IONOSPHERIC DELAY CORRECTION USING THE TAIWAN IONOSPHERIC MODEL (TWIM) FOR SINGLE-FREQUENCY GPS RECEIVER

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ABSTRACT: In this paper, a three dimensional ionospheric electron (*Ne*) density model derived from FormoSat3/COSMIC GPS Radio Occultation measurements, called the TaiWan Ionospheric Model (TWIM), was used to determine ionospheric delay for GPS single-frequency positioning. The *Ne* profiles were used to calculate for the slant TEC (STEC) between a receiver and each GPS satellite. These derived STEC were used to determine the ionospheric delay on the L1 frequency as measured by single-frequency receiver and is used to correct the pseudorange single-frequency observations. The corrected pseudorange for every epoch was used to calculate the position of the receiver. Initial calculations showed that the TWIM can improve positioning to about 90% during daytime and to about 50% during nighttime as compared to uncorrected positions. It was also shown that, in general, it provides better positioning than other ionospheric models, such as the Global Ionosphere Map (GIM), and Klobuchar model, especially during daytime.

1. INTRODUCTION

The ionosphere is one the main sources of propagation delay for GPS signals which affects positioning using single frequency GPS receivers (Camargo et al 2000; Ovstedal 2002). This is brought about by the ability of the ionosphere to delay an oncoming radio wave. The behavior of the electrons and ions in the ionosphere primarily depend on several variables, namely the time of the day, season, solar activity, viewing direction, location of the receiver and the earth's magnetic field (Klobuchar, 1991; Camargo et al 2000), which could cause different effect to the accuracy of GPS positioning. Specifically in middle latitude areas, where the ionosphere is generally well behaved, can result to delay in signal of about 2–5 m (Spencer et al, 2003). However, this can be greater in the polar and equatorial regions, where the ionosphere is characterize to have high electron density and high temporal and spatial variation. Irregularities in the ionosphere that cause rapid fluctuations in the carrier phase (called scintillation) and in amplitude (called fading) of GPS signals could also cause degradation performance n GPS receivers (Misra and Enge 2001; Dubey et al 2006).

In this paper, ionospheric delay correction for single-frequency GPS pseudoranges using a numerical and phenomenological model called the TaiWan Ionospheric Model (TWIM) is presented. Its performance with respect with other ionospheric models will also be presented.

2. METHOD

2.1 Data

Single-frequency GPS data were recorded using a Novatel FLEXG2-STAR-10Hz receiver at 0.5 Hz sampling rate. The receiver operated for 24 hours (0-24UT) for each day of observation at the rooftop of the Center for Space and Remote Sensing Research Building, National Central University, Chung-li, Taiwan.

Raw data output from the receiver in binary format is converted to RINEX format, which includes both observation data and satellite navigation message from each GPS satellite. Satellite positions were calculated using the GPS satellite ephemeris included in the RINEX navigation message of the GPS signal. Single-frequency pseudorange (C1 code) was obtained from the RINEX observation file. Pseudorange corrections, using the satellite clock bias, relativistic clock bias, timing group delay and tropospheric error is used to calculate the receiver position using the least-squares estimate. At this point, ionosphere is not used in the positioning calculations and thus referred to as 'Uncorrected'. Static point positions of the receiver were calculated using the standard least-squares adjustments after removing ionospheric error determined by Klobuchar, GIM and TWIM.

2.2 Pseudorange Components

In an ideal situation, only the receiver and clock biases contribute to the pseudorange:

$$P = \rho(t_r, t_s) + c(\tau_r - \tau_s) \tag{1}$$

where $\rho(t_r, t_S)$ is the true geometric range (m) from receiver position (at receive time t_r) to the satellite position (at transmit time t_s), c is the speed of light in vacuum (299,792,458 m/s), τ_r is the receiver clock bias (s), and τ_S is the satellite clock bias (s). However, there are propagation errors, relativistic effects and other errors that contribute to the pseudorange P measured by a receiver. This can be modeled as:

$$P = \rho + c(\tau_r - \tau_s) + ct_{gd} - d_{rel} + d_{trop} + d_{ion} + \varepsilon \tag{2}$$

where ρ is the true geometric distance (m) between the receiver and a satellite, t_{gd} is the timing group delay (s), d_{rel} is the relativistic effect correction, d_{trop} is tropospheric delay (m), d_{ion} is the ionospheric delay (m) and ε is the unmodelled noise including multipath effects (which are ignored). These errors are measured in meters and several models are used to account for these measurement errors.

2.3 Ionospheric Corrections

Given the total electron content (TEC) along the path, ionospheric delay d_{ion} in the pseudorange can be determined as

$$d_{ion} = -\frac{40.3TEC}{f^2} \tag{3}$$

So for *L1* frequency, one TEC is equivalent to about 16 cm of delay in the pseudorange. Generally, ionospheric effects usually account to about 30 m of error in the pseudorange measurements depending on the elevation angle of the satellite.

Several methods have been used to account for this error. This includes, broadcast models (Klobuchar), mapping functions, ionospheric models (such as IRI, MIDAS, GIM), and dual-frequency corrections. Moreover, among the parameters that contribute to the pseudorange measurements, the ionospheric error is the most variable and difficult to model since the ionosphere is very dynamic and ionospheric radio propagation is dependent on the frequency of the radio wave.

In this study, a three dimensional ionospheric electron density (n_e) model called the TaiWan Ionospheric Model (TWIM) was used to calculate ionospheric delay for GPS single-frequency positioning. It is a numerical and phenomenological model of global ionospheric electron density that is constructed from monthly-weighted and hourly vertical n_e profiles retrieved from Formosat3/COSMIC GPS radio occultation (RO) measurements. Each layer (F2, F1, E, or D) is characterized by a Capman-type function, which is describe by its peak *Ne*, peak density height (h_m), and scale height *H*. Thus, the parameters $n_{e\max}F2$ ($n_{e\max}F1$, $n_{e\max}E$, and $n_{e\max}D$), h_mF2 (h_mF1, h_mE, and h_mD), and *HF2* (*HF1*, *HE*, and *HD*) represent the F2 layer (F1, E, and D layer) and can be used to obtained (with least-squares error fitting of the observed profile to the Chapman functions) the n_e at a specific longitude (θ), latitude (λ) and height (h):

$$n_e(\theta,\lambda,h) = \sum_{i=1}^{n} n_{e\max}(\theta,\lambda)\exp\left\{\frac{1}{2}\left[1 - \frac{h - h_m(\theta,\lambda)}{H(\theta,\lambda)} - \exp\left(-\frac{h - h_m(\theta,\lambda)}{H(\theta,\lambda)}\right)\right]\right\} \tag{4}$$

where each i means a physical layer of F2, F1, E, or D layer. All of the layers could occur during the daytime. The F1 and D layers decay at night and could be hidden within the other layers, but the F1- and D-layer parameters are still derivable in all time by least-squares error fitting (Tsai et al 2009). This enables TWIM to have high spatial and temporal resolution. The n_e profiles are used to calculate for the slant TEC (STEC) between a receiver and each GPS satellite (Tsai et al 2009). These were used to determine the ionospheric delay on the L1 frequency as measured by single-frequency receiver. The corrections made using TWIM was compared with two of the most commonly used ionosphere models for single-frequency positioning, namely the Klobuchar model and the Global Ionospheric Model (GIM).

2.4. Error Analysis

Errors in the horizontal (east and north) and vertical (height) were calculated in terms of the residuals between the measured position and the actual position of the receiver. Mean error, standard deviation, and root mean square error (RMS) were also calculated for each day of observation. In addition, common measures in GPS positioning were also used to describe the accuracies attained from GPS in 1- and 2-dimensions.

Aside from the common RMS, error probable (EP) was also used to describe the interval that contains 50% of the position estimates. For 2-dimensional analysis, circular error probable (CEP) and distance RMS (DRMS) were used. These parameters describe the confidence region along the horizontal direction where estimated positions are likely to be. CEP refers to the radius of a circle in which 50% of the position errors lie, given that the center of the circle is the true position. It is given by

$$CEP = 0.62 \cdot \sigma_e^2 + 0.56 \cdot \sigma_n^2 \tag{5}$$

where σ_e^2 and σ_n^2 are the RMS in the east and north direction, respectively (Leva et al 1996). DRMS, defined as

$$DRMS = \sqrt{\sigma_e^2 + \sigma_n^2} \tag{6}$$

describes the probability of being with in a circle with radius DRMS is about 65%. A circle that expresses 95% probability is given by 2DRMS defined as

$$2DRMS = 2 \times DRMS = 2\sqrt{\sigma_e^2 + \sigma_n^2}\ . \tag{7}$$

3. RESULTS AND DISCUSSION

3.1 Ionospheric Delay

Figure 1 shows an example of calculated ionospheric delays (m) for day 165 (June 14, 2011). It clearly shows the typical diurnal variation of ionosphere where TEC is higher during daytime (22-10UT, 06-18LT) than in nighttime (10-22UT, 18-06LT). And for low-latitude ionosphere, high electron density can extend to post-sunset periods (10-15UT). Figure 2 shows the comparison between the ionospheric delay results between Klobuchar, GIM and Klobuchar at PRNs[*] 2, 11, 31. This shows that TWIM is closer to GIM than Klobuchar, which is expected since both TWIM and GIM are based on actual measurement, whereas Klobuchar is based on a much simpler mathematical model.

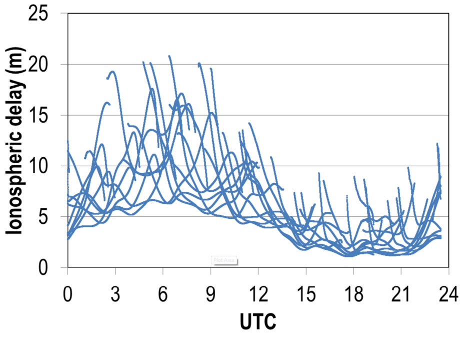

Figure 1. Typical Ionospheric error calculated by TWIM.

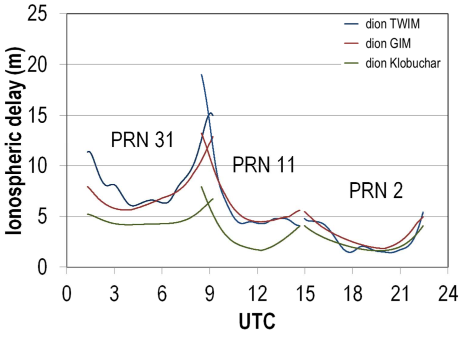

Figure 2. Comparison between ionospheric delays calculated using TWIM, Klobuchar and GIM for PRNs 31, 11 and 2.

3.2 Positioning Results

Figure 3 shows the diurnal variation of the 30-minute average residual errors in the east, north and height (vertical) directions in July 5, 2010 (day 186). The effect of the ionosphere in GPS positioning is clearly shown in the north and vertical directions where residual error is higher in daytime than in nighttime. The residual error could reach to

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[*] PRN (Pseudorandom noise) number is used to identify GPS satellite. PRN codes are unique to every GPS satellite.

more than 10 m in noontime and could approach to zero in nighttime. It can be seen that the TWIM performs better than the Klobuchar and GIM. Also, the corrections made by TWIM could reach to 90% of the total residual error in the day time and 50% in the night time.

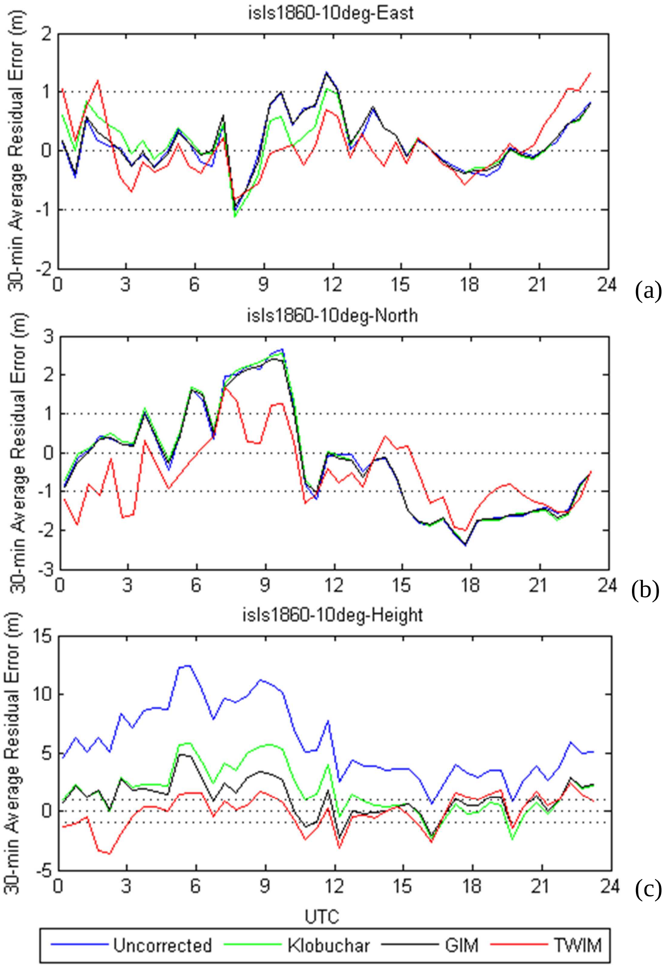
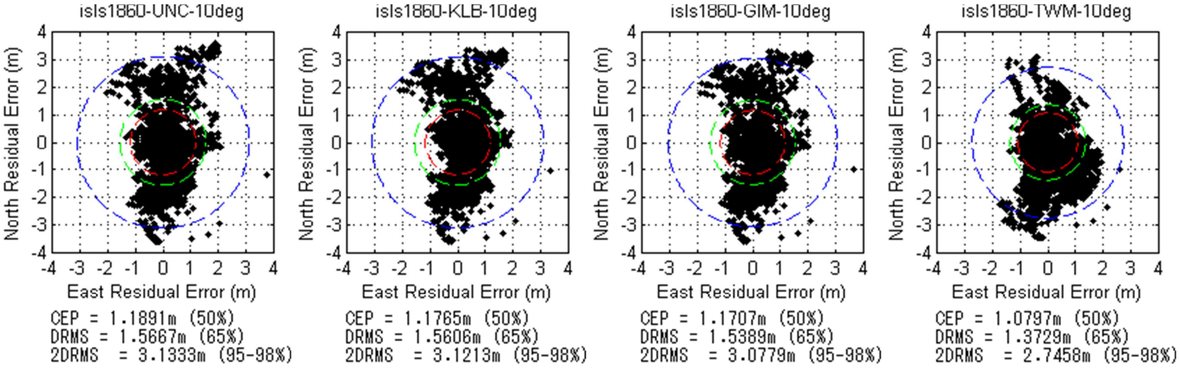


Figure 3. Diurnal variation 30-minute mean residual errors for (a) east, (b) north, (c) height for Day 186.

Moreover, corrections by different models were most evident in the vertical direction. This is because of the asymmetry in the satellite geometry in the vertical direction where the ionosphere effect on GPS propagation is concentrated above the ground. Whereas, the ionospheric effect in the horizontal direction is present in all direction, hence symmetric. This minimal effect of ionosphere in positioning is evident in the east and north direction.

Figure 4 shows the scatter plot of horizontal coordinates of the receiver for day 186. It shows that the order of increasing horizontal accuracy and precision based on the calculated CEP, DRMS and 2DRMS is uncorrected, Klobuchar, GIM and TWIM. It shows that using TWIM, 50% of the positioning errors are found within 1.080-m radius, which is better than the Klobuchar and GIM by 8%. This suggests that 50% of the time, TWIM provides accuracy of sub-meter. The DRMS (1.3729 m, 65%) and 2DRMS (2.7458 m, 95-98%) using TWIM is better than Klobuchar by 12% and GIM by 14%. This plot displays the better accuracy and precision of TWIM. Vertical error probable (VEP) for uncorrected, Klobuchar, GIM and TWIM are 6.692 m, 2.918 m, 2.284m, and 1.871 m. This means that half the time, TWIM can correct positioning errors by 72%.



(a) (b) (c) (d)

Figure 4. Scatter plot of horizontal coordinates (east and north) with circular plots of CEP (red), DRMS (green) and 2DRMS (blue) for (a) uncorrected, (b) Klobuchar, (c) GIM and (d) TWIM for July 5, 2011 (Day 186).

4. CONCLUSIONS AND FUTURE WORK

In general, the order of increasing positioning accuracy and precision is uncorrected, Klobuchar, GIM and TWIM. The diurnal variation showed that the TWIM could correct positioning error by as much as 90% in daytime and 50% in nighttime. Corrections were shown to be more evident in the vertical direction and least in the east direction.

It was shown that half of the time TWIM can yield horizontal positioning better than 1.080 m (CEP). This is about 9% better than uncorrected. Moreover, 65% and 95-98% of the time could provide error of about 1.373 m (DRMS) and 2.746 m (2DRMS), respectively. This corresponds to %diff of about 13% for both DRMS and 2DRMS. Vertically, TWIM showed that it could yield vertical positions of less than 1.871 m, 50% of the time, which is translated to 72% diff as compared with positioning without ionospheric corrections.

In the future, positioning will be further improved by using precise GPS orbit information provided by IGS. Also, the performance of TWIM in GPS positioning at various geographic locations, and geomagnetic and solar activities can be explored in order to establish the applicability of TWIM at different situations related to the receiver position and space weather.

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