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A study of multi-GNSS ionospheric scintillation and cycle-slip over Hong Kong region for moderate solar flux conditions

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Abstract

This study presents the characteristics of Multiple Global Navigation Satellite System (Multi-GNSS) ionospheric scintillation and cycle-slip occurrence through the analysis of Multi-GNSS data collected by a newly installed receiver located at Sha Tin of Hong Kong from 6 October 2015 to 31 December 2016. This period of time was under a moderate solar activity condition with average sunspot number and $F10.7$ as 44 and 92, respectively. Considering the frequent occurrence of loss of lock in satellites measurements in the presence of ionospheric scintillation, a rate of geometry-free (ROGF) combination is proposed to take the time gap size between two data arcs into account in the cycle-slip detection. The results show that most ionospheric scintillation events and cycle-slips are observed from 20:00 LT to 0:00 LT. Under the strong scintillation ($S_4 > 0.6$) conditions, it is found that the time series of wide-land (WL) ambiguity N_{WL} and $ROGF$ vary significantly and their range can reach more than 50 cycles and 0.1 m/s, respectively. However, the variations of the N_{WL} and $ROGF$ are generally small under weak scintillation ($0.2 < S_4 \leq 0.6$) or non-scintillation ($S_4 \leq 0.2$) conditions. A strong correlation of scintillation and cycle-slip occurrence is also verified by the daily and spatial statistics results. In addition, it is found that on average every 1000 strong scintillation events can result in 200, 124, and 171 cycle-slip occurrences in GPS, GLONASS, and BDS, respectively, whereas these values are 7, 12, and 12 per 1000 under weak scintillation conditions. This study suggests that cautions be taken when GNSS measurements are contaminated by the strong ionospheric scintillation in GNSS applications such as real-time kinematic (RTK) and precise point positioning (PPP).

Keywords: Multiple global navigation satellite system; Ionospheric scintillation; Cycle-slip; Low-latitude

1. Introduction

Ionosphere has a significant impact on satellite navigation, communications, and radar systems. As satellite radio signals propagate from space through the ionosphere to the ground, they would suffer various ionospheric effects such as phase fluctuations, amplitude fluctuations, group delay, absorption, scattering, and frequency shifts (Bernhardt et al., 2006; Chen et al., 2008). Ionospheric scintillation is a random fluctuation of amplitude and phase while radio signals pass through ionospheric plasma irregularities. Ionospheric scintillation can be classified into amplitude scintillation and phase scintillation (Crane, 1977), which are usually characterized by indexes S_4 and σ_{φ}, respectively (Van Dierendonck et al., 1993). Scintillations frequently occur in the equatorial, low-latitude and polar region, especially during solar maximum (Li et al., 2010; Meggs et al., 2008; Moreno et al., 2011). Scintillations occurring in equatorial and low-latitude are mainly caused by equatorial F-region irregularities, which encompass a wide range of scale sizes from several hundred kilometers to a few centimeters

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(Kil and Heelis, 1998). Scintillations occurring in polar region are mainly caused by steep ionospheric density gradients associated with auroral arc and cusp precipitation as well as polar cap patches (Prikryl et al., 2013; Weber et al., 1984). Strong amplitude and phase scintillations can be observed at equational and low-latitude regions (Jiao and Morton, 2015). In high-latitude regions, phase scintillations are more frequent and intense than amplitude ones (Jiao et al., 2013; Skone et al., 2008).

Ionospheric scintillation can degrade the data quality of many Earth observation systems such as GNSS, astronomical observations, and Doppler Orbit and Radio Positioning Integration by Satellite (DORIS) (Aquino et al., 2005; Bernhardt et al., 2006; Milan et al., 2005; Sreeja et al., 2011). To GNSS users, amplitude scintillation possibly leads to signal-to-noise-ratio (SNR) of GNSS signal level that drops below the receiver's phase lock loop (PLL), while phase scintillation can cause an apparent Doppler shift that sometimes exceeds the bandwidth of the receiver's PLL. Before reacquiring the signal, a delay in receiver would be generated. This phenomenon is called cycle-slip (Banville et al., 2010). One cycle of slip in GNSS carrier phase data can bring in a range error of $\sim$20 cm to GPS L_1 measurements (Liu, 2011), which may result in an intolerable error to the GNSS positioning solution. In GNSS real-time kinematic (RTK) and precise point positioning (PPP) applications, positioning precision of decimeter and even centimeter depends on reliable and high quality carrier phase measurements that have no cycle-slips or have cycle-slips corrected (Ge et al., 2008; Grejner-Brzezinska et al., 2007). On the other hand, it is a big challenge to detect and especially correct cycle-slip occurring in ionospheric scintillation compared to the case without scintillation. Under scintillations, observational noise will become larger because of the fading of GNSS measurements. In addition, continuous cycle-slips can occur and last several minutes owing to intensive ionospheric scintillations. Therefore, investigating a suitable method of cycle-slip detection and analyzing the characteristics of cycle-slip occurrence in the presence of ionospheric scintillation are of significant value to both GNSS manufacturers and users.

Over the past years, the study of cycle-slip occurrence in the presence of ionospheric scintillation has been an interesting research area, in which there are two focuses in general, i.e. methods of cycle-slip detection and correction (Banville et al., 2010; Banville and Langley, 2013; Ji et al., 2013b) and characteristics of cycle-slip occurrence (Prikryl et al., 2014; Zhang et al., 2010). For the former research topic, Banville and Langley (2013) proposed a geometry-based approach to detect cycle-slip and applied the least-squares adjustment to determine their magnitude. This technique is effective in resolving the discontinuities of carrier-phase measurements caused by ionospheric irregularity. In order to mitigate code measurement noise in the presence of ionospheric scintillation, Ji et al. (2013b) used carrier-phase measurements to combine non-geometry-free and ionosphere-free quantities to detect and correct cycle-slip. However, the threshold of cycle-slip occurrence was not discussed in Ji et al. (2013b). In the study of the characteristics of cycle-slip occurrence, focusing on high-latitude region, Prikryl et al. (2010) reported numerous GPS cycle-slips and strong scintillation observed during solar minimum of 2008–2009, which were associated with auroral arc and polar cap patches. More recently, the characteristics of occurrence of phase scintillation and cycle-slip during high-speed solar wind streams and interplanetary coronal mass ejections are shown in Prikryl et al. (2014). It illustrates that phase scintillation and cycle-slip occur predominantly on the dayside in the cusp and in the nightside auroral oval. However, quantitative analysis of cycle-slips and scintillation events is not shown in the aforementioned two references. For low-latitude region, Zhang et al. (2010) investigated the features of GPS cycle-slip occurrences related to ionospheric irregularities. Based on GPS data collected at China low-latitude region, it is found that cycle-slips frequently occur in 19:00–22:00 local time (LT). Meanwhile, coincided with seasonal occurrence of ionospheric scintillation over the Asia-Pacific longitude sector, most cycle-slips have been detected in the equinox months. Zhang et al. (2010) shows the relationship between the number of cycle-slip occurrences and ionospheric irregularities, which is expressed by the spread F (SF) data as well as Ap index. Nevertheless, different from scintillation indexes S_4 and σ_φ, the SF data or Ap index is unable to completely illustrate the real level of ionospheric scintillation (Jiao and Morton, 2015). Most recently, the aspect of scintillation enhancement and loss of phase lock (cycle-slip) conditions due to field-aligned (longitudinal) propagation for low-latitude region is discussed in de Oliveira Moraes et al. (2017).

Located in the geomagnetic equatorial region, GNSS receivers in Hong Kong area (geographic 22.3°N, 114.2°E) often experience strong scintillations (Chen et al., 2008; Ji et al., 2013a; Xu et al., 2012). Previous studies in Hong Kong showed that ionospheric disturbances were observed in more than one third time of year during the solar maximum of 2001 (Chen et al., 2008). In addition, the number of losses of lock for Leica CRS receiver can reach up to 500 per day in strong scintillations, while in quiet days it significantly decreases to 50 per day (Chen et al., 2008). Compared to previous studies, this work represents the first attempt to investigate the characteristics of ionospheric scintillation and cycle-slip occurrence using multi-GNSS (i.e., GPS, GLONASS, BDS, and Galileo) data collected at Sha Tin station in Hong Kong.

In the following sections, we first describe the data and method used to compute two scintillation indexes and cycle-slip detection. Then, the hourly, daily, spatial distribution of scintillation event and cycle-slip are analyzed. Finally, a conclusion is given at the end of this paper.