A Multi-Constellation Analysis of Global Navigation Satellite System (GNSS) Signals in the Equatorial Region

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ABSTRACT

Recent advances in the availability of Global Navigation Satellite System (GNSS) constellations provides new opportunities to perform Ionospheric scintillation studies using different signal structures and increased spatial diversity. In this paper, we present an analysis of multi-constellation, multi-frequency GNSS receiver data acquired in the Equatorial region throughout the first part of 2017 and during a recent minor geomagnetic storm. The objectives of this research were to investigate the frequency and constellation dependence of scintillation in order to gain insight into the propagation environment and to aid in the future development of mitigation strategies and signal models. Analysis of the data revealed amplitude scintillation excursions reported by GPS and GLONASS that were routinely higher than Galileo, BeiDou and SBAS which utilize more modern signal structures, while elevated values were observed for L2 that may be due to low carrier-to-noise ratio (CN0). Unexplained high phase scintillation was also reported for SBAS signals, the root cause of which along with the apparent resistance of newer constellations to deep amplitude scintillation excursions will be investigated as a continuation of this work.

1. INTRODUCTION

Signals which propagate through the Ionosphere are vulnerable to signal 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 a GPS system [1, 2]. While an extensive amount of Ionospheric scintillation research has been performed using legacy GPS signals, the ever-increasing availability and wide variety of modern Global Navigation Satellite System (GNSS) constellations provides new and largely unexplored opportunities to perform scintillation studies using more advanced signal structures and enhanced spatial diversity. In light of these advancements we performed a statistical analysis of multi-constellation, multi-frequency GNSS scintillation data acquired from a receiver located on Lihue, Hawaii, during the first part of 2017. The results obtained by our analysis enabled a period of increased scintillation activity which coincided with a recent minor geomagnetic storm to be readily identified and a more detailed analysis was then completed. This analysis, which was performed on signals spanning the GPS frequency band included observations from GPS, GLONASS, GALILEO, BeiDou, and SBAS navigation systems, and demonstrated that differences, though often subtle, exist between the response of each constellation under the same regional Ionospheric conditions. While the physical origin and significance of the observed differences cannot be ascertained without a more comprehensive statistical analysis, these data provide valuable insight which could potentially aid in scientific research and serve as motivation for the continued acquisition of data coupled with the development of signal models to support deeper investigation.

2. BACKGROUND

Ionospheric scintillation has been extensively studied within the Equatorial region, defined here as 0-30° geographic latitude, where it has been observed that amplitude scintillation tends to be more prominent than phase scintillation [3]. While extensive research has routinely been done with GPS signals [4, 5], and to a lesser extent a subset of modern signals [6], there are numerous GNSS constellations which have been recently fielded, or that are under development which also operate at center frequencies which span L-band (2-4 GHz) [7]. These modern constellations, which include upgraded GPS and GLONASS, Galileo, BeiDou, QZSS, SBAS and IRNSS, have similarities and unique qualities in their signal structures that could increase their resistance to multipath interference and Ionospheric scintillation [7, 8]. For instance, GPS systems have historically used a maximum length sequence (MLS) unique to each satellite that is implemented with basic Code Division Multiplex (CDMA) while Galileo uses a more complex CDMA structure including variable length pilot channel codes designed to enhance performance in multipath and low signal environments. GLONASS on the other hand uses CDMA for data transmission but relies on Frequency Division Multiple Access (FDMA) for satellite identification [7]. Previous research performed at mid-latitudes comparing multi-constellation, multi-frequency GNSS scintillation data has presented compelling results suggesting that Galileo is less susceptible to scintillation than GPS, while GPS tends to scintillate less than GLONASS [9].

2. DATA

Multi-constellation scintillation data were acquired from February to May, 2017 using a Septentrio PolaRx5S receiver located on Lihue, Hawaii. These data were processed and analyzed statistically to identify noteworthy periods of scintillation. An event which occurred during a minor geomagnetic storm on April 4, 2017 was selected and analyzed in greater detail to compare the response of each of the signals acquired. The following sections detail the acquisition, processing, analysis and results.

2.1 ACQUISITION

Multi-constellation scintillation data were acquired using a Septentrio PolaRx5S receiver and PolaNt Choke Ring B3/E6 antenna located on Lihue, Hawaii (Figure 1). Binary data files were logged at 50 Hz for all available constellations, saved to an external drive for post-processing, and processed into Ionospheric analysis products to facilitate real-time exfiltration.

Figure 1. Septentrio PolaRx5S receiver and PolaNt Choke Ring B3/E6 antenna located on Lihue, Hawaii.

2.2 PROCESSING

The raw binary files were processed into Ionospheric analysis quantities and saved in Septentrio's ISMR asciii file format. Processed signals included GPS (L1CA, L2C, L5), GLONASS (L1CA, L2C), GALILEO (L1BC, E5a, E5b), BeiDou (B1, B2), and SBAS (L1CA, L5). ISMR files were merged and truncated to limit satellites positions to those located at azimuth angles ranging from 90 and 270° in order to focus on the Equatorial region during the longer-term statistical analysis. Additionally, an elevation mask of 25° and a minimum threshold of 0.15 for noise-corrected amplitude scintillation indices S4 were utilized as suggested by [10] in order to minimize multipath interference and identify noteworthy Ionospheric scintillation events.

2.3 RESULTS AND ANALYSIS

After applying the azimuth filter, elevation mask and S4 threshold it was found that scintillation occurred on 44 out of the 80 total days during which data was logged and a total of 653 events were reported. Further analysis revealed that 70% of the events occurred on April 4, 2017 during a minor geomagnetic storm where Kp index values reached 5. Histograms of the amplitude scintillation events, broken out by constellation and frequency band, are included in Figure 2 along with a histogram of the event times. These data include several noteworthy features such as routinely higher excursions reported by GPS and GLONASS in all three bands compared to Galileo, BeiDou and SBAS which all utilize modern signal structures. In addition, SBAS primarily reports low scintillation which is perhaps due to its use of geostationary orbits. These data also show that the majority of the scintillation activity was moderate with S4 typically less than 0.2 and occurred from 7 to 11 AM UTC (9 PM to 1 AM HST). These results, which were reported during a small storm and commenced shortly after sunset, have characteristics consistent with previous findings [9, 10]. It was therefore concluded that the identified events could be primarily attributed to Ionospheric scintillation and were worth analyzing in greater detail.

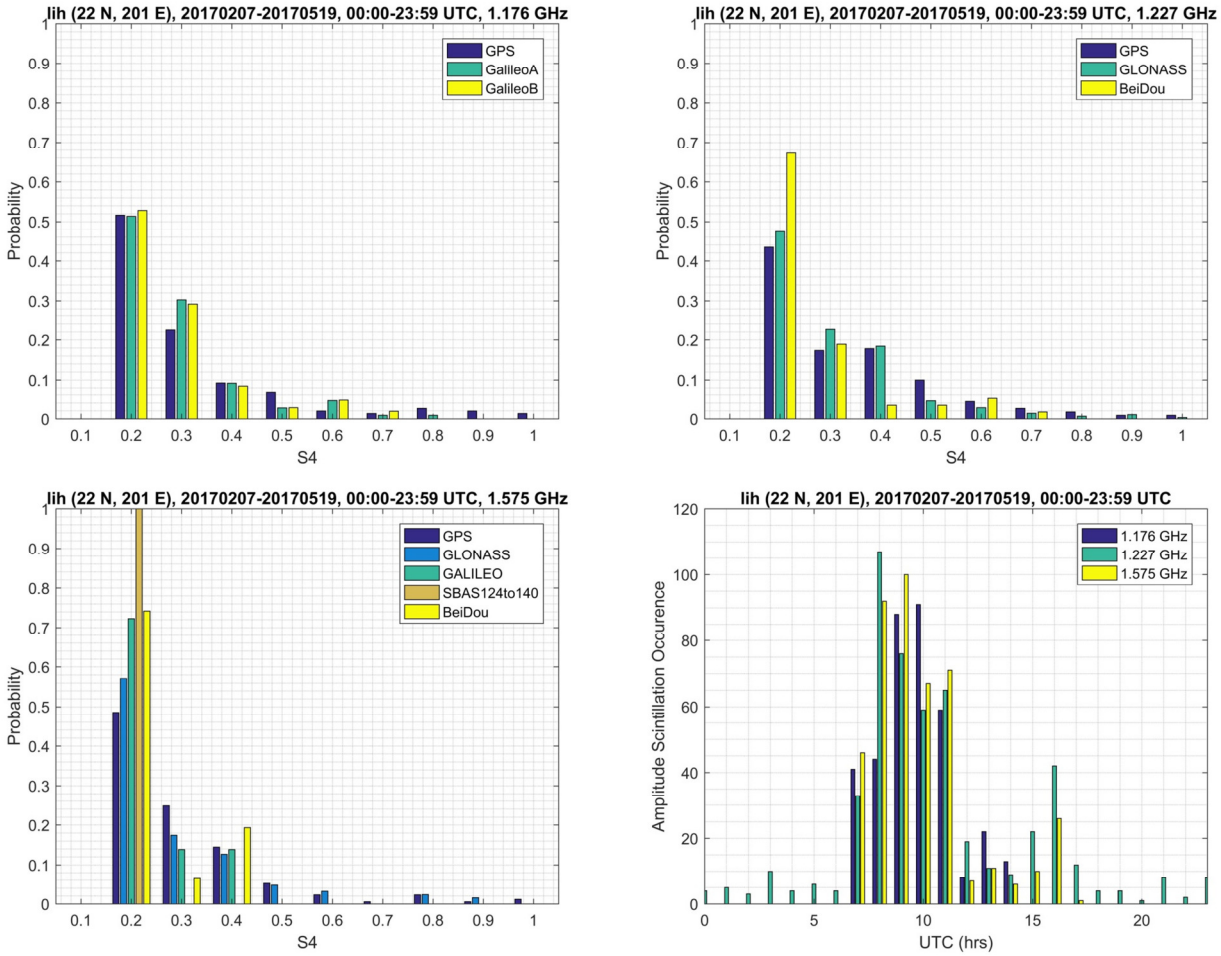

Figure 2. Histograms of the amplitude scintillation events and times for the data acquired at Lihue, Hawaii from February 7 to April 19, 2017, for 90-270° azimuth, 25° elevation mask and S4>0.15. Note: frequency refers to the center of each band.

Following these results a subset of the data was produced for April 19, 2017. For this analysis the observation times were reduced to 7 to 11 PM UTC, the S4 threshold was discarded and all azimuths angles were considered. Sky plots of the amplitude and phase scintillation and carrier-to-noise ratio (CN0) with these modified processing steps are presented in Figure 3. As expected, these data report more significant amplitude scintillation events located south of the receiver (90 to 270 degrees) when the satellites were closer to the geomagnetic equator, with values of S4 approaching 1 at ~190 degrees and a general increase in the southwestern quadrant (180 to 270 degrees). Comparing S4 values for all of the bands the background scintillation levels appear to increase with frequency while numerous elevated values were reported for L2 across all azimuth angles. These results were unexpected as conditions producing moderate scintillation are thought to lead to values of S4 which decrease with frequency [11]. However, this finding may be partially attributed to variations in CN0 in each band as reduction in the CN0 can be expected to reduce the signal-to-interference-and-noise ratio (SINR) and subsequently degrade the natural interference rejection qualities of the GNSS signals. Examining the phase scintillation index, it appears as though it is generally less than S4 which is consistent with past observations [10]. Two notable exceptions are the SBAS data which reports relatively high phase scintillation and the events at ~190 degrees. The SBAS results are somewhat surprising given that two of the BeiDou satellites also have geostationary orbits yet report

low amplitude and phase scintillation. This result merits further investigation and exploration of the root cause will be completed as part of future work. In the case of high phase scintillation at ~190 degrees, this event is clearly correlated with high S4 and low CN0 and loss of receiver lock has presumably occurred. Finally, data acquired to the north where satellites are at mid-latitudes routinely report low scintillation as expected.

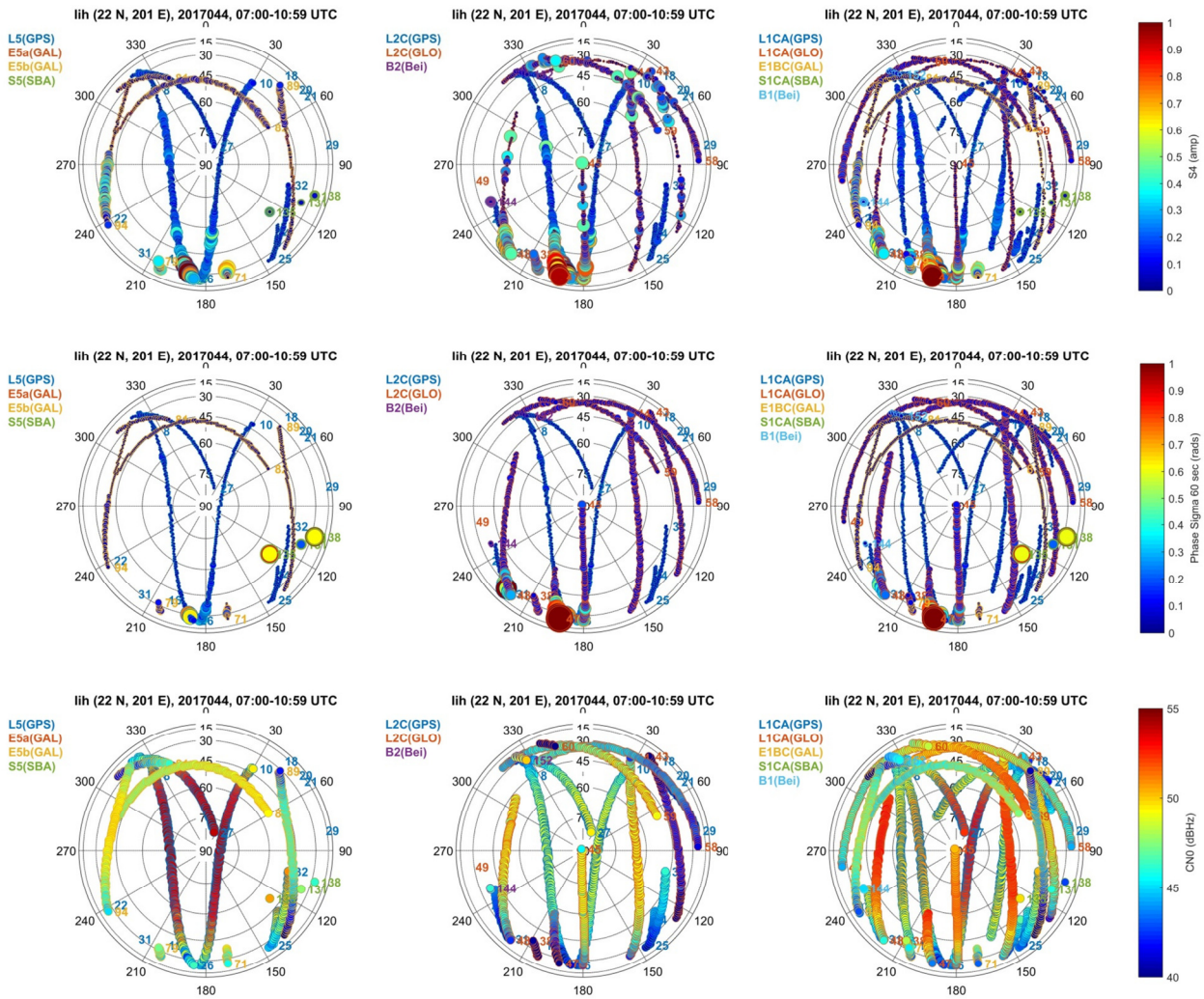

Figure 3. Sky plots of the amplitude and phase scintillation, and carrier-to-noise ratio (CN0) for the data acquired at Lihue, Hawaii on April 4, 2017, from 7-11 UTC, for 0-360° azimuth and 25° elevation mask. The outline of data circles and satellite numbers associated with tracks are colored by constellation and signal. The size of scintillation data points have been scaled for visualization.

3. CONCLUSIONS

In this paper multi-constellation, multi-frequency data acquired on Lihue, Hawaii during the first part of 2017 were analyzed statistically and a set of generally modest amplitude scintillation events where identified after dusk during a minor storm. Histograms of the events and times revealed amplitude scintillation excursions reported by GPS and GLONASS that were routinely higher than Galileo, BeiDou and SBAS which utilize more modern signal structures. Following these results a

subset of data was analyzed in greater detail where it was found that the highest amplitude scintillation levels occurred towards the geomagnetic equator while elevated values were reported for L2 across all azimuth angles which may be due to relatively low CN0. Levels of high phase scintillation were reported during a period of amplitude fading that correlated with high S4 and low CN0 leading to apparent loss of receiver lock. Unexplained high phase scintillation was also reported for SBAS signals, the root cause of which along with the apparent resistance of newer constellations to deep amplitude scintillation excursions will be investigated as part of future research.

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