four separate satellite passes: GPS PRN 24 on 03/08, PRN 29 on 03/09, and PRNs 24 and 31 on 03/10. The satellite passes all occurred during the peak of scintillation, between 20:00 and 1:00 local time. To facilitate a direct comparison between the USRPs and the Septentrio PolaRxS receiver, Septentrio data from the corresponding four satellite passes and periods of time were used. Figure 1 includes a plot of the detrended Doppler frequency of one of the satellite passes for the IF and Septentrio data. The amplitude of the Septentrio Doppler frequency is small compared to that of the IF data, indicating that the Septentrio receiver outputs a filtered version of the carrier phase with higher frequencies attenuated.

After the Doppler frequency is binned into the low and high scintillation regimes, the PDF and CCDF distributions are generated (see Figure 2). From the PDF, it is again clear that the Septentrio receiver filters out larger deviations in the Doppler frequency—the peaks for the low and high scintillation regime are significantly lower than those of the IF data. The PDF also shows the effect of the severity of a scintillation event on the maximum Doppler frequency deviation. Larger Doppler frequency deviations are more probable during high scintillation, as evidenced by the spreading of the distributions. The CCDF reinforces this observation. The probability that the frequency deviation will be above some given frequency threshold is significantly higher in the high scintillation regime than in the low scintillation regime, especially as the frequency threshold increases.

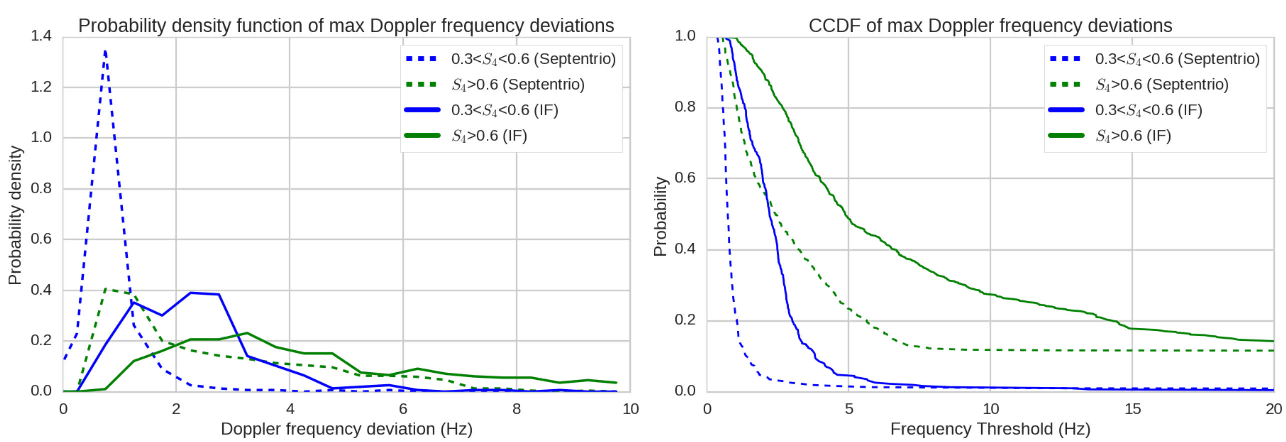

Figure 2. The PDF and CCDF distributions for the Ascension Island data. The distributions are generated by binning maximum Doppler frequency deviation values for the GPS L1CA signal.

Table 2, taken directly from the CCDF distribution, lists the probability that the maximum Doppler frequency deviation will be greater than a threshold of $f_T = 5$ Hz and $f_T = 10$ Hz. For example, consider the results for the IF data. In the high scintillation regime, the maximum Doppler frequency deviation is above 5 Hz nearly half of the time and above 10 Hz more than a quarter of the time. Frequency deviations of this magnitude are significant enough to receiver loss of lock. By contrast, the probability that the frequency deviation would be above these thresholds is only a few percent in the low scintillation regime.

	$P(f > f_T)$			
	Septentrio Data		IF Data	
	$0.3 < S_4 < 0.6$	$S_4 > 0.6$	$0.3 < S_4 < 0.6$	$S_4 > 0.6$
$f_T = 5$ Hz	1.26%	23.25%	4.43%	48.63%
$f_T = 10$ Hz	0.95%	11.62%	0.95%	27.24%

Table 1. Using the CCDF for the Septentrio data and IF data in the low and high scintillation regimes, the probability of experiencing a maximum Doppler frequency deviation greater than a threshold of $f_T = 5$ Hz and $f_T = 10$ Hz is tabulated.

Next, the results from Poker Flat, Alaska are considered. In this case, only data from a Septentrio receiver is utilized, and consists of all available satellite passes from the entirety of 12/20/2015. No elevation mask is applied to the signals. Again, the carrier phase from the GPS L1CA signal is measured and processed to calculate the detrended Doppler frequency deviation. This time, the maximum frequency values are binned instead by the corresponding level of σ_ϕ. The PDFs for the low and high scintillation regimes are depicted in Figure 3.

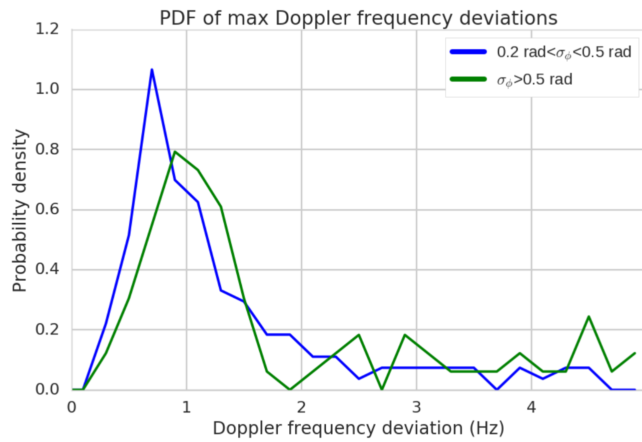

Figure 3. The PDF distributions for the Alaska data. The distribution is generated by binning maximum Doppler frequency deviation values for the GPS L1CA signal.

Like at low latitudes, the behavior of the Doppler frequency deviations is influenced by the severity of a scintillation event. In the high scintillation regime, larger maximum Doppler frequency deviations are more probable. It was seen from the low latitude data that the Septentrio receiver filters out higher frequencies. Assuming this is still the case, the actual Doppler frequencies are larger than depicted here.

4. CONCLUSION

This research illustrates that ionospheric scintillation does indeed have a measurable effect on the signal carrier Doppler frequency, both at low and high latitude locations. These effects should be considered when designing a GNSS tracking loop. Furthermore, the results showed that the carrier phase output of the Septentrio PolaRxS receiver filters out higher frequency variations when compared to the tracked IF data.

In this paper, a relatively small dataset was utilized to provide a brief glimpse into the frequency related effects of scintillation. Certainly, there exists the opportunity for a more in-depth analysis. A more complete characterization of the Doppler frequency effects would include signals from different GPS frequency bands (L2 and L5) and different GNSS constellations (GLONASS, BeiDou, QZSS). Furthermore, processing data from a wider range days throughout the year and a variety of different locations would help to complete the picture.

ACKNOWLEDGEMENTS

Ian Collett's work is supported by NASA grant NNX15AT54G.

REFERENCES

[1] J. Aarons, "Global morphology of ionospheric scintillations," *Proc. IEEE*, vol. 70, no. 4, pp. 360–378, Apr. 1982.

[2] S. H. Skone, "The impact of magnetic storms on GPS receiver performance," *J. Geod.*, vol. 75, no. 9–10, pp. 457–468, Oct. 2001.

[3] K. C. Yeh and C.-H. Liu, "Radio wave scintillations in the ionosphere," *IEEE Proc.*, vol. 70, pp. 324–360, Apr. 1982.

[4] Y. Jiao and Y. T. Morton, "Comparison of the effect of high-latitude and equatorial ionospheric scintillation on GPS signals during the maximum of solar cycle 24," *Radio Sci.*, vol. 50, no. 9, p. 2015RS005719, Sep. 2015.

[5] S. Peng and Y. Morton, "A USRP2-based reconfigurable multi-constellation multi-frequency GNSS software receiver front end," *GPS Solut.*, vol. 17, no. 1, pp. 89–102, Jan. 2013.

[6] A. J. Van Dierendonck, John Klobuchar, and Quyen Hua, "Ionospheric Scintillation Monitoring Using Commercial Single Frequency C/A Code Receivers," in *Proceedings of the 6th International Meeting of the Satellite Division of The Institute of Navigation*, Salt Lake City, 1993, pp. 1333–1342.