QUALITY CONTROL ISSUES ON REAL-TIME ESTIMATION OF IONOSPHERIC DELAY USING GPS MEASUREMENTS

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ABSTRACT: The ionospheric delay is one of the main sources of error in GPS precise positioning and navigation. The magnitude of the ionospheric delay is related to the Total Electron Content (TEC) along the radio wave path from a GPS satellite to the ground receiver. A dual-frequency GPS receiver can eliminate (to the first order) the ionospheric delay through a linear combination of L1 and L2 observables. However, the majority of civilians use low-cost single-frequency GPS receivers that cannot use this option. Consequently, it is beneficial to estimate ionospheric delays over the region of interest, in real-time, for single-frequency GPS positioning and navigation applications. Several factors will affect the quality of real-time ionospheric delay estimation, such as multipath, GPS satellite and receiver L1/L2 differential delays, cycle slips, etc. In order to ensure the quality of real-time ionospheric delay estimation, a series of algorithms were developed: (1) the "multipath template technique" is used to mitigate GPS pseudo-range multipath at static GPS reference stations, (2) the "single-site algorithm" is used to estimate GPS satellite and receiver differential delay, and is applied to regional ionosphere modeling, (3) the "failure detection algorithm" using Robust and Conventional Kalman Filter state estimates is used to detect cycle slips in the GPS carrier phase measurements. Data from different regions, such as National Chengchi University (NCCU), in Taiwan, over 18 consecutive days, the Permanent GPS Geodetic Array (PGGA), in Southern California, over 12 consecutive days, and University of New South Wales (UNSW), in Australia, over 4 consecutive days was used to test the proposed algorithms. The algorithms are briefly described and the test results are presented. Preliminary results indicate that the proposed algorithms can ensure the quality of real-time ionospheric delay estimation effectively and should be implemented at reference stations within LADGPS, WADGPS and WAAS networks, GPS deformation monitoring networks, etc.

1. INTRODUCTION

The ionosphere is a shell of electrons and electrically charged atoms and molecules that surrounds the earth, stretching from a height of about 50 km to more than 1000 km above the earth surface. When radio waves such as the GPS signals propagate through the ionosphere they suffer an extra time delay. This time delay is related to the Total Electron Content (TEC) of the ionosphere. The TEC is defined as the total number of electrons that are contained in a column with cross-sectional area of 1 m^2 along the signal path between the satellite and the receiver. The unit of measurement is (el/m^2). One Total Electron Content Unit (TECU) is defined as: $10^{16} el/m^2$. Please note that 1 m of ionospheric range delay at L1 signal corresponds to about 6.16 TECU (Lin, 1998).

There are several factors which should be considered before using dual-frequency GPS receivers to estimate, in real-time, the ionospheric delay, such as multipath effects on pseudo-range measurements, cycle slip(s) of carrier phase measurements, GPS satellite and receiver L1/l2 differential delays, etc. In order to ensure the quality of real-time ionospheric delay estimation, three algorithms were developed: (1) the "failure detection algorithm" using Robust and Conventional Kalman Filter state estimates is used to detect cycle slips in the GPS carrier phase measurements; (2) the "multipath template technique" is used to mitigate GPS pseudo-range multipath at static GPS reference stations; (3) the "single-site algorithm" is used to estimate GPS satellite and receiver differential delay, and is applied to regional ionosphere modeling. In this paper, the concept and methodology of these proposed algorisms are briefly described and the test results are presented.

2. IONOSPHERIC DELAY ESTIMATION USING GPS MEASUREMENTS

If dual-frequency GPS measurements are available, the absolute measure of the ionospheric delay (TEC), TR, can be computed from the L1/L2 pseudo-range measurements using the following equation (Lin, 1997; Lin, 1998):

$$STEC \ ? \ 9.5196 \ ? \ [(P_2 \ ? \ P_1) \ ? \ (MP2 \ ? \ MP1)] \ ? \ TR \ ? \ 9.5196 \ ? \ (MP2 \ ? \ MP1)$$

(1)

Note that this pseudo-range estimated TEC is noisy due to the effect of multipath and measurement noise.

On the other hand, the relative measure of the TEC, TS, can be calculated from the L1/L2 carrier phase measurements using the following equation (Lin, 1997; Lin, 1998):

$$STEC \ ? \ 9.5196 \ ? \ (F_1 \ ? \ F_2) \ ? \ D \ ? \ TS \ ? \ D \tag{2}$$

where STEC is the slant TEC measurements; P_1, P_2 are the pseudo-range observations made on the L1 and L2 signals respectively; $?_1, ?_2$ are the carrier phase measurements on the L1 and L2 signals respectively; MP1, MP2 are the multipath delays on P_1 and P_2 respectively; D is the product: 9.5196 times the linear combination of the integer ambiguity parameters N_1 and N_2 . Note that STEC, TR, TS are in units of TECU and the rest parameters are in units of m.

3. DEVELOPED ALGORITHMS TO ENSURE THE TEC QUALITY

3.1 Using Failure Detection Algorithm to Detect and Repair Carrier Phase Failures

The failure detection and repair algorithm, based on a statistical test of the difference between the estimated state from a conventional Kalman filter and that from a robust Kalman filter, is used to detect and repair the GPS carrier phase failure(s). Only the basic principles of this algorithm are presented here. Further details can be found in Lin (1997), Lin (1998), Wang et al. (1993), etc.

The following matrices, common to both the robust and conventional Kalman filters, are used to estimate real-time TEC.

$$\underline{x} \ ? \ ?STEC, STEC? \, D?^T, \quad \underline{z} \ ? \ ?TR, TS?^T \tag{3}$$

where $\underline{x}$ is the state vector; $\underline{z}$ is the measurement vector; STEC? is the first derivative of the STEC estimate.

3.1.1 Detection and Identification Step: The failure-indicating signals X are defined as:

$$X_i \ ? \ STEC_i \ ? \ STEC_i^*, \quad i = 1,2,?$$

(4)

where $STEC_i$ and $STEC_i^*$ are the TEC states estimated by the conventional and robust Kalman filter at time i respectively.

The sample mean value $\overline{X}_r$ and the sample variance S_r^2 of the first r observations $\{X_1, X_2, ?, X_r\}$ can be obtained sequentially. A standard normal variable $u(t_r)$ can be derived after a series of transformation. To screen the outliers in this sequential data set, a discordance test using the well-known three-sigma (99% confidence level) identification rule is used:

$$\text{Declare } X_r \text{ as failure if } |u(t_r)| \ ? \ 3 \tag{5}$$

A disagreement between the conventional state estimates and its robust ones indicates that a failure has been detected.

3.1.2 Repair Step: Once the failure is detected and identified, the repair process is taken to correct TS state. Let "?TS" be the failure correction to TS, and "$\overline{TS}$" be the corrected TS. ?TS is set to zero at the initial tracking of a GPS satellite. The relationship between TS and $\overline{TS}$ is:

$$\overline{TS} = TS + ?TS \qquad (6)$$

Let "Inno(TS)" be the innovation of TS, which can be computed from the conventional Kalman filter as:

$$Inno(TS) = TS - [\ TEC(-) + D(-)\ ] \qquad (7)$$

where TEC(-) and D(-) are estimates of TEC and D before measurement update. Then the relationship between ?TS and Inno(TS) is:

$$?TS = ?TS – Inno(TS)$$
(8)

Let "dN_1" and "dN_2", in units of cycles, be the carrier phase cycle slips on the L1 and L2 signals respectively. The combined effects of dN_1 and dN_2 on TS is (cf. equation (2)):

$$dTS\ ?\ 9.5196\ ?\ ??_1 dN_1\ ?\ ?_2 dN_2 ? \qquad (9)$$

Considering the fact that the minimum possible value of "dTS" is ?0.24 TECU (Wanninger, 1994), when dN_1=-5 and dN_2=-4, or dN_1=5 and dN_2=4, the critical value of 0.25 TECU was selected as the criteria for invoking the repair action. Further details can be found in Lin (1997) and Lin (1998).

3.2 Using Multipath Template to Mitigate Pseudo-Range Multipath

3.2.1 Pseudo-Range Multipath Template Generation Procedures: The multipath effect on GPS measurements depends on the physical environment and the receiver-satellite geometry. As the GPS satellites are in nearly circular orbits at an approximate altitude of 20200 km, they will again be over the same position on the earth surface at the end of a sidereal day (approximately 23 hrs 56 mins in length). Thus the viewing geometry is the same each day with respect to solar day, but with a shift of about four minutes per day. When the physical environment remains unchanged from day to day, then the multipath disturbance will be almost constant.

By making these assumptions, the multi-day multipath template at static GPS reference stations has been developed and revised (Lin, 1997; Lin, 1998; Lin, 2002). Note that, for simplicity, only MP1 for a single GPS satellite is considered. The data rate is assumed to be 30 seconds, that is, 2880 epochs for a 24-hour data span. The procedure is summarized below: (i) Compute MP1; (ii) Convert the MP1 file from 2880 epochs in length to 2872 epochs, $MP1^1$; (iii) Transfer the $MP1^1$ of the current day *i* to $MP1^2$, referred to a reference day i_0; (iv) Generate the **multi-day multipath template** for a reference station: $MP1^3$.

3.2.2 Pseudo-Range Multipath Prediction Procedures: The procedure is summarized below: (i) Predict the pseudo-range multipath quantity for a specific day i, $\overline{MP1}$, using the generated multipath template(s), $MP1^3$; (ii) Convert the $\overline{MP1}$ file from 2872 epochs in length to 2880 epochs, $\overline{\overline{MP1}}$.

3.2.3 Application of Multipath Template to Real-Time TEC Estimation: The multipath template can be generated from the GPS measurements of the previous days. In real-time TEC estimation application, the current day multipath for MP1 and MP2 of equation (1) can be predicted beforehand by the generated multipath template (i.e. replaced by $\overline{\overline{MP1}}$ and $\overline{\overline{MP2}}$ respectively) and stored in a file. Then, this multipath file is input to the real-time TEC estimation software. Using equation (1), the multipath effect on pseudo-range derived TEC estimate, TR, is mitigated for each tracked GPS satellite on an epoch-by-epoch basis.

3.3 Using Single-Site Algorithm to Estimate Satellite and Receiver Differential Delay

The codes transmitted by GPS satellites at the two L-band frequencies are carefully synchronized so that they are broadcast simultaneously. Absolute simultaneity is not possible, however, so the time difference between the transmitted times at the two frequencies is called the *satellite differential delay* (Coco, 1991). Each GPS satellite has a unique satellite differential delay. Differential frequency delays may also be present in GPS receivers. These are called the *receiver differential delay*. Each GPS receiver has its individual receiver differential delay. Hence these slant TEC measurements are the sum of the real slant TEC, the GPS satellite differential delay b^S and the receiver differential delay b_R. They can therefore be expressed as:

$$STEC = S(E) \cdot TEC_v + b_R + b^S \tag{10}$$

where STEC is the slant TEC measurement, E (in degrees) is the elevation angle from the receiver to the tracked satellite, S(E) is the obliquity factor with zenith z at the *ionospheric pierce point* (IPP) and TEC_v is the vertical TEC at the IPP.

The proposed estimation algorithm is a single-site modeling technique implemented in post-processed mode (Lin, 1998; Lin, 2001). This technique is based on the following assumptions: (1) A single-layer (or thin-shell) model is adopted for the ionosphere. It is assumed that the vertical TEC can be approximated by a thin spherical shell which is located at an altitude of 400 km above the earth surface, and that all electrons encountered along the signal path from GPS satellite to receiver are contained within this shell. (2) The ionosphere can be modeled well by a 15-term polynomial in the solar-magnetic coordinate system for a period of 3 hours. The results of the single-site algorithm are the sum of satellite differential delay and receiver differential delay for each tracked GPS satellite.

4 TEST RESULTS AND DISCUSSION

4.1 Data Processing Software

Based on the above-mentioned algorithms, several software packages, known as "REALTEC", "MULIPAT", and "L12BIAS", were developed and tested. The features of "REALTEC" are: (1) mitigating the multipath effect on TR using the predicted multipath file, (2) estimating the STEC for all visible GPS satellites in real-time mode. The features of "MULTIPAT" are: (1) generating multipath template(s) from the previous days' GPS data, (2) predicting L1/L2 pseudo-range multipath values, and (3) estimating the STEC for all visible GPS satellites in post-processing mode. The feature of "L12BIAS" is to estimate the satellite and receiver differential delay for each tracked GPS satellite.

4.2 Test Results of Failure Detection Algorithm

The UNSW data set was collected from day 118, 1995 to day 121, 1995 on the roof of the Geography and Surveying Building of The University of New South Wales, Australia, using Leica System 200 GPS receivers. Four astronomical pillars, EC02, EC05, EC14 and EC19, were selected as station sites. Each GPS receiver collected 2 hours of data on four consecutive days. The data rate was 1 second and the elevation cut-off angle was set to 20 degrees. From the earlier tests, it was found that there were measurement failures in the data sets collected from site EC05. Therefore, the data sets from site EC05 were selected to test the performance of the proposed algorithm.

In order to verify the performance of the proposed procedure, the post-processing algorithm involving widelane and $?_{?7,9}$ phase combinations (Han, 1995) is used to detect and repair the carrier phase cycle slips. The data before and after the cycle slip repair process are processed using the carrier "phase levelling" process (Lin, 1998).

Table 1. Post-processing derived phase correction, ?TS, versus real-time derived ?TS.

Mode	Time	dN_1	dN_2	?TS
Post-processing	93350.0	-18	-16	4.614
Real-time	93350.0	N/A	N/A	4.615

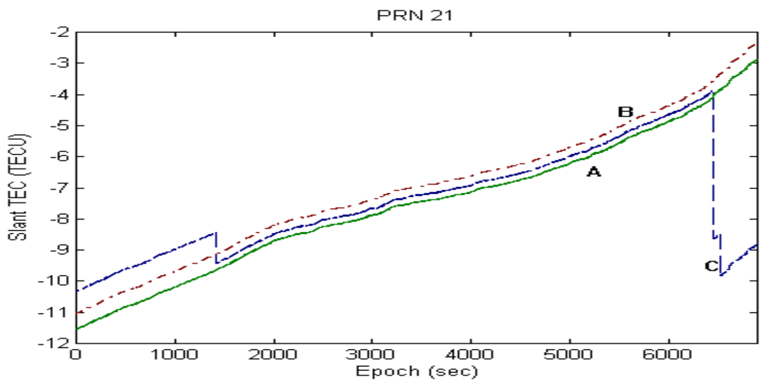

Figure 1. Post-processed TEC estimates versus real-time TEC estimates of PRN 21 for day 119, 1995.

Details of the failure detection and repair process from post-processing, and from the REALTEC software, for PRN 21 are shown in Table 1. The GPS time, indicating the time of occurrence of the cycle slip, is in units of seconds. The other parameters were defined in section 3.1. From these test results it is concluded that: REALTEC is capable of detecting and repairing the carrier phase cycle slips in real-time.

In order to further demonstrate the performance of REALTEC, data from day 119, 1995, were processed. The test results are shown in Figure 1. The post-processing result indicates that there are three cycle slips on PRN 21, as shown by line C. The post-processed TEC estimates with cycle slip free data are indicated by line A. The real-time TEC estimates using REALTEC with raw data are indicated by line B. Again, line B has been shifted from line A by +0.5 TECU. The current day's multipath template is applied. From this Figure it is concluded that REALTEC is able to generate good quality TEC estimates (compared to post-processed TEC estimates) in real-time, even though there are multiple cycle slips in the raw data.

4.3 Test Results of Multipath Template

The NCCU (National Chengchi University) data set was collected from February 23, 2002 (day 54, 2002) to March 12, 2002 (day 71, 2002) at site CUA2 on the roof of the College of Social Sciences Building of National Chengchi University, Taiwan. The CUA2 station is equipped with an ASHTECH Z-12 geodetic receiver, and collects C/A, P1 and P2 pseudo-ranges and L1 and L2 carrier phase data, from all visible GPS satellites every 30 seconds. The cut-off angle is 10 degrees.

The post-processed TEC estimates (i.e. phase levelled TEC estimates) of day 71, 2002, at site CUA2 for each PRN, are assumed to be the true values. The predicted multipath files of day 71 from various multipath templates (either single-day or multi-day multipath templates), and the raw GPS observation file of day 71, are input to real-time TEC estimating software, REALTEC, and used to generate real-time TEC estimates. For PRN 4, the estimated TEC differences between post-processing and real-time processing are computed. The mean values, standard deviations, maximum, and minimum of these differences, in units of TECU, are calculated.

From the test results of "multi-day multipath templates versus single-day multipath templates", it is found that: (1) the accuracy of real-time TEC estimates can be appreciably improved if a (single-day or multi-day) multipath template is applied, (2) the effectiveness of multi-day multipath templates on real-time TEC estimation are better than that of single-day multipath templates.

In order to study the effectiveness of the multi-day multipath template on real-time TEC estimation, various types of multi-day multipath templates were tested. There are 4 types of multi-day multipath templates: 2-day multipath template, 3-day multipath template, 4-day multipath template, and 5-day multipath template. These multi-day multipath templates are generated using a process like moving average. For example, in order to generate 2-day multipath templates, GPS data sets of day 70 and day 69 are used to generate 69-70 multipath template, then, GPS data sets of day 69 and day 68 are used to generate 68-69 multipath template, and so on.

From the test results of "multi-day multipath templates versus multi-day multipath templates", it can be concluded that: (1) most of the absolute mean values are less than 1.00 TECU, (2) the mean values of the multi-day multipath templates are highly correlated to those of single-day multipath templates, (3) the effectiveness of the 2-day, 3-day, and 4-day multipath templates on real-time TEC estimation are better than that of 5-day multipath templates.

4.4 Test Results of Single-Site Algorithm

4.4.1 PGGA Case

In order to verify this estimation technique, a number of data sets from the *Permanent GPS Geodetic Array* (PGGA), in Southern California, USA (PGGA, 1996), were processed and analyzed. Five stations: Blythe (blyt), China Lake (coso), Yucaipa (crfp), Scripps (sio3), and Vandenberg (vndp) were selected for the tests. These stations are equipped with ASHTECH Z-XII3 geodetic receivers, and collect data from all visible GPS satellites every 30 seconds. Data from day 001 to 012, 1996, were processed.

The experimental results (Lin, 2001) indicate that: (1) The estimation precision of the SPR (Satellite-Plus-Receiver) differential delay is of the order of ? 1.23 TECU; (2) The SPR differential delay estimates with daily average removed, as obtained using the proposed algorithm, have been compared with those from other organizations. The standard deviation of "NCCU - DLR" is 1.00 TECU. Note that both the NCCU and the DLR results refer to the same time period. The standard deviation of the differences between NCCU and other organizations (most of their results referring to 1994 data) is at the 2.85 TECU level.

4.4.2 NCCU Case

The NCCU (National Chengchi University) data set was collected at sites CUA1 and CUA2 on the roof of the College of Social Sciences Building of National Chengchi University, Taiwan. Both CUA1 and CUA2 stations are equipped with an ASHTECH Z-12 geodetic receivers, and collects C/A, P1 and P2 pseudo-ranges and L1 and L2 carrier phase data, from all visible GPS satellites every 30 seconds. The cut-off angle is 10 degrees. Data was collected: (1) from December 1, 2000 to December 7, 2000, and (2) from February 23, 2002 to March 12, 2002 at site CUA2. In addition, data was collected from February 23, 2002 to March 12, 2002 at site CUA1.

The geographic regions of the ionosphere can be divided into three regions: equatorial region, mid-latitude region and polar region (Wanninger, 1994). The Ionospheric Pierce Points (IPPs) from GPS sites of Taiwan region will locate at equatorial region approximately. Hence the proposed single-site algorithm was revised. The features of the revised single-site algorithm are: (1) estimating SPR differential delay for each GPS satellite, (2) assuming the estimated satellite differential delays of Jet Propulsion Laboratory (JPL), $\hat{b}^S$ (Yinger, et al., 1999) are true values, (3) estimating the receiver differential delay for each site, $\hat{b}_R$, and (4) computing $\overline{SPR}$? $\hat{b}_R$? $\hat{b}^S$.

The test results indicate that: (1) the estimated receiver differential delays of CUA1 and CUA2 are 13.48 TECU and 16.16 TECU respectively using year 2002 data, and (2) the estimated receiver differential delays of CUA2 is 18.41 TECU using year 2000 data. The standard deviation of the estimated satellite differential delay differences between the values determined by the proposed algorithm and Jet Propulsion Laboratory (JPL) is generally less than 2.85 TECU (from 1.97 TECU to 3.02 TECU).

5. CONCLUSIONS

In order to ensure the quality of real-time ionospheric delay estimation, a series of algorithms were developed: (1) the “multipath template technique” is used to mitigate GPS pseudo-range multipath at static GPS reference stations, (2) the “single-site algorithm” is used to estimate GPS satellite and receiver differential delay, and is applied to regional ionosphere modeling, (3) the “failure detection algorithm” using Robust and Conventional Kalman Filter state estimates is used to detect cycle slips in the GPS carrier phase measurements. Data from different regions was used to test the proposed algorithms. Preliminary results indicate that the proposed algorithms can ensure the quality of real-time ionospheric delay estimation effectively and should be implemented at reference stations within LADGPS, WADGPS and WAAS networks, GPS deformation monitoring networks, etc.

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