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Phase Scintillation Decorrelation Impact on Multi-Frequency Users

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Abstract—**This paper discusses the phase scintillation decorrelation as observed between dual and triple frequency civil GNSS signals. Comparisons are made between the characteristics of data collected in Norway during events of strong and persistent phase activity versus data collected in Hanoi during periods of vigorous amplitude and phase scintillation. Under both types of scintillation activity a degree of decorrelation is observed between the multiple carriers which is not attributable to nominal ionospheric behavior, and in turn the assumption that the ionosphere-free combination is for all intents and purposes free of the influence of the ionosphere is violated.**

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1. INTRODUCTION

Use of multiple signals of distinct centre frequency transmitted from the same Global Navigation Satellite System (GNSS) satellite allows direct observation and removal of the vast majority of the ionospheric delay. With signals available on multiple GNSS frequencies, advanced multi-frequency correction schemes can be applied to further refine the correction terms. While the general assumption of nearly perfect correlation between the effect measured on multiple independent signals is correct in normal conditions, detailed knowledge of scintillation effect correlation between the GNSS frequency pairs is desirable in order to quantify the potential error due to any decorrelation of the effect, as this error decorrelation will dictate the extent to which frequency diversity may be applied to mitigate the scintillation impact on the GNSS measurement accuracy, which is of special concern to differential correction applications where safety of life is a consideration, such as the currently in development multi-frequency ground based augmentation systems.

Several studies investigating the scintillation effect on correlation across GNSS frequencies are already available [1][2], however these studies focus mainly on characterizing the correlation of amplitude scintillation by means of simulated data, or the projection of signal fluctuations observed on GPS L1 on to new frequencies. An investigation based on observations recorded at high latitude regions of Norway on multi frequency enabled satellites has been detailed in [4], where it has been shown that during ‘pure’ phase scintillation events such as those expected at middle to high latitudes, the level of correlation between the GNSS carriers tends to rise with increasing scintillation magnitude. While the absolute magnitude of the residual tends to also grow with scintillation magnitude, it typically does so very slowly.

In contrast to the pure phase scintillation events [4], at low latitude regions amplitude and phase scintillation can co-occur, and the phase relationship between the various carriers can fail during even modest fading resulting in much higher residual noise. Unlike group delay errors, it is not possible to measure and estimate this error contribution a priori. It is effectively an additional noise source present only during scintillation. Based on a data set collected in Brazil in 2012, it has been demonstrated in [3] that residuals of up to 2-3 meters can be observed in the ionosphere-free combination of GPS L1 and L2C carrier phase measurements.

This article presents phase scintillation decorrelation analysis done based a large set of observations recorded at low latitude regions of Hanoi (approximately 21° N, 106° E) on GPS L1/L2/L5 frequencies complementing and expanding earlier work on pure phase scintillation [4]. The purpose of this paper is to show the decorrelation level observed in real data, and discuss the residual noise magnitude as it appears in the ionosphere-free carrier phase combination to provide an indication of the level of uncertainty corrupting the ionosphere-free combinations for the multi-frequency users.

2. IONOSPHERE-FREE COMBINATION

It is well known that the ionosphere is dispersive in the L-band and the refractive effects on the carrier phases are proportional to the wavelengths of the carriers to within the first order. One of the advantages of the multi-frequency GNSS receivers is that one can combine carrier phase measurements at different frequencies to cancel out the first order effect due to ionospheric refraction.

Consider generalized versions of carrier phase measurements on two frequencies, i and j, expressed in meters:

$$\begin{aligned} \Phi_{L_i} &= \rho + \lambda_i N_i - I_i \\ \Phi_{L_j} &= \rho + \lambda_j N_j - I_j \end{aligned} \tag{1}$$

where ρ is the geometric range between the satellite and the receiver; λ_i and λ_j are the wavelengths, N_i and N_j are the integer ambiguity terms, and I_i and I_i are the ionospheric propagation delay errors. For simplicity, the receiver noise and multipath errors are not included. The expression for an arbitrary linear combination of two carrier phase measurements can be written as follows [5]:

$$\Phi_{ij} = \alpha \Phi_{L_i} + \beta \Phi_{L_j}, \tag{2}$$

where α and β are constants. This allows one to model a linear combination of phases in the same way as the individual observables:

$$\Phi_{ij} = \rho + \lambda_{ij} N_{ij} - I_{ij} \eta \tag{3}$$

In (3), λ_{ij} is the wavelength, N_{ij} is the integer ambiguity term, and I_{ij} is the ionospheric propagation delay error for the linear combination. In order to remove the ionospheric error $(\eta = 0)$, but retain the geometric portion unchanged and the resulting ambiguity still an integer, the ionosphere-free combination has been proposed [5]:

$$\Phi_{IFree} = \frac{f_i^2 \Phi_{L_i} - f_j^2 \Phi_{L_j}}{f_i^2 - f_j^2}, \tag{4}$$

where f_i and f_j are the carrier frequencies expressed in Hz.

The phase scintillation is however, caused by both refractive and diffractive effects [3]. The diffractive effects cause rapid transitions in the phase which do not scale with the carrier wavelength resulting in a residual error in the ionosphere-free linear combination (4) of phase measurements.

3. HIGH LATITUDE PHASE SCINTILLATION

To show the magnitude of the ionosphere-free combination residual due to phase decorrelation during ‘pure’ phase scintillation events such as those expected at middle to high latitudes, we use the same data as detailed in [4], collected in Norway using the Septentrio PolaRxS scintillation monitors located at Tromsø and Vega with latitudes of 69.5° and 65.5° North, respectively. During these events the absolute maximum reported S4 index was 0.27, with typical values below 0.1 throughout. To avoid the use of semicodeless GPS L2 measurements that are not suitable for this task because of frequent loss of lock during strong scintillations, GLONASS signals on civil L1 and L2 frequencies are studied instead. This data covers one of the recent, geographically widely distributed events observed on the 14th of November 2012, where over the course of several hours, strong phase scintillation was observed over both of these scintillation monitors simultaneously. This event was sufficiently disruptive that strong to moderate [7] phase scintillation was present on up to 5 simultaneous (within the same one minute period) GLONASS satellites.

Although ionospheric scintillation indices tend to be reported by monitors at 1 minute intervals, many applications operate at a much higher measurement processing rate, therefore it is desirable to examine the higher frequency information content in the scintillation. That is why, in this study an update rate of 2 Hz is used. When utilizing these 0.5 second measurement interval lengths, much higher frequency information is exposed in the ionospheric measurements than is available when using the standard 1 minute period phase or amplitude scintillation indices, such as the level of de-correlation between multiple frequency signals transmitted by the same satellite during vigorous phase scintillation events.

In order to observe the fluctuations due to scintillation and determine the level of decorrelation between frequencies, the raw signal intensity and carrier phase observables are detrended. The intensity of each signal is computed as a sum of the squares of post-correlator samples of in-phase (I) and quadrature (Q) components. The result is then detrended by applying a fourth order polynomial over each 60 second window. To detrend the carrier phase observables, a fourth order polynomial over each 60 second window is subtracted in order to remove the influence of the satellite motion and the slowly changing clock error from the observations, before being high pass filtered by a sixth order Butterworth filter to remove residual content below 0.1 Hz. The epoch-to-epoch changes in the measured L1 carrier phase are then used to predict the expected magnitude of change in the second frequency carrier under the assumption that the entirety of the observed L1 change residual is generated by ionospheric variation, and should therefore vary in inverse proportion to the square of the carrier frequencies of the two signals according to:

$$I_j = \frac{f_i^2}{f_j^2} I_i \tag{5}$$

The ionosphere-free combination is then formed based on both the direct measurements following (4), and a combination of the direct observations on L1 and the expected on the second frequency.

Figure 1 shows the detrended intensity and carrier phase observations for GLONASS SVID 59 from the 14th of November 2012, Tromsø, Norway. The bottom plot shows the ionosphere-free combination computed from the detrended phases on L1 and L2.

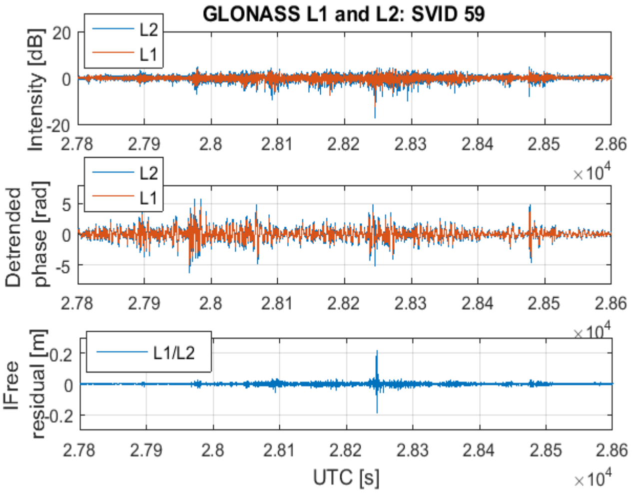

Figure 1. Detrended intensity on L1 and L2; detrended carrier phase on L1 and L2; averaged ionosphere-free combination residual of the L1 and L2 phase measurements, GLONASS SVID 59, Tromsø, (69.5º N).

To quantify the correlation level between the effects on the L1 and L2 frequencies, the phase correlation coefficient was calculated for the observed scintillation events according to the following relationship:

$$\rho_{\delta\phi} = \langle\delta\phi_1\delta\phi_2\rangle/(\langle\delta\phi_1^2\rangle\langle\delta\phi_2^2\rangle)^{1/2}, \qquad -1 < \rho_{\delta\phi} > 1 \tag{6}$$

where the terms $\delta\varphi_1$ and $\delta\varphi_2$ represent phase fluctuations. Figure 2 illustrates an example of the correlation between the L1 and L2 carriers of a GLONASS satellite during periods of varying phase scintillation at high latitude.

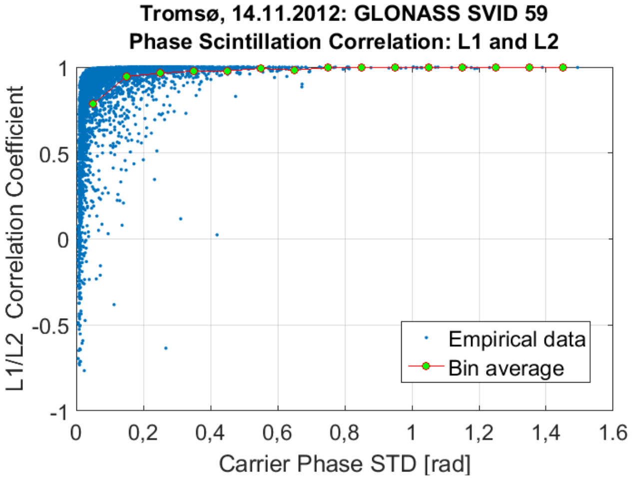

Figure 2. Phase correlation between GLONASS L1 and L2 during high latitude phase scintillation event, based on 0.5 second averaging intervals.

As shown in [4], an almost universal increase in the level of phase correlation between the two carriers can be observed with increasing phase scintillation activity, indicating that despite the increasing absolute residual level the relative de-correlation tends to be constant or decreasing during high latitude phase scintillation events.

Figures 3 and 4 show the average absolute L1/L2 ionosphere-free combination residual from Tromsø and Vega observations.

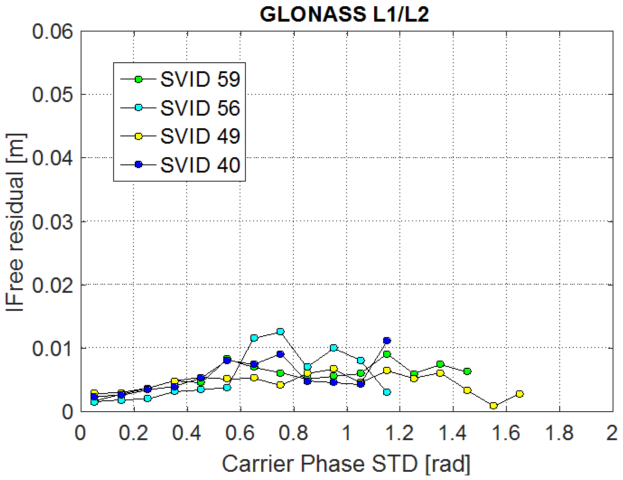

Figure 3. The averaged absolute ionosphere-free combination residual of the L1 and L2 phase measurements on multiple GLONASS satellites during phase scintillation, Tromsø (69.5º N).

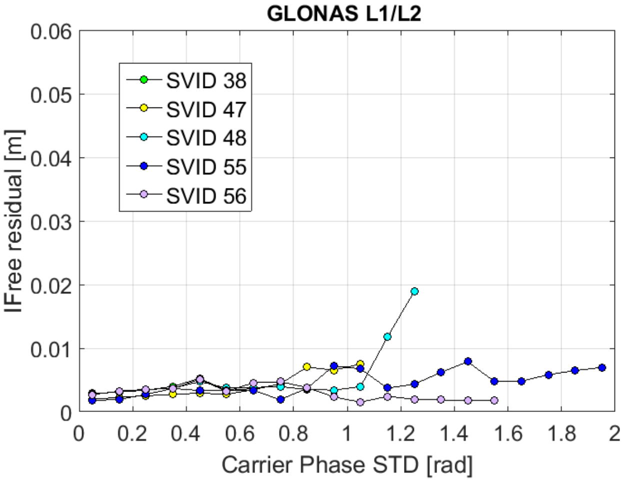

Figure 4. The averaged absolute ionosphere-free combination residual of the L1 and L2 phase measurements on multiple GLONASS satellites during phase scintillation, Vega (65.5º N).

4. LOW LATITUDE PHASE AND AMPLITUDE SCINTILLATION

To extend the analysis and compare the results, scintillation data was provided by a JRC 'Fourtune' receiver of the type shown in Figure 5, deployed in Hanoi. The JRC operates a growing network of such scintillation monitors which simultaneously collect L1/E1, L2 and L5/E5a data while employing a novel open-loop demodulation scheme to process and monitor the collected samples [6]. The Fourtune receivers have the advantage of combining the functions of a scintillation monitor with those of an RF bit grabber, by leveraging a computationally efficient open-loop demodulation and scintillation monitoring process to simultaneously produce scintillation indices and traditional GNSS observables such as carrier phase measurements, while also selecting which batches of RF samples contain scintillation of interest and should be retained for further analysis. Additional details about the architecture and configuration of the Fourtune front-end and the open-loop monitoring software are given in [6].

Figure 5. Fourtune receiver board outside of enclosure casing showing connection to VC-OCXO oscillator. In the deployed configuration each of the four independent RF channels are connected to a common RF feed from the GNSS antenna.

A standard GNSS receiver typically derives carrier phase observations via a closed loop phase-tracking algorithm. Such as a Phase-Lock Loop (PLL) which will produce the entire phase trajectory, including the Doppler-induced phase trend, local oscillator effects and the ionospheric contribution. In contrast, in the open-loop approach, the received signals are demodulated to baseband based on *a priori* knowledge of the receiver position and satellite orbit, removing virtually all of the deterministic phase trend. This phase process is dominated by the ionospheric contribution plus some residual phase trends induced by factors such as, for example, errors in the satellite ephemeris.

There are many benefits of this approach over closed loop tracking architectures. The availability of the correlator values is isolated completely from the receiver's ability to track the signal. As such, the time-series of complex correlator values can be simply post-processed to reconstruct the phase trajectory, allowing forward, forward-backward, or batch processing, facilitating robust phase reconstruction and consistency checking. Of course, the most trivial method of reconstructing the phase is as a summation of phase increments, whereby the phase is computed as the cumulative sum of the differential phase between adjacent correlator values. Indeed, to date this simple method has proved sufficiently accurate and robust.

Multiple combined phase and amplitude scintillation events have been captured by the Fortune receiver deployed in Hanoi. In this study, we will use the data covering the events recorded on the 26th of March and 2nd of April, 2015. Compared to the previously discussed data, the most important features of the Hanoi data used here include the presence of triple-frequency civil signals (L1CA, L2CM and L5Q), and the prominence of amplitude fading activity of which Figure 6 shows a representative example.

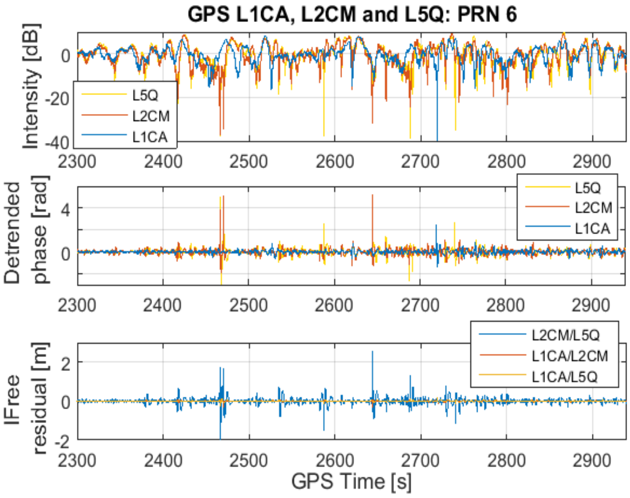

Figure 6. Detrended intensity on L1CA, L2CM and L5Q; detrended carrier phase on L1CA, L2CM and L5Q; averaged ionosphere-free combination residual of L1CA/L2CM, L1CA/L5Q and L2CM/L5Q combinations, GPS PRN 6, Hanoi, (21º N).

In the particular event shown in Figure 6 the depth of fades can reaches 43 dB on L1CA which is severe by any metric, and is a substantial qualitative difference from the previously analyzed high-latitude phase scintillation events where only very weak fading activity was ever observed. Quantitatively, the differences between these data sets can be easily seen when comparing the phase correlation behaviour of the fading data from Hanoi in comparison to the high latitude phase scintillation data. In Figure 7 the level of correlation versus the intensity of the phase variation is plotted for L1CA vs. L2CM, and in contrast to the high latitude examples where increasing phase instability lead to an increasing level of phase correlation between the two carriers, for the Hanoi data the outcome is entirely different. Indeed, the phase correlation between the two carriers appears to be nearly non-existent, as the distribution of correlation measures is bifurcated with half the distribution tending towards higher positive correlation levels, while the other half of the sampled distribution tends towards anti-correlated results.

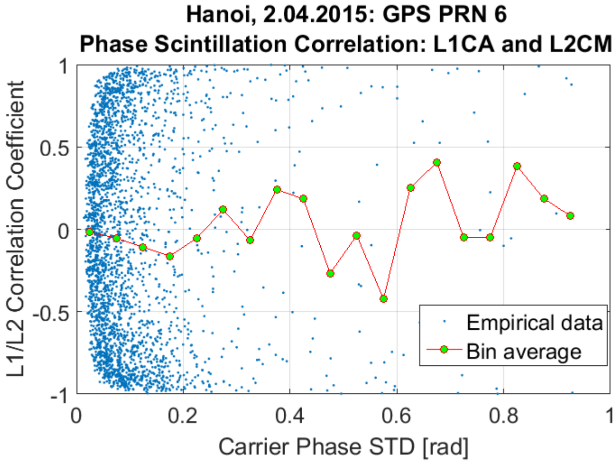

Figure 7. Phase correlation between GPS L1CA and L2CM during low latitude phase and amplitude scintillation event, based on 0.5 second averaging intervals.

Given the nearly equal implied likelihood that any phase deviation caused by the ionosphere on one of the carriers will cause a correlated or anti-correlated response on the other tracked carrier, it is unsurprising that the magnitude of apparent ionosphere-free residuals will be much larger than in the high latitude case as in Figure 8.

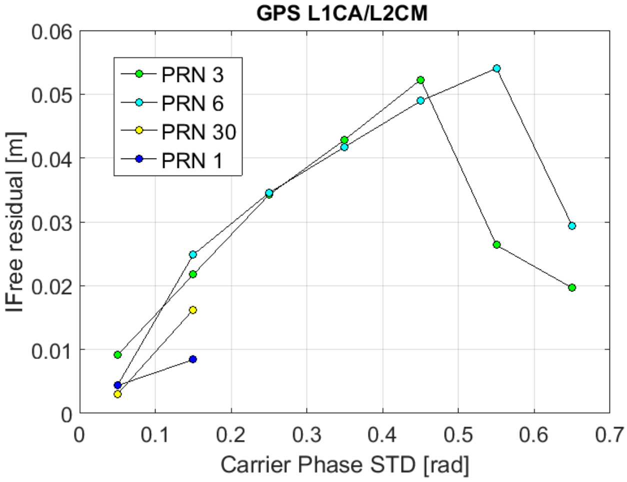

Figure 8. The averaged absolute ionosphere-free combination residual of the L1CA and L2CM phase measurements on multiple GPS satellites during phase and amplitude scintillation, Hanoi (21° N).

Noting that the range of carrier phase standard deviation considered in Figure 8 is smaller than that considered in the high latitude plots, it is obvious that the level of ionosphere-free residual present in the Hanoi data grows much more rapidly with increasing phase standard deviation than was the case with the high latitude observations.

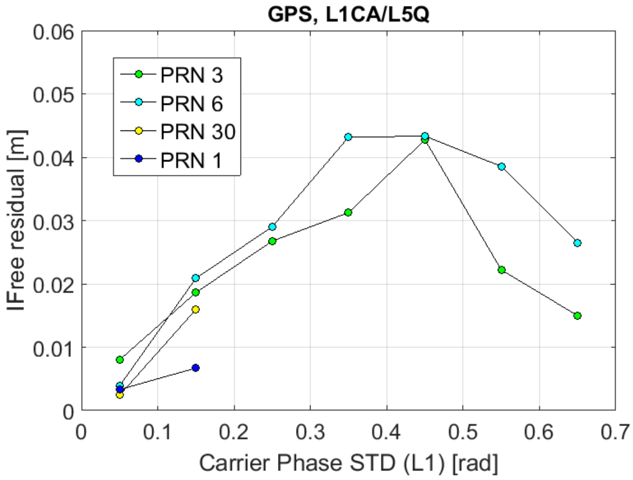

Figure 9. The averaged absolute ionosphere-free combination residual of the L1CA and L5Q phase measurements on multiple GPS satellites during phase and amplitude scintillation, Hanoi (21° N).

While it is not surprising that the L1/L5 combination residual is also substantial as indicated in Figure 9, the more interesting observation is that the L2C and L5 signals also have substantial levels of decorrelation despite their relatively small spectral separation.

In Figure 10 it is seen that for one of the tracked PRNs during this event, the level of ionosphere-free residual in the L2CM/L5Q combination exceeds a metre.

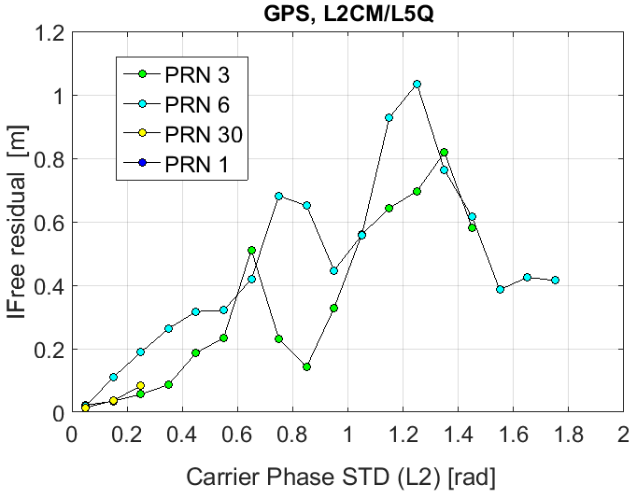

Figure 10. The averaged absolute ionosphere-free combination residual of the L2CM and L5Q phase measurements on multiple GPS satellites during phase and amplitude scintillation, Hanoi (21° N).

It nearly goes without saying that this magnitude of ionospheric contamination of a nominally ‘ionosphere-free’ observable presents a problem to users of the data.

5. CONCLUSIONS

It has been shown that metre level residuals can contaminate the nominally ‘ionosphere free’ linear combinations of multiple frequency GNSS users in situations where the receiver does not appear to have suffered cycle slips or lost locks. This indicates that the differential delay between the signals is actually on the order of multiple nanoseconds due to ionospheric effects. These results are in line with the expectations based on the simulated and L1/L2C measured results found in [3], confirming that users of multi frequency civil GNSS signals can still be substantially affected by ionospheric activity. The conclusion from [3] that the decorrelation effect should be gradual (over several samples) in onset is tentatively confirmed through inspection of the data, further study is needed to determine if this is indeed typical behavior. Indeed it is considered likely that canonical fades as discussed in [7] would exhibit both decorrelation as well as nearly instant phase transitions.

In terms of potential detection proxies for decorrelation events, it is noted that both rapid intensity variation as well as short term phase instability can be considered only necessary conditions for decorrelation, and not sufficient conditions for detecting the onset of such events.

While access to multi frequency civil signals allows users to mitigate most of the influence of the ionosphere, the residual effects that can remain during strong scintillation events are substantial, and may require the use of a 3rd civil signal simultaneously in order to ‘sanity check’ the variations observed in the remaining two signals, or another method of ensuring that the generated ionosphere free combination is in fact free of ionospheric influence.

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REFERENCES

[1]. Carrano C. S., Groves K.M., McNeil W.J, and Doherty P.H., "Scintillation Characteristics across the GPS Frequency Band", in proceedings of the 25th ION ITM, Nashville TN, September 17-21, 2012.

[2]. Gherm V.E, Zernov N.N and Strangeways H. J., "Effects of diffraction by ionospheric electron density irregularities on the range error in GNSS dual-frequency positioning and phase decorrelation", Radio Sci., 46, 2011, RS3002, doi: 10.1029/2010RS004624.

[3]. Carrano, C. S., K. M. Groves, W. J. McNeil, and P. H. Doherty (2013), Direct measurement of the residual in the ionosphere-free linear combination during scintillation, Proceedings of the 2013 Institute of Navigation ION NTM meeting, San Diego, CA, January 28-30, 2013.

[4]. Sokolova N., A. Morrison and J. Curran (2016), High Latitude Phase Scintillation Decorrelation across GNSS Frequencies, European Journal of Navigation 2016; 14(4): 45-51.

[5]. Collins J.P. (1999), An overview of GPS inter-frequency carrier-phase combinations, Geodesy and Geomatics Engineering Report, University of New Brunswick, pp. 1-15.

[6]. Curran, J., T., Bavaro, M., and A. Morrison "Developing a Multi-Frequency Receiver for GNSS-Based Scintillation Monitoring", Proceedings of the 27th International Technical Meeting of The Satellite Division of the Institute of Navigation (ION GNSS+ 2014) September 8 - 12, 2014 Tampa Florida.

[7]. Humphreys, T.E., Psiaki, M.L., Ledvina, B.M., Cerruti, A.P., and P.M. Kintner Jr. “A data-driven test bed for evaluating GPS carrier tracking loops in ionospheric scintillation,” IEEE Transactions on Aerospace and Electronic Systems, Vol. 46, No. 4, October 2010, pp. 1609-1623.

[8]. Hegarty, C., M.B. El-Arini, T. Kim, and S. Ericson (2001) Scintillation modelling for GPS/Wide Area Augmentation System receivers, in Radio Science, Vol.36, No.5, pp 1221-1231.

BIOGRAPHY

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