Received January 25, 2019, accepted March 13, 2019, date of publication March 18, 2019, date of current version April 5, 2019.

Digital Object Identifier 10.1109/ACCESS.2019.2905771

Combination of Asynchronous Array Pseudolites and GNSS for Outdoor Localization

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This work was supported by the Indoor Hybrid Intelligent Positioning and Indoor GIS Technology Project, which is part of the State's Key Project and Development Plan of China, under Contract 2016YFB0502100 and Contract 2016YFB0502101.

ABSTRACT Global navigation satellite systems (GNSS) are usually unable to provide location-based service (LBS) in urban canyons, thus the pseudolite positioning system has become an important way to enhance the availability and the accuracy of GNSS in such environments. However, the challenge of the traditional pseudolite positioning system is time synchronization, which requires complex hardware and visibility between pseudolites and reference receiver. Thus, the positioning in the urban environment becomes very difficult and complex. To solve this problem, a new asynchronous array pseudolites system is proposed in this paper. Multi-channel transmitters in array pseudolites system have an identical clock source and are based on an identical 1 pulse per second (1PPS) as well. The clock deviation of pseudolites' pseudorange can be eliminated by making the difference between array channels. The minimum positioning system consisting of one array pseudolite and three navigation satellites is used for positioning experiment in this paper. The results of the simulation verify the effectiveness of the minimum positioning system based on combined positioning. Compared with four navigation satellites, the horizontal positioning accuracy is improved slightly by exploiting the minimum positioning system.

INDEX TERMS Array pseudolites, satellite navigation, asynchronous, combined positioning.

I. INTRODUCTION

With the development of automatic driving and LBS applications in urban area, the demand for location service with high continuity, precision and integrity is increasing rapidly. However, satellite navigation cannot provide normal location service in urban area because the signal can be blocked by buildings, trees, bridges and so on. Pseudolites have the potential capability to improve positioning accuracy and availability of GNSS by providing additional navigation signal. Pseudolites are often equipped with small transceiver which is an alternative scheme used to create a local, ground-based Global Positioning System (GPS) [1]–[3].

Pseudolites usually include a synchronization unit [4]–[6], which can synchronize all pseudolites at a common time benchmark. Thus, GNSS receivers can use time of arrival (TOA) to calculate the user's position. The principle is similar with GNSS. However, the time synchronization unit is a complex structure, which increases the cost and complexity of the pseudolites [7].

In order to achieve time synchronization between pseudolites, different technologies have been adopted. Based on the feedback processing method of GNSS reference station, the synchronization network among all pseudolites is conducted [8]. The reference station whose position is accurately known is needed for the clock synchronization of the pseudolites. It uses a reference GPS receiver to collect the measurements of the pseudolite signal. The reference station provides the data server with these measurements. Then the data server generates the clock control inputs for each pseudolite. Locata Corporation has invented a new time synchronization technology called TimeLoc [9], [10]. TimeLoc provides an autonomously synchronized network, and it is similar to the process of two-way time synchronization between two ''LocataLites''. Another way of synchronization is to use GNSS timing. Meanwhile, it is also necessary to use the receiver of pseudolites to correct the time synchronization error [11], [12]. To achieve synchronization among all the pseudolites' clock, all the above methods require additional ranging signals (code and carrier) and the visibility between the pseudolites and the reference station. Therefore, it is very difficult to apply and cover wide areas in the complex urban environment.

The associate editor coordinating the review of this manuscript and approving it for publication was Liangtian Wan.

In order to avoid the influence of complex time synchronization, several new positioning algorithms of pseudolites have been proposed. In Japan, the proximity principle is adopted by the indoor messaging system (IMES) [13]–[15] developed by the Japanese Aerospace Exploration Agency (JAXA), and the user's position is determined as that of the transmitter associated with the strongest received pseudolite signal. Its positioning error is usually 10 meters. In addition, a hyperbolic positioning method with antenna array consisting of proximately-located antennas and a multi-channel pseudolite has been proposed by Sakamoto *et al.* [16] to overcome the problem of indoor positioning with conventional pseudolites. Several asynchronous pseudolite/GNSS integration strategies have been developed and combined with pseudolite proximity and receiver signal strength (RSS)-based positioning [17]–[19]. However, the accuracy of proximity, RSS-based and carrier phase difference-based methods are poor, and the coverage is still small. The GPS repeater is also able to overcome the problems of synchronization, the transmission on each antenna is delayed by different periods. Therefore, these methods are not suitable for urban environment.

In this paper, a new asynchronous array pseudolites system is developed, which overcomes the problem of complex time synchronization required of the traditional pseudolite. The multi-channel signal transmitters are used to transmit different PRN codes, and its signals are compatible with GPS and BDS signals. Multiple channels of the pseudolites are driven by the same clock, and received by a commercialized GNSS receiver, such as ublox M8T, Unicorecomm UC6220. Therefore, the time deviation of pseudolites and user receiver can be eliminated by the difference of pseudo-range observations in different channels. In order to test the application scenario of array pseudolites in the urban canyon area, we screened four GPS satellites received by the user terminal in the test area, and the array pseudolites are deployed on a platform on the hillside. In addition, two channels of the transmitter are connected with antennas to transmit signals to the roof. Finally, the positioning performance of the array pseudolites is analyzed, and we find that the multipath error of array pseudolites is less than that of GNSS.

II. POSITIONING THEORY

A. ARRAY PSEUDOLITES-GNSS POSITIONING SYSTEM

The proposed system consists of three parts: the array pseudolites, GNSS and user terminal. Fig. 1 illustrates the structure of the proposed system.

1) ASYNCHRONOUS ARRAY PSEUDOLITES

A schematic of array pseudolites is given in Fig. 2. The baseband unit consists of digital signal processing (DSP) and field programmable gate array (FPGA) drives multiple RF channels (AD9371). Each channel transmits a signal with unique C/A code and navigation message by modulating them on GPS L1 and Beidou System (BDS) B1 carrier waves.

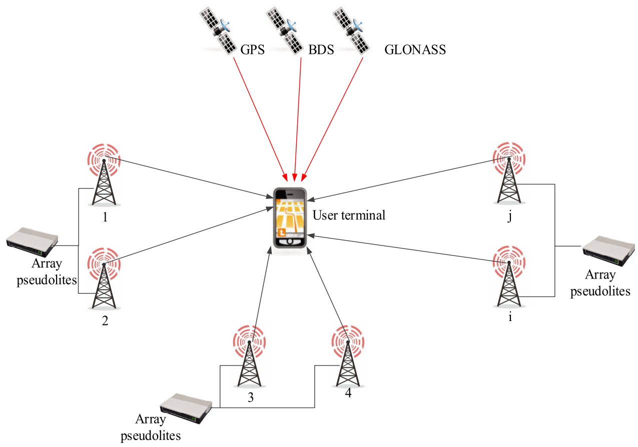


FIGURE 1. Illustration of proposed system.

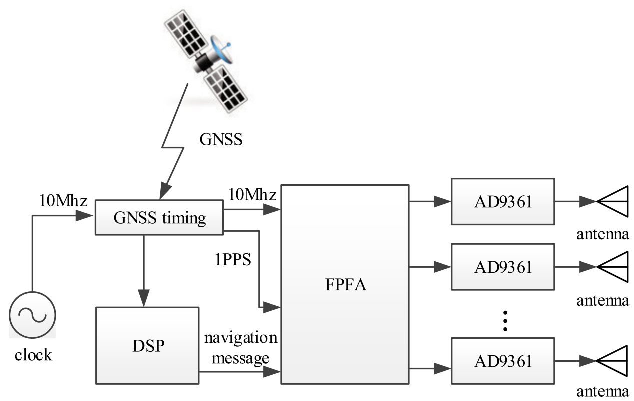


FIGURE 2. Schematic of array pseudolites.

Since signals of array pseudolites are generated at the same time point (the same 1PPS), the clock errors of array pseudolites are same for GNSS receivers. A simple GNSS timing is designed to ensure that commercial GNSS chips can receive both pseudolites and GNSS signals.

A time delay calibration method of the array pseudolites is given in Fig. 3. One channel of the high-speed oscilloscope is connected to the 1PPS signal which is output from the pseudolites' clock. Another channel is connected to the navigation signal (Binary Phase Shift Keying signal, BPSK) from the pseudolites. When 1PPS signal is used as trigger signal, the time delay of pseudolites' channel is obtained by measuring the phase inversion point of navigation signal. The time delay is written into the navigation message of the pseudolites and sent to the user receiver to correct the pseudorange observations.

2) USER TERMINAL

As shown in Fig. 4, The user terminal includes three parts, i.e., receiving antenna, commercialized receiver chip (such as ublox M8T, Unicorecomm UC6220) and ARM processor. The commercialized receiver chip is used to track signals of GNSS and array pseudolites, and the raw observations and navigation message are output to the ARM processor.

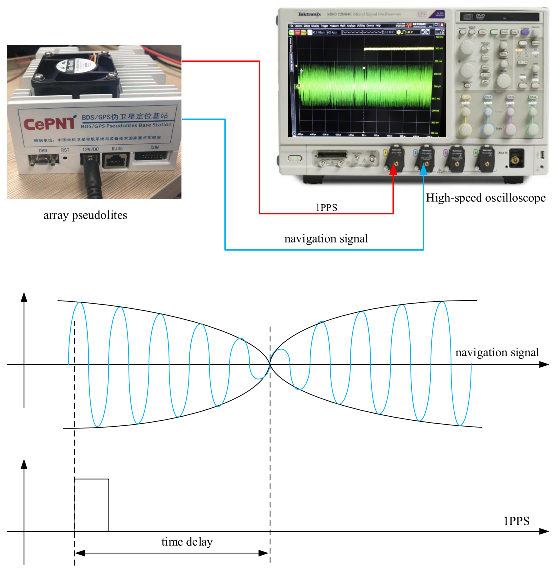


FIGURE 3. Time delay calibration of array pseudolites.

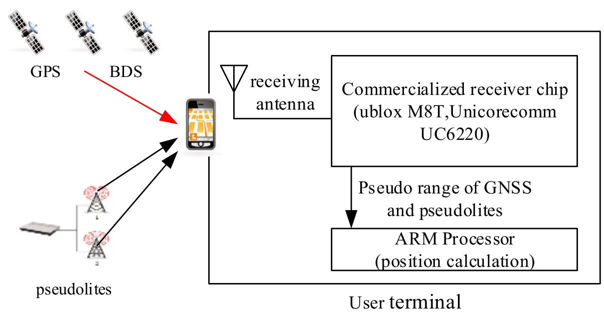


FIGURE 4. Architecture of user terminal.

The observation equation (clock free) of array pseudolites is established on the ARM processor, then the user position is estimated.

B. POSITIONING ALGORITHM

1) ASYNCHRONOUS ARRAY PSEUDOLITES ONLY

Based on the traditional pseudo range measurement equation of GNSS [20], the pseudo range measurements ρ_i from the user terminal to the channel i of array pseudolites is calculated as:

$$\rho_i = \sqrt{(x-x_i)^2+(y-y_i)^2+(z-z_i)^2}+Ti+(t_r-t_i)+\varepsilon_i \tag{1}$$

where ρ_i represents the pseudo range in the ith channel, (x, y, z) is the position of user, (x_i, y_i, z_i) is the position of array pseudolites antenna i, Ti is the tropospheric delay, t_r is the receiver clock error, t_i is the clock error of pseudolites, and ε_i is the multipath and receiver thermal noise error.

The pseudo range measurements ρ_j from the user terminal to the channel j of array pseudolites is calculated as:

$$\rho_j = \sqrt{(x-x_j)^2+(y-y_j)^2+(z-z_j)^2}+Tj+(t_r-t_j)+\varepsilon_j \tag{2}$$

where ρ_j represents the pseudo range from user to the jth channel, (x_j, y_j, z_j) is the position of array pseudolites antenna$j$, Tj is the tropospheric delay,t_j is the clock error of pseudolites, ε_j is the multipath and receiver thermal noise error.

In Eq. (1) and Eq. (2), the term of t_i is equal to t_j, because they use the same clock, the difference between ρ_i and ρ_j can be calculated as:

$$\begin{aligned}\Delta\rho_{ij} &= \rho_i - \rho_j \\ &= \sqrt{(x-x_i)^2+(y-y_i)^2+(z-z_i)^2} \\ &\quad -\sqrt{(x-x_j)^2+(y-y_j)^2+(z-z_j)^2}+\varepsilon_{ij}\end{aligned} \tag{3}$$

Here, if $\sqrt{(x-x_i)^2+(y-y_i)^2+(z-z_i)^2} = ||r^i - r_u||$, $\sqrt{(x-x_j)^2+(y-y_j)^2+(z-z_j)^2} = ||r^j - r_u||$, Eq. (3) can be rewritten as

$$\Delta\rho_{ij} = ||r^i - r_u|| - ||r^j - r_u|| + \varepsilon_{ij} \tag{4}$$

The non-linear term in Eq. (4) is defined as

$$F^{ij}(r_u) = ||r^i - r_u|| - ||r^j - r_u||$$

Its partial derivative with respect to r_u is

$$\frac{\partial F^{ij}(r_u)}{\partial r_u} = -\frac{(r^i - r_u)^T}{||r^i - r_u||} + \frac{(r^j - r_u)^T}{||r^j - r_u||} \tag{5}$$

If the initial value of r_u is used for the solution-updating process, the Newton-Raphson method is described as $r_{u,0} = (x_0, y_0, z_0)$. If the second- and higher-order terms of the Taylor expansion of $F^{ij}(r_{u,0})$ are ignored, the first updated solution can be represented as:

$$F^{ij}(r_{u,1}) = \frac{F^{ij}(r_{u,0})}{\partial r_{u,0}}\Delta r_{u,0} + F^{ij}(r_{u,0}) \tag{6}$$

Therefore, Eq. (4) is modified to

$$\Delta\rho_{ij} = F^{ij}(r_{u,1})+\varepsilon_{ij} \approx \frac{\partial F^{ij}(r_{u,0})}{\partial r_{u,0}}\Delta r_{u,0}+\partial F^{ij}(r_{u,0})+\varepsilon_{ij} \tag{7}$$

The observation equations of array pseudolites can be expressed as the following matrix form:

$$\begin{bmatrix} \frac{\partial F_0^{12}}{\partial x_0} & \frac{\partial F_0^{12}}{\partial y_0} & \frac{\partial F_0^{12}}{\partial z_0} \\ & \cdots & \\ \frac{\partial F_0^{ij}}{\partial x_0} & \frac{\partial F_0^{ij}}{\partial y_0} & \frac{\partial F_0^{ij}}{\partial z_0} \end{bmatrix} \begin{bmatrix} \Delta x_0 \\ \Delta y_0 \\ \Delta z_0 \end{bmatrix} = \begin{bmatrix} \Delta\rho_{12} - F_0^{12} \\ \cdots \\ \Delta\rho_{ij} - F_0^{ij} \end{bmatrix} + \begin{bmatrix} \varepsilon_{12} \\ \cdots \\ \varepsilon_{ij} \end{bmatrix} \tag{8}$$

The matrix on the left-hand side of Eq. (8) is defined as $\mathbf{G}$, and the two column vectors on the right-hand side are defined as $\mathbf{b}$ (left one) and $\boldsymbol{\varepsilon}$ (right one), then Eq. (8) can be expressed as:

$$\mathbf{G} \cdot \Delta r_{u,0} = \mathbf{b} + \boldsymbol{\varepsilon} \tag{9}$$

The solution of Eq. (9) is given as:

$$\Delta r_{u,0} = (\mathbf{G}^T\mathbf{G})^{-1}\mathbf{G}^T\mathbf{b} \tag{10}$$

Then the estimated position can be updated iteratively according to Eq. (11).

$$\hat{r}_{u,1} = r_{u,0} + \Delta r_{u,0} \tag{11}$$

2) COMBINATION OF ARRAY PSEUDOLITES AND GNSS

The pseudo range measurements ρ_s from the user terminal to navigation satellite is calculated as:

$$\rho_s = \sqrt{(x-x_s)^2+(y-y_s)^2+(z-z_s)^2}+I+T+(t_r-t_s)+\varepsilon_s \tag{12}$$

where ρ_s represents the pseudo range from user to satellite s, (x_s, y_s, z_s) is the position of satellite s, T is the tropospheric delay, I is the ionospheric error, t_s is the clock error of satellite s, $\varepsilon_s$is the multipath and receiver thermal noise error.

The first updated solution is denoted as:

$$F^s(\mathrm{r}_{u,1}) = \frac{\partial F^s(r_{u,0})}{\partial r_{u,0}}\Delta r_{u,0} + F^s(\mathrm{r}_{u,0}) \tag{13}$$

Therefore, Eq. (4) is modified to

$$\Delta\rho_s - T - I = F^s(\mathrm{r}_{u,1}) + \Delta\mathrm{t} + \varepsilon_s \approx \frac{\partial F^s(r_{u,0})}{\partial r_{u,0}}\Delta r_{u,0} + F^s(r_{u,0}) + \Delta\mathrm{t} + \varepsilon_s \tag{14}$$

The observation equations of array pseudolites and GNSS can be expressed as the following matrix form:

$$\begin{bmatrix} \frac{\partial F_0^{12}}{\partial x_0} & \frac{\partial F_0^{12}}{\partial y_0} & \frac{\partial F_0^{12}}{\partial z_0} & 0 \\ & \cdots & & \\ \frac{\partial F_0^{ij}}{\partial x_0} & \frac{\partial F_0^{ij}}{\partial y_0} & \frac{\partial F_0^{ij}}{\partial z_0} & 0 \\ \frac{\partial F_0^{s}}{\partial x_0} & \frac{\partial F_0^{s}}{\partial y_0} & \frac{\partial F_0^{s}}{\partial z_0} & 1 \end{bmatrix} \begin{bmatrix} \Delta x_0 \\ \Delta y_0 \\ \Delta z_0 \\ \Delta t \end{bmatrix} = \begin{bmatrix} \Delta\rho_{12} - F_0^{12} \\ \cdots \\ \Delta\rho_{ij} - F_0^{ij} \\ \Delta\rho_s - F_0^{s} \end{bmatrix} + \begin{bmatrix} \varepsilon_{12} \\ \cdots \\ \varepsilon_{ij} \\ \varepsilon_s \end{bmatrix} \tag{15}$$

Then Eq. (15) can be expressed as:

$$\mathbf{G} \cdot \Delta r_{u,0} = \mathbf{b} + \boldsymbol{\varepsilon} \tag{16}$$

The solution of Eq. (16) is given as:

$$\Delta r_{u,0} = (\mathbf{G}^T\mathbf{G})^{-1}\mathbf{G}^T\mathbf{b} \tag{17}$$

Then the estimated position is updated iteratively according to Eq. (18).

$$\hat{r}_{u,1} = r_{u,0} + \Delta r_{u,0} \tag{18}$$

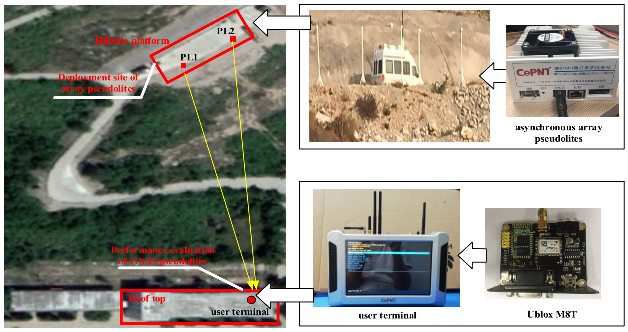


FIGURE 5. Experimental environment of asynchronous array pseudolites.

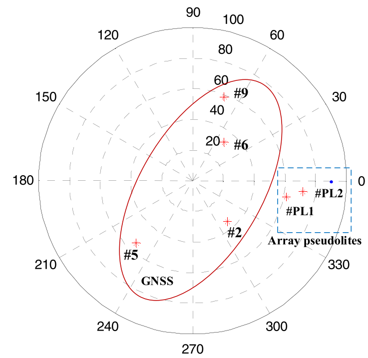


FIGURE 6. The distribution of GNSS and pseudolites.

III. POSITIONING EXPERIMENT

A. EXPERIMENTAL SETUP

The positioning accuracy test site of array pseudolites is shown in Fig. 5. The pseudolites are deployed on a platform on the hillside, and the two channels of its transmitter are connected with the antennas to transmit signals to the roof. As the user terminal, a M8T ublox receiver and a measuring antenna are used for the positioning accuracy test. The antenna coordinates of pseudolites and receiver should be measured with total station in advance. The precise position of receiver will be known as a ground truth, which is compared with the positioning results of pseudolites and GNSS.

B. EXPERIMENTAL RESULTS

In order to test the application scenario of array pseudolites in the urban canyon area, we screened four GPS satellites received by the user terminal in the test area. Several data collection works are conducted in different scenarios, i.e., four GPS, four GPS and one array pseudolites, three GPS and one array pseudolites.

In this scenario, the GPS signal is collected at the roof with high elevation (PRN 9, 6, 5 and 2), the sky plot is shown in Fig. 6. The figure shows that the distribution of navigation satellites is relatively centralized and linear, and the Position Dilution of Precision (PDOP) value reaches 6.2. The array pseudolites are deployed on a platform on the hillside (PL1 and PL2), and the horizontal dilution of precision (HDOP) of the combination of GNSS and pseudolites reaches 4.2.

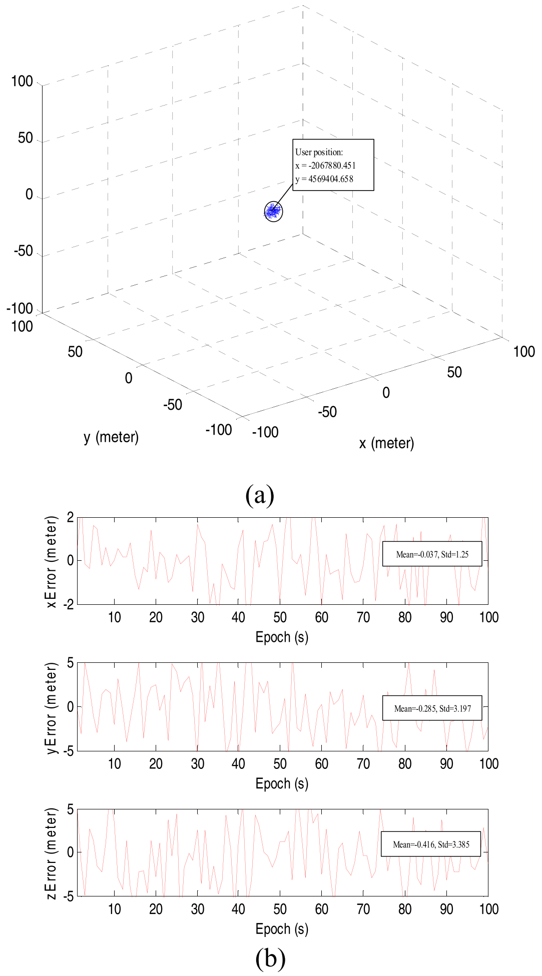


FIGURE 7. Static test of four GNSS satellites: (a) positioning results and (b) positioning error.

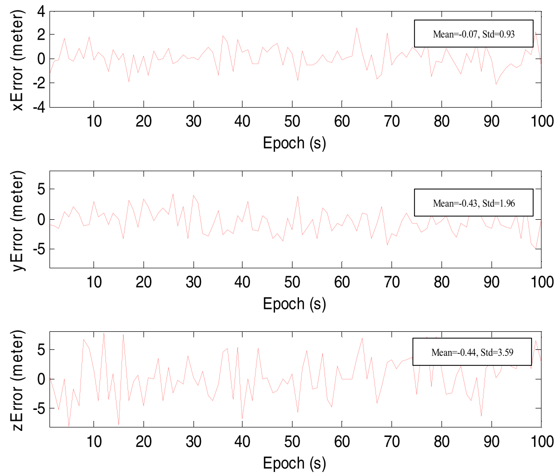


FIGURE 8. The combination positioning error of three GNSS and one pseudolites.

Fig. 7 shows the 3-D static positioning results for GNSS only, the average positioning error is 0.03 m in X axis, −0.28 m in Y axis and −0.416 m in Z axis. The standard deviation (Std) of the X-axis, Y-axis and Z-axis errors are 1.25 m, 3.197 m and 3.385 m, respectively. It is shown that the position accuracy is influenced greatly by the geometry distribution of satellites.

Fig. 8 shows the 3-D static positioning results for three GNSS and one pseudolites, the average positioning error is 0.07 m, −0.43 m and −0.44 m in X axis, Y axis and Z axis, respectively. The standard deviation (Std) of the X-axis, Y-axis, and Z-axis errors are 0.93 m, 1.96 m and 3.59 m, respectively. As shown, the combination of one pseudolites and three GNSS can achieve combined positioning. Compared with four GNSS, the horizontal positioning accuracy is improved slightly based on the proposed method.

IV. ARRAY PSEUDOLITES POSITIONING ERROR ANALYSIS

The minimum positioning system including one array pseudolites and three navigation satellites which can provide positioning service, but the positioning accuracy has not been significantly improved. There are three aspects affecting the positioning accuracy: one is "dilution of precision" (DOP), the second is the ranging error of satellite navigation [21], [22], and the third is the ranging error of array pseudolites [23]. The positioning error of array pseudolites is analyzed in this section.

A. DILUTION OF PRECISION

1) HDOP AND GDOP

The positioning error is estimated by the DOP [24], which is expressed as:

$$\mathrm{cov}(\Delta r_u) = \sigma_\varepsilon^2 \cdot (\mathbf{G}^T\mathbf{G})^{-1} \tag{19}$$

If $(\mathbf{G}^T\mathbf{G})^{-1}$ is defined as $\mathbf{H}$, the DOP can be expressed as the diagonal elements of $\mathbf{H}$ as follows

$$\mathbf{H} = \begin{bmatrix} xDOP^2 & & \\ & yDOP^2 & \\ & & zDOP^2 \end{bmatrix} \tag{20}$$

The variance of positioning error is given by

$$\begin{aligned} \sigma_x^2 &= \sigma_\varepsilon^2 \cdot xDOP^2 \\ \sigma_y^2 &= \sigma_\varepsilon^2 \cdot yDOP^2 \\ \sigma_z^2 &= \sigma_\varepsilon^2 \cdot zDOP^2 \end{aligned} \tag{21}$$

HDOP is defined as:

$$\sigma_{xy} = \sqrt{\sigma_x^2 + \sigma_y^2} = \sigma_\varepsilon \cdot \sqrt{xDOP^2 + yDOP^2} = \sigma_\varepsilon \cdot HDOP \tag{22}$$

PDOP is defined as:

$$\begin{aligned} \sigma_{xyz} &= \sqrt{\sigma_x^2+\sigma_y^2+\sigma_z^2} = \sigma_\varepsilon \cdot \sqrt{xDOP^2+yDOP^2+zDOP^2} \\ &= \sigma_\varepsilon \cdot PDOP \end{aligned} \tag{23}$$

2) DOP ANALYSIS

Fig. 9 shows the result of geometric distribution simulation, which is plotted as a function of user position. Three navigation satellites (PRN 9, 5 and 2) in the test area are

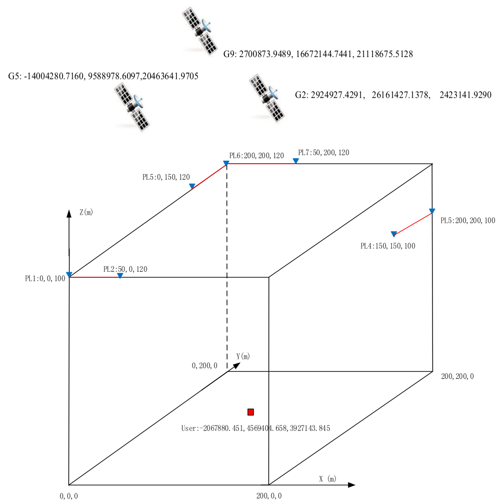
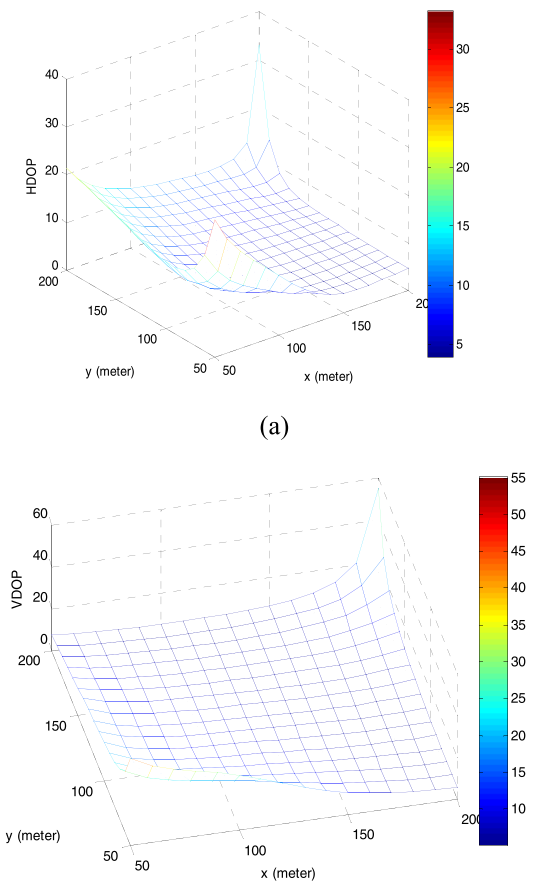


FIGURE 9. Geometric distribution simulation.



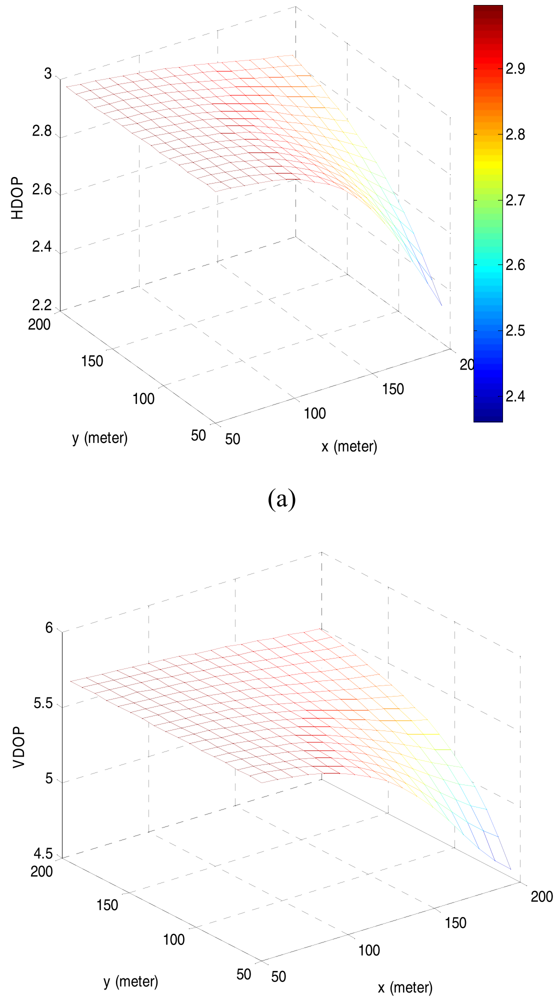
(a)

(b)

FIGURE 10. Geometry distribution of array pseudolites: (a) HDOP and (b) VDOP.

selected at the same time, and three sets of pseudolites are simulated.

Fig. 10 shows the geometry distribution results for array pseudolites only. The minimum value of HDOP is 3.3 and the maximum value is 40. The minimum value of VDOP is 5 and the maximum value is 55. The HDOP and VDOP value is larger in the area near the pseudolites.



(a)

(b)

FIGURE 11. Geometry distribution of 1 pseudolites and 3 GNSS: (a) HDOP and (b) VDOP.

Fig. 11 shows the geometry distribution results for combination of GNSS and pseudolites. The minimum value of HDOP is 2.3 and the maximum value is 2.9. The minimum value of VDOP is 4.4 and the maximum value is 5.6. The result shows that array pseudolites are more suitable for combination positioning with GNSS.

B. MULTIPATH AND RECEIVER NOISE ERROR

Because the antenna coordinates of the two transmitting channels and the antenna coordinates of the user terminal of the array pseudolites have been measured by the total station, these known coordinates are substituted into Eq. (24), and a new equation of pseudorange and multipath is obtained as follows

$$(\Delta\rho_{ij} - ||r^i - r_u|| + ||r^j - r_u||) = \varepsilon_{ij} \tag{24}$$

where ε_{ij} includes multipath error, tropospheric residual error and noise error of user thermal. Because the baseline of

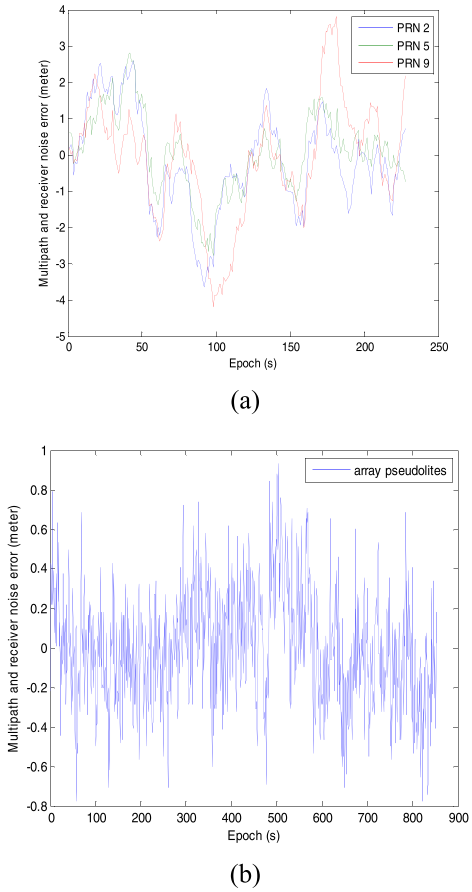


FIGURE 12. **Multipath and receiver noise error (a) of GNSS and (b) of array pseudolites.**

the pseudorandom array is relatively short, the tropospheric residual error is small and negligible. Under the condition of receiving the different pseudolites signals at the same user terminal, the noise error is also at the required level. Therefore, the main pseudorange error of array pseudolites is multipath error.

GNSS can use double different processing to observe the influence of multipath and receiver noise [25], [26], the multipath and receiver noise error of GNSS is given in Fig. 12 (a), which ranges from −4 to 4. The multipath and receiver noise error of GNSS is given in Fig. 12 (b), which ranges from −0.8 to 1. The result shows that the ranging error of navigation satellite is much larger than that of array pseudolites.

V. CONCLUSIONS

This paper proposes a new array pseudolites positioning system. and the main advantage of this system is that the time synchronization is not required. Since multi-channel transmitters have the same clock source, each channel's navigation signal is based on the same 1PPS. The clock deviation of receiver and pseudolites can be eliminated by making the difference among the pseudorange of different array channels. Another advantage is that the pseudorange measurement equation of array pseudolites can be combined with GNSS, and the array pseudolites' signals are compatible with GPS and BDS signals. The performance of the proposed system is evaluated using the commercialized GNSS receiver. The test results show that one pseudolites and three GNSS can achieve the combined positioning. Compared with four GNSS, the horizontal positioning accuracy is improved slightly based on the proposed scheme.

The minimum positioning system composed of one array pseudolites and three navigation satellites can provide positioning services in this work. The minimum value of HDOP is 2.3 and the maximum value is 2.9, but the positioning accuracy has not been significantly improved. The main reason for this phenomenon is that the ranging error of navigation satellite is much larger than that of array pseudolites. In this paper, only one array pseudolites is used for the positioning calculation. Therefore, some methods of pseudorange difference and carrier phase difference [27], [28] can be used for combination of pseudolites and GNSS to improve positioning accuracy in the future.

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