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A new method for mining deformation monitoring with GPS-RTK

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Abstract: Based on ranging intersection theory, a new method which is simple and easy to operate was proposed for data collection in the mine surface deformation monitoring with GPS-RTK centering rod measurements. It can fully eliminate the inevitable shaking error and the vertical deflection, and to some extent weaken the multipath effect on the estimates of coordinates in a relatively short period of time, using high-frequency observations. The results show that three-dimensional coordinates with a height accuracy better than 1 cm, horizontal accuracy better than 2−4 cm can be achieved through only 15−30 s continuous observation by 20 Hz high-frequency and effectively improve the measurement accuracy and efficiency of RTK, fully satisfying the high-speed and high-precision data acquisition in mine surface subsidence deformation monitoring.
Key words: GPS; rover pole; multipath delay; deformation monitoring

1 Introduction

In order to develop, utilize and protect the coal resources rationally, and promote and ensure the development of the coal industry, the Chinese government has enacted and improved some rules and regulations. A key problem of the rules is that how to confirm the range of protecting coal column by different coal mining methods, burial depth, seam thickness, roof and floor lithologic characters, geologic structure [1]. Typically, a series of observation stations arranged at regular intervals (15−25 m), measuring relative displacements of the stations by the traditional techniques (leveling, total station, etc), were established to summarize the change law of parameters of surface movement for production and construction of mine [2].

However, the surface deformation is expensive to carry out or cannot be measured by traditional techniques in some coal mine areas, especially in the mountain. Hence, it is necessary to employ effective techniques to obtain the deformation data. Recent years, interferometric synthetic aperture radar (InSAR) [3−4], three-dimensional (3D) laser scanner [5−6], digital close-range photogrammetry [7−8] have received increasingly great attentions and have achieved firstfruits. However, at present they have boundedness to be used for deformation monitoring of mine surface and related theories should be continuously perfected in future research.

Recent advantages in GPS receivers, antennas and data processing softwares, have made GPS RTK technique a very effective tool for deformation monitoring in coal mining areas [9], but the data-acquired quality still needs to be improved. With the main error sources including rover pole deflection of the vertical, un-modeled systematic error (gross error, multipath error, etc) and the height transformation error, plane accuracy can only reach 5−10 cm, the height accuracy can only 3−5 cm, which restrict the further application of this technology. Using tripod instead of rover pole and with longer observation to take full advantage of the cyclical nature of multipath can effectively eliminate or reduce the system error, but for a large number of mining ground deformation observation stations, the method means a huge amount of tasks.

In the present work, a simple high-precision GPS-RTK measurement was proposed with the rover pole. That is, the position of the station can be obtained by ranging intersection with the coordinate series collected

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by continuously shaking GPS antenna. The relevant theory was deduced, the accuracy factor in different directions was given, and the feasibility of increasing sampling frequency and reducing the observation time to weaken the effect of multipath was analyzed in this mode. Two experiments were done to evaluate the precision and accuracy of the models.

2 Theoretical foundation

Usually, rover pole is used instead of tripod to improve operational efficiency, but the deflection and the shaking errors will appear inevitably. While the length of the rover pole is 2 m and the deflection angle of the vertical is 3°, the the horizontal and the vertical deflections can reach 104.7 and 2.8 mm, respectively, which are main restrictive factors of GPS RTK technique applicable to mining subsidence monitoring and should be corrected.

Without consideration of observation errors, the coordinate series collected by continuously shaking GPS antenna were on a sphere as discrete points (Fig. 1). Therefore, the positions of the stations can be obtained by ranging intersection with the length of the rover pole as the side length.

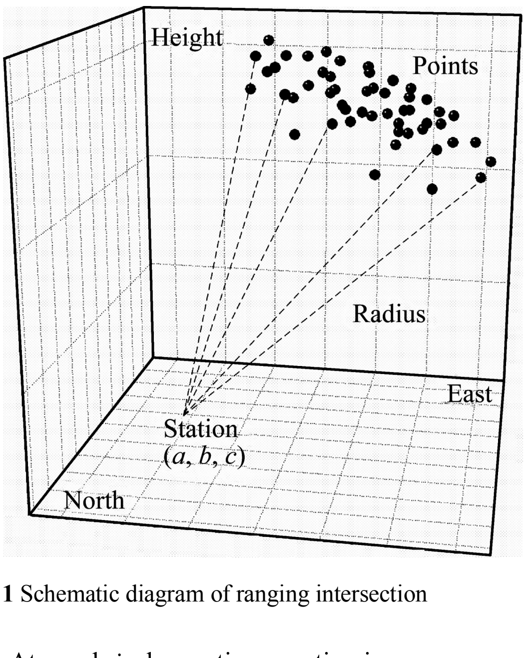

Fig. 1 Schematic diagram of ranging intersection

At epoch i, observation equation is

$$\sqrt{(\boldsymbol{X}(i)-a)^2+(\boldsymbol{Y}(i)-b)^2+(\boldsymbol{Z}(i)-c)^2}=r+\boldsymbol{\delta}_{\text{multipath}}(i)+\boldsymbol{\varepsilon}(i) \tag{1}$$

where $[\boldsymbol{X}(i)\ \boldsymbol{Y}(i)\ \boldsymbol{Z}(i)]$ is coordinate of the GPS antenna at epoch i; $[a\ b\ c]$ is coordinate of the unkown point; r is the real distance from the antana phase center to the unkown point; $\boldsymbol{\delta}_{\text{multipath}}(i)$ is the multipath errors; $\boldsymbol{\varepsilon}(i)$ is the observation noise at epoch i.

Let $\boldsymbol{f}_i(\boldsymbol{x})=\sqrt{(\boldsymbol{X}(i)-a)^2+(\boldsymbol{Y}(i)-b)^2+(\boldsymbol{Z}(i)-c)^2}$ ($\boldsymbol{x}$ is the vector representation of $[a\ b\ c]$). The second-order Taylor series expansion for the left part of equation (1) about $\boldsymbol{x}_0$ (which is $[a_0\ b_0\ c_0]$) is

$$\boldsymbol{f}_i(\boldsymbol{x})=f_i(\boldsymbol{x}_0)+f_i'(\boldsymbol{x}_0)\cdot(\boldsymbol{x}-\boldsymbol{x}_0)+\frac{1}{2}(\boldsymbol{x}-\boldsymbol{x}_0)^{\mathrm{T}}f_i''(\boldsymbol{x}_0)\cdot(\boldsymbol{x}-\boldsymbol{x}_0)+o(\|\boldsymbol{x}-\boldsymbol{x}_0\|^2) \tag{2}$$

where $f_i''(\boldsymbol{x}_0)$, which is Hesse matrix, can be treated as a residual for the insignificant impact of the quadratic terms on the parameter estimation with a long distance of 2×10^4 km between the satellite and the station in a GPS surveying. In this work, it is necessary to evaluate the influence of the quadratic terms as the rover pole is only 2 m long.

TEUNISSEN [10] presented a border estimate of the size of the quadratic terms:

$$\frac{1}{2}\lambda_{\min}\cdot\|\boldsymbol{x}-\boldsymbol{x}_0\|^2\le\boldsymbol{R}\le\frac{1}{2}\lambda_{\max}\cdot\|\boldsymbol{x}-\boldsymbol{x}_0\|^2 \tag{3}$$

where $\lambda_{\min}$ and $\lambda_{\max}$ are the minimum and maximum eigenvalues of the Hesse matrix, respectively, and the maximum possible eigenvalue could be $1/r$ (r is the length of the rover pole), the maximum possible eigenvalue could be 0, then the influence values of the quadratic terms is [11]

$$0\le R\le\frac{(\delta x)^2}{2r} \tag{4}$$

where δx is the observation errors of the receiver.

Figure 2 gives the relationship between the maximum nonlinear error and the receiver positioning errors. With the influence of multipath effect, under the most adverse conditions, the positioning error is about 5 cm and the maximum nonlinear error is about 0.6 mm for L_1 frequency. So, only the first-order Taylor series expansion is adequate and the nonlinear error can be ignored. Equation (1) can be expressed as [12]:

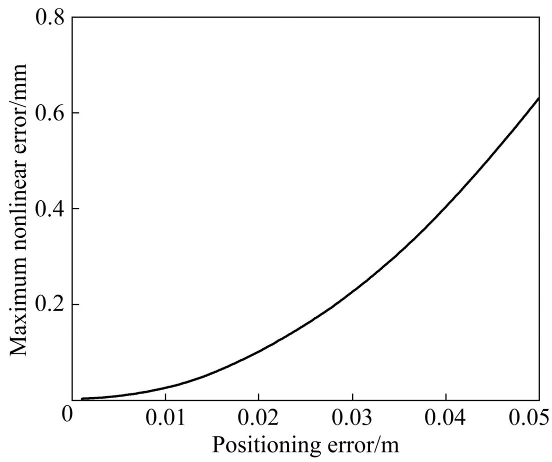

Fig. 2 Estimation of the maximum nonlinear error

$$V(i)=\begin{bmatrix} l(i) & m(i) & n(i) \end{bmatrix}\begin{bmatrix} \delta a \\ \delta b \\ \delta c \end{bmatrix}-(\rho_0(i)-r) \quad (5)$$

where [$l(i)$ $m(i)$ $n(i)$] is unit vector component in the three orthogonal directions (N, E, U) of the distance between the GPS antenna and station point at epoch i; $[\delta a\ \delta b\ \delta c]^T$ is the corrected value for the coordinates of the unknown point; $\rho_0(i)$ is the approximation of geometric distance between the antenna to the satellite.

N-error equations are obtained like equation below, when the observation epoch is n

$$V=A\cdot X-L \quad (6)$$

where $V=[V(1)\ V(2) \cdots V(n)]^T$;

$$A=\begin{bmatrix} l(1) & m(1) & n(1) \\ l(2) & m(2) & n(2) \\ \vdots & \vdots & \vdots \\ l(n) & m(n) & n(n) \end{bmatrix};$$

$X=[\delta a\ \delta b\ \delta c]^T$; $L=[\rho_0(1)-r\quad \rho_0(2)-r\quad \cdots\quad \rho_0(n)-r]^T$.

According to the principle of the least square method, the co-factor matrix of unknown parameter is

$$Q=(A^T\cdot A)^{-1} \quad (7)$$

Resembling the theory of GPS point positioning, introduce the DOP in different direction:

$$\mathrm{DOP_P}=\sqrt{Q_{1,1}+Q_{2,2}+Q_{3,3}};$$

$$\mathrm{DOP_H}=\sqrt{Q_{1,1}+Q_{2,2}};$$

$$\mathrm{DOP_V}=\sqrt{Q_{3,3}}.$$

After the field experiment, we can find that the centering rod of 2 m can succeed to wobble in the angle between 70° and 90° with ground.

In order to solve the change of DOP in different observation time, the continuously uniform distribution function is used. As shown in Fig. 3, 50 groups data were gathered and every group had 300 epochs. The DOP decreases when the observation time increases. Because the sway range of GPS receiver is small, the $\mathrm{DOP_V}$ is far less than the $\mathrm{DOP_P}$. While the epoch is 110, the $\mathrm{DOP_V}$ decreases to 0.1 and the $\mathrm{DOP_H}$ decreases to 0.8. The result indicates that the new method can weaken the influence of the receiver position error to unknown point coordinate parameter estimation and improve the height measurement precision effectively.

The main position error of GPS receiver is multipath. Multipath is a phenomenon whereby a signal is reflected or diffracted from nearby obstacles and

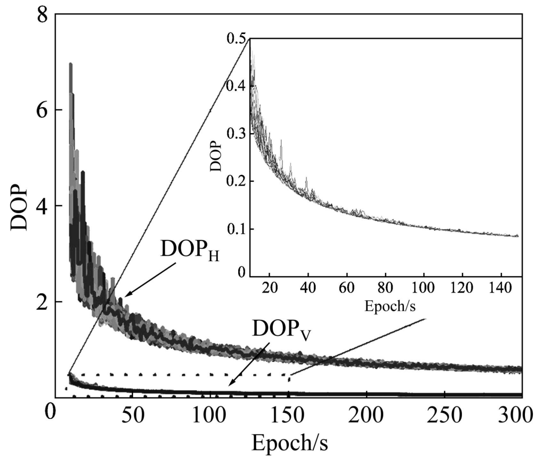

Fig. 3 DOP values of different epochs

arrives at a receiver's antenna via two or more different paths (Fig. 4). Multipath delay due to single reflected signal component can be described as [13]:

$$S=\alpha_0 A\sin(\omega t+\Delta_0) \quad (8)$$

where [14]

$$\Delta_0=\frac{D}{\sin\theta}[1-\cos(2\theta)] \quad (9)$$

According to Eq. (9), the phase excursion caused by receiver multipath is determined by the relative position of receiver, satellite and diffracting object in space. Tiny GPS receiver change will bring to large degradation of multipath relativity [15]. In order to decrease the observation time and improve the measurement efficiency, the sampling frequency should be increased and the sway rate should be accelerated.

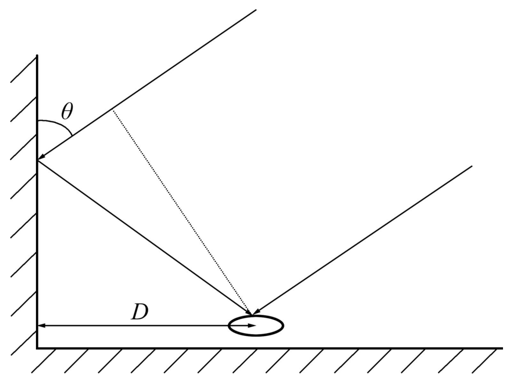

Fig. 4 Multipath phenomenon of GPS signal

3 Experiments

To examine the performance of the procedure, an extensive study was conducted on a data set collected from different baselines in The National Science Park of CUMT (CNUSP) on Oct. 31st, 2010(DOY304 GPS week 1608) from 2:00−4:45 UTC(10:00−12:45 local time). The experience was performed by the tripod, traditional centering rod and the new method of this paper under four different sheltered conditions. The data were obtained at the sampling rate of 1 Hz and 20 Hz; the measure time is 180 s. The environment of four points is shown in Fig. 5.

Figure 6 shows the calculation height in the observation time of 150, 60, 30 and 15 s by different

Fig. 5 Tests in different environments: (a) Point 1; (b) Point 2; (c) Point 3; (d) Point 4

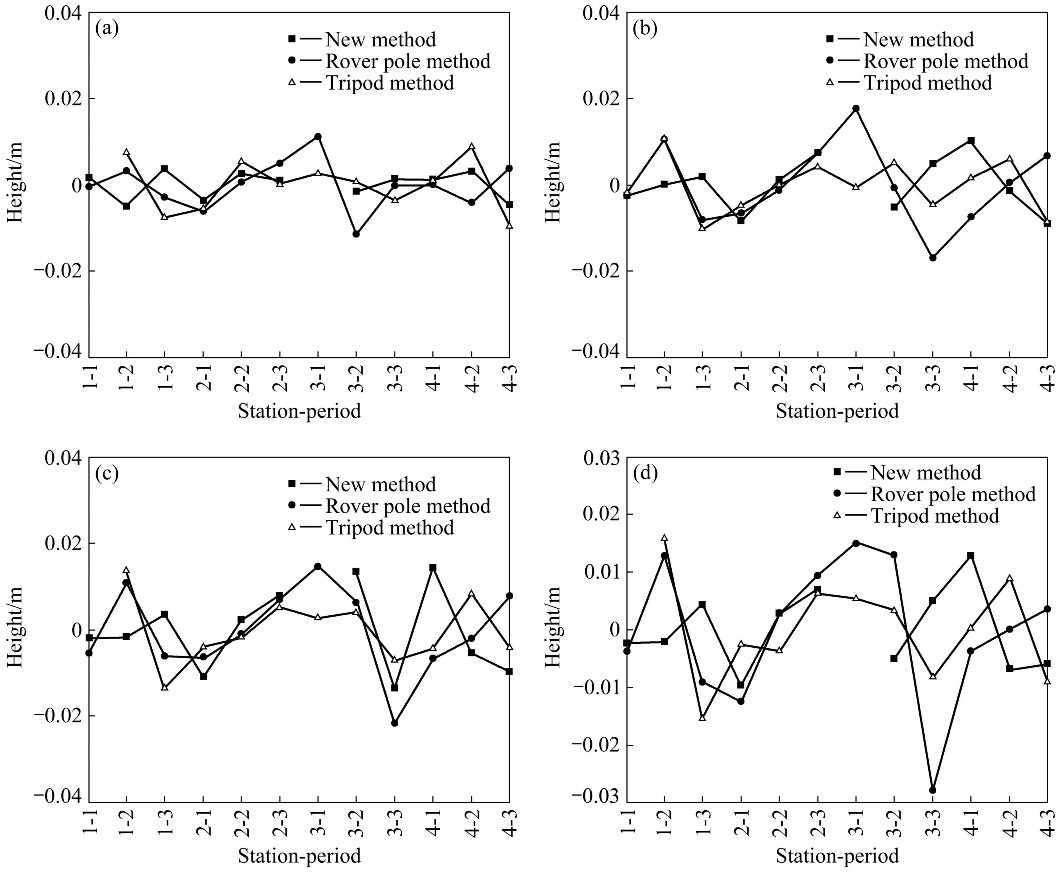

Fig. 6 Heights based on different periods (1 Hz): (a) 150 s; (b) 60 s; (c) 30 s; (d) 15 s

methods. The sampling rate is 1 Hz. While the observation time is decreasing, the bias of the three methods increases in various degrees and the new method of this paper is influenced largely. On the contrary, the new method gets the most excellent result that the precision is better than 1 cm in the observation time of 150 s and 60 s. Figure 7 shows the different point plane coordinates observed by various methods at 1 Hz and in 150 s. The tripod method can get the best outcome and the plan bias of new method is between 2 cm and 3 cm, which is better than traditional centering rod method.

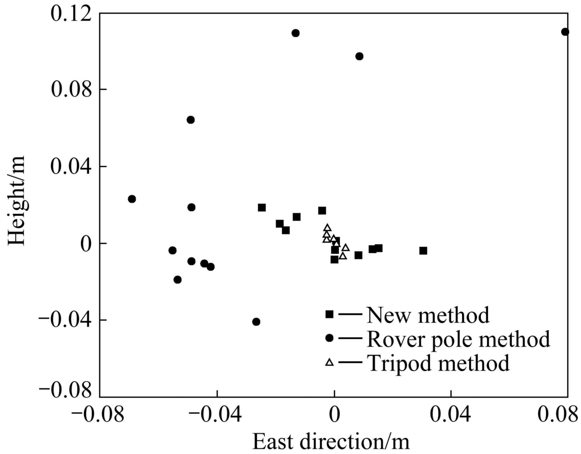

Fig. 7 Horizontal coordinates of different methods (150 s, 1 Hz)

The data sampling frequency is changed in different observation length to test the above methods. Figure 8 shows the contrastive height result of different methods at 20 Hz. The observation time is 15 s and 30 s. Because the tripod and traditional centering rod position does not vary and multipath period is almost fixed, the two methods are able to improve the precision tinily. The new method can get the height with an accuracy of 1 cm, which improves the observation precision. Because the new method can weaken the influence of the receiver position error to unknown point coordinate parameter estimation, it can get better outcome than the tripod method and traditional centering rod.

Futher analysis is studying the feasibility of new method by increasing the sampling frequency and reducing the observation time. The three-dimensional coordinate of the first point observed in different sampling frequency is shown in Fig. 9. The observe time is 150 s. The result indicates that constringency rate at 20 Hz sampling

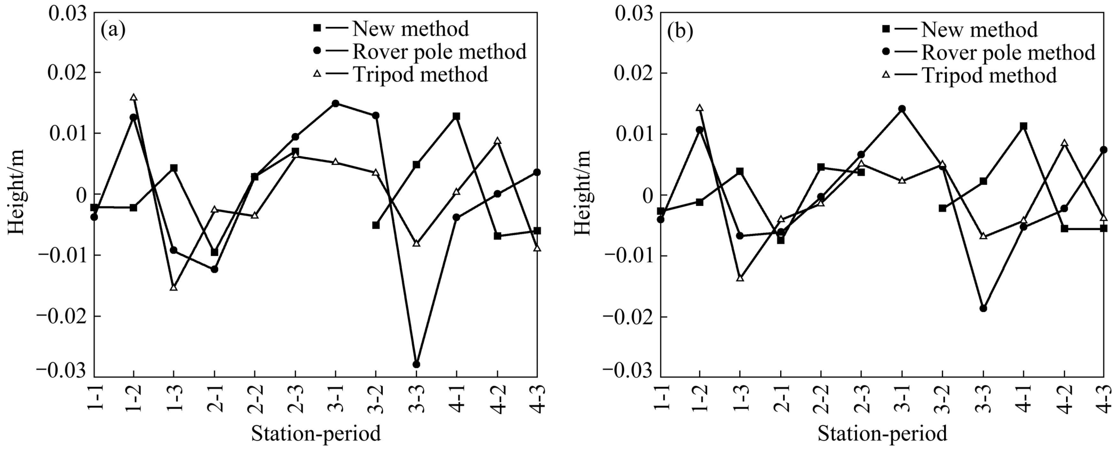

Fig. 8 Heights based on different periods (20 Hz): (a) 15 s; (b) 30 s

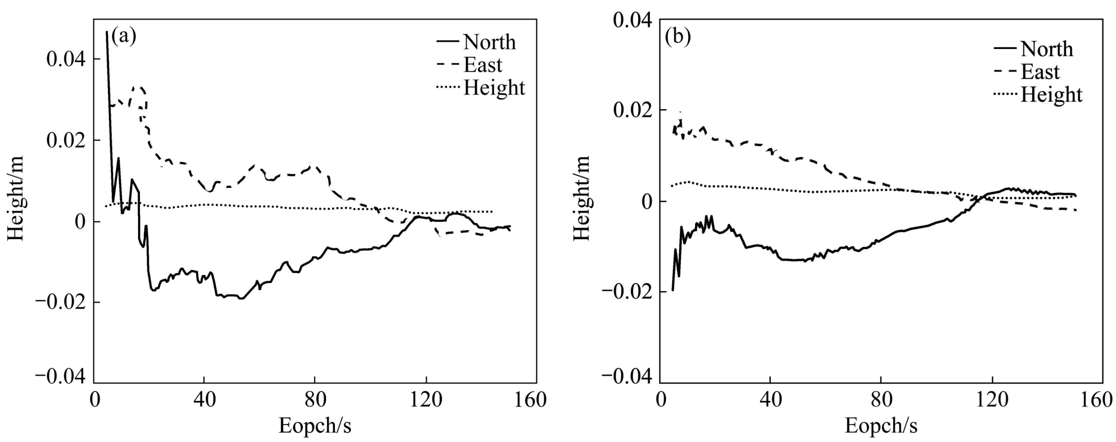

Fig. 9 Convergence rates of coordinates (No.1 point-2nd period): (a) 1 Hz; (b) 20 Hz

frequency is faster than 1 Hz sampling frequency, especially in N-direction and in E-direction.

Figure 10 shows the plane coordinates of different methods at 20 Hz. The observation time is 15 s and 30 s. The new method can get the plan metric position with an accuracy between 3 cm and 4 cm, which improves the observation precision largely than traditional centering rod.

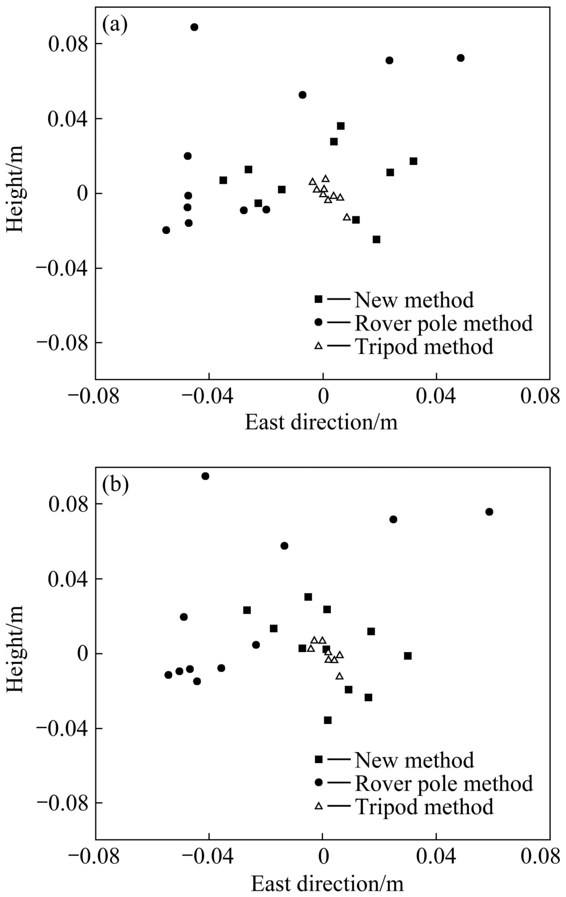

Fig. 10 Horizontal coordinates based on different periods (20 Hz): (a) 15 s; (b) 30 s

4 Conclusions

1) In order to improve the accuracy and reliability of mine surface subsidence monitoring, GPS RTK technique was introduced and the mechanism of the main systematic errors was analyzed subsequently, based on different theories and methodologies.

2) The new method can fully eliminate the inevitable shaking error and the vertical deflection, and to some extent weaken the multipath effect, which improves the precision of estimates.

3) The experience proves that a good result can be obtained after increasing the sampling frequency and decreasing the observation time.

4) Three-dimensional coordinates with height accuracy better than 1 cm, horizontal accuracy better than 2−4 cm can be achieved through only 15−30 s continuous observation by 20 Hz high-frequency and effectively improve the measurement accuracy and efficiency of RTK in mining area observation station of surface movement.

5) The method should be studied future to remove the mutation error of centering rod and diffraction and long period multipath.

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