GPS Network-Based Approach to Mitigate Residual Tropospheric Delay in Low Latitude Areas

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ABSTRACT

A strong spatio-temporal variation of the wet component in the troposphere leaves us in a peculiar predicament. The residual tropospheric delay will remain in the measurements and therefore affect the estimation of related parameters. In the areas of hot and wet climate conditions, especially in the equatorial or low latitude regions, the strong tropospheric effect on GPS measurements is unquestionable. This study proposes geometric modeling through the network-based approach to mitigate the residual tropospheric delay in such regions. A part of Southeast Asia is selected as a test area for the study, which covers Malaysia and Singapore. Tests are conducted in post-processing but in the “simulating RTK” mode, and evaluated by the number of ambiguity fixes and the accuracy of the coordinate results. Network-based RTK positioning in low latitude areas has shown that the proposed technique can enhance ambiguity resolution by pivoting the ionosphere-free measurements through the mitigated residual tropospheric delay.

INTRODUCTION

Distance-dependent errors such as the ionospheric delay and orbit biases as well as the tropospheric delay have complicated GPS carrier phase ambiguity resolution. Due to these errors, ambiguity resolution will take a longer time. In particular, reliable ambiguity resolution is only restricted to the short inter-receiver distances, typically of the order of 10km. Thus, reducing the distance-dependent errors is essential for network-based GPS applications such as long range Real-Time Kinematic (RTK) positioning.

The ionospheric effect is the most critical factor in resolving the ambiguities. A standard approach is to eliminate the effect by forming an ionosphere-free (IF) linear combination. In case of orbit errors, a GPS user can get reasonable accuracy by using real-time ultra-rapid orbits from the International GNSS Service (IGS) (see http://igscb.jpl.nasa.gov). The tropospheric delay can be mitigated by applying *a priori* or physical tropospheric model that effectively removes the dry component of the delay. So far, a strong spatio-temporal variation of the wet component in the troposphere cannot be well-modeled because the wet component is associated with the variation (in time and space) of the water vapor density in the atmosphere. As a result, the residual tropospheric delay will remain in the measurements and affect the estimation of related parameters. A common approach is to employ additional unknown parameters in the least square estimation, for example, a scale factor for every station per session can be added and estimated. However, the scale factor is only a constant offset to the *a priori* model and does not reflect the time varying nature of the atmosphere. Furthermore, the approach is not appropriate for the RTK mode.

Over the past few years, network-based RTK techniques have been extensively implemented in many countries. The techniques have been supporting users within the network coverage so as to minimize the distant-dependent errors. Previous work has shown that the network-based techniques are efficient in improving the long-range ambiguity resolution to support high accuracy positioning. As a result, RTK positioning can be undertaken for longer baselines than the "traditional" single-base station techniques. In addition, the network techniques can generate a "non-dispersive" correction that is very useful for mitigating the residual tropospheric delay in (near) real-time applications.

In areas of hot and wet climate conditions, especially in the equatorial or low latitude regions, the tropospheric effect on GPS measurements is most likely strong. Therefore such challenging regions are good for testing network-based techniques for mitigating the residual tropospheric delay. In this study, a part of South-East Asia covering the Malaysian peninsula and Singapore is selected as the test area. Existing GPS Continuous Operating Reference Stations (CORS) network in this area gives us an opportunity to utilize networked modeling of the residual tropospheric delay.

SCENARIO OF RESISUDAL TROPOSPHERIC EFFECT IN LOW LATITUDE AREA

In this section, some general ideas about mitigating the residual tropospheric delay in the study area are discussed. Initially, it is essential to understand that the area has two monsoon seasons: the North-East monsoon (November to early March) and the South-West monsoon (early May to August). The monsoons carry heavy rain, which sometimes leads to a monsoon flood in the east part of the Malaysian peninsula. There are no distinct wet or dry periods during the whole year but the mean monthly rainfall indicates rather dry weather conditions from May to early July and more wet conditions from November to January.

A three month long dataset of selected stations (UTMJ, BEHR, KUAN, NTUS and SEGA) from a CORS network has been analyzed (see Figure 1 for location of the stations). Tests have been conducted in static mode during the monsoon and inter-monsoon periods. Every raw measurement observed with 10° cut-off elevation has been corrected by the Saastamoinen *a priori* model. The data processing strategy requires the double-differenced (DD) IF combination in order to extract information about the residual tropospheric delay. All baselines are fixed relative to UTMJ and the data is processed using the Bernese scientific software. The baseline length of each GPS station wrt UTMJ is given in Table 1.

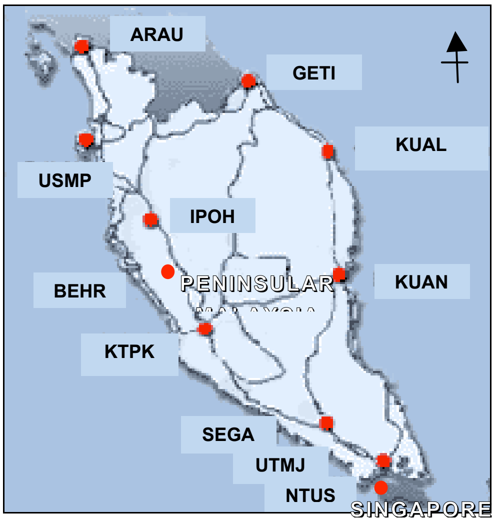

Figure 1. GPS CORSs in the study area (latitude range from 1°N to 7°N and longitude from 100°E to 105°E).

Table 1. Baseline length of each station from UTMJ

Stn UTMJ to:	Baseline (km)	Stn Height (m)
BEHR	339	68.690
KUAN	253	25.415
SEGA	143	25.232
NTUS	25	75.425
UTMJ	0	80.421

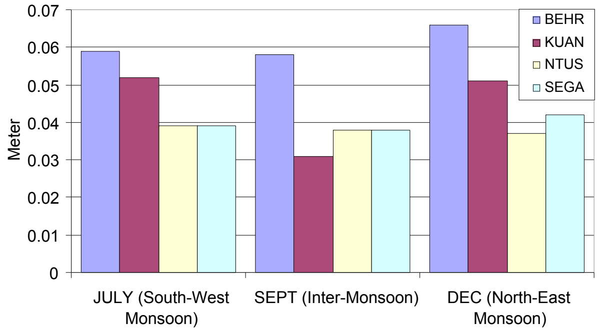

Figure 2. Average RMS errors of DD IF residuals for all stations relative to UTMJ. *A priori* Saastamoinen applied.

Figure 2 shows the average Root Mean Squares (RMS) errors of DD IF residuals for each month. The figure shows that the errors vary between 3cm and 6.6cm depending on the baseline length and the seasonal period. Maximum values are observed in July and December, *i.e.* during the two monsoon seasons. This result is consistent with the previous work by Tajul *et. al*, (2005) in which the same data was analyzed except for the different *a priori* model applied.

Figures 3, 4 and 5 show the RMS of the coordinate precision for different seasons. A close investigation of these figures indicates that the large RMS on the vertical component occurs during the two monsoon seasons. Larger variations between each month also occur on the vertical component than on the horizontal component. Assuming that other errors such as geometric errors and multipath effect are minimized (e.g. by using the precise GPS orbit, being in a multipath-free environment and precise receiver coordinates), these variations can be explained by the effect of the residual tropospheric delay.

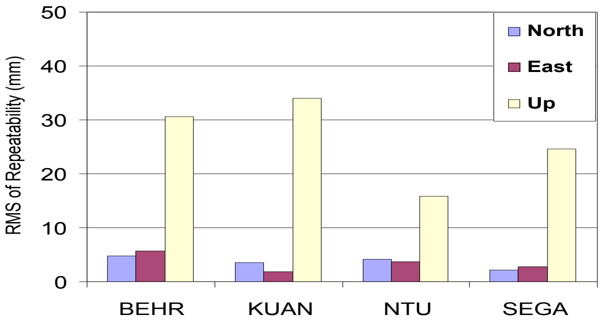

Figure 3. RMS of the coordinate repeatability (inter-monsoon period)

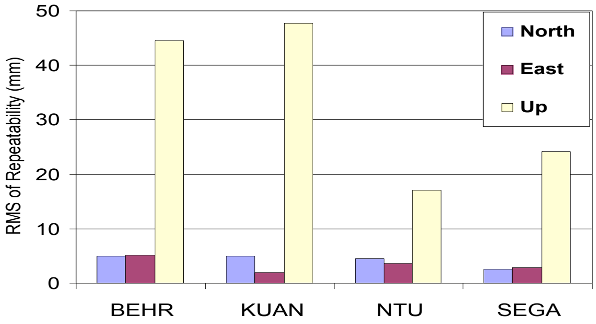

Figure 4. RMS of the coordinate repeatability (South-West monsoon period)

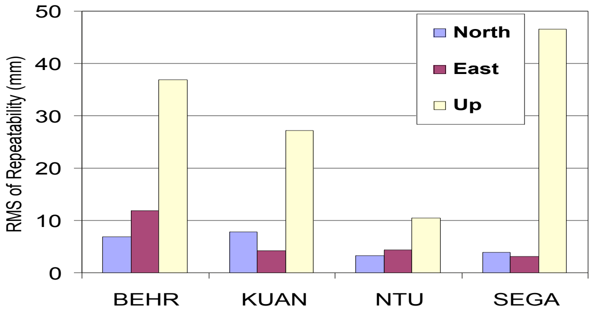

Figure 5. RMS of the coordinate repeatability (North-East monsoon period)

NETWORK-BASED RTK APPROACH

The concept and technique of carrier phase network-based RTK positioning was introduced by Wanninger (1995), by utilizing at least three reference stations from a local GPS CORS network. The technique allows users to better estimate the effect of distance-dependent errors in the surrounding area. The estimated errors can be geometrically modeled in (near) real-time mode and transmitted to RTK users within the network coverage. Figure 6 illustrates the basic concept of the network-based RTK technique.

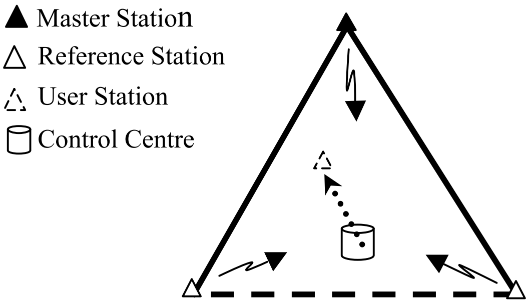

Fig. 6. Basic concept of the network-based RTK

In general, the technique requires all GPS reference stations to transmit their measurements to the control centre. The network algorithm at the control centre will select one of them as a master station, then calculate and distribute the network corrections to all users. This process is described in a few steps in Figure 7.

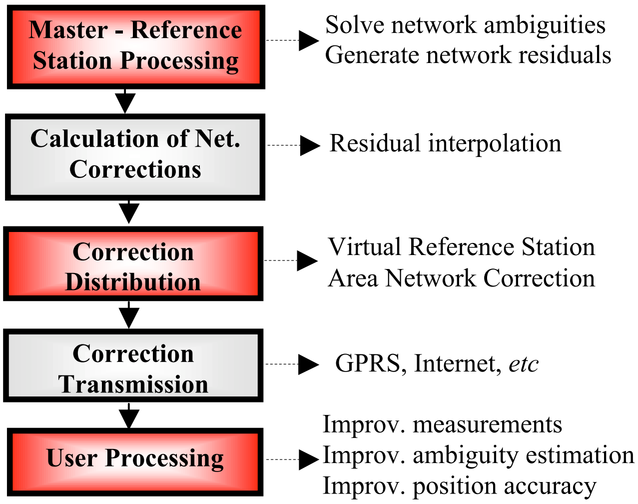

Figure 7. Network-based RTK processing

For the master-reference station processing, the main objective is to resolve the network ambiguities (between the master and other reference stations). Once network ambiguities are "fixed" or resolved to their correct integer value, the residuals are better used to approximate distance-dependent errors within the area (while assumptions in the previous section apply). The use of fixed network residuals will ensure that high-quality network corrections can be generated through the interpolation process. A linear interpolation algorithm is adequate to perform this task for a local network. Dai (2002) has discussed the different interpolation methods that can be used for this purpose. The network corrections, containing information about the distance-dependent errors, need to be distributed to users. Currently, two distribution options are popular: Virtual Reference Station (VRS) (Lynn & Anil, 1995; Wanninger, 1997) and Area Correction Parameter (FKP) (Wubbena & Bagge, 1998). Advantages and disadvantages of the two techniques can be found in Landau *et. al* (2003). The next step is to transmit the network corrections to users via various media such as internet, radio modems, *etc*. Any transmission delay needs to be addressed properly, which is beyond the scope of this paper. Finally, the corrections can be applied to users' measurements so as to improve the ambiguity resolution process and positioning results.

Generation of Non-Dispersive Correction

The approach is not to combine the residuals into a single network correction term, but to separate them into dispersive (ionosphere-related) and non-dispersive terms (troposphere- and orbit-related). The separation can be easily done via Geometry-Free (GF) and IF combinations. Properties of these combinations can be found in Rizos (1997).

Typically, dispersive errors change rapidly with high variations due to the effect of free electrons in the atmosphere (Hernandes *et. al*, 1999; Odijk, 2002). Therefore the interpolation has to be performed as frequently as possible (e.g. epoch-by-epoch). On the other hand, non-dispersive errors change slowly and smoothly over time due to the behavior of the tropospheric delay (Tajul *et al.,* 2005). Rapid variations in non-dispersive errors can be associated with multipath and measurement noises in the IF combinations. Hence, a similar attempt to interpolate this type of errors as in the case of dispersive errors will likely increase the residuals. For this reason it is suggested that non-dispersive errors should not be interpolated on an epoch-by-epoch basis. In addition, a simple running average can be applied to the non-dispersive correction. This smoothed result remains valid up to few epochs (within 5 to 10 minutes) and the process should be continuously running for the next "window".

Ambiguity Resolution Process - Estimation, Validation and Adaptation

Both phase and code measurements of dual GPS frequencies should be used in the ambiguity estimation process. Linear combinations such as the wide-lane and IF are useful for the long-range ambiguity estimation (Han, 1997; Sun *et. al*, 1999). The methodology resolves the wide-lane ambiguity first, and then fixes the narrow-lane ambiguity via the IF combinations during the subsequent processing (Blewitt, 1989). For the user side processing, the non-dispersive correction that is valid up to a few epochs, as described in the previous sub-section, should be used to improve the IF measurements.

Least squares ambiguity decorrelation adjustment (LAMBDA) (Teunissen, 1994) is introduced for the ambiguity search and decorrelation. Additionally, the ambiguity validation procedure and the F-ratio test (Frei & Butler, 1990) are used to validate the ambiguity estimates. This statistical test validates whether the most likely integer ambiguity combination is statistically better than the second best. The larger the values of these statistics are, the more reliable is the ambiguity resolution. Details and problems associated with these statistics are discussed in Veerhagen (2004).

To improve the reliability of the fixed ambiguities, two adaptation methods are suggested, based on the satellite elevation dependence and the post-fit residual check. If the ambiguity validation fails and six or more satellites are in view, the procedure will remove some low elevation satellites. The ratio is then recalculated, and the process has to be repeated until it passes a critical value (in this study the critical value is set to 3). Once it passes the validation test, a check is performed on the fixed residuals against a "threshold" value. The rationale behind this is that measurements with large residuals may contain wrong ambiguities. Measurements beyond this threshold should be rejected. If the ambiguity validation still fails or has insufficient number of satellites, the ambiguity resolution should proceed through a sequential approach.

SMALL NETWORK TEST IN A LOW LATITUDE AREA

In order to test the network-based approach for the purpose of mitigating the residual tropospheric delay, a small network of the Singapore Integrated Multiple Reference Station (SIMRSN) located near the equator (latitude range from 1°15' – 1°30'N and longitude from 103°40' – 103°59' E) is selected. The SIMRSN consists of five CORS stations which cover almost the whole island. Figure 8 shows the SIMRSN network setup for this study. Station LOYA is selected as the master station and SEMB, KEPC and NTUO as the other reference stations. Meanwhile, NYPC is treated as a user station. The selection of the user station is made to avoid severe multipath because the network algorithm is not optimised to mitigate such effects. Distance from LOYA to SEMB, KEPC, NTUO and NYPC is 20km, 22km, 33km and 14km respectively. It is assumed that the network has access to IGS ultra-rapid orbit data and each station is equipped with communication facilities.

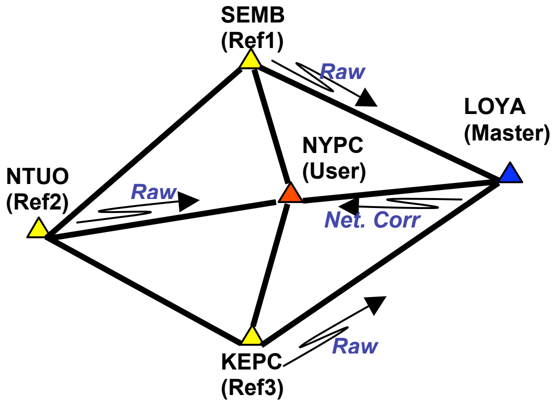

Figure 8. SIMRSN network

Test Description and Condition

The test is conducted in post-processing but "simulating RTK" mode (i.e. processing on an epoch by epoch basis). For verification purposes, the data has been processed in static mode and information such as "true" station coordinates is provided by the network administration. The network ambiguities have been maintained and checked on a continuous basis, once they are resolved. It is important to solve the network ambiguities as many as possible in order to generate high-quality network corrections per epoch per satellite for the user station. Figure 9 shows the number of satellites viewed from the user station and the number of satellites available for corrections. The test period is about 3 hours at 15s intervals (in total 680 epochs) on the 166th day of the year 2003.

For the user side processing, the test has been conducted in the single-base RTK mode and the network-based RTK mode. During the period of the test, instantaneous (single-epoch) integer ambiguity resolution has been tried for both modes and the average geometrical dilution of precision (GDOP) is less than 5. The test is further categorized by changing the satellites' cut-off elevation angles from 10° to 15° and 20°.

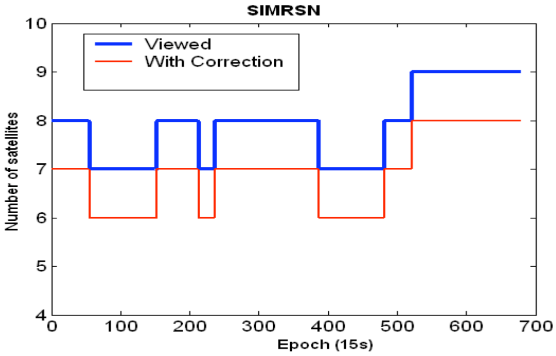

Figure 9. Number of satellites viewed (from user station) and available for corrections

Result and Analysis

Figure 10 shows the DD non-dispersive residuals generated for all satellite combinations of master-to-user station. Associated network corrections are also highlighted in the figure. Inspecting the original correction, it is found that the magnitude is approximately a half of or less than the original residuals. The corrections also exhibit some trends and are clearly contaminated by IF measurement noise. The suggested filter has smoothed the corrections by averaging the measurement noises. Nevertheless, the magnitude of the smoothed corrections is still in the range of the non-dispersive residuals.

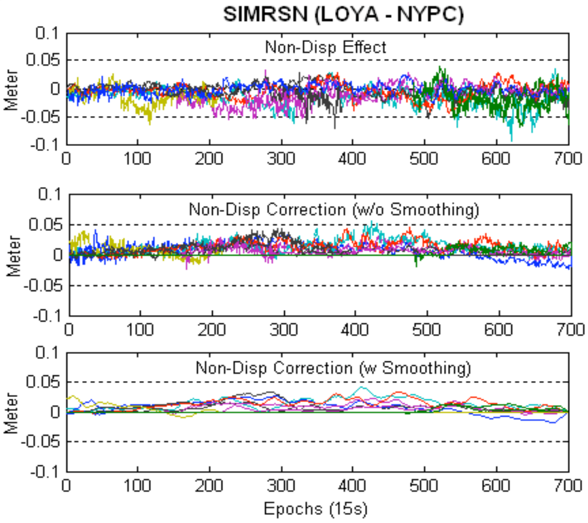

Figure 10. Residuals of DD non-dispersive effect (top), original correction (middle) and smoothed correction (bottom) for baseline LOYA-NYPC

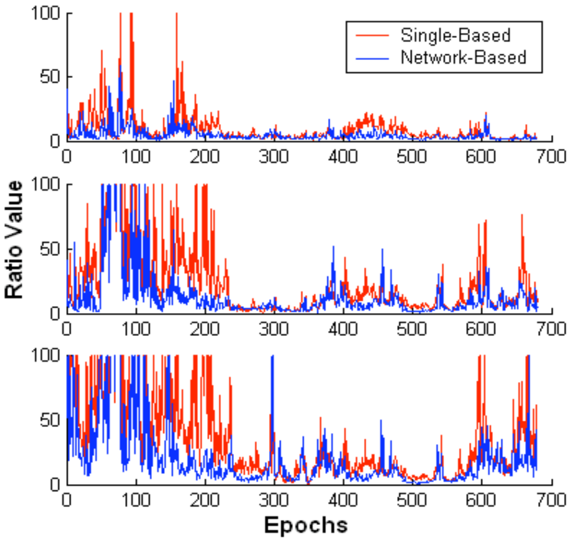

Figure 11. The F-Ratio test for 10° (top), 15° (middle) and 20° (bottom) cut-off elevation

Figure 11 highlights the F-ratio validation values for the narrow-lane ambiguities for the single-base and network-based RTK techniques. The figure shows that the network-based technique produces higher ratio values than the single-base technique. For those three cases of the cut-off elevation by 10°, 15° and 20°, there are 4665, 3584 and 3033 initializations of the instantaneous ambiguities respectively. Every instantaneous ambiguity is compared with the "true" ambiguity (from the static mode) and percentages of correct-, rejected- and wrong ambiguities are given in Figures 12, 13 and 14. As expected, the network-based technique produces the larger percentage of correct ambiguities and the smallest for the rejected and wrong ambiguities.

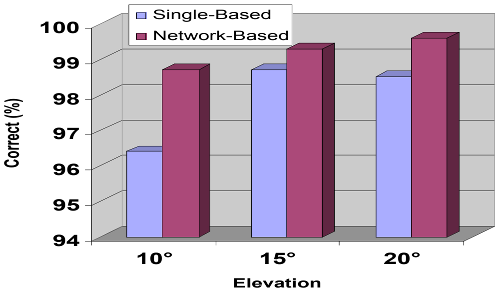

Figure 12. Percentage of correct ambiguities

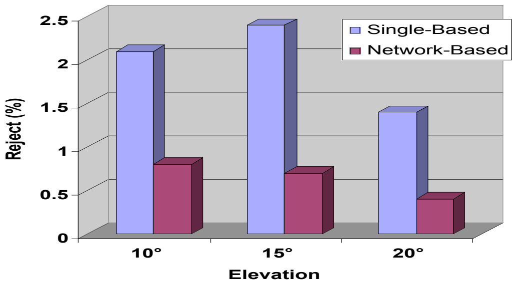

Figure 13. Percentage of rejected ambiguities

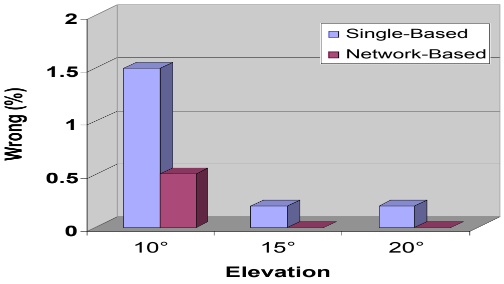

Figure 14. Percentage of wrong ambiguities

The time series in Figure 15 visibly indicates some improvements over the DD IF residuals for the network-based approach. It shows that the non-dispersive correction (in Figure 10) performs very well in mitigating the residual tropospheric delay in the DD IF combination.

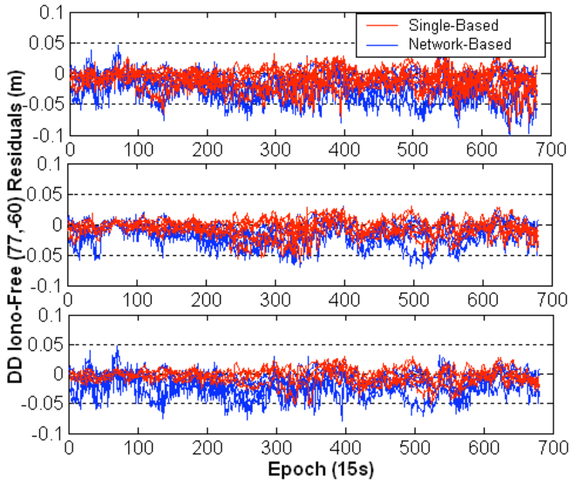

Figure 15. Residuals of DD IF for for 10° (top), 15° (middle) and 20° (bottom) cut-off elevation

Instantaneous positioning has been calculated after removing the fixed ambiguities from the measurements. It should be noted that, for this process, both dispersive and non-dispersive network corrections are applied in order to account for the ionospheric effect and the residual tropospheric delay that still remain in the fixed measurements. Figure 16 compares the results of single-base and network-based techniques with the "true" coordinates of the user station. From the figure, it can be seen that a much better result for the vertical component is achieved through the network-based approach.

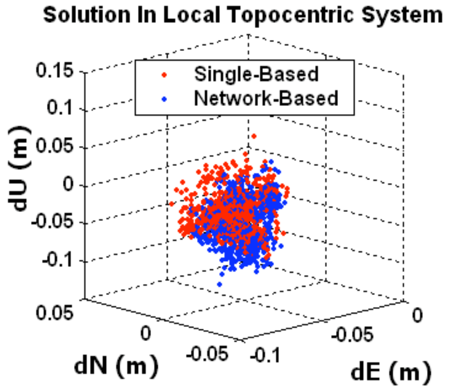

Figure 16. Positioning accuracy results

Table 2. Positioning statistics for single-base and network-based techniques

	Mean (cm)			Deviation (cm)		
	dE	dN	dUp	dE	dN	dUp
Single	-4.7	0.5	-5.1	1.0	1.0	2.8
Network	-5.0	0.5	-3.4	1.1	0.9	2.3

Table 2 presents the positioning statistics for both single-base and network-based techniques. Understanding that the residual tropspheric delay affects more the vertical component, the improvement by the network-based technique over the single-base technique is evident in the vertical component.

CONCLUDING REMARKS

Strong residual tropospheric delay in low latitude areas significantly impacts on the positioning accuracy. The effect degrades the vertical accuracy of positioning noticeably, and lowers the performance of the RTK ambiguity resolution as well. Tests on the network-based RTK in a low latitude area have indicated that the technique can enhance the ambiguity resolution process by pivoting the IF measurements through the residual trpospheric delay. The technique is also found to be useful for improving the vertical accuracy. Based on these results, it is possible to extend inter-receiver distances while the positioning accuracy remains ar the same level.

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