Survey Review

ISSN: 0039-6265 (Print) 1752-2706 (Online) Journal homepage: http://www.tandfonline.com/loi/ysre20

New data processing strategy for single frequency GPS deformation monitoring

S-Q. Huang & J-X. Wang

To cite this article: S-Q. Huang & J-X. Wang (2015) New data processing strategy for single frequency GPS deformation monitoring, Survey Review, 47:344, 379-385

To link to this article: http://dx.doi.org/10.1179/1752270614Y.0000000138

Published online: 08 Oct 2014.

New data processing strategy for single frequency GPS deformation monitoring

S.-Q. Huang* and J.-X. Wang

Although the application of the single frequency receiver in GPS deformation monitoring is limited mainly by the effect of the ionospheric delays, the relevant studies have never been stopped due to the much cheaper price of the single frequency receivers. In this paper, we introduce a new data processing strategy for the deformation monitoring network where the baselines between any two nearest stations are processed instead of the baselines formed only between the reference stations and monitoring stations in the traditional strategy. As a result, most of the baselines in the monitoring networks are very short so as to the ionospheric effects can be safely ignored. The results from the experiments show that the new strategy can eliminate the effect of ionospheric delay by processing the short baselines in the network mode. The accuracy and integrity of the deformation solutions can be improved by the presented strategy.

Keywords: GPS, Deformation monitoring, Single frequency, Ionospheric delay

Introduction

Global navigation satellite systems (GNSS) have been widely used in deformation monitoring of the natural features, such as landslide, slope and crustal plate, and the constructions, such as tower buildings, cross-sea bridges and high speed railway etc. In the GNSS deformation monitoring, the ambiguity resolution is the key to achieve the precise monitoring solutions. Therefore, the dual frequency GNSS receivers are usually used to trivially mitigate the atmospheric biases and enhance the model strength for fast ambiguity resolution and then the precise positioning. However when the single frequency receiver is used, the ionospheric delays as the dominated errors affect the fast and reliable ambiguity resolution (Li *et al.*, 2010). Nevertheless, the relevant studies of making use of the single-frequency receiver in deformation monitoring have been never stopped due to its much cheaper price compared with the dual frequency receivers. Roughly, the single frequency receivers in deformation monitoring are only 1/6 expenses of the dual frequency ones. Moreover, several tens to hundreds of receivers are needed in a deformation monitoring campaign and some receivers have to be replaced once they are damaged in the terrible disaster. Therefore, one can image that the huge money can be saved if the single frequency receivers are used instead of dual frequency receivers in a monitoring campaign.

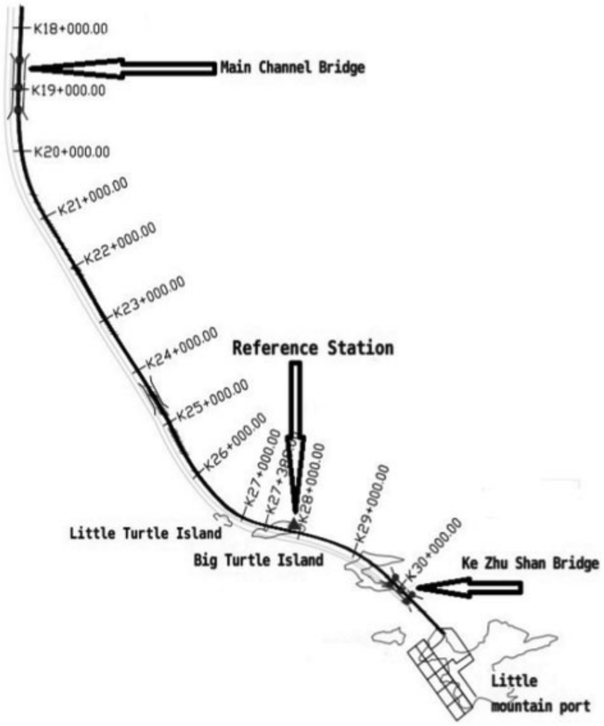
It is very crucial to mitigate the ionospheric effects when the single frequency receiver is used. There are some approaches for processing the ionospheric effects. For instance, the combination of summation of pseudorange and phase observations (Schüler *et al.*, 2011; Parkinson and Spilker, 1996); the regional ionospheric modelling (Wanninger, 1995; Rocken *et al.*, 2000) with network RTK concept. For a short baseline, the simple method is the double difference. When the baseline is short, the residuals of the double differenced (DD) ionospheric effects are usually so small that can be basically ignored. Hence, it is important that this simple processing can be used only when the baseline length is short enough, typically 5 km or shorter. Besides mitigating the ionospheric biases, the reliable and fast integer ambiguity resolution of single frequency is also very challenging though many research efforts have been done, see e.g. (Verhagen *et al.*, 2012; Ou and Wang, 2004; Li *et al.*, 2010). In addition, the reliability of single frequency solutions deserves to pay more attention since it is usually very low due to the few redundant observations.

In the data processing of traditional deformation monitoring, the baselines are formed between the reference station and monitoring stations. As a result, the baseline length cannot be guaranteed to be short enough to ignore the residual DD ionospheric effects. In fact, it is usually that the distance from the reference station to the monitoring stations are long (usually longer than 10 km), but the distance between the monitoring stations themselves are very short, i.e. several hundred meters only. In this contribution, we present a new strategy of data processing where some baselines between monitoring stations are solved instead of the baselines between them to the reference station. As a consequence, most of the baselines in the monitoring network will be very short and their ambiguities can then be fast and reliably fixed. In the following, we will first present the mathematic model of

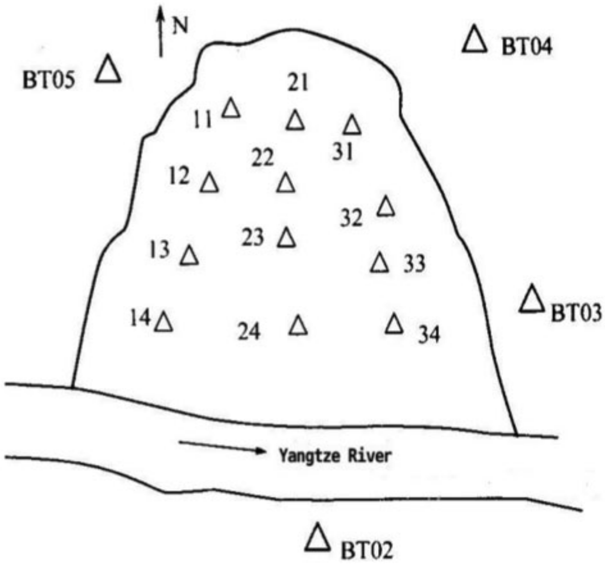
College of Surveying and Geo-Informatics, Tongji University, Shanghai, China

*Corresponding author, email koumeat@hotmail.com; koumeat286@163.com

Received 15 March 2014; accepted 16 September 2014
DOI 10.1179/1752270614Y.0000000138



1 Deployment of Donghai Bridge Monitoring Network



2 Deployment of Baota Landslide Monitoring Network

the proposed data processing strategy compared with the traditional processing strategy. The issue of cycle slip detection and identification is particularly presented in detail since it is very important to achieve the stable monitoring solutions. Then two sets of real data are implemented to show the performance of the presented strategy. Finally, some conclusions are summarised.

Mathematic models and comparing of two processing strategies

In this section, we start with the important feature of the GNSS deformation monitoring network. Then we analyse the traditional processing strategy for real time deformation monitoring and its limitations. After that, we introduce our new strategy and its advantages are elaborated.

There are two kinds of stations involved in a deformation monitoring system, namely, the reference stations and the monitoring stations. The reference stations are built on stable bedrock with precisely known coordinates, providing the service for the whole region they can cover. The monitoring stations are mounted on the construction locations we are interested to monitor. Since the monitoring region is assumed to be instable, the locations of reference stations are usually far away from this region. In other words, the distance of the baseline formed by reference station and monitoring station is usually long. However, the distance of monitoring stations are usually very short since the monitoring stations are mounted very close to reflect the structure characteristics in detail. This important property can be visualised in many deformation monitoring networks. Figure 1 shows the Donghai Bridge Deformation Monitoring Network. The solid triangle denotes the reference station while the solid circles the monitoring station. The average distance between the reference station and the monitoring stations is about 6 km with the longest distance more than 10 km. The distance between any two nearby monitoring stations is only 500 m or even shorter, of which the shortest distance is less than 200 m. Another example is from the Baota Landslide Monitoring Network (Zeng, 2004) shown in Fig. 2, which is a landslide monitoring network. The points, BT02, BT03, BT04 and BT05, are the reference stations, and they are all outside of the monitoring stations. Again, the distance between any two nearby monitoring stations are still very close with each other.

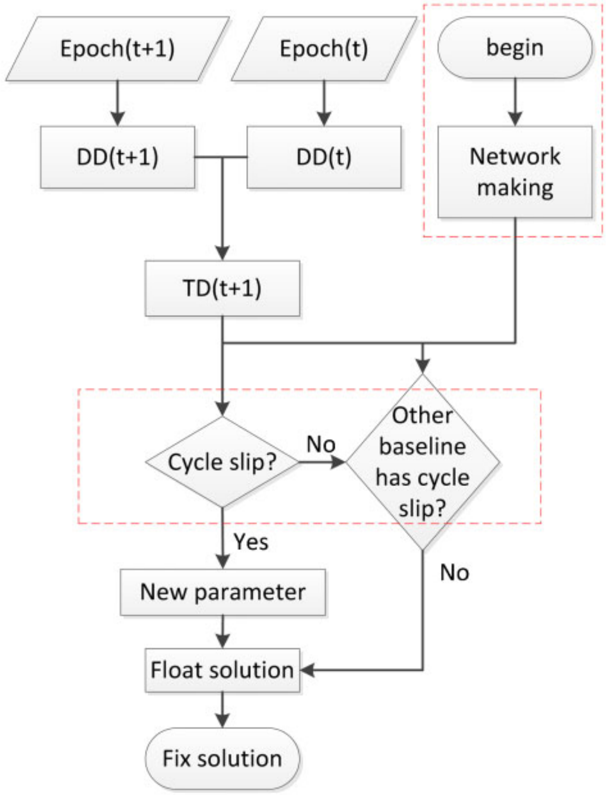
Mathematic models

We start with the single frequency phase and pseudorange DD observation equations

$$E\begin{pmatrix} p \\ \phi \end{pmatrix} = (e_2 \otimes G)\mathbf{x} + (e_2 \otimes m)\tau_z + \begin{bmatrix} 1 \\ -1 \end{bmatrix} \otimes \imath + \left(\begin{bmatrix} 0 \\ 1 \end{bmatrix} \times \lambda \right) \otimes a \tag{1}$$

where $E()$ is the expectation operation; p and φ are the phase and pseudorange observable respectively; $\mathbf{x}$ is the unknown baseline vector with design matrix G; τ_z is the zenith tropospheric delay with the mapping function m after correcting by a standard troposphere model; $\imath$ is the DD slant ionospheric delay; λ is the wavelength with respect to the DD integer ambiguity unknown a. $\otimes$ denotes the Kronecker product.

We discuss the processing of tropospheric parameter first. Since we have already used a standard troposphere model (like SAAS model) to correct the most of tropospheric delay, the residual tropospheric bias is usually the wet part of troposphere and very small. The zenith tropospheric delay (ZTD, τ_z in model (1)) is then estimated per half hour. Note that only one ZTD parameter is needed to be estimated to absorb the residual slant tropospheric delays of all satellites. For the ionospheric parameter $\imath$, it is very challenging since the different ionospheric parameter is assumed for different DD pair of satellites. To enhance the model



3 Flowchart of new processing strategy

strength, the additional constraint of prior ionospheric information is introduced (Li *et al.*, 2014)

$$E(\iota^0) = \iota : \ D(\iota^0) = \sigma_{\iota^0} \tag{2}$$

where ι^0 is the prior DD ionospheric delay and can take 0 in our case with baseline length smaller than 5 km. Meanwhile, its accuracy σ_{ι^0} can be set to a small value for short baseline. If $\sigma_{\iota^0} = 0$, it means that we ignore the ionospheric delays in the processing, which is the case for processing the short baselines between monitoring stations.

Traditional processing strategy

Traditionally, the deformation of the monitoring station is detected by solving its baseline formed with reference station. In a small region, the tropospheric and ionospheric behaviours are strongly correlated. Thus the deformation in this small region affected by atmospheric delay will be similar. Especially, the saltation will be similar when some unexpected problem happens in the transmission path, e.g. magnetic storm.

New processing strategy

The new processing strategy of deformation monitoring will be elaborated as follows. The baselines will be formed not only between the reference station and the monitoring station, but most of them formed between the monitoring stations themselves. The baselines formed in the network should satisfy with the following principles. First, all baselines are formed by two stations as close as possible. Their baseline lengths can be calculated by their approximate coordinates estimated with code based single point positioning. Second, all stations must be used at least one time in the baseline formation. Third, cycle slip detection of one station should be done by checking all baselines connecting with this station. The flowchart of this new data processing strategy is shown in Fig. 3. It is quite similar to the traditional strategy besides some additional works (as shown in the dashed boxes). Different from the traditional strategy, many closed loops that start from the reference station and end in the same or the other reference station would be formed in the new processing strategy. Hence the number of long baselines that need to be processed is significantly reduced. Thus the short baselines have become the main part of the entire processing baselines. In the short baselines, the atmospheric delays can be simply ignored and then the processing becomes very simple. Even if some outlier happens in the transmission path, it would not influence the solutions of all stations. This will obviously increase the integrity and reliability (the ability to detect and avoid outliers effect) of the system.

Cycle slip detection for new processing strategy

Cycle slip detection and identification are the key issues in single frequency data processing. Many methods were proposed, e.g. the polynomial fitting (Jia and Wu, 2001), the high order differential method (Li, 2006), the pseudorange and phase combination method (Cheng and Jiexian, 2012), etc. These methods are not necessarily reliable in single baseline mode. However, the reliability of some method would increase when it is dealing with in the network mode, such as the high order differential method. The cycle slip will be checked twice for one monitoring station based on the two baselines where this monitoring station is used for both these baselines in order to avoid error adjustment. Although the cycle slip detection and identification are still a very difficult task in the new strategy, the performance will be considerably increased comparing to that in the traditional strategy.

In this contribution, we employ the triple differential method to detect the cycle slips. However, we do not repair the cycle slips since it is not reliable to estimate the values of cycle slips in the case of single frequency. Once the cycle slip is wrongly solved, the solution must be polluted. This will cause a false warning, which is a big mistake in GNSS deformation monitoring.

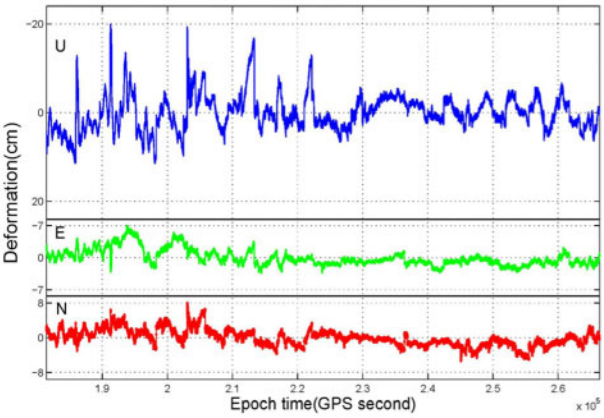
Ignoring the DD ionospheric and tropospheric affects, the observation equation of single satellite reads

$$\begin{aligned} E\left(\varphi_{\mathrm{m,r}}^{\mathrm{j,bs}}\right) &= \left(\varphi_{\mathrm{m}}^{\mathrm{j}} - \varphi_{\mathrm{m}}^{\mathrm{bs}}\right) - \left(\varphi_{\mathrm{r}}^{\mathrm{j}} - \varphi_{\mathrm{r}}^{\mathrm{bs}}\right) \\ &= -\rho_{\mathrm{m,r}}^{\mathrm{j,bs}}/\lambda + \Delta\phi_{\mathrm{m,r,mult}}^{\mathrm{j,bs}} + N_{\mathrm{m,r}}^{\mathrm{j,bs}} \end{aligned} \tag{3}$$

where the j superscript means the satellite number; bs superscript means the reference satellite. The subscripts denote the stations (r is the reference station, while m the monitoring station). Adding the epoch time in model (3), the triple differential observation equation is symbolised

$$\begin{aligned} &E\left(\varphi_{\mathrm{m,r}}^{\mathrm{j,bs}}(t_{\mathrm{i+1}},t_{\mathrm{i}})\right) = -\rho_{\mathrm{m,r}}^{\mathrm{j,bs}}(t_{\mathrm{i+1}},t_{\mathrm{i}})/\lambda + \\ &dN_{\mathrm{m,r}}^{\mathrm{j,bs}} + \varepsilon_{\mathrm{m,r}}^{\mathrm{j,bs}}(t_{\mathrm{i+1}},t_{\mathrm{i}}) \end{aligned} \tag{4}$$

where $dN_{\mathrm{m,r}}^{\mathrm{j,bs}}$ is the difference of the DD ambiguities between epochs t_{i} and $t_{\mathrm{i+1}}$. It will be zero in case of no cycle slip. If no cycle slip happens, the ambiguity term will vanish and only the term $\rho_{\mathrm{m,r}}^{\mathrm{j,bs}}(t_{\mathrm{i+1}},t_{\mathrm{i}})$ introduced by deformation term and noise term remain in equation (4).



4 Deformation of CCBZ station

Generally, the triple difference observation is much smaller than 0.5 cycles. Thus there is cycle slip in epoch t_{i+1} when it is larger than 0.5. The experiment experience shows that almost all cycle slips can be detected and identified when the coordinate variation is small enough (Li, 2006).

However, there is a disadvantage of model (4). The detection will fail under the situation

$$\rho_{m,r}^{j,bs}(t_{i+1},t_i)/\lambda \geq dN_{m,r}^{j,bs} \tag{5}$$

Equation (5) would be satisfied in the case of deformation between adjacent epochs is not small enough, e.g. when bridge shaking violently, or when landslide really happens. It is very difficult to identify the cycle slip in single baseline mode when the equation (5) is satisfied. However, the identification will be not difficult anymore in network mode. There are usually more than two baselines connected with one station (no matter reference station or monitoring station). It is almost impossible that equation (5) is satisfied at the same time for all these baselines of one station.

Real data processing

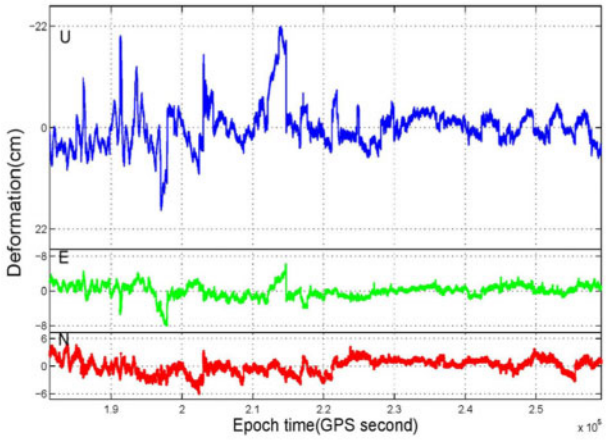
We choose two sets of real data to evaluate the presented strategy. The first set of 24 h GPS data is from a bridge deformation monitoring network with four stations in Shanghai, China. In this network, the reference stations are more than 13 km far away from monitoring region. The second set of 24 h data is from a testing network with six stations in California USA.

First experiment

The Shanghai Yangtze River Bridge (SYRB) is a bridge that connects Chongming Island and Changxing Island in Shanghai China. Chongming Island is the third biggest island in China, and Changxing Island is its affiliated island. There are two piers in this bridge. The current monitoring network monitors the deformation of these two piers. Table 1 presents the plane coordinates of all four stations.

Table 1 Coordinates of all four points

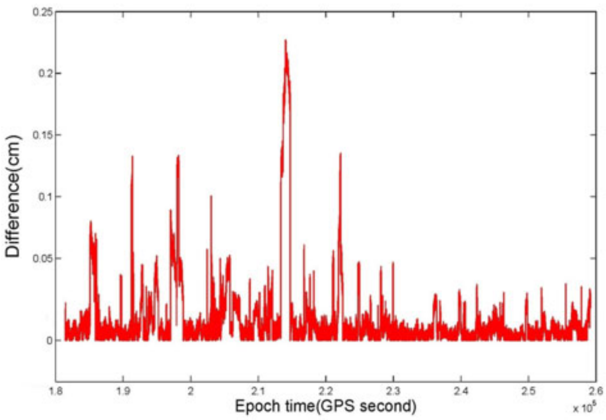
Name	Type of station	X	Y	H
CCNZ	Monitoring	3 462 704.355	539 390.542	21.015
CCBZ	Monitoring	3 463 274.165	539 849.240	21.094
CMDT	Reference	3 489 322.496	563 757.023	37.282
CMMZ	Reference	3 510 606.879	516 845.829	38.030



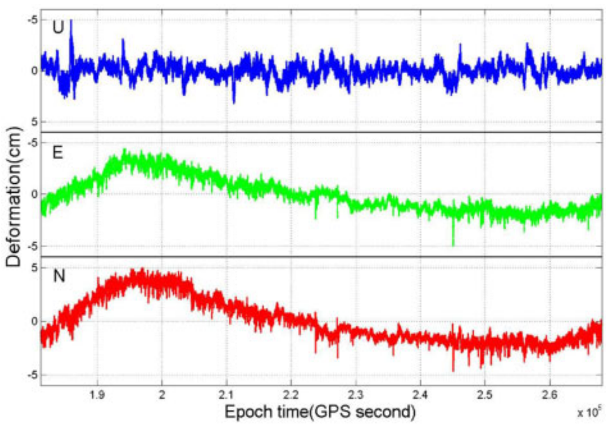
5 Deformation of CCNZ station

The 24 h data were collected with 1 Hz sampling interval on DOY 80, 2013. In the traditional processing strategy, two monitoring stations were connected with CMDT reference station since the reference station CMMZ is much further away from two monitoring stations. The baseline length of CCNZ-CMDT is about 13.75 km, while that of CCBZ-CMDT about 13.02 km. The deformation series of CCNZ and CCBZ station are shown in Figs. 4 and 5 respectively.

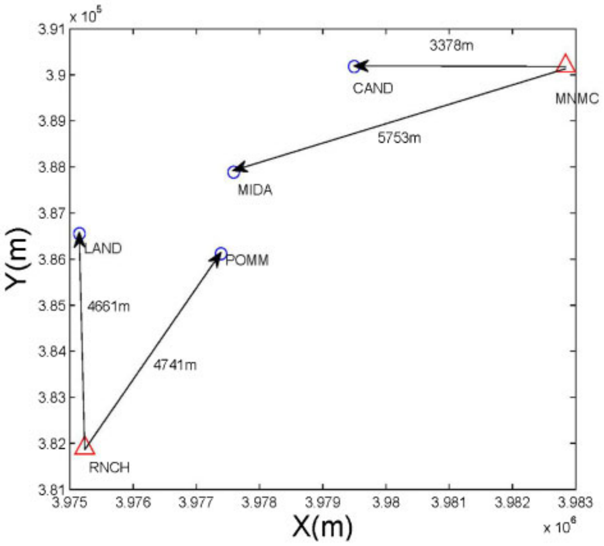
It is obvious that the deformation solutions of vertical direction are larger than those of horizontal directions.



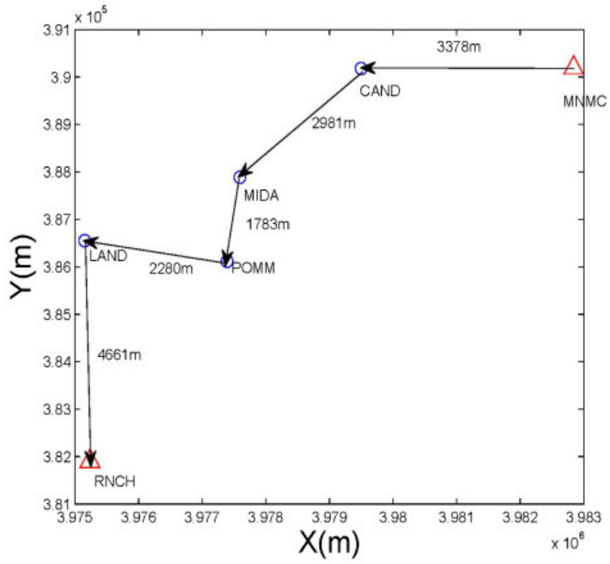
6 Vertical deformation difference between CCBZ, CCNZ



7 Result of baseline of CCBZ-CCNZ

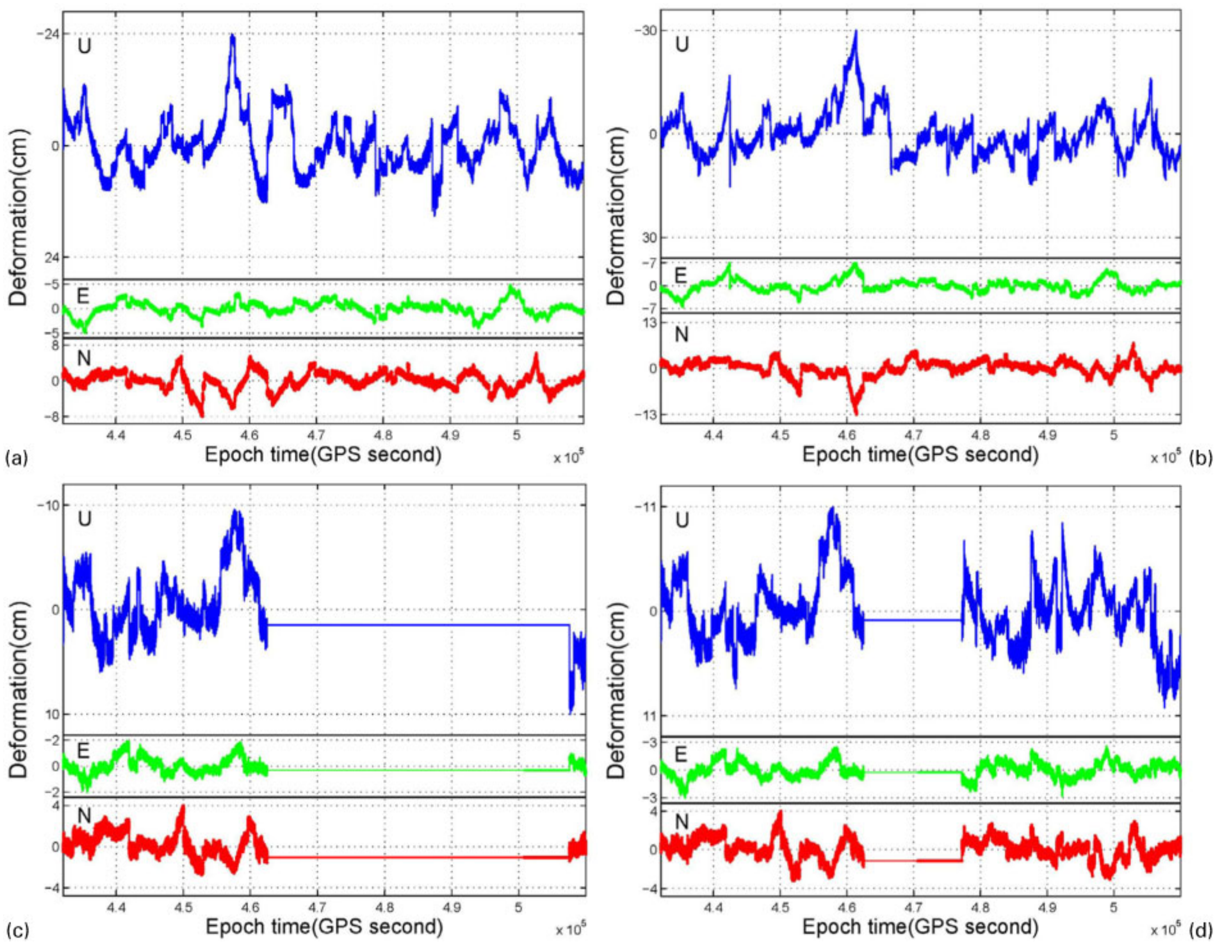


8 Old strategy baseline



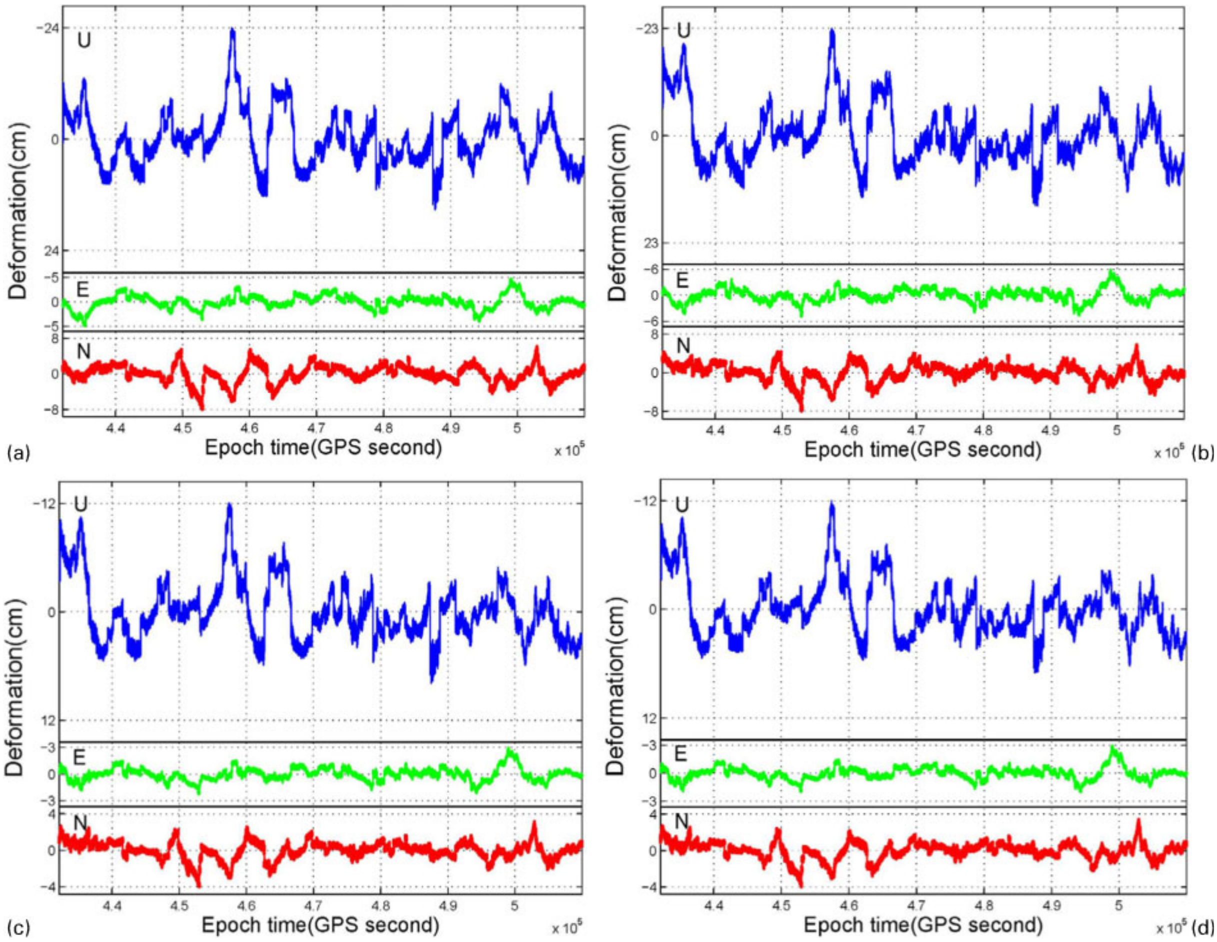
9 New strategy baseline

The errors of vertical deformation solutions are mainly affected by the ionospheric effects. The most important property is that there is a strong consistency between vertical deformations of these two stations. In order to analyse the relative deformation of the two monitoring stations, we illustrate the absolute values of their vertical deformation differences in Fig. 6. About 90% of absolute values are smaller than 3 cm. The big difference (>10 cm) mainly appears on the day when the ionospheric is active (from epoch 190 000 to 220 000, local time ~10 : 00am to ~5 : 00pm). However, the values are very small and stable during the night (from epoch 230 000 to 260 000, local time ~6 : 00 pm to ~6 : 00am). The CCBZ-CCNZ baseline is about 500 m, the solutions of this short baseline can be used as true values



a CAND; *b* MIDA; *c* POMM; *d* LAND

10 Result of traditional strategy



a CAND; *b* MIDA; *c* POMM; *d* LAND

11 Result of new strategy

(as shown in Fig. 7). The vertical solutions of this baseline are almost all smaller than 3 cm. In other words, the wrong solutions are about 10% when the traditional strategy is used. In addition, there are also some wrong solutions in horizontal components. However, the incorrect rate of horizontal solutions is obviously smaller than the vertical one.

From this experiment, it has clearly shown the implementation of new data processing strategy, where we need to compute the baselines, CCBZ-CCNZ and CCBZ-CMDT. The difference from the traditional strategy is that the baseline CCBZ-CCNZ is solved instead of CCNZ-CMDT. Therefore, deformation solutions of CCNZ can be easily obtained by adding the baseline solutions of CCBZ-CCNZ to the deformation solutions of CCBZ solved CCBZ-CMDT.

Second experiment

In order to further test our new strategy, another more complicated network in the southwest of USA is processed. The data of these stations, CAND, LAND, MIDA, MNMC and POMM, in this network are collected from the SOPAC web. The baseline formation with traditional strategy is shown in Fig. 8, where baseline lengths are from about 3 km to about 6 km. The formed baselines with new strategy are shown in Fig. 9. The baseline lengths in new strategy are from only 1 km to about 3 km. Obviously, the baselines need to be processed are now much shorter than those in the traditional strategy. And a closed loop is formed with starting and ending points are two reference stations, respectively.

In this case, it is exactly the same to compute the deformation solutions of CAND station using the traditional or the new strategy respectively. Both are based on solving the same baseline CAND-MNMC. While it is different to compute the deformation solutions of the other monitoring stations, MIDA, POMM and LAND. With LAND station as example, in the new strategy, the deformation solutions are

Table 2 Summary of difference of traditional and new workflow

Station		Traditional Workflow	New workflow
MIDA	Standard Deviation(U)/cm	6.59	5.68
	Rate of available solutions/%	100	100
POMM	Standard Deviation(U)/cm	4.25	4.55
	Rate of available solutions/%	47.6	100
LAND	Standard Deviation(U)/cm	4.98	4.67
	Rate of available solutions/	88.7	100

computed based on the baseline chain, MNMC-MIDA-POMM-LAND, which is significantly different from those computed directly based on the baseline RNCH-LAND.

The deformation solutions of all monitoring stations computed using the traditional strategy are shown in Fig. 10; while the solutions with new strategy in Fig. 11. Comparing these results, we get some conclusions.

First, the accuracies of MIDA station from new strategy are higher than those of traditional strategy. We do not compare the accuracies of POMM and LAND, because the results of traditional strategy for these stations are incomplete as shown in Fig. 10. As shown in Table 2, the standard deviation (STD) of POMM even better in traditional strategy.

Second, the discontinuity of deformation solutions for POMM and LAND in traditional strategy indicates the lower integrity of the traditional strategy relative to the new strategy. Because of some unexpected effects, such as the limited number of visible satellites and the considerable residual atmospheric effects, etc., in the longer baselines in the traditional strategy, the stability and integrity of deformation solutions become lower with single frequency receiver. Since only very short baselines are processed in the new strategy, such unexpected effects can be avoided well and then the integrity is increased. The rates of available deformation solutions are summarised for all monitoring stations in Table 2.

Conclusions

The application of a single frequency receiver in GPS deformation monitoring is limited mainly by the ionospheric effects due to the long baselines commonly formed between the reference stations and the monitoring stations. In this contribution, we introduce a new data processing strategy in the single frequency deformation monitoring. In the new strategy, the baselines of the network formed by any two nearest stations instead of baselines only between the reference stations and monitoring stations. As a result, most of baselines need to be processed are very short such that the residual ionospheric effects can be basically ignored. A cycle slip detection processing was also advised in this new data processing strategy. The results from two experimental deformation monitoring networks show that the new strategy can safely eliminate the ionospheric effects and then both accuracies and integrities of deformation solutions can be significantly improved.

Acknowledgement

Prof. Bofeng Li from Tongji University is appreciated for carefully polishing the manuscript. The work is supported by the Natural Science Foundation of China (41174023), the Major State Basic Research Development Program of China (973 Program) (no. 2013CB733314).

References

Cheng, W. and Jiexian, W., 2012. Cycle slip detection and correction of single-frequency un-differenced phase observation. *Journal of Tongji University (Natural Science)*, 40(09), p.6.

Jia, P.-Z., and Wu, L.-D., 2001. An algorithm for detecting and estimating cycle slips in single-frequency GPS. *Chinese Astronomy and Astrophysics*, 25(4), pp.515–21.

Li, B., 2006. GPS cycle slip detection and correction on the base of trip difference. *Journal of Geotechnical Investigation & Surveying*, 8, p.011.

Li, B., Shen, Y., and Feng, Y., 2010. Fast GNSS ambiguity resolution as an ill-posed problem. *Journal of Geodesy*, 84(11), pp.683–98.

Li, B., Verhagen, S. and Teunissen, P. J. G., 2014. Robustness of GNSS integer ambiguity resolution in the presence of atmospheric biases. *GPS Solutions*, 18(2), pp.283–296.

Ou, J., and Wang, Z., 2004. An improved regularization method to resolve integer ambiguity in rapid positioning using single frequency GPS receivers. *Chinese Science Bulletin*, 49(2), pp.196–200.

Parkinson, B. W. and Spilker, J. J., 1996. *Global positioning system: theory and applications (volume one)*. Aiaa.

Rocken, C., Johnson, J. M., Braun, J. J., Kawawa, H., Hatanaka, Y., and Imakiire, T., 2000. Improving GPS surveying with modeled ionospheric corrections. *Geophysical Research Letters*, 27(23), pp.3821–24.

Schüler, T., Diessongo, H. and Poku-Gyamfi, Y., 2011. Precise ionosphere-free single-frequency GNSS positioning. *GPS Solutions*, 15(2), pp.139–47.

Verhagen, S., Teunissen, P. J. and Odijk, D., 2012. The future of single-frequency integer ambiguity resolution. ed. *VII Hotine-Marussi Symposium on Mathematical Geodesy*, 2012, 33–38.

Wanninger, L., 1995. Enhancing differential GPS using regional ionospheric error models. *Bulletin géodésique*, 69(4), pp.283–91.

Zeng, X., 2004. GPS data processing of landslide vertical deformation monitoring. *Geomatics and Information Science of Wuhan University*, 29(3), pp.201–04.