IMPROVING GPS KINEMATIC POSITIONING ACCURACY WITH MULTIPLE REFERENCE STATIONS

Kang-Wen chu, Joz Wu, Chi-Hsiu Hsieh
Research assistant, Center for Space and Remote Sensing Research
Professor, Center for Space and Remote Sensing Research
PhD candidate, Department of Civil Engineering
National Central University
No. 300, Jhongda Rd., Jhongli City, Taoyuan County 32001, Taiwan
Tel: +886-3-4227151 ext 57615
E-mail: 943202090@cc.ncu.edu.tw, jozwu@csrsr.ncu.edu.tw, jieshio.hsieh@msa.hinet.net

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ABSTRACT: The distance-dependent GPS errors, notably atmospheric refraction, reduce the success rate of epoch-by-epoch ambiguity resolution, and limit the GPS positioning accuracy, especially for medium- to long-range baselines. Using multiple reference stations to model (or interpolate) the distance-dependent biases between the reference station and a rover can extend the distance or improve the positioning accuracy. The objective of this research is to find out the relative tropospheric zenith delays (RTZD) between different reference stations by using known coordinates and to provide rovers with interpolated corrections for more precise positioning. The project consists of three major steps: (1) finding out the RTZDs between reference stations, (2) modeling the RTZDs; (3) kinematic positioning. In the first step, a pseudo observation equation of RTZD is added in order to reduce the impact of RTZD on ambiguity resolution. In the second step, different model is used according to the numbers of reference stations. These two steps are the emphases of this investigation. The proposed method needs only one to three epochs to resolve ambiguities, so the effects of cycle slip or data gap are not very serious. A multiple reference stations network located in north Taiwan is used in this research. There are six permanent GPS stations in the network. Two different interpolation models will be compared in this paper. Test result indicates that if the RTZDs between different reference stations can be resolved successfully, and a proper interpolation model is used, it is possible to improve the positioning accuracy.

1. INTRODUCTION

The requirement of GPS RTK (Real-Time Kinematic) positioning is increasing recently years. The most important issue of kinematic positioning is how to resolve integer ambiguities using only a few epochs' observations. Although single-baseline RTK could provide satisfying accuracy, it is still constrained by the distance of baseline, due to the atmospheric refraction caused by ionosphere and troposphere. The idea of additional parameter is applied to solve the problem of ionopheric refraction and it is a great benefit to medium-to-long rang baselines. As to tropospheric delays, it is common to estimate by an atmospheric model. However, there is no perfect model for tropospheric delays, and some residuals remain and make ambiguity resolution failure. Using multiple reference stations (MRS) instead of single reference station lengthens the distance between user and reference station. A significant advantage of MRS approach is the increasing in reliability and availability of the service. If one or two reference stations fail at the same time, their contribution can be eliminated from the solution and the remaining reference stations can still provide the user with corrections (Hu *et al.*, 2003). Another important aspect of MRS approach is that it allows us to model the distance-dependent or spatially correlated errors, such as ionospheric, tropospheric and satellite orbit effects. A direct result of modeling the spatially correlated errors is the ability to improve the resolution of carrier phase ambiguities, which are particularly important to medium-to-long-range positioning (Dai et al., 2003).

The correctness of these spatially correlated errors contributed by reference stations is affected by the correctness of ambiguities. But when the distance between reference stations increases, the atmospheric effects destroy the ambiguity resolution. A real-time ambiguity resolution approach for medium-to-long-range reference baselines is proposed in this investigation, and then estimating the corrections of residual tropospheric zenith delays (RTZD) to improve the rover's positioning accuracy. The proposed method uses only one to three epochs' observation data to avoid the influences of cycle slips or data gap.

2. METHODOLOGY OF MRS APPROACH

2.1 Linear Combination of Carrier Phase Observations

Double-difference observation equations are the most common used differential technique, because of its ability in elimination of clock errors, and while applying in short baseline, the atmospheric refraction can be ignored. Sometimes we combine the dual frequency observations for specific purpose. In this research, we base on the double-difference observations and produce new observation equations by linear combination (Leick, 2004), i.e.

$$\Phi_{ij\ m,n}^{gh} = \lambda_{m,n}\varphi_{ij\ m,n}^{gh} = R_{ij}^{gh} + \lambda_{m,n}N_{ij\ m,n}^{gh} + I_{ij\ m,n}^{gh} + T_{ij}^{gh} + v_{\Phi_{ij\ m,n}^{gh}} \tag{1}$$

where m and n are the linear combination coefficients, $\lambda_{m,n}$ is the new wave length:

$$\lambda_{m,n} = \frac{c}{mf_1 + nf_2} \tag{2}$$

$N_{ij\ m,n}^{gh} = mN_{1ij}^{gh} + nN_{2ij}^{gh}$, $I_{ij\ m,n}^{gh}$ and T_{ij}^{gh} are ionospheric and tropospheric effects (m):

$$\frac{I_{ij\ m,n}^{gh}}{I_{1ij}^{gh}} = \frac{f_1}{f_2}\left(\frac{mf_2 + nf_1}{mf_1 + nf_2}\right) \tag{3}$$

2.2 MRS Kinematic Positioning Approach

This research focus on the residual tropospheric zenith delays (RTZD). By the accurate coordinates of reference stations, the RTZDs between reference stations are solved trough the integer ambiguity searching technique. Then the rover's RTZD corrections are given by a correction surface model. The procedure of the MRS approach is shown in Figure 1.

The first step is using the known coordinates of reference stations to calculate the RTZDs between reference stations. Both ionospheric refraction and tropospheric delays should take into account because of the long range baselines. This step will go to two major steps further: (1) the tropospheric delays are ignored and the ionospheric refraction is treated as additional parameters; (2) an ionosphere-free linear combination is here to remove the ionospheric refraction and the tropospheric delays in ranges will be mapped to zenith by a mapping function. Figure 2 is the flowchart of RTZDs resolution.

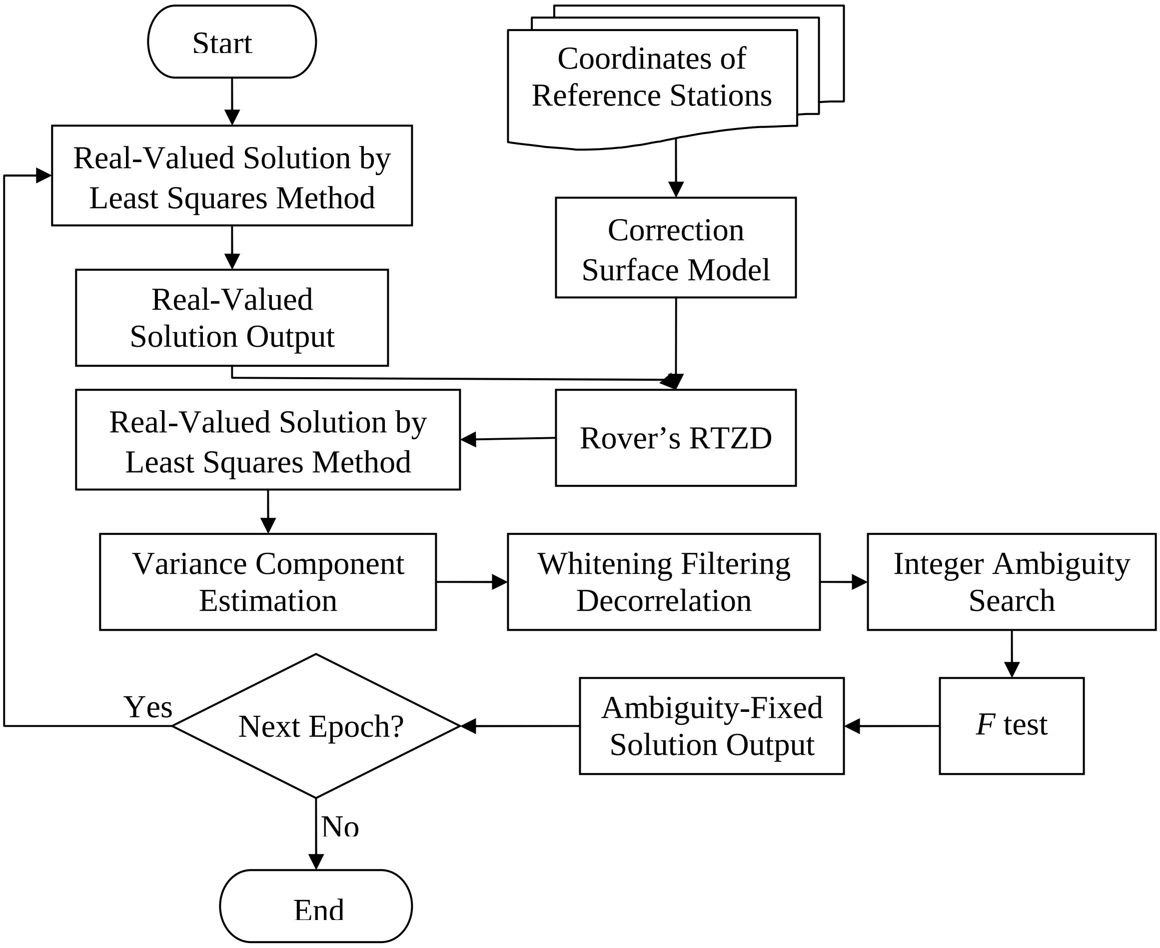

Figure 1 Workflow of MRS kinematic positioning.

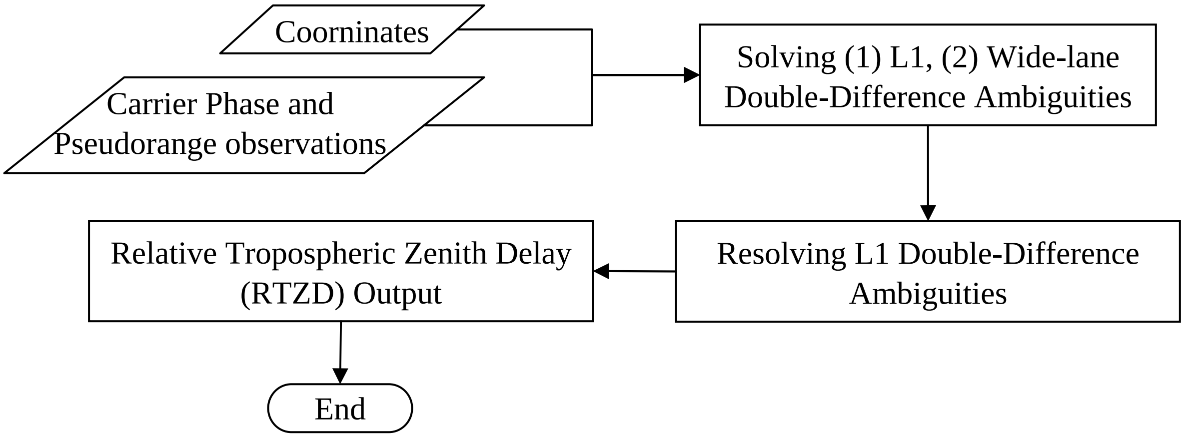

Figure 2 Workflow of RTZDs resolution.

According to equation (1), let $m = 1$ and $n = -1$, which is usually called wide-lane linear combination, it has a longer wave length, and the double-difference L1, P1, P2 observation equations are also used. The aim of this step is to resolve the double-difference L1 and wide-lane ambiguities. As a result of the high correlation between ionospheric and tropospheric effects, the tropospheric delays are ignored in this step and take ionospheric refraction to be additional parameters. Ionospheric pseudo observation equations are added to absorb the effect of ionosphere (Goad & Yang, 1997). The equation is written as follow:

$$m = (I_{1ij}^{gh})_0 + \varepsilon_m \tag{4}$$

where m is the ionosphere pseudo observation, whose initial value and variance are 0 and $(\frac{1}{2}\sigma_\infty^2)(1-\mathrm{e}^{-2d/D})$ respectively.

The next step is resolving L1 double-difference ambiguities. The purpose is to correct the probable mistakes of ambiguities due to the ignored tropospheric delays. The dual frequency ionospheric refraction has the following ratio: $I_{1,\varphi} / I_{2,\varphi} = f_2 / f_1$, and in order to keep the ambiguities integers, the ionosphere-free linear combination coefficients are $m = 77$ and $n = -60$, because the ratio of GPS signal is $f_1 / f_2 = 77/-60$. Therefore, the ionosphere-free observation equation can be express as:

$$\begin{aligned} \Phi_{77,-60ij}^{gh} &= \lambda_{77,-60}(77\varphi_{1ij}^{gh} - 60\varphi_{2ij}^{gh}) \\ &= R_{ij}^{gh} + 17\lambda_{77,-60}N_{1ij}^{gh} + 60\lambda_{77,-60}N_{wij}^{gh} + T_{ij}^{gh} + \varepsilon_{\Phi_{77,-60ij}^{gh}} \end{aligned} \tag{5}$$

The tropospheric delay in range T_{ij}^{gh}, can be mapped to zenith by a mapping function:

$$MF = \frac{1}{2}[(\frac{1}{\cos\theta_j^h} - \frac{1}{\cos\theta_j^g}) + (\frac{1}{\cos\theta_i^h} - \frac{1}{\cos\theta_i^g})] \tag{6}$$

So the T_{ij}^{gh} term in equation (5) can be written as:

$$T_{ij}^{gh} = MF \times z_{\mathrm{RTZD}} \tag{7}$$

where z_{RTZD} is the goal of this research ,RTZD. The idea of adding pseudo ionospheric observation equation is also used here, so that the integer ambiguity searching can be success. After solving all RTZDs of reference baselines, the coefficients of a linear surface model are derived and the rover's tropopheric correction can be computed using these coefficients and the approximate coordinates.

3. EXPERIMENT AND RESULT

The experimental area is in north Taiwan, and five permanent stations are used. The relative location of these stations is shown in figure 3, and the equipment is listed in table 1. In figure 3, the dotted lines are the reference baselines and the solid line is the user's baseline. The dataset used was measured using dual-frequency receivers with a 1 s sampling interval on 19 April 2007 from 17:00 to 17:10 local time (GMT+8:00).

Table 1 Equipment of staions.

ID	Receiver	Antenna
CSRF	LEICA SR530	LEIAT504
NTPU	LEICA SR530	LEIAT504
SINP	LEICA SR530	LEIAT502
SPP0	LEICA SR530	LEIAT502, LEIAT504
XINU	LEICA GRX1200PRO	LEIAX1202

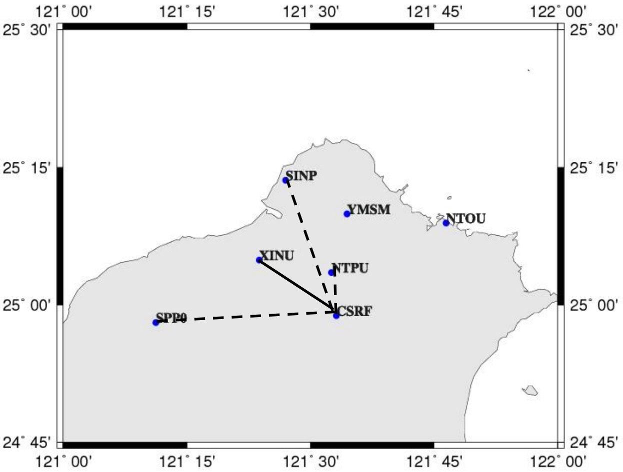

Figure 3 Location map of stations.

The baselines distances are listed in table2. In this experiment, CRSF is as the master reference station and XINU is the simulated user. All station observed statically but kinematical resolved. It means every epoch is independent, and each epoch has an independent solution.

Figure 4 to figure 7 are the RTZDs time series plots between reference stations. Theoretically, when it is a high sampling rate, single-epoch RTZD changes slightly, and these figures show this phenomenon. And because that the RTZDs are double-differenced, the quantities are quite small.

Table 2 Baseline distances.

	CSRF_NTPU	CSRF_SINP	CSRF_SPP0	CSRF_XINU
Distance (km)	8.8	29.2	36.9	19.3

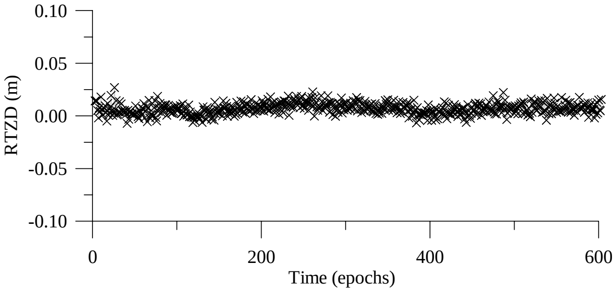

Figure 4 RTZDs of CSRF_NTPU

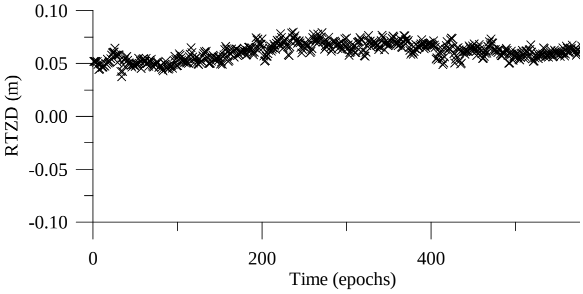

Figure 5 RTZDs of CSRF_SINP

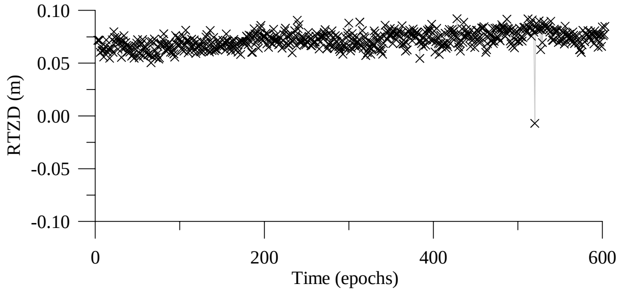

Figure 6 RTZDs of CSRF_SPP0

Figure 7 is the positioning error plot of XINU in easting, northing, and ellipsoidal height. The proposed method is verified by comparing the single baseline positioning (SBL) and multiple reference stations approach (MRS). It is shown that single-epoch kinematic positioning is relatively accurate than SBL, especially the height positioning. Table 3 to table 5 are the statistical tables of easting, northing, and ellipsoidal height positioning. According to the tables, the proposed method is helpful to not only positioning stability (decreasing in standard deviations), but also positioning accuracy (RMSE, Root Mean Squares Errors). The improvement in height positioning shows that RTZD has high correlation with ellipsoidal height.

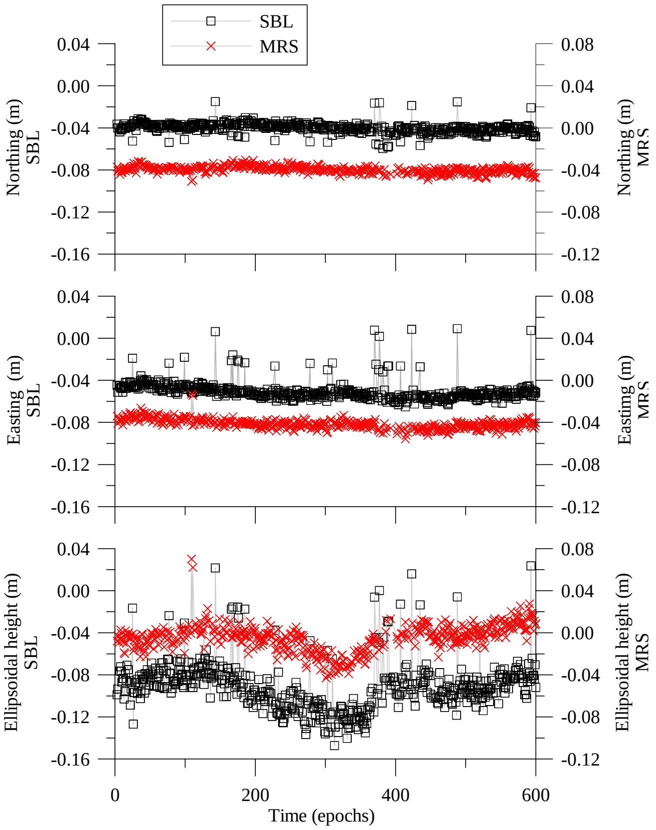

Figure 7 Positioning errors of XINU.

Table 3 Statistics of northing (cm).

	Mean	Sigma	RMSE
SBL	-4.00	0.49	4.02
MRS	-3.97	0.32	3.98

Table 4 Statistics of easting (cm).

	Mean	Sigma	RMSE
SBL	-5.01	0.94	5.10
MRS	-4.14	0.46	4.16

Table 5 Statistics of ellipsoidal height (cm).

	Mean	Sigma	RMSE
SBL	-9.10	2.32	9.38
MRS	-0.46	1.29	1.37

4. CONCLUTIONS

According to thetest result, there are some conclusions. (1) The RTZD between two stations can be obtained successfully trough the combination of ionosphere-free equation, pseudo tropospheric observation equation, and appropriate mapping function. (2) Modeling the RTZDs with multiple reference stations can improve the positioning accuracy, especially the height positioning accuracy. (3) Only one to three epochs' data is used in this method, so the affection of cycle slips or data gap is slighter, and it may be applied in the RTK positioning.

Future work will be emphasized on optimizing the MRS positioning technique. A more appropriate mapping function, for example Niell's mapping fuction, may be considered to advantage the RTZD solving process. The linear correction surface model may not suit the true tropospheric phenomenon; a more complicate correction surface model can be used if the numbers of reference stations increase.

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