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REMOTE SENSING OF IONOSPHERE USING GPS MEASUREMENTS

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ABSTRACT: The ionospheric delay in the propagation of Global Positioning System (GPS) signals is one of the main sources of error in GPS precise positioning and navigation. A dual-frequency GPS receiver can eliminate (to the first order) the ionospheric delay through a linear combination of the L1 and L2 observations. On the other hand, taking this advantage, a dual-frequency GPS receiver can be used to remote sensing the ionosphere. One of the challenging problems in making absolute ionospheric delay measurements using the dual-frequency observations to the GPS satellites is to estimate satellite and receiver L1/L2 differential delays. In this paper an algorithm is proposed which can estimate the sum of the satellite and receiver L1/L2 differential delays of each tracked GPS satellite using a single-site modeling technique. The estimation method, test results, and comparison with the results of other organizations are described here. The test results indicate that the estimation precision of the proposed algorithm is about 0.43 nanosecond (ns) in differential delay. The standard deviation of the estimated satellite differential delay differences between the values determined by the proposed algorithm and other organizations is generally less than 1 ns (from 0.33 ns to 1.07 ns).

1. INTRODUCTION

When radio waves propagate through the ionosphere they suffer an extra time delay. This time delay is a function of the total electron content (TEC) of the ionosphere. Since the ionosphere acts as a dispersive medium to GPS signals, dual-frequency (L1 at 1575.42 MHz, L2 at 1227.60 MHz) GPS receivers can eliminate (albeit to the first order) ionospheric delay through a linear combination of the L1 and L2 observations. On the other hand, taking this advantage, we can use dual-frequency GPS measurements to remote sensing the ionosphere (i.e. to estimate the TEC of the ionosphere).

One of the challenging problems in making absolute TEC measurements using dual-frequency observations of the GPS satellites is to estimate the satellite and receiver L1/L2 differential delays (Coco 1991; Bishop et al., 1992; Klobuchar et al., 1993). In this paper the author proposes an alternative algorithm, based on the single-site modeling technique, to estimate the sum of the satellite and receiver L1/L2 differential delay for each tracked GPS satellite, using 24-hour data sets. The basic assumptions and estimation technique are described in section 2. Methods of verifying the estimation method, the experimental results and discussion are given in the "experiments and results" section. Finally, some conclusions are drawn based on the experimental results.

2. A PROPOSED ALGORITHM TO ESTIMATE GPS SATELLITE AND RECEIVER DIFFERENTIAL DELAYS

2.1 Definition of GPS Satellite and Receiver L1/L2 Differential Delay

The codes transmitted by GPS satellites at the two L-band frequencies (L1 and L2) 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 L1/L2 differential delay* or *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 L1/L2 differential delay* or *receiver differential delay*, because the L1 and L2 signals must travel through different hardware paths or electronic circuitry inside the receiver. Each GPS receiver has its individual receiver differential delay.

Both the satellite and receiver differential delays introduce error in the measurement of TEC. According to Wilson et al. (1994), ignoring the *satellite differential delays* and the *receiver differential delay* when computing line-of-sight TEC measurements from GPS observables may result in an error of ± 3 ns and ± 10 ns respectively. Note that 1 ns of differential delay is 2.852 TECU (Klobuchar, et al., 1993).

2.2 Assumptions on the Proposed Algorithm

The proposed estimation algorithm is a single-site modeling technique implemented in post-processed mode (Lin, 1998). 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. (3) The satellite and receiver differential delays are assumed to be constant over the observation sessions. (4) The slant and vertical TEC are assumed to be related by a constant obliquity factor (or mapping function).

2.3 Estimation Procedure

The estimation procedure, with the above-mentioned assumptions, is as follows:

2.3.1 TEC Estimation Using GPS Measurements: A dual-frequency GPS receiver measures pseudo-ranges and carrier phases at L1/L2 and its observables are used to compute TEC. The "phase leveling" technique (e.g. Coco et al., 1991; Lin, 1998) is used to compute precise phase-derived slant TEC for each tracked satellite at each observation epoch. 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:

$$TEC_m = S(E) \times TEC_v + b_R + b^S \tag{1}$$

where TEC_m 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. TEC_m, TEC_v, b^S, and b_R are in units of ns. The IPP is the intersection of the user line-of-sight to the tracked satellite with the center of the ionosphere slab (i.e. the single-layer is located at an altitude of 400 km above the earth surface).

The obliquity factor, S(E) of equation (1), may be defined as (Mannucci et al., 1993):

$$S(E) = \frac{1}{\cos z} = [1 - (\frac{R_e \cos E}{R_e + h})]^{-0.5} \tag{2}$$

where R_e is the mean radius of the earth in km, h is the ionosphere height above the earth surface, here, assumed to be 400 km, and z is the zenith angle.

2.3.2 Computing the Geographic Latitude and Longitude of the IPP: If the geographic latitude and longitude of the GPS receiver (f_u, l_u) are known, the geographic latitude and longitude of an IPP can be computed according to the observed azimuth and elevation angle to the tracked satellite, and the single-layer ionosphere model (Klobuchar, 1987). The latitude of a pierce point f_{pp} is computed from:

$$f_{pp} = \sin^{-1}(\sin f_u \cdot \cos y_{pp} + \cos f_u \cdot \sin y_{pp} \cos A) \tag{3}$$

where y_{pp} is the angle subtended at the center of the earth between the user position vector and the earth projection of the pierce point, computed from:

$$y_{pp} = \frac{p}{2} - E - \sin^{-1}(\frac{R_e}{R_e + h} \cos E) \tag{4}$$

A is the azimuth angle of the satellite at the user's location. The longitude of the pierce point l_{pp} is:

$$l_{pp} = l_u + \sin^{-1}(\frac{\sin y_{pp} \sin A}{\cos f_{pp}}) \tag{5}$$

2.3.3 Computing the geomagnetic latitude of the IPP: The geomagnetic coordinate system with its dipole axis intersecting the geographic sphere, or Boreal pole (f_p, l_p), at approximately $78.7^\circ N$ latitude and $290.1^\circ E$ longitude (Biel, 1990), is used to compute the geomagnetic latitude, f_m, of the IPP:

$$\sin f_m = \sin f_{pp} \sin f_p + \cos f_{pp} \cos f_p \cos(l_{pp} - l_p) \tag{6}$$

2.3.4 Computing the longitude of the IPP in the co-rotating reference frame: The longitude of the IPP in the co-rotating reference frame depends on both the IPP longitude in an earth-fixed frame and the rotation of the earth-fixed frame relative to the sun (Coco et al., 1991):

$$l_{cr} = l_{ef} + T_e \cdot w_e \tag{7}$$

where l_{cr} is the longitude of the IPP in the co-rotating reference frame; l_{ef} is the longitude of the IPP in an Earth-fixed reference frame; T_e is Universal Time (UT); and w_e is the angular velocity of the earth.

2.3.5 Modeling the Ionosphere using a 15-term Polynomial: TEC_v at the IPP is represented by the following polynomial:

$$\begin{aligned} TEC_v(f_m, l_{cr}) = {} & a_0 + a_1 \cdot f_m + a_2 \cdot l_{cr} + a_3 \cdot f_m{}^2 + a_4 \cdot l_{cr}{}^2 + a_5 \cdot f_m \cdot l_{cr} \\ & + a_6 \cdot f_m{}^3 + a_7 \cdot l_{cr}{}^3 + a_8 \cdot f_m{}^2 \cdot l_{cr} + a_9 \cdot f_m \cdot l_{cr}{}^2 + a_{10} \cdot f_m{}^4 \\ & + a_{11} \cdot l_{cr}{}^4 + a_{12} \cdot f_m{}^3 \cdot l_{cr} + a_{13} \cdot f_m{}^2 \cdot l_{cr}{}^2 + a_{14} \cdot f_m \cdot l_{cr}{}^3 \end{aligned} \tag{8}$$

where $a_0, \cdots, a_{14}$ are ionosphere model coefficients.

2.3.6 Estimation of Satellite-Plus-Receiver (SPR) Differential Delay: A 24-hour data set at a site is divided into eight 3-hour sessions. For each session, the Satellite-Plus-Receiver (SPR) differential delay $(b_R + b^S)$, for each tracked satellite, and the 15 terms of the ionosphere model of equation (8), can be estimated by a least squares procedure. The SPR term is a lumped the estimate of the satellite and receiver differential delays, as it is impossible to separate b^S from b_R unless the internal hardware calibration value for the receiver differential delay b_R is available.

2.3.7 Computing the Mean SPR Differential Delay: Finally, a weighted average procedure is used to compute the mean SPR differential delay for each tracked GPS satellite. These SPR differential delays can be used to calibrate the measured slant TEC in order to provide precise TEC measurements.

3. EXPERIMENTS AND RESULTS

3.1 Description of Test Data

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.

3.2 Daily Variation of the Satellite-Plus-Receiver Differential Delay

The Satellite-Plus-Receiver (SPR) differential delay $(b_R + b^S)$, for the 25 GPS satellites at the five PGGA sites, during the period from day 001 to 012, 1996, were estimated. Then, the mean SPR differential delay for each satellite over the 12-day period was computed for each site. The standard deviation of the mean SPR differential delay for the 12-day period was computed for each satellite over each site. Finally, the average values of the standard deviations at the five PGGA stations for the 25 GPS satellites were computed and are shown in Table 1. These standard deviation values indicate the day-to-day variability of the SPR differential delay estimates. The average value of the standard deviations of the SPR differential delay estimates for the whole experiment is 0.43 ns.

The mean standard deviation of 0.43 ns represents an error estimate of the lumped satellite-plus-receiver differential delays. This value also provides an upper bound for the day-to-day variation of the lumped satellite-plus-receiver differential delays.

Table 1. Mean standard deviation ($\bar{s}$) of the mean SPR differential delay, in units of ns, for each tracked GPS satellite at the five PGGA stations, over the period day 001 to 012, 1996.

PRN	**1**	**2**	**4**	**5**	**6**	**7**	**9**	**12**	**14**	**15**	**16**	**17**	**18**
$\bar{s}$	0.53	0.44	0.35	0.33	0.35	0.47	0.60	0.44	0.50	0.48	0.41	0.38	0.42
PRN	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**29**	**31**	***Mean***
$\bar{s}$	0.36	0.28	0.41	0.41	0.41	0.31	0.53	0.55	0.48	0.49	0.43	0.49	***0.43***

3.3 Estimation of Receiver Differential Delays

The estimated SPR differential delay, SPR_j, for a certain receiver to a tracked GPS satellite j, can be expressed as (Coco et al., 1991):

$$SPR_j = b_j^S + b_R + M_j + I_j + I_c \tag{9}$$

where b_j^S is the differential delay from satellite j, M_j is the bias (unique to an individual satellite) attributed to multipath, I_j is the bias (unique to an individual satellite) due to mis-modeling of the ionosphere, I_c is the bias (common to all satellites) due to mis-modeling of the ionosphere, and b_R is the receiver differential delay (common to all satellites).

According to equation (9), the receiver differential delay, $\mathrm{b_R}$, and the bias due to mis-modeling of the ionosphere common to all satellites, I_c, are common to all satellites and cause the estimated SPR differential delays of a common satellite to vary across different sites. In order to remove these common biases, b_R and I_c, *the daily average of the SPR differential delay estimates* over all 25 GPS satellites, for a specific site, is first computed. The mean of the daily average of the SPR differential delay estimates over all 25 GPS satellites for each site provides an estimate of the receiver differential delay for that site. Then, the arithmetic means of those daily receiver differential delay estimates over period day1 to day 12, for each site were computed and are summarized in Table 2. From Table 2 it is found that the receiver differential delays of the five PGGA sites range from 7.72 ns to 12.60 ns. The mean value of the standard deviations of the means is 0.29 ns.

Table 2. Mean of daily averages of the SPR differential delay estimates over all 25 GPS satellites (estimate of the receiver differential delay), in units of ns, at the five PGGA sites, over the period day 001 to 012, 1996.

Site	**blyt**	**coso**	**crfp**	**sio3**	**vndp**
Estimate of Receiver Differential Delay	*10.18*	*7.72*	*8.30*	*9.84*	*12.60*
Standard Deviation	0.39	0.16	0.33	0.38	0.23

3.4 Estimation of Satellite Differential Delays

In the next step, the difference between the estimate of SPR differential delay and its daily average (i.e., receiver differential delay estimate), SAT, is computed for each satellite. Then, the average value of these SAT estimates over the 12-day period for each satellite for a specific site are computed. These average values represent the biases from each satellite, including the b_j^S, M_j, and I_j terms of equation (9). The mean satellite biases for each satellite from the five PGGA sites are summarized in Table 3. It can be seen that the GPS satellite biases are in the range -3.11 ns to 4.44 ns. The standard deviation, ó, of the satellite bias estimates from the five sites are also given in Table 3. The mean standard deviation of the mean SAT estimate is the precision of the satellite differential delay estimate from applying this algorithm. It is 0.35 ns.

Table3. The average values of SAT estimates for each satellite, in units of ns, at the five PGGA stations, over the period day 001 to 012, 1996.

PRN	**1**	**2**	**4**	**5**	**6**	**7**	**9**	**12**	**14**	**15**	**16**	**17**	**18**
SAT	*0.35*	*1.62*	*-1.22*	*-0.20*	*-1.13*	*1.65*	*-0.56*	*4.44*	*0.23*	*0.97*	*1.35*	*1.05*	*-1.32*
ó	0.12	0.18	0.17	0.13	0.22	0.15	0.15	0.26	0.22	0.18	0.06	0.28	0.31
PRN	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**29**	**31**	
SAT	*0.33*	*1.06*	*1.09*	*-1.30*	*0.83*	*1.75*	*-2.72*	*-1.78*	*-0.39*	*-1.71*	*-3.11*	*-1.22*	
ó	0.21	0.18	0.31	0.34	0.26	0.19	0.09	0.30	0.23	0.13	0.29	0.24	

3.5 Comparison with the Results of Other Organizations

Before making the comparison, the average of all satellite biases of each organization, SAT-Mean, is first computed (Coco et al., 1991; Bishop et al., 1994). Then, the average, SAT-Mean, is removed from each satellite bias estimate.

The results from the DLR Neustrelitz (DLR) tests (DLR, 1996), and the USAF Phillips Laboratory (PL) tests (Bishop et al., 1994) are compared to results obtained from the proposed algorithm (NCCU). These averages, SAT-Means, are, for PL and DLR, -0.26 ns and 9.87 ns respectively. Note that PL results are referred to 1994 and DLR results refer to day 001 to 012, 1996 (i.e. the same period as this experiment). Satellite differential delay differences between the NCCU solutions and those from PL and DLR are given in Table 4. The standard deviations for "NCCU - DLR" and "NCCU - PL" are 0.35 ns and 0.39 ns respectively.

Table 4. Satellite differential delay differences between the NCCU solution and solutions from DLR and PL, in units of ns.

PRN	**1**	**2**	**4**	**5**	**6**	**7**	**9**	**14**	**15**	**17**	**18**
NCCU-DLR	*-0.04*	*0.20*	*0.42*	*0.29*	*-0.20*	*0.66*	*0.67*	*-0.55*	*-0.11*	*-0.33*	*-0.45*
NCCU-PL	0.38	0.43	-0.23	-0.21	-0.49	0.92	0.51	-0.05	-0.17	-0.43	-0.32
PRN	**19**	**20**	**21**	**23**	**24**	**25**	**26**	**27**	**29**	**31**	**ó**
NCCU-DLR	*-0.19*	*0.04*	*-0.20*	*-0.30*	*0.26*	*-0.28*	*-0.15*	*0.19*	*-0.54*	*0.27*	***0.35***
NCCU-PL	-0.23	0.07	0.43	0.29	0.10	-0.23	-0.62	0.15	-0.43	0.16	***0.39***

In order to further check the NCCU estimation algorithm, comparisons were also made with other organizations. The following comparisons are based on the data quoted by Gao et al. (1994), including the following organizations: Natural Resources Canada (NRCan), Canada; Instituto de Astronomia y Geodesia (IAG), Spain; Institut fuer Erdmessung (IfE), Germany. These averages, SAT-Means, are, for NRCan, IAG and IfE, -0.96 ns, -2.04 ns, and -1.72 ns respectively. The satellite differential delay differences between the NCCU solutions and those of NRCan, IAG and IfE are shown in Table 5. The standard deviations for "NCCU - NRCan", "NCCU - IAG", and "NCCU - IfE" are 1.07 ns, 0.75 ns, and 0.77 ns respectively.

Table 5. Satellite differential delay differences between the NCCU solution and solutions from NRCan, IAG, and IfE, in units of ns.

PRN	**1**	**2**	**4**	**5**	**7**	**9**	**12**	**14**	**15**	**16**	**17**	**18**	
NCCU-NRCan	*-1.06*	*1.41*	*-0.03*	*0.79*	*1.65*	*0.63*	*1.14*	*-1.48*	*0.16*	*0.64*	*0.74*	*-1.43*	
NCCU-IAG	-0.22	0.91	-0.23	0.62	1.52	-0.03	0.75	-0.66	0.52	-0.18	0.32	-1.21	
NCCU-IfE	*-0.09*	*0.91*	*-0.27*	*0.73*	*1.52*	*0.15*	*0.95*	*-0.70*	*0.37*	*-0.37*	*0.47*	*-1.34*	
PRN	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**29**	**31**	**ó**
NCCU-NRCan	*0.72*	*0.05*	*-0.32*	*-1.31*	*0.63*	*0.94*	*-1.94*	*0.41*	*0.60*	*-0.82*	*-2.12*	*0.07*	***1.07***
NCCU-IAG	0.57	0.16	0.15	-0.90	0.74	0.56	-1.22	-0.49	0.25	-0.58	-1.50	0.05	***0.75***
NCCU-IfE	*0.25*	*0.15*	*0.35*	*-0.91*	*0.72*	*0.54*	*-1.13*	*-0.41*	*0.23*	*-0.61*	*-1.61*	*0.02*	***0.77***

4. CONCLUSIONS

Based on the experimental results obtained so far, the following conclusions can be drawn:

- An alternative algorithm has been proposed to estimate the GPS satellite and receiver L1/L2 differential delays using a single-site method. Features of this algorithm are: (1) a 24-hour data set at a site is divided into eight 3-hour sessions, (2) a fifteen-term polynomial is used to model the ionosphere at each session, and (3) it can be used to calibrate the dual-frequency GPS receivers for precise TEC measurements even when the receiver internal hardware calibration is not available.

- The experimental results indicate that the estimation precision of the SPR (Satellite-Plus-Receiver) differential delay is of the order of ± 0.43 ns.

- 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 0.35 ns. 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 1 ns level.

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