32nd URSI GASS, Montreal, 19–26 August 2017

Multi-Constellation GNSS Scintillation at Mid-Latitudes

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Abstract

Radio wave scintillation can result in severe channel fading and random phase variations that can interfere with the performance of a radar, communication or GPS system. While it is well known that Ionospheric scintillation occurs within the high and low latitude regions, there has been minimal research done within the middle latitudes. However, recent observations have shown that mid-latitude scintillations, while perhaps different in size and extent, may occur more frequently than previously thought. In light of the ever-increasing coverage and availability of Global Navigation Satellite System (GNSS) satellites, we performed an analysis of multi-constellation, multi-frequency GNSS scintillation receiver data acquired during a recent minor geomagnetic storm and identified several noteworthy mid-latitude scintillation events. Data from these events were correlated by inspection with measurements made with the Super Dual Auroral Radar Network (SuperDARN) High Frequency (HF) radar network. GNSS data from the identified events and subsequent analysis demonstrate that amplitude scintillation at mid-latitudes can be severe even during relatively minor geomagnetic storm activity with amplitude scintillation levels exceeding 0.9 resulting in deep channel fading. It was also observed that L5 may be less affected by amplitude scintillation while GLONASS may be more susceptible to the impacts.

1 Introduction

Signals which propagate through the Ionosphere are vulnerable to signal degradation due to irregularities in the background electron density [1]. Radio wave scintillation, which is the temporal fluctuation in amplitude and phase of a signal, can result in severe channel fading and random phase variations that can interfere with the performance of a radar, communication or GPS system [2]. While it is well known that Ionospheric scintillation occurs within the high and low latitude regions [3, 4], there has been minimal research done within the middle latitudes where the impacts of scintillation are not routinely observed. However, recent observations [5, 6] have shown that plasma density structures which may lead to mid-latitude scintillations, while perhaps different in size and extent, may occur more frequently than previously thought. In light of the continued advancement of Ionospheric measurement capabilities, including the ever-increasing coverage and availability of Global Navigation Satellite System (GNSS) satellites, we performed an analysis of multi-constellation, multi-frequency GNSS scintillation receiver data acquired during a recent period of increased geomagnetic activity and identified several noteworthy mid-latitude scintillation events. Data from these events were correlated with measurements made with the Super Dual Auroral Radar Network (SuperDARN) High Frequency (HF) radar network which enabled us to confirm to some degree the spatial location and extent of the measurements. GNSS data from the identified events where then analyzed in detail for each constellation and their characteristics reported for comparison to results previously obtained at high, middle, and low latitudes. The goals of this research were to begin to determine the nature, severity, frequency and constellation dependence of scintillation at mid-latitudes. The results from this study provide some of the first insights into mid-latitude Ionospheric scintillation which could potentially aid in scientific research and in the development of models that will enable the physical origin and nature of the underlying perturbations to be better understood.

2 Background

Scintillation of Global Positioning Systems (GPS) signals have been extensively studied at low and high latitude regions, defined here as 0-30° and 60-90° latitude respectively, where it is often observed that amplitude scintillation is more severe at low latitudes while phase scintillation is more severe at high latitudes [3]. GNSS constellations in current operation or under development include, GPS, GLONASS, Galileo, BeiDou, QZSS and IRNSS [7], all of which contain different signal structures which operate at center frequencies which span L-band (2-4 GHz). Due to its age and availability, the most extensive research has been done with GPS signals [8, 4, 9], where it has been found that L1 (1.575 GHz) tends to scintillate less than L2 (1.227 GHz) and L5 (1.176 GHz). Research performed using GLONASS has suggested that GLONASS frequency band G1 (1.5980625 to 1.6093125) often scintillates less than G2 (1.2429375 to 1.2516875 GHz) [4, 5]. While the principles of operation of each of these systems is similar, there are differences in each of their signal structures. GPS and GLONASS, which are the only systems included in this study, all use maximum length sequences (MLS) for data transfer. GPS systems use a MLS unique to each satellite that is implemented with basic Code Division Multiplex (CDMA) while Galileo uses a more complex CDMA structure designed for enhanced performance in multipath environments [10]. GLONASS also utilizes MLS sequences for data transmission but relies on Frequency division multiple access (FDMA) for satellite identification [7].

3 Data Acquisition and Processing

GNSS signals were acquired from August 15-16, 2015, during a minor geomagnetic storm where Kp index values as high as 7 were reported. The storm began at 12:00 PM UTC time and continued through the 16^{th} of August. As shown in Figure 1, Kp index values as high as 7 where observed when the storm began and reduced to 4 as it faded out on August the 16^{th}.

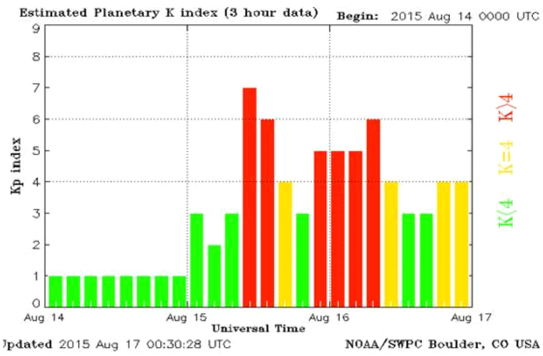

Figure 1. Kp index plot during the geomagnetic storm that occurred during August 15^{th} and 16^{th} of 2015.

Data were collected for the GPS and GLONASS constellations with a Novatel GPStation-6 receiver located at 37.205° North latitude and 80.417° West longitude using a 50 Hz sampling rate [11]. The data products include amplitude scintillation (S_4), phase scintillation (σ_ϕ^2) in radians, carrier to noise ratio density (CNR) in dB-Hz, and satellite elevation (θ) and azimuth (ϕ). Following acquisition, data were detrended over 60 seconds time segments, using a 6^{th} order Butterworth high pass filter and points with elevation angles below 10° were discarded to minimize multipath contributions from the ground.

4 Results and Analysis

Results from data acquired for the GPS and GLONASS satellites on August the 16^{th} are presented in Figure 2 as a roll-up sky plot of S_4. These results show that the most significant S_4 is consistently observed within the azimuth range 90 to 270°, which corresponds to satellites located south of the receiver. Within azimuth angles from 0 to 90° and 270 to 360° there are extensive spans of moderate amplitude scintillation at elevations angles $< 30°$ for both the GPS and GLONASS signals with values of S_4 as high as 0.4. Perhaps most significant though, are several instance where S_4 is observed to be as high 1 at elevation angles of $> 30°$. These features, which are reported in both the GPS and GLONASS data, demonstrates that high scintillation events, whose origin may be attributed to plasma processes unique to the mid-latitudes which are not yet entirely understood, can indeed occur within the mid-latitude region more frequently than previously thought.

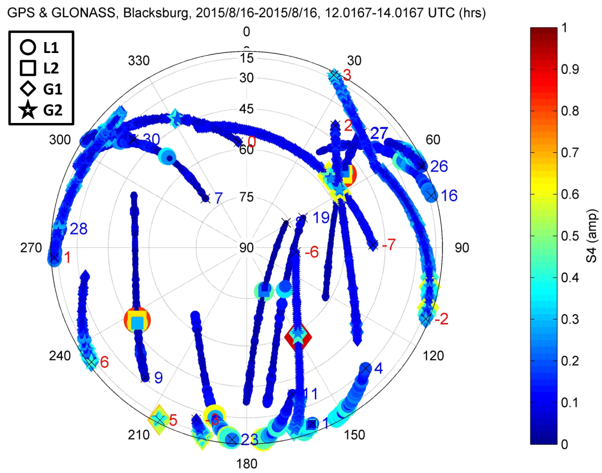

Figure 2. Sky plot of S_4 for GPS and GLONASS data acquired by a GNSS receiver located in Blacksburg, VA on August the 16^{th}, 2015 during a minor geomagnetic storm.

Results for the phase scintillation (σ_ϕ^2) data acquired on August the 16^{th} are presented in Figure 3. These data show several instances where satellites at elevations angles $< 30°$ return values of σ_ϕ^2 that reach or exceed 1 (rads), and values on the order of 0.4 (rads) are observed for elevation angles of $> 30°$. It is not clear from these data whether there is any correlation between the occurrence of amplitude and phase scintillation at mid-latitudes.

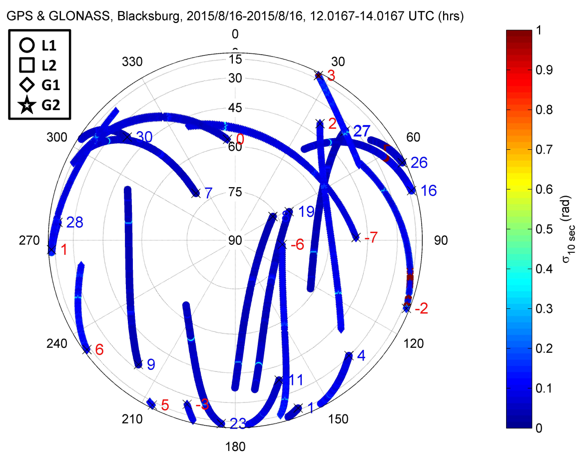

Figure 3. Sky plot of σ_ϕ^2 for GPS and GLONASS data acquired by a GNSS receiver located in Blacksburg, VA on August the 16^{th}, 2015 during a minor geomagnetic storm.

In order to gain further insight, a subset of these data were analyzed in greater detail for each constellation over the azimuth ranges of 0 to 180° and 180 to 360°.

Results for the GPS constellation, including S_4, σ_ϕ^2 and CNR, from 0 to 180° azimuth are included in Figure 4. These data show S_4 exceeding 0.8 for PRN 1 at 13.3 UTC along with a severe drop in CNR for L1 while the degree of scintillation and associated impact is not as significant for L5. In addition, rapid increase in σ_ϕ^2 is observed for PRN 26 at 12.4 UTC though the CNR for this satellite is low which may have resulted in a cycle slip.

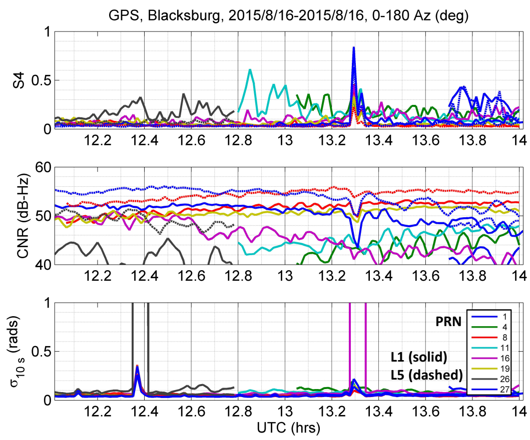

Figure 4. Results for the GPS constellation, including S_4, σ_ϕ^2 and CNR, from 0 to 180° azimuth.

Results for the GLONASS constellation for 0 to 180° azimuth angles are included in Figure 5. These data show S_4 0.9 for CHAN -6 at 13.3 UTC along with a severe drop in CNR for G1 while the degree of scintillation and associated impact may not as significant for G2. In addition, rapid increase in σ_ϕ^2 begins for CHAN -2 and 3 at 13.3 UTC. While a low CNR for this satellite may have resulted in a cycle slip it could also be the result of a loss of lock due to low signal during the amplitude fade.

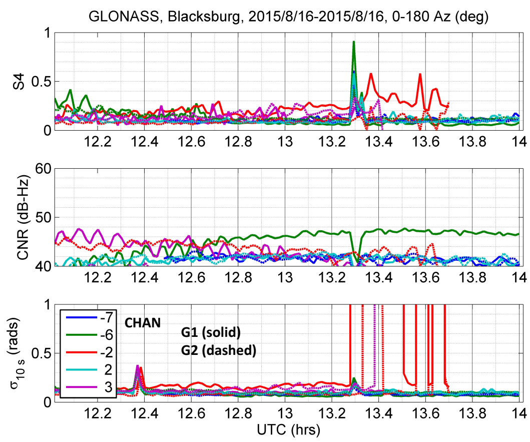

Figure 5. Results for the GLONASS constellation, including S_4, σ_ϕ^2 and CNR, from 0 to 180° azimuth.

Data from the events presented in Figure 4 and Figure 5 were correlated with measurements made by the Blackstone and Wallops Island SuperDARN radars (Figure 6). The SuperDarn data were processed over a 5 minute interval centered at the approximate time of the scintillation events. The backscatter from the Blackstone radar correlates with the scintillation events in the northwest quadrant of Figure 4 while the Wallops Island radar correlates with the scintillation events in the northeast quadrant. Unfortunately, SuperDarn does not have a field of view which overlaps the events to the south of the receiver. By inspection it is clear that there is a slow-moving feature which has been classified as Ionospheric plasma backscatter located in approximately the same location and time as the scintillation events identified in Figure 4. These results enable us to confirm ,to some degree, the spatial location extent of the features which have perhaps resulted in the scintillation in the mid-latitude GNSS measurements.

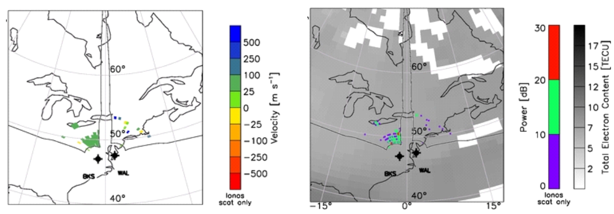

Figure 6. Velocity (left) and radar backscatter (right) plots generated by the SuperDARN radars at Blackstone and Wallops Island at 13:18:00 UTC during the minor geomagnetic storm that occurred from August 15^{th} to the 16^{th}, 2015.

5 Conclusions

The GNSS scintillation data and subsequent analysis shows that amplitude scintillation at mid-latitudes can be severe even during relatively minor geomagnetic storm activity. In the data presented in this paper it was found that for a short duration of time, amplitude scintillation levels exceeding 0.8 and 0.9 which severely degraded the CNR of the GPS and GNSS constellation signals respectively. In addition, it was observed that L5 may be less affected by amplitude scintillation while GLONASS may be more susceptible to the impacts, perhaps due to differences in their signal structures and/or power levels. While further research needs to be performed over a longer duration of time and over a wider range of conditions to draw more definitive conclusions, it is clear from the results presented in this study that scintillation at mid-latitude regions can occur even during a relatively mild geomagnetic storm and therefore may happen with greater frequency than previously thought.

6 Acknowledgments

AMDG.

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