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ScienceDirect

Advances in Space Research 54 (2014) 871–882

ADVANCES IN SPACE RESEARCH
(a COSPAR publication)

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Estimation of GPS instrumental biases from small scale network

Guanyi Ma [a,*], Wei Gao [b], Jinghua Li [a,c], Yanhong Chen [d], Hua Shen [d]

[a] National Astronomical Observatories, Chinese Academy of Sciences, 20A Datun Road, Chaoyang District, Beijing 100012, China
[b] National Library of China, No. 33 Zhongguancun Nandajie, Hai Dian District, Beijing 100081, China
[c] Graduate University of Chinese Academy of Sciences, Beijing, China
[d] Center for Space Science and Applied Research, Chinese Academy of Sciences, No. 1 Nanertiao Zhongguancun, Haidian Dsitrict, Beijing 100080, China

Abstract

With 4 GPS receivers located in the equatorial anomaly region in southeast China, this paper proposes a grid-based algorithm to determine the GPS satellites and receivers biases, and at the same time to derive the total electron content (TEC) with time resolution of 15 min and spatial resolution of 1° by 3.5° in latitude and longitude. By assuming that the TEC is identical at any point within a given grid block and the biases do not vary within a day, the algorithm arranges unknown biases and TECs with slant path TEC from the 4 receivers' observations into a set of equations. Then the instrumental biases and the TECs are determined by using the least squares fitting technique. The performance of the method is examined by applying it to the GPS receiver chain observations selected from 16 geomagnetically quiet days in four seasons of 2006. It is found that the fitting agrees with the data very well, with goodness of fit ranging from 0.452 TECU to 1.914 TECU. Having a mean of 0.9 ns, the standard deviations for most of the GPS satellite biases are less than 1.0 ns for the 16 days. The GPS receiver biases are more stable than that of the GPS satellites. The standard deviation in the 4 receiver bias is from 0.370 ns to 0.855 ns, with a mean of 0.5 ns. Moreover, the instrumental biases are highly correlated with those derived from CODE and JPL with independent methods. The typical precision of the derived TEC is 5 TECU by a conservative estimation. These results indicate that the proposed algorithm is valid and qualified for small scale GPS network.

Keywords: GPS; Radiowave propagation; Ionosphere; TEC; Instrumental biases

1. Introduction

Correlated with the peak electron density of the ionosphere, TEC is one of the most important parameters in the study of the ionosphere. Since the civilian use of the Global Positioning System (GPS) was enabled, the ionospheric TEC has been measured with dual frequency GPS receivers economically and effectively. The principle is based on the frequency dependence of the refractive index of radio waves in the ionospheric plasma. As the GPS receivers being set up to form networks, characteristics of the ionosphere have been studied extensively with GPS-TEC (Saito et al., 1998; Maruyama et al., 2004; Mendillo, 2006; Shim et al., 2008). The NASA Jet Propulsion Laboratory (JPL) produces global maps of the TEC by using data from over 100 continuously operating GPS receivers in a global network (http://iono.jpl.nasa.gov/gim.html). Real-time TEC maps derived from the GPS Earth Observation Network (GEONET) in Japan are published in the web site http://wdc.nict.go.jp/IONO/index_E.html of National Institute of Information and Communications Technology (NICT). These maps are used to monitor ionospheric weather, and to nowcast ionospheric storms that often occur responding to activities in solar wind and Earth's magnetosphere as well as thermosphere.

However, an instrumental delay bias exists in each GPS signal which is originated in the hardware of the GPS satellite and receiver. The difference between the instrumental

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* Corresponding author. Tel.: +86 10 64807619.
E-mail addresses: guanyima@nao.cas.cn (G. Ma), zbgwnick@163.com (W. Gao), jhli@nao.cas.cn (J. Li), chenyh@cssar.ac.cn (Y. Chen), shenh@cssar.ac.cn (H. Shen).

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http://dx.doi.org/10.1016/j.asr.2013.01.008

delays in the two signals, referred to as instrumental or differential instrumental bias, affects the accuracy of the TEC estimation greatly. The combined satellite and receiver biases can even lead to a negative TEC. For accurate estimation of TEC, satellite and receiver instrumental biases should be removed from GPS measurements properly, which have been accomplished by researchers with different methods (Lanyi and Roth, 1988; Coco et al., 1991; Wilson et al., 1995; Sardón et al., 1994; Mannucci et al., 1998; Iijima et al., 1999; Otsuka et al., 2002; Ma and Maruyama, 2003; Miyake, 2007; Arikan et al., 2008; Zhang et al., 2009, 2010). In the early times the ionosphere was observed with a single GPS receiver, the instrumental biases and the TEC were assessed by representing the TEC as a polynomial of latitude and longitude based on the assumption of a smooth ionospheric behavior (Lanyi and Roth, 1988; Coco et al., 1991). Later with data from several GPS receivers, the TEC and the biases were simulated with random walk stochastic process and solved by using a Kalman filter approach (Sardón et al., 1994; Sunehra et al., 2010). Based on a spherical surface harmonic expansion of the TEC in latitude and longitude, the instrumental biases were removed and the Northern hemisphere map of TEC was obtained with an early sparse global GPS network (Wilson et al., 1995). With the global network of over 100 GPS receivers, JPL models the vertical TEC in a solar-geomagnetic reference frame using bi-cubic splines on a spherical of 2.5° by 5.0° latitude and longitude. Then a Kalman filter is applied to solve simultaneously for TEC and instrumental biases (Mannucci et al., 1998; Iijima et al., 1999). Using around 300 GPS receivers selected homogeneously from GEONET, and assuming that the TEC is identical at any point within a 2° by 2° grid block, the TEC over Japan and instrumental biases were determined with least squares fitting technique (Ma and Maruyama, 2003). MIT Haystack Observatory developed a software package MIT Automated Processing of GPS (MAPGPS) to automate the process of downloading and processing GPS data to produce global TEC maps. The data is provided as estimates of TEC in 1° by 1° bins every 5 min distributed over those locations where data is available (Rideout and Coster, 2006). Recently, a Matlab based software was designed to estimate GPS differential code biases for both global and regional GPS networks (Jin et al., 2012).

Aimed to study the equatorial anomaly region, a small scale GPS receiver network has been established in southeast China. As a first step, an appropriate algorithm should be proposed to estimate the instrumental biases and derive the TEC based on the GPS observation of this network. This paper presents the algorithm and analyzes the results from its applications. Starting from the radio propagation theory, Section 2 describes the development of the algorithm on deriving the TEC and estimating the instrumental biases in detail. Section 3 presents the results of an application of the proposed algorithm to three geomagnetically quiet days in the four seasons of 2006. It shows the day-to-day variation and the stability of the instrumental biases over a 10-month time, and analyzes the characteristics of the derived TEC over the anomaly region. Comparison of the satellite biases is made with those obtained with independent methods. Section 4 evaluates how accurate the observation data is fitted by using the proposed method. The precision of the derived TEC is estimated roughly. Section 5 draws the conclusions of the study.

2. Derivation of TEC from the GPS receiver chain

2.1. Transionospheric radio propagation

For GPS satellite signals propagating through the ionosphere, the refractive index can be expressed as

$$n_p = 1 - \frac{e^2 N_e}{8\pi^2 \varepsilon_0 m_e f^2} \tag{1}$$

where f is the frequency, e, the electron charge, m_e, the electron mass, ε_0, the permittivity of free space, and N_e, the electron density of the ionosphere. And the group refractive index is given by

$$n_g = 1 + \frac{e^2 N_e}{8\pi^2 \varepsilon_0 m_e f^2} \tag{2}$$

If denoting $\frac{e^2}{8\pi^2 \varepsilon_0 m_e}$ with b, the phase advance and the group delay caused by the ionosphere to the radio wave can be calculated from

$$\Delta t_p = \int_l \frac{1}{c}(n_p - 1)dl = -\frac{b}{cf^2}\int_l N_e dl = -\frac{b}{cf^2} N_T \tag{3}$$

$$\Delta t_g = \int_l \frac{1}{c}(n_g - 1)dl = \frac{b}{cf^2}\int_l N_e dl = \frac{b}{cf^2} N_T \tag{4}$$

where $N_T = \int_l N_e dl$ is the electron density integrated over the propagation path length, and is known as the vertical TEC or just TEC for simplicity if the ray path is vertical, otherwise slant path TEC.

2.2. Slant path TEC extraction from GPS observables

There are 24 GPS satellites designed to orbit the Earth at an inclination of 55° and at a height of 20,200 km. They broadcast information on two frequency carrier signals, which are 1.57542 GHz (referred to as f_1) and 1.2276 GHz (referred to as f_2), respectively. For a dual frequency GPS receiver, it has 4 basic observables, two distances (known as pseudorange), P_1 and P_2; and two phase measurements, L_1 and L_2, corresponding to the two signals. The pseudorange is related with the group delay,

$$P_1 = \rho + c\Delta t_{g1} + c\Delta t_0 \tag{5}$$

$$P_2 = \rho + c\Delta t_{g2} + c\Delta t_0 \tag{6}$$

and the carrier phase with the phase advance,

$$L_1 = \frac{P_1}{\lambda_1} - \varphi_1 = \frac{\rho}{\lambda_1} + f_1\Delta t_{p1} + f_1\Delta t_0 - \varphi_1 \tag{7}$$