Application of Multipath Template Technique to Real-Time Ionospheric Delay Estimation Using Global Positioning System Measurements

Lao-Sheng Lin[1]

Abstract: When global positioning system (GPS) signals propagate through the ionosphere, they experience an extra time delay. The ionospheric delay can be estimated using $L1/L2$ GPS measurement. In order to mitigate the pseudorange multipath effect on real-time ionospheric delay estimation, the multiday multipath template technique has been developed. The algorithm permits the pseudorange multipath error for a specific day to be corrected using the generated multipath template. Data from National Chengchi University, in Taiwan was used to test the application of the multipath template to real-time ionospheric delay estimation. Test results indicate that: (1) The performance of the various 5 day multipath templates is better than that of other multiday multipath templates and (2) the multipath template technique is an effective method to mitigate the GPS pseudorange multipath and should be implemented at reference stations within local-area differential GPS, wide-area differential GPS, and wide-area augmentation system networks, GPS deformation monitoring networks, etc.

DOI: 10.1061/(ASCE)0733-9453(2004)130:2(104)

CE Database subject headings: Global positioning; Delay time; Estimation; Measurement.

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 1,000 km above the earth surface. When radio waves such as global positioning system (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 a 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).

The ionospheric delay is one of the main sources of error in precise global positioning system (GPS) positioning and navigation. A dual-frequency GPS receiver can eliminate (to the first order) the ionospheric delay through a linear combination of $L1$ and $L2$ measurements (Hofmann-Wellenhof et al. 1994). However, low-cost, single-frequency GPS receivers cannot use this option. Consequently, it is beneficial to estimate ionospheric delays over a region of interest, in real time, to support single-frequency GPS positioning and navigation applications.

There are several factors which should be considered before using dual-frequency GPS receivers to estimate, in real time, the ionospheric delay. One of them, the pseudorange multipath effect on real-time ionospheric delay estimation, is considered in this paper. Various methods for reducing multipath have been developed. The multipath template technique has been proposed for the reduction of the effects of pseudorange multipath on a real-time GPS ionospheric monitoring system (Coco et al. 1993). The writers used single-day data to generate a template, and demonstrated that it was an effective way to reduce multipath effects for ionospheric monitoring applications.

A multiday multipath template technique (Lin 1997; Lin and Rizos 1997) was proposed which used dual-frequency GPS receivers at known stations to estimate and reduce the multipath for each pseudorange measurement, on an epoch by epoch basis. It was shown that the performance of the multi-day multipath template technique is superior to that of the single-day technique.

In order to improve the accuracy of the real-time ionospheric delay estimate, the multiday multipath templates, generated from the previous days' GPS data, are applied to mitigate the pseudorange multipath and improve the accuracy of the absolute ionospheric delay estimation.

In this paper, the concept and methodology of the revised multiday multipath template approach are first introduced. Then, test results from the National Chengchi University (NCCU) data are presented to demonstrate the improved performance of this approach for real-time ionospheric delay estimation using GPS measurements.

Multipath Template Technique

Pseudorange Multipath Detection Equations

It is assumed that the carrier phase multipath (plus noise) is small compared to the pseudorange multipath (plus noise), and can be accounted for in the following development. By forming the appropriate linear combination of dual-frequency GPS measure-

[1]Assistant Professor, Dept. of Land Economics, National Chengchi Univ., 64, Section 2, Chihnan Rd., Taipei 116, Taiwan.

Note. Discussion open until October 1, 2004. Separate discussions must be submitted for individual papers. To extend the closing date by one month, a written request must be filed with the ASCE Managing Editor. The manuscript for this paper was submitted for review and possible publication on August 30, 2002; approved on April 26, 2003. This paper is part of the ***Journal of Surveying Engineering***, Vol. 130, No. 2, May 1, 2004. ©ASCE, ISSN 0733-9453/2004/2-104–111/$18.00.

J. Surv. Eng. 2004.130:104-111.

ments, expressions for pseudorange multipath (Rocken et al. 1994; Rizos 1997) can be obtained (in units of meters):

$$\mathrm{MP1}+\varepsilon(P_1)+K_1=P_1-4.0915\Phi_1+3.0915\Phi_2 \quad (1)$$

$$\mathrm{MP2}+\varepsilon(P_2)+K_2=P_2-5.0915\Phi_1+4.0915\Phi_2 \quad (2)$$

where P_1,P_2 = pseudorange observations made on the $L1$ and $L2$ signals, respectively; $\varepsilon(P_1),\varepsilon(P_2)$ = the measurement noises at $L1$ and $L2$ respectively; Φ_1,Φ_2 = carrier phase measurements on the $L1$ and $L2$ signals respectively; MP1,MP2 = multipath delays on P_1 and P_2, respectively; and K_i ($i=1,2$) = linear combinations of integer ambiguity parameters (in cycles) N_1,N_2 at $L1,L2$, respectively.

Since MP1 is assumed to be a zero-mean quantity, K_1 can be computed by averaging all values of MP1 (it is constant if there are no cycle slips), and then this value can be subtracted from the MP1 values computed at each epoch. The same procedure can be applied to MP2.

After removing the constant terms K_1 and K_2, the simplified Eqs. (1) and (2) are

$$\mathrm{MP1}=P_1-4.0915\Phi_1+3.0915\Phi_2 \quad (3)$$

$$\mathrm{MP2}=P_2-5.0915\Phi_1+4.0915\Phi_2 \quad (4)$$

Pseudorange Multipath Template Generation Procedure

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 20,200 km, they will again be over the same position on the earth surface at the end of a sidereal day (approximately 23 h 56 min in length). Thus the viewing geometry is the same each day with respect to the solar day, but with a shift of about 4 min 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 multiday multipath template at static GPS reference stations has been developed (Lin 1997, 1998, 2002; Lin and Rizos 1997). Note that, for simplicity sake, only the MP1 for a single GPS satellite is considered. The data rate is assumed to be 30 s, that is, 2,880 epochs for a 24 h data span. The procedure is summarized below.

1. Step 1: Compute constant K_1 for each continuous GPS satellite arc using Eq. (1). Then, compute MP1 using Eq. (3), after removing the K_1 term, so that the general form of MP1 for any epoch can be expressed as

$$\mathrm{MP1}(i,j,k) \quad (5)$$

where i ($=1,2,\ldots,365$) denotes the day number of a year; j ($=1,2,\ldots,2{,}880$) denotes the epoch number; and k ($=1,2,\ldots,31$) denotes the GPS satellite PRN number.

2. Step 2: Convert the MP1 file from 2,880 epochs in length to 2,872 epochs. The new data sequence $\mathrm{MP1}^1$ is expressed as (8 epochs corresponds to a 4 min shift)

$$\mathrm{MP1}^1(i,j,k)=0.5\cdot[\mathrm{MP1}(i,j,k)+\mathrm{MP1}(i,j+2872,k)] \quad \text{when } j\leqslant 8$$
$$\mathrm{MP1}^1(i,j,k)=\mathrm{MP1}(i,j,k) \quad \text{when } 9\leqslant j\leqslant 2872 \quad (6)$$

3. Step 3: Transfer the $\mathrm{MP1}^1$ of the current day i to $\mathrm{MP1}^2$, referred to as reference day i_0, using the following relation:

$$\mathrm{MP1}^2(i_0,j,k)=\mathrm{MP1}^1(i,\mathrm{temp},k) \quad (7)$$

where $\mathrm{temp}=[j+2872-(i-i_0)\cdot 8]$, if temp⩾2,873 then temp = temp-2,872; i_0 is the reference day chosen to be several days prior to the current day i.

4. Step 4: Generate the multiday multipath template for a reference station

$$\mathrm{MP1}^3(i_0,j,k)=\sum_{l=1}^{n}\mathrm{MP1}^2(i_0,j,k)/n \quad (8)$$

where: (1) If $n=1$, then $\mathrm{MP1}^3(i_0,j,k)$ = single-day multipath template; and (2) if $n>1$, then $\mathrm{MP1}^3(i_0,j,k)$ = multiday multipath template.

Pseudorange Multipath Prediction Procedure

Once the multipath template for MP1 is generated, it can be used to predict the pseudorange multipath quantity if the parameters i, j,k are given. The procedure is summarized below.

1. Step 1: Predict the pseudorange multipath quantity $\overline{\mathrm{MP1}}$ for a specific day i

$$\overline{\mathrm{MP1}}(i,j,k)=\mathrm{MP1}^3(i_0,\mathrm{temp1},k) \quad (9)$$

where $\overline{\mathrm{MP1}}(i,j,k)$ = predicted multipath (2,872 epochs in length), and $\mathrm{temp1}=[j+(i-i_0)\cdot 8]$, if temp1⩾2,873 then temp1 = temp1-2,872.

2. Step 2: Convert the $\overline{\mathrm{MP1}}$ file from 2,872 epochs in length to 2,880 epochs, $\overline{\overline{\mathrm{MP1}}}$. The new data sequence is expressed as

$$\overline{\overline{\mathrm{MP1}}}(i,j,k)=\overline{\mathrm{MP1}}(i,\mathrm{temp2},k) \quad \text{when } j\leqslant 2872$$
$$\overline{\overline{\mathrm{MP1}}}(i,j,k)=\overline{\mathrm{MP1}}(i,\mathrm{temp3},k) \quad \text{when } j\geqslant 2873 \quad (10)$$

where $1\leqslant j\leqslant 2{,}880$, $1\leqslant \mathrm{temp2}\leqslant 2{,}872$, $\mathrm{temp3}=j$-2,872.

The above procedure is also applicable for the prediction of MP2. In addition, it can be used to predict the multipath for pseudoranges with a varied data rate. However, the j, temp, temp1, temp2, temp3 terms in Eqs. (5)–(10) must be modified according to the data rate.

Application of Multipath Template to Real-Time Ionospheric Delay Estimation Using Global Positioning System Measurements

Ionospheric Delay Estimation Using Global Positioning System Measurements

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

$$\mathrm{TR}=9.5196\times[(P_2-P_1)-(\mathrm{MP2}-\mathrm{MP1})] \quad (11)$$

Note that this pseudorange estimated TEC, TR, 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 1998):

$$\mathrm{TS}=9.5196\times[(\Phi_1-\Phi_2)-(\lambda_1 N_1-\lambda_2 N_2)]$$
$$=9.5196\times(\Phi_1-\Phi_2)+D \quad (12)$$

J. Surv. Eng. 2004.130:104-111.

Table 1. Statistics of Real-Time Total Electron Content Estimate Difference after Applying Various Single-Day Multipath (MP) Templates

Day of year	Mean	σ	Maximum	Minimum
71	0.00	0.00	0.00	0.00
70	0.33	0.09	0.39	0.10
69	0.41	0.09	0.51	0.12
68	−0.68	0.09	−0.60	−0.96
67	2.15	0.30	2.69	1.47
66	1.62	0.19	1.90	1.35
65	1.89	0.26	2.36	1.28
64	1.43	0.16	1.64	1.14
63	1.79	0.19	2.06	1.36
62	0.02	0.04	0.06	−0.12
61	−1.11	0.18	−0.66	−1.43
60	0.79	0.11	0.94	0.44
59	0.22	0.11	0.30	−0.03
58	−1.33	0.23	−1.11	−1.89
56	−1.21	0.19	−1.02	−1.75
55	0.69	0.16	0.92	0.45
No MP	1.95	0.18	2.36	1.71

where λ_1, λ_2 = carrier wavelengths (in meters) of $L1$, $L2$, respectively; and D = product 9.5196 times the linear combination of the integer ambiguity parameters N_1 and N_2. Note that TR and TS are in units of TECU.

Application of Multipath Template Real-Time Total Electron Content Estimation

In order to improve the accuracy of real-time ionospheric delay estimation using GPS measurements, a novel approach was proposed (Lin 1997, 1998). Based on the proposed approach, a real-time TEC estimation software package, known as *REALTEC*, was developed. The main features of *REALTEC* are: (1) Application of a statistical test on the state, TEC, difference estimated from robust and conventional Kalman filters in order to detect and identify the carrier phase failure(s); (2) application of a Kalman filter algorithm to repair the identified carrier phase failure(s), and (3) application of a multipath template to mitigate the pseudo-range multipath effect on pseudoranges derived TEC, TR, to improve the accuracy of real-time TEC estimation.

The multipath template at a static GPS reference station can be generated from the GPS measurements of the previous days. In a real-time TEC estimation application, the current day multipath delays for MP1 and MP2 of Eq. (11) can be predicted beforehand by the generated multipath template (i.e., MP1 and MP2 will be replaced by $\overline{\overline{MP}}1$ and $\overline{\overline{MP}}2$, respectively) and stored in a file. Then, this multipath file is input to the real-time TEC estimation software, *REALTEC*. Using Eq. (11), the multipath effect on the pseudorange derived TEC estimate, TR, is mitigated for each tracked GPS satellite on an epoch by epoch basis.

Test Results and Discussion

Test Data

The NCCU data set was collected from March 3, 2002 (Day 62, 2002) to March 9, 2002 (Day 68, 2002) at site CUA1 and from February 24, 2002 (Day 55, 2002) to March 12, 2002 (Day 71, 2002) at site CUA2. Both sites CUA1 and CUA2 are located on the roof of the College of Social Sciences Building of National Chengchi Univ., Taiwan. Stations CUA1 and CUA2 are equipped with ASHTECH Z-12 geodetic receivers, and collect C/A, $P1$, and $P2$ pseudoranges and $L1$ and $L2$ carrier phase data, from all visible GPS satellites every 30 s. The distance between site CUA1 and site CUA2 is about 70 m in length. The cutoff angle is 10°.

Table 2. Statistics of Real-Time Total Electron Content Estimate Difference after Applying Various Multiday Multipath Templates (md MT)

md MT	Mean	σ	Maximum	Minimum
1 day	0.33	0.09	0.39	0.10
2 day	0.21	0.08	0.29	0.02
3 day	−0.40	0.09	−0.33	−0.67
5 day	0.44	0.08	0.54	0.31
7 day	0.69	0.09	0.83	0.53
8 day	0.96	0.11	1.12	0.72
9 day	0.30	0.06	0.39	0.17
10 day	−0.70	0.10	−0.56	−0.95
11 day	−0.24	0.08	−0.19	−0.51
12 day	−0.30	0.11	−0.21	−0.60
13 day	−1.23	0.20	−1.03	−1.73
15 day	−1.57	0.22	−1.35	−2.15
16 day	−0.83	0.12	−0.75	−1.21

Data Processing

In order to generate multipath templates from previous days' GPS data for a static reference station, a set of software, known as *MULTIPAT* (Lin 1998) was developed and revised based on the above-mentioned multipath template technique. Hence, the main functions of *MULTIPAT* are: (1) Detecting the arc numbers for each tracked GPS satellite in a 24 h data; (2) computing constants K_1 and K_2 for each arc of each tracked GPS satellite; (3) estimating pseudorange multipath delays MP1,MP2 for each satellite on an epoch by epoch basis; (4) generating various types of multipath templates; (5) predicting the multipath file of a specific day from the multipath template; and (6) calculating the TEC estimates for all visible GPS satellites in a postprocessing mode. In the postprocessing option, the phase leveling procedure is commonly used. This is accomplished by fitting the carrier phase

Table 3. Statistics of Real-Time Total Electron Content Estimate Difference after Applying Various Two-Day Multipath (MP) Templates

Two-day multipath template	Mean	σ	Maximum	Minimum
69–70	0.21	0.08	0.29	0.02
68–69	−0.13	0.05	−0.05	−0.34
63–64	1.57	0.16	1.79	1.22
62–63	0.75	0.08	0.87	0.54
61–62	−0.55	0.09	−0.40	−0.77
60–61	−0.17	0.08	−0.10	−0.41
59–60	0.50	0.09	0.61	0.22
58–59	−0.67	0.17	−0.51	−1.10
55–56	−0.25	0.10	−0.15	−0.56
No MP	1.95	0.18	2.36	1.71

J. Surv. Eng. 2004.130:104-111.

Table 4. Statistics of Real-Time Total Electron Content Estimate Difference after Applying Various Three-Day Multipath (MP) Templates

Three-day multipath template	Mean	σ	Maximum	Minimum
68–70	−0.40	0.09	−0.33	−0.67
67–69	−0.13	0.08	−0.05	−0.34
66–68	0.47	0.110	0.61	0.30
65–67	1.62	0.19	1.90	1.35
64–66	1.51	0.17	1.74	1.25
63–65	1.57	0.16	1.79	1.22
62–64	1.02	0.11	1.18	0.78
61–63	0.06	0.05	0.10	−0.10
60–62	−0.11	0.06	−0.04	−0.31
59–61	−0.04	0.09	0.03	−0.28
58–60	−0.18	0.12	−0.09	−0.52
57–59	−0.67	0.17	−0.51	−1.10
56–58	−1.27	0.21	−1.07	−1.82
55–57	−0.25	0.10	−0.15	−0.56
No MP	1.95	0.18	2.36	1.71

derived TEC estimates, TS, to the unambiguous, but noisy, pseudorange derived TEC estimates, TR. The outputs are then the so-called phase levelled TEC estimates. The multipath effects on the pseudorange derived TEC estimates will be mitigated after phase leveling. Note that the postprocessed TEC estimates mentioned in the following test results are referred to as the phase leveled TEC estimates from *MULTIPAT*. On the other hand, another software package, *REALTEC*, can process the TEC estimates for all visible GPS satellites in a real-time mode.

In order to test the effectiveness of applying the multipath template technique to real-time TEC determination, the NCCU data set of site CUA2 was processed first. The postprocessed TEC estimates (i.e., phase-leveled 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 multiday 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. The reference day i_0 in Eq. (7) is set to 01 (that is Day 01, 2002). There were 28 GPS satellites that were tracked during the test period. Since the PRN 4 GPS satellite was tracked continuously about 8 h (approximately 930 epochs) each day in the test data set, it was selected as the test object in the following tests. For PRN 4, the estimated TEC differences between postprocessing and real-time processing are computed. Then the statistical values, such as mean value (Mean), standard deviation (σ), maximum (Maximum), and minimum (Minimum) of these differences, in units of TECU, are calculated and shown in Tables 1–9.

Table 5. Statistics of Real-Time Total Electron Content Estimate Difference after Applying Various Four-Day Multipath (MP) Templates

Four-day multipath template	Mean	σ	Maximum	Minimum
67–70	−0.40	0.09	−0.33	−0.67
66–69	0.45	0.08	0.55	0.31
65–68	0.47	0.110	0.61	0.30
64–67	1.51	0.17	1.74	1.25
63–66	1.57	0.17	1.80	1.27
62–65	1.03	0.11	1.18	0.78
61–64	0.47	0.06	0.56	0.34
60–63	0.19	0.05	0.26	0.02
59–62	−0.03	0.07	0.03	−0.24
58–61	−0.44	0.12	−0.32	−0.76
57–60	−0.18	0.12	−0.09	−0.52
56–69	−0.93	0.18	−0.76	−1.41
55–58	−0.61	0.12	−0.54	−1.00
No MP	1.95	0.18	2.36	1.71

Table 6. Statistics of Real-Time Total Electron Content Estimate Difference after Applying Various Five-Day Multipath (MP) Templates

Five-day multipath template	Mean	σ	Maximum	Minimum
66–70	0.44	0.08	0.54	0.31
65–69	0.47	0.10	0.61	0.30
64–68	0.72	0.11	0.89	0.54
63–67	1.57	0.19	1.80	1.27
62–66	1.16	0.12	1.34	0.92
61–65	0.47	0.06	0.56	0.34
60–64	0.53	0.07	0.63	0.35
59–63	0.16	0.07	0.22	−0.03
58–62	−0.34	0.11	−0.25	−0.64
57–61	−0.43	0.12	−0.32	−0.76
56–60	−0.49	0.14	−0.37	−0.89
55–59	−0.58	0.13	−0.50	−0.96
No MP	1.95	0.18	2.36	1.71

Multiday Multipath Templates versus Single-Day Multipath Templates

Table 1 shows the real-time TEC estimate difference statistics, a comparison of applying different single-day multipath templates, for PRN 4 at site CUA2, from Days 55 to 71, 2002. Day of a year is denoted DoY. Note that the corresponding statistical values of Day 71 on Table 1 are all zero. The reason is that the achieved TEC accuracy from *REALTEC* is identical to that obtained from postprocessing if the single-day multipath template is generated from the GPS data from the current day (i.e., Day 71 in this case) (Lin 1997, 1998). Besides, No MP denotes the real-time TEC estimate result without applying any multipath template. Note that no test result of Day 57 (i.e., DoY 57) was shown on Table 1 since PRN 4 data was not available on that day. It can be seen that the mean of TEC estimate differences is 1.95 TECU if no multipath template is applied. On the other hand, the accuracy of TEC

Table 7. Mean Values Statistics of Tables 1–6

Multipath template type	Group mean	Group σ
1 day	0.64	1.20
Multiday	−0.18	0.76
2 day	0.14	0.71
3 day	0.23	0.89
4 day	0.24	0.78
5 day	0.31	0.68

Table 8. Absolute Mean Values Statistics of Tables 1–6

Multipath template type	Group mean	Group σ
1 day	1.15	0.68
Multiday	0.63	0.42
2 day	0.53	0.45
3 day	0.66	0.61
4 day	0.64	0.49
5 day	0.61	0.39

estimation can be appreciably improved if a single-day multipath template is applied, even though the single-day multipath template of DoY 55 was generated from the GPS data of 15 days earlier.

Table 2 shows the real-time TEC estimate difference statistics, a comparison of applying various multiday multipath templates, for PRN 4 at site CUA2, from Day 55 to 71, 2002. Column 1 of Table 2, md MT, denotes the multipath template (MT) was generated using all previous multidays' GPS data (relative to Day 71). For example, 1 day indicates that the multipath template was generated using the GPS data from the previous 1 day (that is, Day 70, in this case), 2 day indicates the multipath template was generated using the previous 2 days' GPS data (that is, from Days 69 to 70, in this case), and so on. Since the mean values of DoY 65 and DoY 67 are at the level of 2 TECU (referring to Table 1) and the PRN 4 data was not available on DoY 57, there was no test result of 4, 6, 14, or 17 day shown in Table 2. From this table, it can be seen that: (1) Most of the mean values after applying various multiday multipath templates are at the level of ±1.00 TECU and (2) the accuracy of TEC estimation can be appreciably improved if a multiday multipath template is applied.

From these two tables, it is obvious that: (1) The accuracy of real-time TEC estimates can be appreciably improved if a (single-day or multiday) multipath template is applied and (2) generally speaking, the effectiveness of multiday multipath templates on real-time TEC estimation are better than that of single-day multipath templates.

Multiday Multipath Templates Versus Multiday Multipath Templates

According to the above-mentioned test results, in most cases the effectiveness of multiday multipath templates on real-time TEC estimation are better than that of single-day multipath templates. However, several issues should be considered before applying the multipath template technique to real-time TEC estimation. For example, how many days' GPS data should be used to generate a multipath template? Hence, in order to further study the effectiveness of the multiday multipath template on real-time TEC estimation, various types of multiday multipath templates were tested.

Table 9. Absolute Mean Values (Less Than 0.90 Total Electron Content Unit) Statistics of Tables 1–6

Multipath template type	Group mean	Group σ
1 day	0.68	0.44
2 day	0.40	0.24
3 day	0.36	0.38
4 day	0.36	0.18
5 day	0.46	0.15

Table 10. Statistics Indicating Arc Number, Epoch Number, and Elevation Angle for Each Tracked Satellite at Site CUA2

PRN	Arc (s)	Epoch (s)	E-Max-1	E-Max-2	E-Max-3
1	3	891	42	22	50
2	2	941	57	50	X
3	2	730	70	88	X
4	1	930	51	X	X
5	2	740	18	52	X
6	2	820	35	32	X
7	1	849	73	X	X
8	2	892	50	22	X
9	1	541	82	X	X
10	1	916	55	X	X
11	1	720	85	X	X
13	3	934	32	35	32
14	1	821	72	X	X
15	3	820	12	55	15
17	1	617	65	X	X
18	1	764	82	X	X
20	2	859	53	18	X
21	1	665	75	X	X
22	2	879	35	62	X
23	1	923	60	X	X
24	1	913	60	X	X
25	2	930	20	55	X
26	1	793	75	X	X
27	2	701	61	11	X
28	1	686	81	X	X
29	1	890	55	X	X
30	1	630	65	X	X
31	2	824	72	62	X

Again, for a PRN 4 GPS satellite, the postprocessed TEC estimate of Day 71, 2002 are assumed to be the true values. Then, the predicted multipath files of Day 71 from various multiday multipath templates and the raw GPS observation file of Day 71 are input to *REALTEC*, and used to generate real-time TEC estimates. The mean value (Mean), standard deviation (σ), maximum (Maximum), and minimum (Minimum) of these TEC differences, in units of TECU, are computed.

Four types of multiday multipath templates are generated: A 2 day multipath template (2 day MT), a 3 day multipath template (3 day MT), a 4 day multipath template (4 day MT), and a 5 day multipath template (5 day MT). Their corresponding test results are summarized in Tables 3–6, respectively. These multiday multipath templates are generated using a process similar to a moving average. For example, in order to generate 2 day multipath templates, GPS data sets of Days 70 and 69 are used to generate the 69–70 multipath template; then, GPS data sets of Days 69 and 68 are used to generate the 68–69 multipath template, and so on. Due to their poor accuracy or availability, some of the single-day multipath templates are not used to generate multiday multipath templates, such as the single-day multipath templates of Days 67, 65, and 57.

From Tables 3 to 6, it can be seen that: (1) Most of the absolute mean values are less than 1.00 TECU and (2) the mean values of the multiday multipath templates are highly correlated to those of the corresponding single-day multipath templates (for example, the mean values of DoY 63 and 64 of Table 1 are 1.79 and 1.43 TECU, respectively, and the mean value of 63–64 of Table 3 is 1.57 TECU).

J. Surv. Eng. 2004.130:104-111.

Table 11. Comparisons of Means of Real-Time Total Electron Current Estimate Difference for 28 Tracked Satellites at Site CUA2 after Applying Various Multipath Templates

PRN	1 day (70)	2 day (55–56)	3 day (56–58)	4 day (55–58)	5 day (55–59)	No multipath
1	0.60	0.31	1.02	1.02	1.09	5.07
2	0.49	−0.03	0.09	−0.26	−0.36	−0.16
3	0.65	1.03	1.48	1.19	1.39	1.1
4	0.33	−0.25	−1.27	−0.61	−0.58	2.03
5	2.62	3.32	2.76	2.98	2.69	2.66
6	−0.21	−2.02	−0.73	−0.65	−0.29	0.27
7	−0.52	−0.27	−0.20	−0.12	−0.02	−0.78
8	−1.24	0.38	−0.47	−0.60	−0.80	8.48
9	0.52	0.05	0.36	0.02	0.11	0.00
10	−0.20	−2.52	−0.52	−0.92	−0.27	−0.19
11	−1.00	−0.40	−1.13	−0.68	−0.45	1.34
13	−0.20	0.13	−0.12	−0.13	−0.14	0.46
14	0.25	0.01	0.77	0.03	0.03	0.01
15	0.67	0.68	1.54	0.57	0.51	6.68
17	0.43	−0.44	−0.76	−1.42	−0.97	0.68
18	0.04	−0.02	0.22	0.20	0.03	0.09
20	−0.07	−0.36	−0.63	−0.47	−0.46	−0.83
21	0.58	−3.05	−2.53	−2.40	−2.29	0.87
22	0.18	1.09	1.21	1.04	0.94	1.69
23	−0.14	−0.45	−0.42	−0.39	−0.39	−0.41
24	2.01	0.47	−0.63	0.31	−0.24	2.01
25	1.25	−0.06	−0.07	−0.07	−0.06	0.02
26	13.69	13.57	13.69	13.57	11.87	13.69
27	−0.49	−0.48	−0.49	−0.49	−0.50	−0.43
28	−0.83	0.62	0.46	0.25	0.41	0.45
29	−0.12	−0.15	−0.18	−0.16	−0.14	−0.11
30	8.13	5.05	6.02	5.05	3.1	8.77
31	0.4	0.29	0.17	0.17	0.28	−0.95

In order to further study the effectiveness of various types of multiday multipath templates, the averages (group mean) and standard deviations (group σ) of mean values (Mean) of Tables 1–6 are computed and summarized in Table 7. Column 1 of Table 7, MT type, denotes the multipath template type. From Table 7, it is obvious that: (1) The smallest average is −0.18 TECU of the multiday multipath template, and (2) the averages of 2, 3, 4, and 5 day are about 0.14–0.31 TECU.

Besides, the absolute values of those mean values from Tables 1 to 6 are computed and shown in Table 8. From Table 8, it can be seen that: (1) The average from 2-day multipath templates is 0.53 TECU (the smallest) and (2) the averages from 3, 4, and 5 day multipath templates are about 0.60 TECU.

From Tables 1 to 6, it can be seen that some absolute mean values are larger than 0.90 TECU. In order to further analyze the test results, if the absolute mean values of Tables 1–6 are smaller than 0.90 TECU, then they are included in the following Group mean and Group σ computations. The results are shown in Table 9. From Table 9, it can be seen that: The averages from 3 or 4 day multipath templates are 0.36 TECU (the smallest). However, the standard deviation of 4 day is 0.18 TECU only. The averages from 2, and 5 day multipath templates are 0.40 and 0.46 TECU, respectively.

From these test results it is concluded that: (1) The absolute mean values of real-time TEC estimate differences after applying 2–5 day multipath templates are in the range of 0.36–0.46 TECU and (2) the GPS data sets from previous days at a static site can be used to generate various types of multipath templates.

Performance Evaluation Using Other Satellites

The above-mentioned test results were derived from those tests on a PRN 4 satellite at site CUA2 using the proposed multipath template approach. Besides, those test results indicate that multipath templates are useful for mitigating the multipath effects on GPS pseudorange derived TEC at a static site. However, is it still valid to apply the proposed multipath template to other GPS satellites at site CUA2 or at other sites? The following test results presented in this section attempt to answer this question.

First, the GPS data set at site CUA2 was processed. As mentioned before, the postprocessed TEC estimates of Day 71, 2002, at site CUA2 for each tracked satellite, are assumed to be the true values. The predicted multipath files of Day 71 from various multipath templates, and the GPS *RINEX* files (observation file and navigation file) of Day 71, are input to real-time TEC estimating software. Accordingly, the means of the estimated TEC differences between postprocessing and real-time processing are computed and analyzed. According to the test data, there were 28 GPS satellites tracked at site CUA2.

Table 10 shows the statistics for arc number, epoch number, and elevation angle for these 28 satellites. E-Max-1, E-Max-2, and E-Max-3 (all in units of degrees) of Table 10 represent the maximum elevation angle of a GPS satellite along arcs 1, 2, and 3, respectively. Since the cutoff angle of the test data is 10°, the minimum elevation angles for all satellites are 10°. Arc denotes the arc number of a tracked satellite during a 24 h period, and Epoch denotes the epoch number of a tracked satellite during a 24

J. Surv. Eng. 2004.130:104-111.

Table 12. Comparisons of Means of Real-Time Total Electron Current Estimate Difference for Two Tracked Satellites, with Cutoff Angle Set at 15° at Site CUA2 after Applying 5 Day Multipath Template

PRN	5 day (55–59) multipath template				No multipath			
	Mean	σ	Maximum	Minimum	Mean	σ	Maximum	Minimum
26	−1.77	0.14	−1.53	−2.00	0.15	0.03	0.22	0.10
30	3.75	0.21	4.21	3.42	3.96	0.24	4.41	3.63

h period. One epoch corresponds to 30 s. From Table 10, it can be seen that: (1) 15 satellites have only 1 arc, (2) ten satellites have 2 arcs, and (3) only three satellites have 3 arcs.

Five types of multipath templates were selected to predict the multipath files of Day 71. The selected multipath templates were 1 day (70), 2 day (55–56), 3 day (56–58), 4 day (55–58), and 5 day (55–59). Note that 1 day (70) denotes the 1 day multipath template generated from the GPS data of day 70, 2 day (55–56) denotes the 2 day multipath template generated from the GPS data of Days 55 and 56, and so on. Comparisons of the means (in units of TECU) of real-time TEC estimate differences for each PRN at site CUA2 after applying the above-mentioned multipath templates are summarized in Table 11. Please note that No MP on Table 11 denotes the test result without application of any multipath template.

From Table 11, it can be seen that: (1) The pseudorange multipath effects on real-time TEC estimates can be mitigated significantly for most of the tracked satellites (except PRN 21) if various multipath templates were applied; (2) usually the performance of 4 and 5 day multiday multipath templates are better than that of other types of multipath templates, such as 2 or 3 day, and (3) there are a few satellites with very low means in cases of applying no multipath template, for example the No MP mean is 0.01 TECU for PRN 14. On the other hand, the means of 5 day for those satellites are very small, too. However, from a practical point of view, it is suggested that if the absolute value of the mean of No MP for a satellite is less than a threshold value (e.g., 0.5 TECU) then this satellite be free from any further multipath mitigating process.

According to the results of Table 11, the means of 5 day for PRN 26 and 30 are larger than 3.0 TECU. Besides, these two satellites have only 1 arc each as indicated in Table 10. In order to further study the relationship between the multipath effects on TEC estimates and the elevation angles of satellites, the data set of CUA2 were tested again using the above-mentioned data processing procedure. However, several factors are different from the above-mentioned tests: (1) Only 5 day (55–59) multipath template and No MP were tested; (2) only the results of PRN 26 and 30 were analyzed and displayed; (3) the cutoff angle of the data set was changed to 15°, the results being shown in Table 12, and (4) the cutoff angle of the data set was changed to 20°, with the results shown in Table 13.

From Table 12, for PRN 26, the mean of 5 day is reduced from 11.87 TECU (with a cutoff angle of 10°) to −1.77 TECU. On the other hand, the mean of No MP is reduced from 13.67 TECU (with a cutoff angle of 10°) to 0.15 TECU. Based on the foregoing discussion, PRN 26 should be free from any further multipath mitigating process if its cutoff angle is 15°. However, for PRN 30, the means of 5 day and No MP are still larger than 3.0 TECU even if its cutoff angle is 15°.

From Table 13, for PRN 26, the means of 5 day and No MP are −0.01 and −0.04 TECU, respectively, if its cutoff angle is 20°. On the other hand, for PRN 30, the mean of 5 day is reduced from 3.75 TECU (with a cutoff angle of 15°) to −1.69 TECU and the mean of No MP is reduced from 3.96 TECU (with a cutoff angle of 15°) to −1.71 TECU.

From the above-mentioned test results of over 28 satellites, it can be concluded that: (1) The pseudorange multipath effects on real-time TEC estimates can be mitigated significantly for most of the tracked satellites if various multipath templates were applied; (2) the performance of 4 and 5 day multiday multipath templates are better than that of other types of multipath templates; and (3) if the absolute value of the mean of No MP for a satellite is less than the threshold value (e.g., 0.5 TECU) then this satellite is free from any further multipath mitigating process.

Performance Evaluation Using Different Site

In order to further study the validation of the proposed approach using different sites, another NCCU data set from site CUA1 was processed. The cutoff angle was 10°. In the following tests, the postprocessed TEC estimates (i.e., phase-leveled TEC estimates) of Day 68, 2002, at site CUA1 for each PRN, are assumed to be the true values. The predicted multipath files of Day 68 from various multipath templates [i.e., 1 day (62), 2 day (62–63), and 3 day (62–63–65)], and the raw GPS observation file of Day 68, are input to real-time TEC estimating software, *REALTEC*, and used to generate real-time TEC estimates. For each PRN, the estimated TEC differences between postprocessing and real-time processing are computed. Then the mean values (Mean), standard deviations (σ), maximum (Maximum), and minimum (Minimum) of these differences, in units of TECU, are calculated.

Since sites CUA1 and CUA2 are located on the roof of the same building, and their distance is only about 70 m apart, the statistics of arc number, epoch number, and elevation angle for each tracked satellite at site CUA1 is similar to that of site CUA2 (refer to Table 10). The test results of site CUA1 are shown in Table 14. Note that those satellites with small No MP means (i.e., 1.0 TECU) are not shown in Table 14. From Table 14, it can be seen that: (1) The pseudorange multipath effects on real-time TEC

Table 13. Comparisons of Means of Real-Time Total Electron Content Estimate Difference for Two Tracked Satellites, with Cutoff Angle Set at 20° at Site CUA2 after Applying 5 Day Multipath Template

PRN	5 day (55–59) multipath template				No multipath			
	Mean	σ	Maximum	Minimum	Mean	Σ	Maximum	Minimum
26	−0.01	0.02	0.01	−0.05	−0.04	0.02	0.00	−0.08
30	−1.69	0.11	−1.50	−1.88	−1.71	0.09	−1.50	−1.88

J. Surv. Eng. 2004.130:104-111.

Table 14. Comparisons of Mean of Real-Time Total Electron Content Estimate Difference for 13 Tracked Satellites at Site CUA1 after Applying Various Multipath Templates

PRN	1 day (62)	2 day (62–63)	3 day (62–63–65)	No multipath
1	3.83	4.27	4.12	4.38
6	0.00	0.10	0.10	3.84
7	0.72	0.87	0.29	1.96
9	5.42	5.17	2.49	4.77
11	4.2	2.83	1.9	2.14
14	−0.43	−0.10	−0.69	1.37
18	0.90	1.69	2.33	3.22
20	2.24	0.84	−0.24	4.21
21	6.83	5.58	5.82	5.87
23	−0.09	−0.77	0.49	1.65
25	1.36	2.74	1.70	2.00
27	2.88	1.64	−0.28	4.18
28	4.09	4.17	3.85	6.61

estimates can be mitigated significantly for most of the tracked satellites if various multipath templates were applied and (2) most often the performance of 3 day multiday multipath templates are better than that of other types of multipath templates.

Conclusions

In order to improve the accuracy of real-time ionospheric delay estimation, a multiday multipath template algorithm has been implemented and tested. The algorithm can be used to generate either a single-day multipath template or a multiday multipath template. According to the test results, both single-day and multiday multipath templates are useful for mitigating the multipath effects on the GPS pseudorange derived TEC at a static site. However, the performance of the multiday multipath template is superior to that of the single-day multipath template. Hence, this technique is suitable for mitigating pseudorange multipath at reference stations for local-area differential GPS, wide-area differential GPS, and wide-area augmentation system networks, GPS deformation monitoring networks, etc.

On the other hand, some issues should be considered before applying the proposed multiday multipath template technique to practical applications: (1) The $L1/L2$ dual frequency GPS measurements of previous days at a static site are required; (2) the parameters j, temp, temp1, temp2, and temp3 in Eqs. (5)–(10) must be modified according to the real data rate; (3) the single-day multipath templates should be generated and tested initially in order to get the qualified GPS data sets; (4) then, the 5 day multipath templates can be generated using the qualified GPS data sets; and (5) the generated 5 day multipath template must be evaluated periodically (for example, after 20 days).

Acknowledgment

The work presented in this paper was funded, in part, by the National Science Council, Taiwan, R.O.C., Project No. NSC 90-2211-E-004-001.

References

Coco, D. S., Coker, C., Dahlke S. R., and Bishop, G. J. (1993). "A real-time GPS ionospheric monitor system." *Proc., 1993 Ionospheric Effects Symp.*, J. H. Goodman, ed., Springfield, Va., 219–227.

Hofmann-Wellenhof, B., Lichtenegger, H., and Collins, J. (1994). *Global positioning system: Theory and practice*, 3rd Ed., Springer, New York.

Lin, L. S. (1997). "A novel approach to improving the accuracy of real-time ionospheric delay estimation using GPS." *Proc., ION GPS-97, 10th Int. Technical Meeting of the Satellite Division of the Institute of Navigation*, Kansas City, Mo., 169–178.

Lin, L. S. (1998). "Real-time estimation of ionospheric delays using GPS measurements." *UNISURV S-51, Rep. from the School of Geomatic Engineering*, The Univ. of New South Wales, Sydney, Australia.

Lin, L. S. (2002). "Using multipath template technique to improve the real-time ionospheric delay estimation accuracy." *J. Taiwan Land Econ.*, 2, 1–29.

Lin, L. S., and Rizos, C. (1997). "Use of the multipath template technique for mitigating pseudo-range multipath: Methodology and test results." *Proc., 1st Trans Tasman Surveyors Conf.*, Newcastle, Australia, 22.1–22.9.

Rizos, C. (1997). "Principles and practice of GPS surveying." *Monograph 17*, School of Geomatic Engineering, The Univ. of New South Wales, Australia.

Rocken, C., Johnson, J., Braun, J., Meertens, C., and Perry, S. (1994). "UNAVCO facility GPS receiver tests." *Draft 7/2/94*.

J. Surv. Eng. 2004.130:104-111.