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NEAR REAL-TIME MONITORING OF THE IONOSPHERE USING DUAL FREQUENCY GPS DATA IN A KALMAN FILTER APPROAC

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Abstract: *The ionosphere is an important source of errors for the GPS signals that travel through the ionosphere on their way to the ground-based receivers by introducing a frequency dependent path delay proportional to the total electron content (TEC) along the signal path. For dual-frequency GPS receivers, the ionospheric effects can be accounted for by taking advantage of the dispersive nature of the ionosphere in the microwave region of the electromagnetic spectrum, while for the single frequency GPS receivers the ionospheric effects can be minimized by modeling them using, for example, empirical or physics-based ionospheric models. On the other hand, the errors imposed by the ionosphere on the GPS signals can provide important temporal and spatial information about the electron density distribution in the ionosphere. Besides the ionospheric errors, there are some other sources of errors that can affect the GPS signals, such as the satellite and receiver instrumental biases, carrier phase ambiguities, multipath effects, clock errors, orbital errors, tropospheric errors, but which can be compensated for, estimated, or neglected depending on the particular application. In this paper, we are only concerned with the ionospheric effects on the GPS signals, and describe a Kalman filter-based algorithm for near real-time estimation of the line-of-sight and vertical ionospheric TEC and of the combined satellite and receiver instrumental biases, using data from dual-frequency GPS receivers.*

Keywords: *ionosphere, Kalman filters, real-time monitoring*

1. INTRODUCTION

Text of paper, 76 mm (3in) column width, with 8 mm (.3in) space between. Use full 253 mm (10 in) column length. Paragraphs should be justified, using single spacing, with no paragraph indentation. Use Times Roman font, 10 point. Leave one clear line between paragraphs within a section; two clear lines before a main or secondary heading.

The Global Positioning System (GPS) constellation of satellites, in conjunction with a large number of GPS receivers in continuous operation worldwide, represents a reliable source of ionospheric data. The ionosphere is a conducting ionized layer of the Earth's upper atmosphere that extends between about 90 km to 1000 km in altitude, and impacts the propagation of electromagnetic waves in a wide range of frequencies (Tascione, 1994). For the GPS signals, the ionosphere is a dispersive medium. There are two sinusoidal carrier L-band signals on which the GPS satellites transmit L1 and L2, with f_1 = 1575.42 MHz ($\lambda_1 \approx$ 19 cm) and f_2 = 1227.6 MHz ($\lambda_2 \approx$ 24 cm), and two Pseudorandom Noise (PRN) Codes, unique for each satellite, that are modulated on the carrier signals (Hoffmann-Wellenhof et al. 1998). As the GPS signals travel through the ionosphere on their way to the ground-based receivers, the ionosphere introduces a frequency-dependent path delay proportional to the integrated electron density along the signal path, which provides important information about the temporal and spatial variability and distribution of the electron density in the ionosphere.

Over the last two decades, several groups have developed different techniques to monitor the state of the ionosphere using data from the GPS satellites. In this paper, we present a Kalman filter-based ionospheric model, named *WinTEC*, that uses dual frequency GPS data for near real-time estimation of the ionospheric total electron content (TEC), and implicitly, of the combined satellite and receiver instrumental biases (Anghel et al. 2008). In our model, the ionosphere is approximated as a thin spherical shell located at a fixed height above the Earth's surface, and the vertical TEC above each GPS station is modeled as a first order polynomial in a solar-geomagnetic reference frame (Coster et al. 1992). The *WinTEC* model can process data from a single site or from several dual-frequency GPS receivers simultaneously, in near-real time, using hourly or daily RINEX observation files available at different Internet sites, to produce state estimates every 30 seconds in a Kalman filter approach. In *WinTEC* the satellite coordinates are calculated based on algorithms described in (Hoffmann-Wellenhof et al. 1998) and (Mohinder et al. 2007), using information available in the RINEX navigation files.

In the following sections, we provide some background information about the ionosphere impact on the GPS signals, review the thin-shell ionospheric model and the ionospheric TEC observables, describe the Kalman filter processor, and conclude the paper with some examples obtained using the *WinTEC* model

2. ESTIMATION STRATEGY

2.1. Ionosphere Impact on the GPS Signals - Ionospheric Refraction

The ionosphere is a dispersive medium for the GPS signals, having frequency-dependent phase and group refractive indices. By integrating the refractive indices along the signal path, one can calculate the satellite-receiver phase and code ranges. It has been shown that, by neglecting the collision and magnetic field effects, the difference between the measured and the true geometric satellite-receiver ranges can be approximated as:

$$\Delta^{Iono} = \frac{40.3}{f^2} \cdot TEC \tag{1}$$

where f is the carrier frequency and TEC is the total electron content along the entire satellite-receiver path measured in TEC Units, with 1 TECU $=10^{16}$ electon·m^{-2} corresponding to a range delay of 0.16 m and a time delay of 0.56 ns at L_1 frequency. The quantity in (1) is known as the ionospheric path delay, and is negative for the phase and positive for the code measurements.

2.2. Ionospheric TEC Observables

The two fundamental GPS observables are the code and phase measurements. For a satellite-receiver pair, the observation equations for the two observables, also known as pseudorange P and carrier phase Φ, in distance units, are:

$$\begin{aligned} P &= \rho + c \cdot \Delta\tau + \Delta^{Iono} + \Delta^{Trop} + \\ &+ b^R_{P,L} + b^S_{P,L} + m_P + \varepsilon_P \\ \Phi &= \rho + c \cdot \Delta\tau + \lambda \cdot N - \Delta^{Iono} \\ &+ \Delta^{Trop} + b^R_{\Phi,L} + b^S_{\Phi,L} + m_\Phi + \varepsilon_\Phi \end{aligned} \tag{2}$$

where ρ is the true satellite-receiver geometric range, $\Delta\tau$ the satellite-receiver clock errors, f the carrier frequency, λ the wavelength, c the speed of light, N the phase ambiguity number, Δ^{Iono} the ionospheric path delay, Δ^{Trop} the tropospheric path delay, $b^R_{P,L}$ $b^S_{P,L}$, $b^R_{\Phi,L}$,$b^S_{\Phi,L}$ the satellite and receiver biases, m_P, m_Φ the multipath errors, and ε_P, ε_Φ the random noise processes on P and Φ. N is the integer ambiguity number, and represents the initial number of cycles between the satellite and receiver. Jumps in N are called cycle slips, and they need to be detected and corrected for before the Kalman filter processing of the data.

For a dual frequency GPS receiver, same equations like in (2) can be written for both the GPS frequencies, and then combined with (1) to produce the differential pseudorange TEC_P and the differential carrier phase TEC_Φ observables, which expressed in TECU are:

$$\begin{aligned} TEC_P &= 9.52 \cdot (P_2 - P_1) \\ TEC_\Phi &= 9.52 \cdot (\Phi_1 - \Phi_2) \end{aligned} \tag{3}$$

The differential pseudorange TEC_P is an unambiguous but noisy and biased measure of the actual line-of-sight TEC. The bias in TEC_P is caused by the satellite and receiver differential delays introduced by the analog hardware in the GPS signal paths. The differential carrier phase TEC_Φ is very precise but ambiguous, and is a biased measure of the actual line-of-sight TEC by a term caused by the carrier phase ambiguities. Like in (Coster et al. 1992), to take advantage of the very precise but ambiguous TEC_Φ, and the unambiguous but less precise TEC_P, we use a phase-leveling technique where a new ionospheric TEC observable is obtained by combining the TEC_Φ and TEC_P data over an observation arc. The new ionospheric TEC observable for a satellite-receiver pair is an unambiguous and precise measurement of the actual line-of-sight TEC but still biased by the satellite and receiver instrumental biases, and at a certain epoch i is:

$$\begin{aligned} TEC_{comb_i} &= TEC_{\Phi_i} - \\ &- \frac{\sum_{j=i-n}^{i+n} p_j \cdot \left(TEC_{\Phi j} - TEC_{P_j}\right)}{\sum_{j=i-n}^{i+n} p_j} \end{aligned} \tag{4}$$

where the p_j coefficients are elevation angle dependent. In *WinTEC*, the summation in the above formula is performed over a 30 minutes arc length centered at epoch i after detecting and correcting for the potential cycle-slips in the TEC_Φ data within this time interval. The minimum cutoff elevation angle is chosen at 10°.

2.3. Thin-Shell Ionospheric Model

In the *WinTEC* model, the ionsophere is approximated as a thin spherical shell located at a specified fixed height above the Earth's surface, such that each satellite-receiver link intersects the ionosphere exactly at one location, called ionospheric pierce point (IPP). The consequence is that, by using this approximation, only the horizontal variation of the electron density in the ionosphere can be retrieved. Moreover, since the phase-leveled ionospheric TEC observables are affected by the receiver and satellite instrumental biases, in a first approximation, they can be modeled as the sum of the receiver bias, satellite bias, and the line-of-sight ionospheric TEC. To estimate the actual line-of-sight TEC, we need to set up a mathematical model that takes into account that the ionospheric path delay is a function of the elevation angle of a GPS satellite with respect to a receiver, whereas the satellite and receiver differential delays are elevation angle independent. Therefore, by using a single-layer thin-shell approximation for the ionosphere, the line-of-sight TEC observable in (4) can be modeled, in a solar-geomagnetic reference frame, as:

$$\begin{aligned} &TEC^{RS}_{comb_i} = M\left(e^i_{RS}\right) \cdot \\ &\left[a^i_{0,R} + a^i_{1,R} \cdot d\lambda^i_{RS} + a^i_{2,R} \cdot d\varphi^i_{RS}\right] + b^i_R + b^i_S \end{aligned} \tag{5}$$

where b^i_S, b^i_R are the slow varying satellite and receiver biases, $a^i_{0,R}$, $a^i_{1,R}$, $a^i_{2,R}$ are three ionospheric parameters describing the vertical TEC above the receiver, $d\lambda^i_{RS}$ is the difference between the longitude of the IPP and that of the mean sun, and $d\varphi^i_{RS}$ is the difference between the geomagnetic latitude of the IPP and that of the receiver. $M(e)$ is a standard mapping function which relates the slant and vertical TEC values, and depends on the ionospheric shell height (h), Earth's radius (R_E), and the elevation angle (e_{RS}):

$$M(e_{RS}) = \left(1 - \left(\frac{\cos(e_{RS})}{1 + \frac{h}{R_E}}\right)^2\right)^{-1/2} \tag{6}$$

Note that by using (5), only the combined contribution of the satellite and receiver biases to the line-of-sight TEC measurements can be estimated unless additional assumptions are made.

2.4. Short Description of the Kalman Filter Method

The sequential Kalman filter provides an alternative way of formulating the least-squares filtering problem using state-space methods (Mohinder et al. ,2007, Tapley et al., 2004), where the process to be estimated can be modeled in the form:

$$\begin{aligned} \mathbf{X}_k &= \Phi_{k,k-1} \cdot \mathbf{X}_{k-1} + \mathbf{w}_{k-1} \\ \mathbf{y}_k &= \mathbf{H}_k \cdot \mathbf{X}_k + \mathbf{v}_k \end{aligned} \qquad (7)$$

$\mathbf{X}_k$ being the state vector, $\mathbf{\Phi}_{k,k-1}$ the state transition matrix, $\mathbf{w}_k$ the process noise, a zero-mean white Gaussian noise with a known covariance matrix $\boldsymbol{Q}$, $\mathbf{y}_k$ the measurement or observation vector, $\mathbf{H}_k$ the mapping matrix between observations and states, and $\mathbf{v}_k$ the measurement noise, a zero-mean white Gaussian noise with a known covariance matrix **R**. In our approach the state variables were approximated as random walk processes as described in (Anghel et al. 2008). The process noise represents the uncertainties in the model, and different models can be used for the process noise by augmenting the state vector (Tapley et al. 2004).

In a sequential Kalman filter algorithm, as new measurements become available, both the estimate of the current state as well as the error of that estimate can be updated or refined. The Kalman filter equations are presented in detail in (Mohinder et al. ,2007, Tapley et al., 2004). For the *WinTec* model, the three ionospheric parameters in (5) that describe the vertical TEC above the monitoring station, and the satellite and receiver differential delays constitute the state vector, while the measurement vector contains the line-of-sight TEC observations calculated as in (4) for each satellite in view. For a network of GPS receivers, the state vector includes three ionospheric parameters and a receiver bias for each station, and a bias for each satellite. Both the single and the network solutions prove to be robust with the filter stabilizing after about one day, the geometric configuration of the system repeating on a daily basis as seen in Fig. 1 and 2.

3. RESULTS

In this section, we present some results obtained with the *WinTEC* model using GPS data from the DSRC station located in Boulder, Colorado, USA, over a ten-day period in February 4-13, 2005, with the station coordinates given in Fig. 2. During this time interval, the daily Ap values were less than 10 for the first three days, then raised to values grater than 20 for the following three days, and then decreased back to values less then 10 by the end of the interval. The RINEX observation and navigation files were obtained from the Continuously Operating Reference Stations (CORS) (ftp://www.ngs.noaa.gov/cors/rinex/).

In Fig. 1, the upper and lower panels display the differential pseudoranges and the differential carrier phases for all the satellites in view calculated with (3). As shown in this figure, the differential pseudoranges are contaminated with a high level of stochastic noise and are biased throughout the entire interval, while the differential carrier phases are very precise but ambiguous. For plotting purposes, the differential carrier phases are plotted starting at 0 TECU at the beginning of each satellite track.
The line-of-sight phased-leveled TEC values, calculated as in (4) are shown in the upper panel of Fig. 2, after the cycle-slips in the differential carrier phase data were detected and removed in each observational arc. As seen in this panel, the obtained line-of-sight TEC values are more precise than the original differential pseudoranges but still biased, and are used as observations in the Kalman filter for estimating the state vector.

The middle panel of Fig. 2 shows the unbiased line-of-sight TEC values and the vertical TEC values (thick red line) estimated with the Kalman filter, and the combined satellite and receiver biases are plotted in the lower panel of Fig. 2. Over the ten-day interval, the biases are slowly varying in time and have values between -20 and -60 TECU. In both Fig. 1 and 2, the satellites are color-coded to better illustrate the periodic changes in the geometrical configuration of the system.

4. CONCLUSION

In this paper, we described the Kalman filter-based WinTEC model for near real-time monitoring of the Earth's ionospheric TEC. The estimation procedure assumes a very simple model of the ionosphere, approximated as a thin spherical shell at the 350 km height, and a first-order polynomial model for the vertical TEC, but more elaborate models can be used. For example, the algorithm presented in here is easily adjustable to a multi-shell structure of the ionosphere (Komjathy et al., 2002) and higher-order polynomials for the vertical TEC (Rho and Langley, 2002). As seen in Fig. 2, the Kalman estimator works well when the configuration of the GPS satellites in view changes, and although, the method was developed for a quiet ionosphere with smooth variations in the electron density distribution, it also provides good estimates of the ionospheric parameters even under geomagnetically disturbed conditions.

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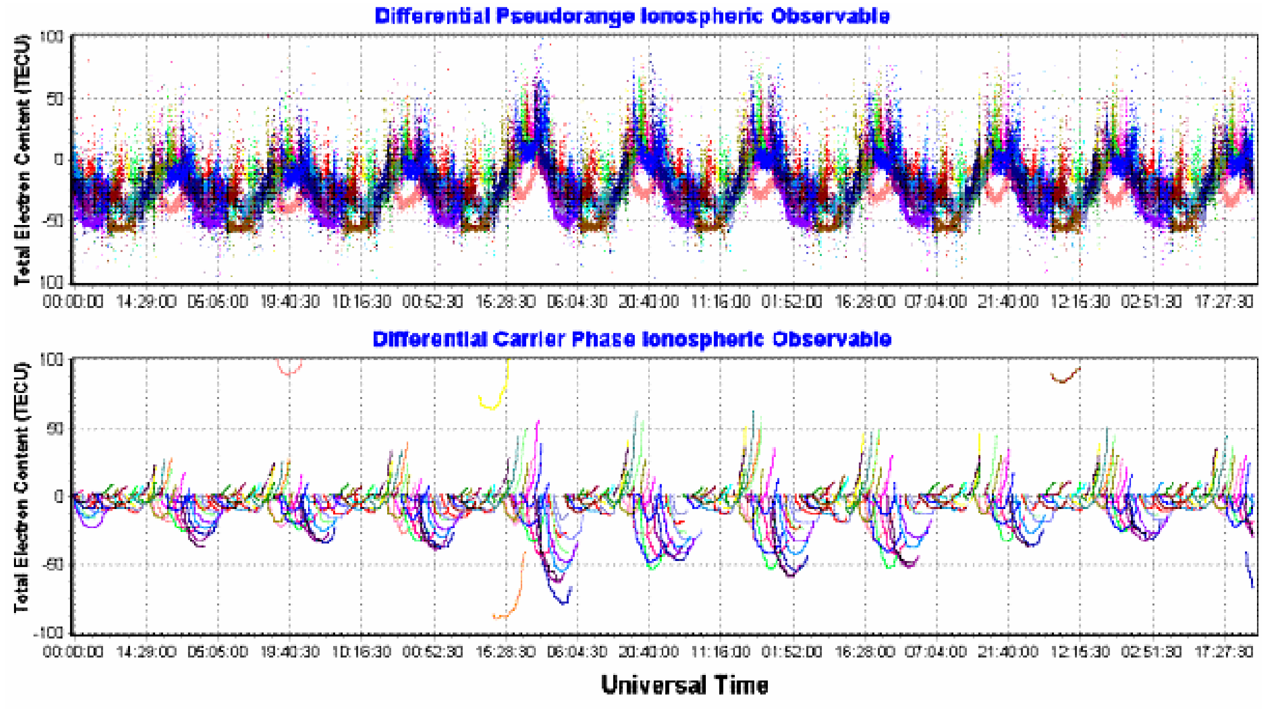

Fig. 1. Differential pseudoranges (top) and differential carrier phases (bottom) in TECU at DSRC for February 4-13, 2005

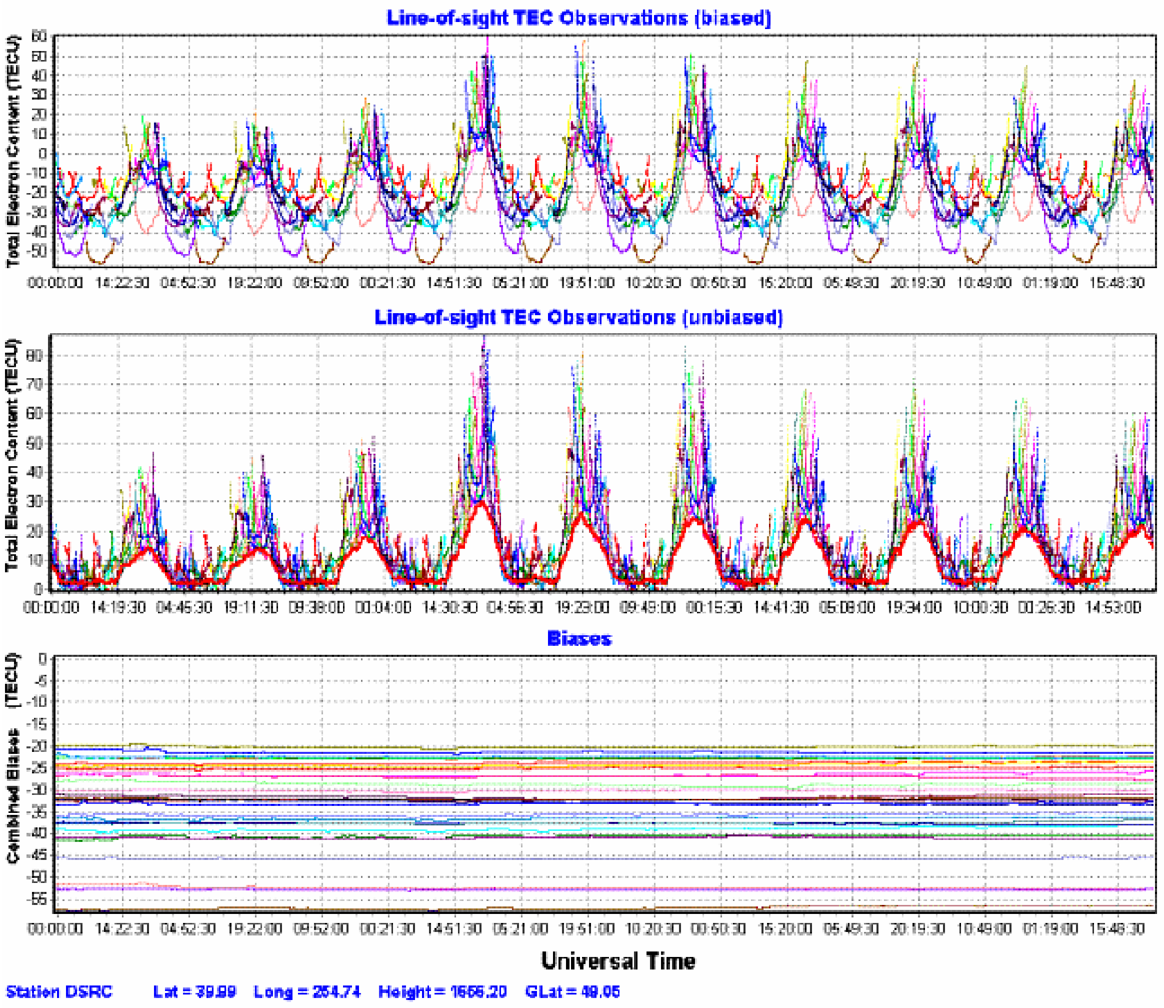

Fig. 2. Biased (top) and unbiased (middle) line-of-sight TEC observations, and the combined satellite-receiver biases (bottom) at DSRC for February 4-13, 2005