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ScienceDirect

Advances in Space Research 55 (2015) 605–616

ADVANCES IN SPACE RESEARCH
(a COSPAR publication)

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Evaluation of Precise Point Positioning accuracy under large total electron content variations in equatorial latitudes

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Received 13 June 2014; received in revised form 16 October 2014; accepted 3 November 2014

Abstract

The ionosphere is one of the largest contributors to errors in GNSS positioning. Although in Precise Point Positioning (PPP) the ionospheric delay is corrected to a first order through the ‘iono-free combination’, significant errors may still be observed when large electron density gradients are present. To confirm this phenomenon, the temporal behavior of intense fluctuations of total electron content (TEC) and PPP altitude accuracy at equatorial latitudes are analyzed during four years of different solar activity. For this purpose, equatorial plasma irregularities are identified with periods of high rate of change of TEC (*ROT*). The largest *ROT* values are observed from 19:00 to 01:00 LT, especially around magnetic equinoxes, although some differences exist between the stations depending on their location. Highest *ROT* values are observed in the American and African regions. In general, large *ROT* events are accompanied by frequent satellite signal losses and an increase in the PPP altitude error during years 2001, 2004 and 2011. A significant increase in the PPP altitude error RMS is observed in epochs of high *ROT* with respect to epochs of low *ROT* in years 2001, 2004 and 2011, reaching up to 0.26 m in the 19:00–01:00 LT period.

Keywords: Ionosphere; GNSS; PPP; Equatorial plasma irregularities

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1. Introduction

Precise Point Positioning (PPP) is a technique in which single-receiver (un-differenced) GNSS (Global Navigation Satellite System) code and carrier phase observations are processed along with precise satellite orbits and clocks to obtain high accuracy receiver position (Zumberge et al., 1997; Bisnath and Gao, 2007). After the application of satellite precise products, ionosphere is the major error source in the receiver–satellite range, and thus in positioning. The ionospheric bias in the receiver–satellite range reaches several tens of meters. Due to the dispersive nature of the ionosphere, dual frequency PPP offers the chance to linearly combine the observables and remove the first order effect of the ionospheric refraction (Seeber, 2003). The remaining ionospheric errors, which include higher order terms, the bending of the optical path and total electron content (TEC) differences at two frequencies, depend on the satellite line of sight and Earth’s magnetic field, and

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http://dx.doi.org/10.1016/j.asr.2014.11.004
0273-1177/

may reach several centimeters in GNSS ranges (Brunner and Gu, 1991; Hoque and Jakowski, 2007; Kashcheyev et al., 2012).

PPP may be performed in either static or kinematic mode, both in real time or post-processing, providing different levels of accuracy. In real time kinematic PPP position accuracy may reach, after a short time of initialization, 5 cm in the horizontal and 10 cm in the vertical (Zhang et al., 2010). Moreover, ambiguity resolution may significantly improve these accuracies, although convergence time would increase (Geng et al., 2011; Ge et al., 2012). In post-processing, after 30 min, cm-level accuracy is expected in static mode while dm-level is reached in kinematic mode (Bisnath and Gao, 2007). However, under large ionospheric electron density gradients, significant errors may still be observed in position estimation (Moreno et al., 2011; Pi et al., 2013).

Low latitude F-region nighttime plasma irregularities are a concern for GNSS users, since they may scatter and diffract signals and produce strong variations in phase and amplitude, effect known as scintillation (Basu et al., 1986; Kintner et al., 2007; Jakowski et al., 2008). The presence of scintillation may significantly degrade navigation signals and, in last instance, positioning (Pi et al., 2013). PPP accuracy in periods of abrupt changes in the ionosphere electron density depends on the receiver ability to deal with the presence of scintillation, which may cause cycle slips, loss of lock or a complete loss of the signal tracking. Signal losses constitute a serious threat for positioning, since the ambiguities re-estimation is required which takes some minutes to converge. In this context, a big effort has been accomplished to improve the robustness of GPS receivers to deal with GNSS signals affected by scintillation (Aquino et al., 2009). However, as it will be shown in the present study, high TEC variations still may cause accuracy deterioration in positioning. The reason of these large errors, beside the signal loss and higher order ionospheric effects, may be related in one hand, to the diffraction effect that will not be canceled in the “iono-free” combination (Carrano et al., 2013) and, in the other hand to unexpected large residual ionospheric delays which may exceed the default thresholds set in the cycle slip detection algorithms, resulting in a flagged cycle slip that may not be real cycle slip, causing ambiguities estimation to be re-initialized unnecessarily (Zhang et al., 2014). All these contributions to positioning errors will depend on which satellite of the constellation geometry is the affected one.

Ionospheric irregularities evolve in the domain of the Equatorial Ionospheric Anomaly (EIA) from plasma density perturbations originated in the bottomside of the F region by means of the Rayleigh–Taylor mechanism (Sultan, 1996). They rise to the topside, creating low density structures inside a denser plasma zone, where smaller scale irregularities may coexist generating sharp electron density gradients (Basu et al., 1978). The uplift of the F region is necessary for the generation and evolution of these irregularities (Fejer et al., 1999). Moreover, the E region eastward electric field pre-reversal enhancement (PRE), that takes place before sunset, intensifies the plasma raise and favors the irregularities formation (Abdu, 2001). As a result, a clear correlation exists between the maximum PRE and the irregularity occurrence periods (Li et al., 2007) with maximums in years of high solar activity (Fejer et al., 1999; Whalen, 2004) and showing also both seasonal–longitudinal variability (Burke et al., 2004; Gentile et al., 2006, 2011; Ren et al., 2009; Magdaleno et al., 2012) and magnetic activity dependencies (Fejer et al., 1989; Abdu et al., 2003, 2009a). However, this is not enough to explain the daily variation in the occurrence of electron density irregularities, since under quiet geomagnetic conditions, an instability trigger that leads to irregularities development seems to be necessary (Singh et al., 1997; Tsunoda, 2006; Abdu et al., 2009b). The L-band scintillation occurrence observed by de Paula et al. (2007) or Paznukhov et al., (2012) follows a similar climatology as the irregularities studied by other authors such as Gentile et al. (2006, 2011). This is not surprising, since there are numerous studies that characterize equatorial plasma irregularities by means of both ionospheric total electron content (TEC) or phase fluctuations and L-band scintillation indices, and a huge effort has been made in the last years trying to find a correlation among these parameters to better monitor irregularities and their effects on signal propagation (Basu et al., 1999; Beach and Kintner, 1999).

In this work, equatorial plasma irregularities are identified by means of the analysis of GNSS-derived ROT at low latitudes and different longitudes. The analyzed time period corresponds to four years with different solar activity (low, moderate and high). The influence of intense ROT on GNSS signals loss and PPP accuracy is studied. For this purpose, the CSRS-PPP online program, developed by Natural Resources Canada, Canadian Spatial Reference System (NRCan’s CSRS, Banville et al., 2009) is used to obtain kinematic PPP estimates. As far as we know, this is the first time that a ROT threshold value is used for a phenomenological description of equatorial plasma irregularities occurrence. It is also the first time that PPP errors are presented as a function of local time and day of the year (season), covering different solar activities and geographical longitudes.

2. Data description

A dataset of GNSS dual frequency code and phase observations at 30 s sampling rate from years 2001, 2004, 2008 and 2011 has been selected. The data were collected at six permanent stations integrated in the international GNSS service (IGS) and located in the proximities of the magnetic equator at different longitudes (Fig. 1). An effort was made to select IGS equatorial stations with a considerable amount of yearly observations but, unfortunately, during 2008 in NKLG station the quality of the data was poor and during 2011 no data files were found for MALI. Depending on the stations longitude, three groups can be