Network-based RTK Positioning: Impact of Separating Dispersive and Non-dispersive Components on User-side Processing Strategy

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ABSTRACT

The concept of network-based positioning has been extensively developed in order to better model the distance-dependent errors of GPS carrier-phase measurements. These errors can be separated into a frequency-dependent or *dispersive* component (e.g. the ionospheric delay) and a *non-dispersive* component (e.g. the tropospheric delay and orbit biases). In fact, dispersive and non-dispersive errors have different dynamic effects on the GPS network corrections. The separation of the two is useful for modelling the network corrections and can provide network users with more options for their data processing strategy. A simple running average is proposed in this paper to provide a stable network correction for the non-dispersive term. It is found that the non-dispersive correction can be used to obtain better ionosphere-free measurements, and therefore helpful in resolving the long-range integer ambiguity of the GPS carrier-phase measurements. Once the integer ambiguities have been resolved, dispersive and non-dispersive corrections can be applied to the fixed carrier-phase measurements for positioning step so as to improve the accuracy of the estimated coordinates. Instantaneous positioning, i.e. single-epoch positioning, has been tested for two regional networks: Sydney Network (SYDNET) and Singapore Integrated Multiple Reference Station (SIMRSN), Singapore. The test results have shown that the proposed strategy performs well in generating the network corrections, in fixing ambiguities and in computing a user's position.

1. INTRODUCTION

Real-time kinematic (RTK) ambiguity resolution, a key step for precise GPS positioning, is complicated due to many error sources in the carrier-phase measurements. These errors can be grouped into station- and distance-dependent errors. Station-dependent errors such as receiver-based errors, multipath and measurement noise notably degrade the ambiguity resolution. As a lot of research on reducing these errors is currently being undertaken, RTK ambiguity resolution is now seriously affected by the presence of the distance-dependent errors: ionospheric delay, tropospheric delay and orbit biases. Due to the distance-dependent errors, reliable RTK ambiguity resolution is limited to relatively short inter-receiver distances, typically of the order of 10km or so. However, there exists always a strong demand to extend the baseline length, without sacrificing RTK performance. The use of multiple GPS reference stations, or a GPS network, makes it possible.

GPS networks have been deployed for many years, providing opportunities to mitigate distance-dependent errors in different ways. A good example is the network of the International GNSS Service (IGS), and its products (IGS 2005). To date the coverage of IGS is not dense enough to be sensitive to small-scale errors, and therefore does not meet the requirement of regional or local GPS users. Although the IGS products are improving, many countries have developed their own regional or local GPS networks. The inter-station distances in these networks are kept below 200km in order to model the distance-dependent errors adequately. The concept and the technique of carrier-phase network-based RTK positioning were introduced by Wanninger (1995), based initially on utilising three reference stations of a GPS network. Estimated distance-dependent errors for each reference station are combined to interpolate and estimate the same types of errors for users within the network coverage. A variety of algorithms for estimating such 'network corrections' exist. Previous work has shown that the network-based technique is an efficient means of improving long-range ambiguity resolution, in order to enable high accuracy positioning with less dense GPS reference station networks than would be the case if single-baseline RTK techniques were used.

The network corrections can be separated into dispersive (ionosphere-related) and non-dispersive (troposphere- and orbit-related) components according to their dependency on GPS signal frequency. Separation of the two at the time of estimating the network corrections has been investigated by a few researchers, but its benefits have not been studied in detail. Euler *et al.* (2004) discussed the impact of incorrectly determined network integer ambiguity on the separated dispersive and non-dispersive corrections. Keenan *et al.* (2002) proposed a user standard correction transmission format that separates the network corrections. Dispersive and non-dispersive components have different dynamic effects. Typically dispersive components exhibit rapid changes, with high variations due to the effect of free electrons in the ionosphere (Hernandes *et al.* 1999; Odijk 2002). On the other hand, non-dispersive components change slowly and smoothly over time due to the characteristic behaviour of the tropospheric delay and the nature of orbit biases (Tajul *et al.* 2005). Further attention should be given to the separation, and the dynamic effect, of the network corrections.

In this paper the emphasis is placed on the user-side processing strategy that benefits from the separated corrections. Firstly, non-dispersive corrections are assumed to provide users with better ionosphere-free (IF) measurements, and therefore assist in resolving RTK ambiguity. In addition, a simple running average function is proposed to improve non-dispersive corrections. To validate this proposition, tests of instantaneous ambiguity resolutions are conducted and compared with conventional and 'corrected' IF measurements. Secondly, it is expected that residuals of distance-dependent errors in the calculation of users' positions can be reduced when the ambiguity bias from the carrier-phase measurements is removed using both dispersive and non-dispersive corrections. To evaluate this approach, the user position is estimated with and without applying the corrections. Since both cases show similar ambiguity levels their results can be directly compared. It must be noted that this processing strategy is only available if the user is provided with the measurements of the reference/master station and is able to recognise the network correction components. Test results have shown that the proposed strategy performs well in generating the network corrections, fixing ambiguities and computing a user's position. The proposed methodology of the network-based RTK is described in the next section.

2. METHODOLOGY OF NETWORK RTK

Figure 1 illustrates the basic concept of network-based RTK. In general, the technique needs all GPS reference stations to transmit their raw GPS measurements to a control centre. The network algorithm at the control centre will select one of them as a master station and calculate the network corrections. Then the network corrections need to be distributed to users. Currently, two distribution options are popular: Virtual Reference Station (VRS) (Lynn and Anil 1995; Wanninger 1997) and Area Correction Parameter (FKP) (Wubbena and Bagge 1998). Advantages and disadvantages of these two techniques can be found in Landau (2003).

The procedure for network-based positioning consists of three major steps: i) master-to-reference data processing, ii) the generation of network corrections, and iii) user-side data processing. These steps are further explained in the following subsections. To support network-RTK users, all computations need to be performed as fast as possible. Furthermore, any transmission delay is a critical problem that needs to be addressed carefully, which is beyond the scope of this paper.

2.1 Fundamental Observables

The fundamental observations used in this study are based on double-differenced (DD) carrier-phase ranges and pseudo-ranges on both L1 (f_{L1} = 1575.42MHz) and L2 (f_{L2} = 1227.60MHz) frequencies. Major advantage of using the DD observations is the cancellation of correlated error such as the satellite-receiver clock errors and some distance-dependent errors. Uncorrelated error terms such as station-dependent errors and residual distance-dependent errors will remain in the DDs. It is assumed that all raw measurements have been corrected for by an *a priori* tropospheric model. A further assumption is that the quality of the raw measurements can be characterised by a simple stochastic model.

2.2 Network Ambiguity Resolution – Master to Reference

The aim of this section is to discuss the ambiguity resolution between a master station and other reference stations, i.e. the network ambiguity resolution in order to generate high-quality network corrections. Because of the long distances between the stations in the network, the task of the network ambiguity resolution is challenging. Furthermore, the process needs to be done in (near) real-time. Several discussions about this process can be found in Hu *et al.* (2005), Chen *et al.* (2004), Dai *et al.* (2002) and Odijk (2002). For the static mode, the ambiguity resolution process can take advantage of long observation sessions. In the (near) real-time mode, however, the degree of freedom is less. Hence, all measurement errors need to be appropriately modelled, and a fast ambiguity search and validation methodology is required.

To assist network ambiguity resolution, the data from dual-frequency receivers is processed, choke-ring type antennas are used, as well as knownledge of the network baseline lengths and precise (predicted) ultra-rapid orbits from the IGS, low multipath environment is assumed, and the reference stations are static. The processing takes advantage of various linear combinations of carrier-phase and code measurements. Well-known linear combinations, such as the widelane and the ionosphere-free, are often used for network ambiguity resolution (Han 1997; Sun *et al.* 1999). The process can be divided into four steps:

Step 1: Estimate the widelane ambiguity (with a combination of the narrowlane code-range or phase-range only).
Step 2: Estimate the narrowlane ambiguity via the IF combination along with the fixed widelane ambiguity.
Step 3: Ambiguity search, decorrelation and validation.
Step 4: Adaptation.

Some advantages of the widelane plus code narrowlane combinations in Step 1 are: (1) it is geometry-free (GF) and IF, and therefore independent on the baseline length, (2) it has a longer wavelength of ~86.2cm, and, most important of all, (3) the widelane ambiguity at each epoch for each satellite can be estimated. Typically, multipath in the pseudo-ranges reduces the quality of the estimated ambiguity because of its long wavelength (30m). Thus, since the beginning of operation, or since a new satellite signal is acquired, a sequential approach is implemented to smooth the pseudo-ranges and enhance the estimated wide-lane ambiguity. In the case of loss-of-lock, the process needs to be restarted as the integer clearly 'jumps' to a new value. In low multipath environments, plus if hardware and firmware can reject multipath, and if the widelane measurement residuals are less than a half of its wavelength, real-time ambiguity resolution is possible simply by rounding-off to the nearest integer value. Another approach is to use the classical wide-lane (phase only), however the combination is contaminated by the atmospheric effects that need to be reduced, for example, by using IGS global ionospheric estimation. In Step 2, cancelling the ionospheric delay (at least up to 1^{st} order) is the main reason why the IF combination is used. Despite its short wavelength (~0.63cm), the IF combination preserves the integer ambiguity. Thus, it is useful to estimate L1 and L2 ambiguity independently when the widelane ambiguity in Step 1 is fixed (Blewitt 1989). In this case, the effective wavelength of L1 is only 10.7cm. Hence, measurement errors related to residual tropospheric delay and measurement noises become problematic and should be kept to a minimum.

In Step 3, 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 and Butler 1990) can be used to validate the ambiguity estimates. The process evaluates the ratio based on probabilistic properties of the best and the second best ambiguity residuals against a critical value. This statistical process has its own problems, and these are discussed in Verhagen (2004). For this reason, Step 4 is included. In this step, the procedure removes some low elevation satellites (and repeats Step 3) when the ambiguity validation fails. If the validation check is passed, a check is performed on the 'fixed' residuals against a 'threshold' value. The rationale behind this is that measurements with large residuals may have wrong ambiguities. Measurements beyond this threshold should be rejected. Hence, Step 4 can improve the reliability of the fixed ambiguities. If real-time ambiguity validation still fails, 'near' real-time ambiguity resolution should proceed through a sequential approach. Once the network ambiguities are resolved, they do not have to be resolved again, but need to be maintained and checked on a continuous basis.

2.3. Network Correction – Dispersive and Non-dispersive

Once network ambiguities are fixed, the residuals are used to approximate the distance-dependent errors within the area. The approach is not to combine the residuals into a single network correction; hence they are separated according to whether they are dispersive or non-dispersive. The separation can be easily done via GF and IF combinations. Properties of these combinations can be found in Rizos (1997). The next step is to interpolate these residuals relative to the user's approximate position, which in turn provides the user with the network correction. Dai (2002) discussed several interpolation methods that can be used for this purpose. A linear interpolation algorithm is adequate to perform this task for a local network setup. In this study, the linear combination method (LCM) (Han 1997) is used.

Due to the rapid changes and high variability of the ionosphere effect, interpolating the dispersive component has to be performed as frequently as possible (e.g. epoch-by-epoch). Conversely, rapid variations can be observed in the non-dispersive component because of remaining multipath and noises in the IF measurements. Hence, a similar attempt to interpolate this component, as in the case of dispersive component, will have a tendency of increasing 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 smooth the non-dispersive correction. This smoothed result remains valid for many epochs (say 5 to 10 minutes) and the process should be continuously running for the next 'windows'.

2.4 User-side Processing – Master to User Stations

For master-to-user data processing, the ability to resolve the long-range ambiguities is very dependent on the quality of the dispersive network correction. However, it is not guaranteed that good quality dispersive corrections are always available at each epoch and for each satellite. For example, there is a possibility of temporal failure of a reference station or unresolved network ambiguity for a certain satellite which results in a degradation of the network correction. This problem will lead to less satellites being processed and increased difficulty in resolving the ambiguity for master-to-user stations. Therefore the dispersive correction is not used initially to eliminate the dispersive effect to aid master-to-user ambiguity resolution. As an alternative the IF combination is recommended. The non-dispersive correction that is valid up to a few epochs, as described in Section 2.3, should be used to improve the IF measurements. The strategy is the same as described in Section 2.2, except that it is now aided by the network correction. During the process it is assumed that the user is able to download IGS ultra-rapid orbit. Applying the LAMBDA method, the ambiguity should be fixed to its integer value unless the narrowlane measurement residuals are greater than 5.4cm. The ambiguity validation and adaptation procedure mentioned in Section 2.2 should then be applied.

The fixed L1 and/or L2 ambiguity should be removed from the original measurement equations before performing the user's position computation. The positioning accuracy is now dependent on the satellite geometry and the station-/distance-dependent residuals. The distance-dependent errors are dominant in that they are still present in the fixed measurements. Both dispersive and non-dispersive corrections are now applied to each epoch and each satellite with an expectation that it reduces the distance-dependent errors in the users' position computation.

3. TESTS FOR LOCAL GPS NETWORKS

3.1 Test Area and Description

Two local GPS networks in different geographical locations were used in this study. The first one is the Sydney Network (SYDNET) located in the mid-latitudes (latitude range 33° 36' – 34° 08'S, and longitude range 150° 34' – 151°12'E), and the second is the Singapore

Integrated Multiple Reference Station Network (SIMRSN) located near the equator (latitudes 1° 15' – 1° 30'N, and longitudes 103° 40' – 103° 59'E). It is expected that atmospheric effects are more severe in the equator area. Figures 2 and 3 show the locations of the stations within SYDNET and SIMRSN, respectively.

To investigate the proposed network processing strategy, tests were conducted in post-processed, but 'simulated' RTK, mode. For verification purposes, the data has been processed in static mode. Stations SPWD of SYDNET and LOYA of SIMRSN were selected as the two networks' master station. Meanwhile, the station VILL of SYDNET and NYPC of SIMRSN were treated as user stations. The selection is made to avoid severe multipath for the user station because the proposed network algorithm is not aimed at mitigating such effects at the moment. Other stations were considered to be reference stations (see Figures 2 and 3). It was assumed that the two networks had access to IGS ultra-rapid orbit data and were equipped with data transmission facilities. Reductions to the user's and the master's raw GPS measurements by the network correction were avoided in the first place, except for an *a priori* tropospheric model. The network correction (i.e. dispersive and non-dispersive terms) was generated by removing satellites in the master-to-reference combinations whose elevations were less than 10°. For master-to-user processing, it was further categorised by changing the satellites' cut-off elevation angles from 10° to 15° and 20°.

3.2 Test Result and Analysis

The following discussions are restricted to the result, an analysis of the generated network corrections and the user-side processing. Figures 4 (SYDNET) and 5 (SIMRSN) show the original master-to-user DD residuals of dispersive and non-dispersive effects for all satellite combinations. Associated network corrections are also highlighted in these figures.

As can be seen in Figure 4, both dispersive and non-dispersive corrections have performed reasonably well. The magnitude of the corrections is approximately almost the same or half the magnitude of the original residuals. Inspecting the residual patterns, it obvious that the network corrections exhibit some trends. In Figure 5, however, there are less accurate corrections even though the baseline length in this network is shorter. This can be attributed to stronger atmospheric activity in the equatorial region. Therefore, this complicates the master-to-reference ambiguity resolution, which in turn results in lower quality network corrections.

The non-dispersive correction performed well in both tests when the smoothing function is applied. The magnitudes and trends of the smoothed corrections are in the range of the non-dispersive residuals. It can be noticed from both figures that network corrections for some epochs are not available, especially for low elevation satellites. Figures 6 and 7 indicate the number of satellites in view and the available corrections for the VILL and NYPC stations.

During the period of the tests, instantaneous (single-epoch) integer ambiguity resolution was attempted using both single-base and network-based modes of processing. Tables 1 and 2 show the statistics of L1 DD ambiguity resolution for SYDNET and SIMRSN respectively. In the tables, the first column is the satellite cut-off elevation angles used in the processing. The second column is the number of DD L1 ambiguities which have been initialised during the period of the tests. The other columns indicate the percentile ambiguity resolution statistics (correct, rejected, wrong) for single-base and network-based techniques. As seen in the tables, the network-based technique performs better, i.e. a higher percentages for the correct fix rates and lower percentages for the rejected fix rates and wrong fix rates, compared to the single-base mode. It also can be noted that, the higher the cut-off elevation angle the better the results for both techniques.

Figures 8 and 9 highlight the F-ratio validation values for both tests. The figures show that the network-based technique, in most cases, results in higher ratio values than the single-base mode. For this ratio test the critical threshold value is set to 3.

Further analysis is possible by checking the critical ratio value against the correct and wrong ambiguity results given in Tables 1 and 2. The analysis provides percentages for the ambiguities passed and were correctly accepted, passed but incorrectly rejected (type I error), failed and correctly rejected, failed but incorrectly accepted (type II error), as given in Tables 3 and 4 for SYDNET and SIMRSN respectively. It is noted that the results of the network-based technique in both tables give higher percentages for correctly accepted ambiguity using the critical value, and lower percentages in making a type I error, compared to the single-base results. The same conclusion can be made for the correctly rejected wrong ambiguity and the type II error, except in the case of SYDNET. Inspecting Table 1, this is only from the percentage calculation. It should be mentioned that the results differ only by applying the network correction or not. Hence, the network correction evidently strengthens the ambiguity resolution and the validation test.

After removing the ambiguity biases, the DD L1 measurements are still contaminated by residual distance-dependent errors and station-dependent errors. These biases, together with geometry of the satellites, impact on the positioning results. Based on the fact that the user is static and is a part of the network stations, station-dependent errors such as multipath are assumed to be at a minimum level. During these tests, the geometry of the satellites for both stations was good, with geometric dilutions of precision (GDOP) less than 5 (see Figure 10).

To reduce distance-dependent errors remaining in the measurements after the removal of the ambiguity biases, dispersive and non-dispersive corrections are applied. Figures 11 and 12 show the DD L1 residuals (for 10º cut-off elevation only) with and without applying the corrections for SYDNET and SIMRSN respectively. It can be seen that the network corrections have reduced the magnitude of the residuals compared with the results without the corrections.

Figures 13 and 14 show the results of single-epoch positioning (with and without corrections) after differencing the known positions for VILL and NYPC respectively (for 10º cut-off elevation only). Their corresponding statistics are given in Tables 5 and 6 for each cut-off elevation on both stations. It can be observed from Figures 13 and 14 that the differences in Easting (dE) and Northing (dN) are at the centimetre level, while the Up differences (dUp) reach the decimetre level, mostly due to residual tropospheric biases.

From Tables 5 and 6 an improvement on the mean Up component (see column 5 of both tables) can be obtained once the corrections are applied. This result can be derived from the non-dispersive correction that reduces the residual tropospheric biases in the measurements. There are no significant differences found in the horizontal components in the case of VILL, but some improvements to the Easting component of NYPC is noticed. It is not clear why the large mean value on Easting component of NYPC were obtained. Perhaps it is because the known position is offset by the 'true' coordinate. Both examples do not indicate much deviation of the coordinate differences in Easting and Northing, however large a variation is noticed in the Up component despite applying the corrections (improvement up to 2.7cm in the case of NYPC at 20° cut-off elevation). In the case of station VILL (SYDNET), the Up component variation increases slightly after the correction, but overall, the pattern is reasonable. It shows that applying the correction does not always guarantee better precision of the positioning results, especially in the Up component. It is dependent on the quality of the network corrections and other residual biases that still exist when performing the position computation.

4. CONCLUDING REMARKS

The ability to capture and model small-scale distance-dependent errors by the network GPS technique enables RTK ambiguity resolution even for longer inter-receiver distances. Information about these distance-dependent errors is included in the network corrections which can be separated into dispersive and non-dispersive components. This separation is useful for advancing network error modelling, and in order to provide more options for the network users' processing strategy.

This paper has demonstrated some benefits of the separation of network corrections. The dispersive effect that changes rapidly in time and space is modelled as frequently as possible. On the other hand, the slowly and smoothly varying non-dispersive effect is modelled less frequently than the dispersive effect. Furthermore, a simple running average is proposed to smooth the non-dispersive correction. For the network user's data processing, this study shows that the separation can be used to improve the IF measurements as well. Such improvement is important especially for (near) real-time ambiguity resolution. The combination of dispersive and non-dispersive corrections is also useful for the user-side computation, if the high quality of both corrections can be assured.

Experiments with local GPS networks in two different geographical locations have demonstrated some advantages of the proposed strategy. Test results and analyses have shown that the proposed strategy performed reasonably well in generating the network correction, resolving the network ambiguities and computing the user's position.

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Table 1 Statistics of single-epoch ambiguity resolution for the baseline SPWD-VILL in SYDNET

Cut-off Elevation	Case Initialize	Single-Base			Network-Based		
		Correct %	Reject %	Wrong %	Correct %	Reject %	Wrong %
10°	4103	84.5	5.8	9.7	91.5	3.0	5.6
15°	3916	87.8	2.9	9.3	94.6	1.4	4.0
20°	3345	93.6	0.5	5.9	98.1	0.4	1.5

Table 2 Statistic of single-epoch ambiguity resolution for the baseline LOYA-NYPC in SIMRSN

Cut-off Elevation	Case Initialize	Single-Base			Network-Based		
		Correct %	Reject %	Wrong %	Correct %	Reject %	Wrong %
10°	4665	96.4	2.1	1.5	98.7	0.8	0.5
15°	3584	97.4	2.4	0.2	99.3	0.7	0
20°	3033	98.5	1.4	0.2	99.6	0.4	0

Table 3 Statistics of ambiguity validation for SYDNET

Single-Based				Network-Based			
Passed %		Failed %		Passed %		Failed %	
Accept	Reject	Accept	Reject	Accept	Reject	Accept	Reject
47.8	52.2	18.3	81.7	58.7	41.3	29.4	70.6
47.5	52.5	19.4	80.6	61.7	38.3	28.5	71.5
66.6	33.4	13.9	86.1	85.1	14.9	20.0	80.0

Table 4 Statistics of ambiguity validation for SIMRSN

Single-Based				Network-Based			
Passed %		Failed %		Passed %		Failed %	
Accept	Reject	Accept	Reject	Accept	Reject	Accept	Reject
55.6	44.4	5.0	95.0	74.6	25.4	4.5	95.5
82.1	17.9	0	100	90.6	9.4	0	100
90.3	9.7	0	100	96.6	3.4	Nil	Nil

Table 5 Position statistics for VILL (SYDNET) with and without (w/o) corrections compared to known position

Cut-off	Corr	Mean (cm)			Deviation (cm)		
		dE	dN	dUp	dE	dN	dUp
10°	w/o	-1.5	-0.6	4.5	1.0	2.5	2.7
	With	-1.0	-0.2	1.8	1.2	2.7	3.9
15°	w/o	-1.5	-0.6	4.4	1.0	2.5	2.8
	With	-1.0	-0.1	1.3	1.1	2.8	3.8
20°	w/o	-1.2	-0.8	2.9	1.3	3.5	3.4
	With	-0.6	-0.6	-0.8	1.3	3.7	4.2

Table 6 Position statistics for NYPC (SIMRSN) with and without (w/o) corrections compared to known position

Cut-off	Corr	Mean (cm)			Deviation (cm)		
		dE	dN	dUp	dE	dN	dUp
10°	w/o	-4.7	0.5	-5.1	1.0	1.0	2.8
	With	-2.4	0.4	-2.8	1.3	0.7	2.8
15°	w/o	-4.5	0.4	-4.4	1.5	1.1	3.5
	With	-2.1	0.5	-1.8	1.8	0.8	2.5
20°	w/o	-4.1	0.4	-5.4	1.5	1.5	5.9
	With	-1.8	0.5	-1.8	1.7	0.9	3.2

Fig. 1 Basic concept of network-based positioning

Fig. 2 SYDNET network

Fig. 3 SIMRSN network

Fig. 4 SYDNET Test. Top two: residuals of DD dispersive effect (top) and dispersive correction (bottom). Bottom three: residuals of DD non-dispersive effect (top), original correction (middle) and smoothed correction (bottom) for non-dispersive. Baseline: SPWD-VILL (~43km) in Sydney. Day of Year (DoY): 131/05 and the observation period of 3hrs (10.00pm-1.00am, local time)

Fig. 5 SIMRSN Test. Top two: residuals of DD dispersive effect (top) and dispersive correction (bottom). Bottom three: residuals of DD non-dispersive effect (top), original correction (middle) and smoothed correction (bottom) for non-dispersive. Baseline: LOYA-NYPC (~14km) in Singapore. DoY: 166/03 and the observation period of 3hrs (8.00am-11.00am, local time)

Fig. 6 Number of satellites in view (at 10º elevations and above) and available corrections for the station VILL in SYDNET

Fig. 7 Number of satellites in view (at 10º elevations and above) and available corrections for the station NYPC in SIMRSN

Fig. 8 F-Ratio values of single-base and network-based techniques at 10º (top), 15º (middle) and 20º (bottom) elevation cut-off angles in SYDNET (SPWD-VILL)

Fig. 9 F-Ratio values of single-base and network-based techniques at 10º (top), 15º (middle) and 20º (bottom) elevation cut-off angles in SIMRSN (LOYA-NYPC)

Fig. 10 GDOP values for VILL (SYDNET) and NYPC (SIMRSN) during the tests

Fig. 11 DD L1 residuals for SPWD-VILL (SYDNET) with (w) correction and without (w/o) correction

Fig. 12 DD L1 residuals for LOYA-NYPC (SIMRSN) with (w) correction and without (w/o) correction

Fig. 13 Differences of calculated L1 positions (with and without correction) compared to the known position VILL (SYDNET); dE (top), dN (middle) and dUp (bottom)

Fig. 14 Differences of calculated L1 positions (with and without correction) compared to the known position of NYPC (SIMRSN); dE (top), dN (middle) and dUp (bottom)