Accuracy Analysis on GDOP of Pseudolite Positioning System Based on TDOA Technology

Li Li(✉), Yiqin Cao, and Hongwei Zhao

School of Electronics and Information, Northwestern Polytechnical University, Xi'an 710072, China
lilinwpu@126.com

Abstract. In the case that the GNSS satellite signal is interfered and the satellite constellation visibility is affected, an independent pseudolite navigation and positioning system can be constructed to achieve the positioning operation of the target user. This paper proposes an independent navigation and positioning system consisting of four pseudolites based on the principle of Time Difference of Arrival (TDOA). In this paper, the geometric dilution of precision (GDOP) expression of the positioning system under the TDOA technology is derived. In view of the influence of pseudolites geometric layout on GDOP, this paper proposes two layout schemes, Y-type and T-type, and simulates the distribution of GDOP values under each layout scheme. After comparing and analyzing the simulation graphs, it is concluded that the T-shaped geometric layout can significantly reduce the GDOP value compared with the Y-shaped layout.

Keywords: Pseudolite · Positioning system · TDOA · GDOP

1 Introduction

The emergence of the Global Navigation Satellite System (GNSS) has driven new developments in the field of navigation and positioning on the Earth's surface and near the ground [1]. With the continuous improvement of hardware technology, GNSS systems have been widely used in geodesy and measurement-oriented industries [2], including GPS, GLONASS and Chinese Beidou satellite navigation system (BDS). Since the availability of GNSS systems and the accuracy of the positioning results depend on the number of visible satellites and the geometric distribution of the satellites, poor positioning conditions such as indoors, canyons and underground in which if the user receivers are located, can severely affect the number and geometry of traceable satellites, and even making the GNSS system unable to meet the needs of positioning operations. In order to solve the above problems, the introduction of pseudolite technology can provide new methods and approaches.

B. Li et al. (Eds.): IoTaaS 2019, LNICST 316, pp. 456–467, 2020.
https://doi.org/10.1007/978-3-030-44751-9_38

Pseudolites are generators that can propagate signals similar to GNSS signals. The simplest form is the GNSS signal generator and transmitter [3]. There are three main modes of operation for pseudolite technology: (a) an enhanced GNSS system based on pseudolite; (b) a completely independent pseudolite navigation and positioning system; (c) a pseudolite-based reverse positioning system [4]. Among them, a pseudolite-based navigation and positioning system, that is, a navigation constellation network composed of a sufficient number of pseudolites, in the case where the GNSS satellite signal is completely obscured by artificial and natural obstacles and GNSS technology cannot be applied for navigation and positioning, can perform independent navigation and positioning operations.

In this paper, a completely independent navigation and positioning system consisting of four pseudolites based on the principle of Time Difference of Arrival (TDOA) is proposed to achieve user receiver positioning in three-dimensional space under the circumstance that the GNSS satellite signal is interfered and the satellite constellation visibility is affected. In addition, this paper deduces the geometric dilution of precision (GDOP) expression of the positioning system based on the TDOA principle, and analyzes the main factors affecting the value of GDOP: time difference measurement accuracy, pseudolite position measurement accuracy and pseudolite geometry layout. In view of the pseudolite geometric layout, this paper proposes two layout schemes, Y-type and T-type, and simulates and analyzes the distribution of GDOP values under each layout scheme.

2 Pseudolite Independent Navigation and Positioning System

The pseudolite independent navigation and positioning system proposed in this paper adopts four pseudolites to form an independent positioning network. Each pseudolite transmits a satellite signal similar to GNSS.

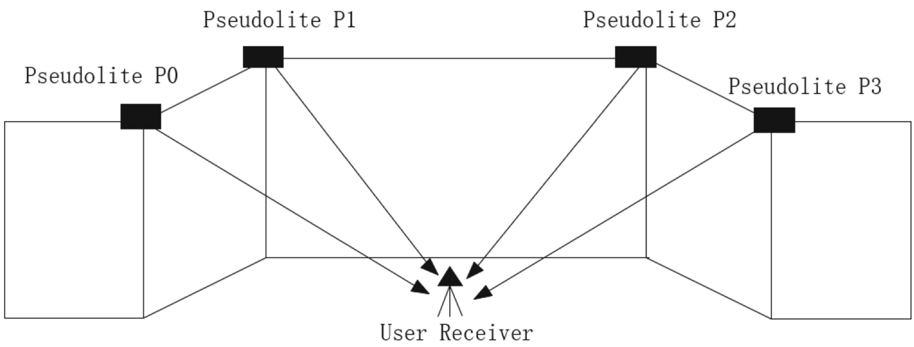

Fig. 1. The independent navigation and positioning system composition with 4 pseudolites.

The user to be located (R_T) receives the pseudolite (P_i, $i = 0, 1, 2, 3$) signal, and the receiver finally solve the three-dimensional position coordinates of its own in three-dimensional space through applying the TDOA positioning principle. The system composition diagram is shown in Fig. 1.

In different practical applications, the specific pseudolite geometric arrangement is also different, but the position information of each pseudolite itself is known in advance.

Compared with GNSS systems, pseudolite positioning systems have the following advantages [5]:

(1) The geometric distribution of the pseudolite can be designed in advance to obtain the best positioning effect.
(2) The position of the pseudolite transmitter can be arbitrarily arranged and changed in a three-dimensional space in which GNSS satellite signal is completely invisible.
(3) The economic cost of pseudolite equipment is relatively low, and a larger number of pseudolites may be considered for further research and improvement of the system.

3 TDOA Positioning Principle

Time Difference of Arrival (TDOA) [6] measures the time data of a signal sent from multiple transmitting terminals in a straight line to the receiving terminal, and obtains the distance differences between each transmitting ends and the receiving end according to the propagation speed of the electromagnetic wave in the air. So that the receiving end is able to be positioned. Considering the geometric space, in the three-dimensional space, the signal time difference between some two transmitting terminals to the receiving end determines a pair of hyperboloids with the two emitting ends as the focus. Therefore the time difference positioning technology is also called hyperbolic positioning technology.

As shown in Fig. 2, the three-dimensional time difference positioning requires at least four transmitting terminals to determine three pairs of hyperboloids, and the positioning of the user receiver is realized by the principle that the surface lines intersect to determine one point.

In this paper, four pseudolites are used to form an independent navigation and positioning system. Figure 3 shows the geometrical diagram of the positioning system. In the three-dimensional space, the position of the user to be located R_T is (x_T, y_T, z_T), the position of the four pseudolites $(P_i, i = 0, 1, 2, 3)$ is (x_i, y_i, z_i), $i = 0, 1, 2, 3$, and the time difference TDOA between the pseudolite P_0 received by the user receiver and the remaining three pseudolites P_i is Δt_i, $i = 0, 1, 2, 3$. The distance difference of the user to pseudolite P_0 and to the rest three pseudolites is recorded as Δr, $i = 1, 2, 3$, and the propagation rate of the electromagnetic wave in the air is c, According to the speed distance formula, there are:

$$\Delta r_i = c \times \Delta t_i, i = 1, 2, 3 \tag{1}$$

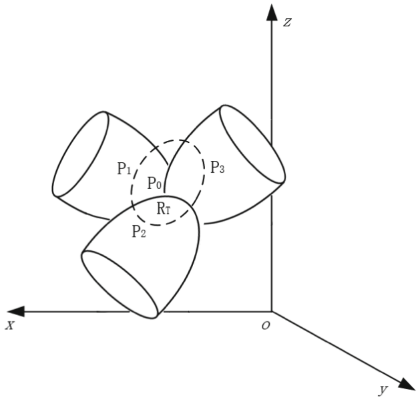

Fig. 2. Principle of three-dimensional time difference positioning.

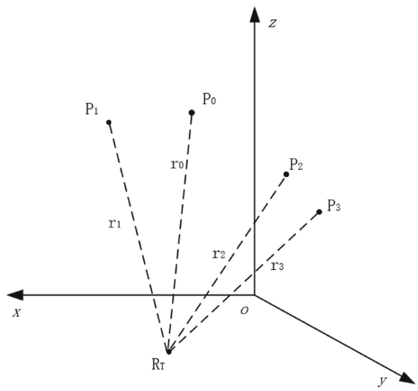

Fig. 3. Three-dimensional time difference positioning geometry.

According to the geometric principle of three-dimensional space, the linear distance r_i, $i = 0, 1, 2, 3$ of the user to be positioned R_T to the pseudolite P_i and the distance difference between the user to the pseudolite P_0 and the other three pseudolites can be calculated by the following formula:

$$\begin{cases} \Delta r_i = r_i - r_0, i = 1, 2, 3 \\ r_0 = \sqrt{(x_T - x_0)^2 + (y_T - y_0)^2 + (z_T - z_0)^2} \\ r_i = \sqrt{(x_T - x_i)^2 + (y_T - y_i)^2 + (z_T - z_i)^2}, i = 1, 2, 3 \end{cases} \tag{2}$$

The user receiver measures the time difference of arrival (TDOA) value of the transmitted signals of each pseudolite. Then, after substituting the known position information of each pseudolite into formula (1) and formula (2) respectively, a set of equations with three unknown parameters is obtained. The equations are expressed in matrix form as:

$$AX = B \tag{3}$$

where,

$$A = \begin{bmatrix} x_0 - x_1 & y_0 - y_1 & z_0 - z_1 \\ x_0 - x_2 & y_0 - y_2 & z_0 - z_2 \\ x_0 - x_3 & y_0 - y_3 & z_0 - z_3 \end{bmatrix} \tag{4}$$

$$X = \begin{bmatrix} x_T \\ y_T \\ z_T \end{bmatrix} \tag{5}$$

$$B = \begin{bmatrix} r_0 \cdot r_1 + d_1 \\ r_0 \cdot r_2 + d_2 \\ r_0 \cdot r_3 + d_3 \end{bmatrix} \tag{6}$$

Thereinto, $d_i = \frac{1}{2}(\Delta r_i^2 + x_0^2 + y_0^2 + z_0^2 - x_i^2 - y_i^2 - z_i^2), i = 1, 2, 3$. It is worth noting that since the TDOA value is measured, $\Delta r_i (i = 1, 2, 3)$ in the above equation can be directly solved, so $d_i (i = 1, 2, 3)$ can be regarded as a known constant value.

The Eq. (3) obtained by the simultaneous Eqs. (1) and (2) is a nonlinear equation set, where r_i $i = 0, 1, 2, 3$ is a nonlinear function with respect to the unknowns x_T, y_T, z_T, hence the explicit expressions for directly finding the unknowns is more difficult. An important solution method to this problem is nonlinear least squares (NLS) [8]. Based on the initial guess of the target position, the method achieves the linearization of the TDOA measurement by taylor series expansion. Another influential method is the closed-form weighted least squares method [11] developed from least squares minimization, which linearizes the TDOA equation by introducing an unknown distance from a measurement station to the target, improves the positioning accuracy. Besides, methods such as particle filter [12] and maximum likelihood estimation [13] have also been applied to TDOA measurements.

In addition, there are two common methods for user receiver to measure the time difference of arrival of transmit signal of each pseudolite: (a) directly measuring the TOA (Time of Arrival) value of transmit signal of each pseudolite and then obtaining the difference; (b) use the cross-correlation operation technique for each pseudo-satellite signal received to obtain the TDOA value. In order to ensure the positioning accuracy, the former method requires that each pseudolite in the positioning system and the user receiver maintain time synchronization.

4 Analysis for System Positioning Accuracy

The positioning error of the pseudolite independent navigation and positioning system is related to the geometric position of the pseudolite. In order to quantitatively analyze this relationship, a conventional positioning accuracy analysis method is introduced. Define the geometric precision factor GDOP (Geometric Dilution of Precision) to describe the geometric distribution of positioning errors in three-dimensional space. GDOP in three-dimensional space is usually expressed by the following formula:

$$GDOP = \sqrt{\sigma_x^2 + \sigma_y^2 + \sigma_z^2} \tag{7}$$

where, σ_x, σ_y, σ_z respectively indicate the standard deviation of the positioning error in the x, y, and z directions.

For the distance difference $\delta r_i (i = 1, 2, 3)$ in Eq. (2), the differential is obtained:

$$\begin{aligned} d(\Delta r_i) &= \frac{\partial \Delta r_i}{\partial x_T} dx_T + \frac{\partial \Delta r_i}{\partial y_T} dy_T + \frac{\partial \Delta r_i}{\partial z_T} dz_T \\ &+ (\frac{\partial \Delta r_i}{\partial x_0} dx_0 + \frac{\partial \Delta r_i}{\partial y_0} dy_0 + \frac{\partial \Delta r_i}{\partial z_0} dz_0) - (\frac{\partial \Delta r_i}{\partial x_i} dx_i + \frac{\partial \Delta r_i}{\partial y_i} dy_i + \frac{\partial \Delta r_i}{\partial z_i} dz) \end{aligned} \tag{8}$$

where, $\frac{\partial \Delta r_i}{\partial x_T} = \frac{x_T - x_i}{r_i} - \frac{x_T - x_0}{r_0}$, $\frac{\partial \Delta r_i}{\partial y_T} = \frac{y_T - y_i}{r_i} - \frac{y_T - y_0}{r_0}$, $\frac{\partial \Delta r_i}{\partial z_T} = \frac{z_T - z_i}{r_i} - \frac{z_T - z_0}{r_0}$, $i = 1, 2, 3$, $\frac{\partial \Delta r_i}{\partial x_i} = \frac{x_T - x_i}{r_i}$, $\frac{\partial \Delta r_i}{\partial y_i} = \frac{y_T - y_i}{r_i}$, $\frac{\partial \Delta r_i}{\partial z_i} = \frac{z_T - z_i}{r_i}$, $i = 0, 1, 2, 3$.

To solve for dx_T, dy_T, and dz_T, the Eq. (5) is converted to a matrix form as:

$$dr = Cdx + K_0 ds_0 - K_1 ds_1 - K_2 ds_2 - K_3 ds_3 \tag{9}$$

where: $dr = \begin{bmatrix} d(\Delta r_1) \\ d(\Delta r_2) \\ d(\Delta r_3) \end{bmatrix} = \begin{bmatrix} cd(\Delta t_1) \\ cd(\Delta t_2) \\ cd(\Delta t_3) \end{bmatrix}$, $dx = \begin{bmatrix} dx_T \\ dy_T \\ dz_T \end{bmatrix}$, $ds_i = \begin{bmatrix} dx_i \\ dy_i \\ dz_i \end{bmatrix}$, $i = 0, 1, 2, 3;$

$$C = \begin{bmatrix} \frac{x_T - x_1}{r_1} - \frac{x_T - x_0}{r_0} & \frac{y_T - y_1}{r_1} - \frac{y_T - y_0}{r_0} & \frac{z_T - z_1}{r_1} - \frac{z_T - z_0}{r_0} \\ \frac{x_T - x_2}{r_2} - \frac{x_T - x_0}{r_0} & \frac{y_T - y_2}{r_2} - \frac{y_T - y_0}{r_0} & \frac{z_T - z_2}{r_2} - \frac{z_T - z_0}{r_0} \\ \frac{x_T - x_3}{r_3} - \frac{x_T - x_0}{r_0} & \frac{y_T - y_3}{r_3} - \frac{y_T - y_0}{r_0} & \frac{z_T - z_3}{r_3} - \frac{z_T - z_0}{r_0} \end{bmatrix},$$

$$K_0 = \begin{bmatrix} \frac{x_T - x_0}{r_0} & \frac{y_T - y_0}{r_0} & \frac{z_T - z_0}{r_0} \\ \frac{x_T - x_0}{r_0} & \frac{y_T - y_0}{r_0} & \frac{z_T - z_0}{r_0} \\ \frac{x_T - x_0}{r_0} & \frac{y_T - y_0}{r_0} & \frac{z_T - z_0}{r_0} \end{bmatrix}, K_1 = \begin{bmatrix} \frac{x_T - x_1}{r_1} & \frac{y_T - y_1}{r_1} & \frac{z_T - z_1}{r_1} \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix},$$

$$K_2 = \begin{bmatrix} 0 & 0 & 0 \\ \frac{x_T - x_2}{r_2} & \frac{y_T - y_2}{r_2} & \frac{z_T - z_2}{r_2} \\ 0 & 0 & 0 \end{bmatrix}, K_3 = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ \frac{x_T - x_3}{r_3} & \frac{y_T - y_3}{r_3} & \frac{y_T - y_3}{r_3} \end{bmatrix}.$$

dr in Eq. (6) represents the system measurement error of the TDOA, ds_i represents the measurement error of each pseudo-satellite position information, and dx is the positioning error of the user to be located in the x, y, and z directions. The weighted least squares (WLS) method can be used to solve the positioning error:

$$d\hat{x} = (C^T C)^{-1} C^T (dr + K_1 ds_1 + K_2 ds_2 + K_3 ds_3 - K_0 ds_0) \tag{10}$$

Here let $B = \left(C^T C\right)^{-1} \cdot C^T$.

Since the TDOA value of each pseudolite signal measured by user receiver incorporates error, and the error exists in each time difference, hence the measurement error of each $\Delta r_i = c\Delta t_i$ is correlated, and the position measurement error of the pseudolite is irrelevant. Assume that after the system correction, the mean value of the measurement error is zero, and the variance of the pseudo-satellite position measurement error is the same, then the positioning error covariance matrix of the user receiver is as follows:

$$\begin{aligned} P_{d\hat{x}} &= Cov(d\hat{x}) = E[d\hat{x} \cdot d\hat{x}^T] \\ &= B(E[dr \cdot dr^T] + K_1 E[ds_1 \cdot ds_1^T] + K_2 E[ds_2 \cdot ds_2^T] \\ &+ K_3 E[ds_3 \cdot ds_3^T] - K_0 E[ds_0 \cdot ds_0^T]) B^T \end{aligned} \tag{11}$$

where, $E[dr \cdot dr^T] = \begin{bmatrix} \sigma^2_{\Delta r_1} & \rho_{12}\sigma_{\Delta r_1}\sigma_{\Delta r_2} & \rho_{13}\sigma_{\Delta r_1}\sigma_{\Delta r_3} \\ \rho_{21}\sigma_{\Delta r_2}\sigma_{\Delta r_1} & \sigma^2_{\Delta r_2} & \rho_{23}\sigma_{\Delta r_2}\sigma_{\Delta r_3} \\ \rho_{31}\sigma_{\Delta r_3}\sigma_{\Delta r_1} & \rho_{32}\sigma_{\Delta r_3}\sigma_{\Delta r_2} & \sigma^2_{\Delta r_3} \end{bmatrix},$

$$E[ds_i \cdot ds_i^T] = Cov\left(\begin{bmatrix} dx_i \\ dy_i \\ dz_i \end{bmatrix}\right) = \begin{bmatrix} \sigma_{xi}^2 & 0 & 0 \\ 0 & \sigma_{yi}^2 & 0 \\ 0 & 0 & \sigma_{zi}^2 \end{bmatrix}, i = 0, 1, 2, 3.$$

Thereinto, $\sigma^2_{\Delta r_i}(i = 0, 1, 2, 3)$ is the variance of the measured distance difference error between pseudolite $P_i(i = 1, 2, 3)$ and pseudolite P_0, and ρ_{ij} is the correlation coefficient of the measured distance difference error between pseudolite $P_i(i = 1, 2, 3)$ and pseudolite P_0:

$$\rho_{ij} = \frac{Cov(\Delta r_{i0}, \Delta r_{j0})}{\sigma_{\Delta r_{i0}} \cdot \sigma_{\Delta r_{j0}}} \tag{12}$$

where, σ^2_{xi}, σ^2_{yi}, and $\sigma^2_{zi}(i = 0, 1, 2, 3)$ are the variances of the measurement errors of the pseudo-satellite position information in the x, y, and z directions, respectively, and $\sigma^2_{xi} = \sigma^2_{yi} = \sigma^2_{zi}$.

Then the positioning error covariance matrix of the user receiver to be located can be written as follows:

$$Cov\left(\begin{bmatrix} dx_T \\ dy_T \\ dz_T \end{bmatrix}\right) = E\left(\begin{bmatrix} dx_T \\ dy_T \\ dz_T \end{bmatrix}\begin{bmatrix} dx_T \ dy_T \ dz_T \end{bmatrix}\right) = \begin{bmatrix} \sigma_x^2 & 0 & 0 \\ 0 & \sigma_y^2 & 0 \\ 0 & 0 & \sigma_z^2 \end{bmatrix} \tag{13}$$

Therefore, according to the definition of GDOP, the positioning geometric accuracy of the pseudo-satellite independent navigation and positioning system based on the TDOA principle in three-dimensional space can be obtained as: $GDOP = \sqrt{\sigma_x^2 + \sigma_y^2 + \sigma_z^2}$.

It can be seen from the above derivation process that reducing the measurement error variance of the TDOA and the pseudo-satellite position information can reduce the GDOP value, thereby improving the positioning accuracy of the system.

5 Simulation for Positioning Performance

In the above analysis of positioning accuracy, the final expression of the geometric dilution of precision (GDOP) in three-dimensional space shows that the GDOP of the proposed system is related to the accuracy of time difference measurement and the accuracy of pseudo-satellite position measurement. The larger both of the errors, the larger the geometric dilution of precision value, which means that the system positioning performance is worse. In addition, the geometry layout of the four pseudolites has a crucial impact on GDOP. Two kinds of pseudo-satellite layout designs are proposed below, and the GDOP distribution of the two schemes are simulated and analyzed.

Assume that the user receiver is located in a three-dimensional space of 200 m in length, 200 m in width and 10 mm in height, and establish a pseudolite positioning system in this space, setting the standard deviation of the

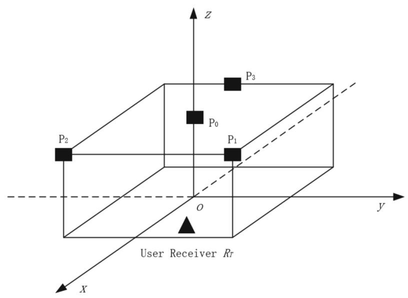

Fig. 4. Four pseudolites in Y-shaped layouts.

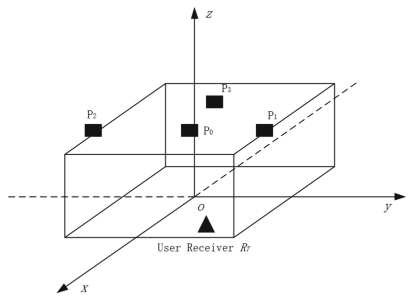

Fig. 5. Four pseudolite in T-shaped layouts.

time difference measurement error to 0.0075, and the standard deviation of the pseudolite absolute position measurement error is 0.5. The correlation coefficient of the measured distance difference error between pseudolite $P_i (i = 1, 2, 3)$ and pseudolite P_0 is 0.35.

The Y-shaped layout scheme is shown in Fig. 4. The three-dimensional Cartesian coordinate system is established based on the geometric center of the bottom surface of the three-dimensional geometric figure. The coordinate information of the set pseudolite $P_i (i = 0, 1, 2, 3)$ is $(0, 0, 10)$, $(100, 100, 10)$, $(100, -100, 10)$, $(-100, 0, 10)$ in turn; And assume that the user is in the horizontal plane of $z = 0$. The corresponding GDOP distribution map under this layout scheme is shown in Figs. 6 and 7.

Under the same assumptions, the T-shaped layout scheme is shown in Fig. 5. The coordinate information of the set pseudolite $P_i (i = 0, 1, 2, 3)$ is $(60, 0, 10)$, $(60, 100, 10)$, $(60, -100, 10)$, $(-60, 0, 10)$ in turn; Also assume that the user is in the horizontal plane of $z = 0$. The corresponding GDOP distribution map under this layout scheme is shown in Figs. 8 and 9.

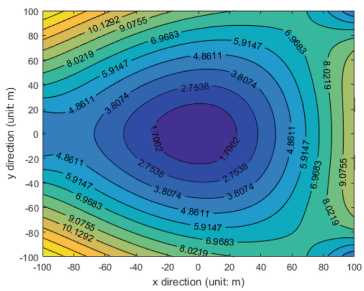

Fig. 6. GDOP contour map in Y-shaped layout.

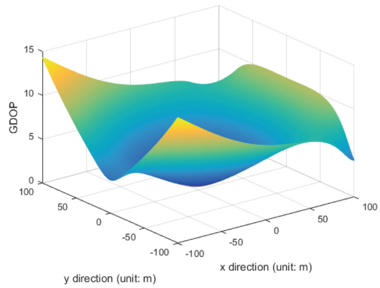

Fig. 7. GDOP distribution in Y-shaped layout.

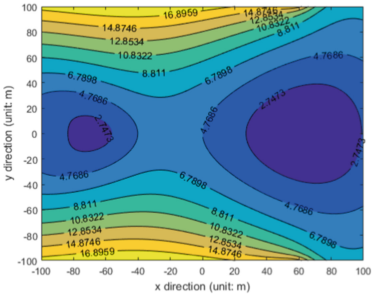

Fig. 8. GDOP contour map in T-shaped layout.

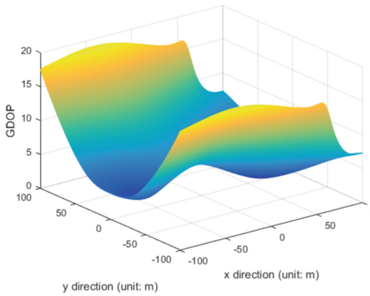

Fig. 9. GDOP distribution in T-shaped layout.

Observing Figs. 6, 7, 8 and 9, it can be seen that the GDOP contour map in Y-shaped layout is more uniform than that in T-shaped layout, and in the lower contour level, the overall growth rate of the GDOP value in the Y-shaped layout is larger than that of the T-type. When the GDOP value is less than 5, there are two parts of the contour line of the same level in the distribution map of the T-type scheme, indicating that the area with the same positioning accuracy is larger under the T-shaped layout than the Y-type scheme.

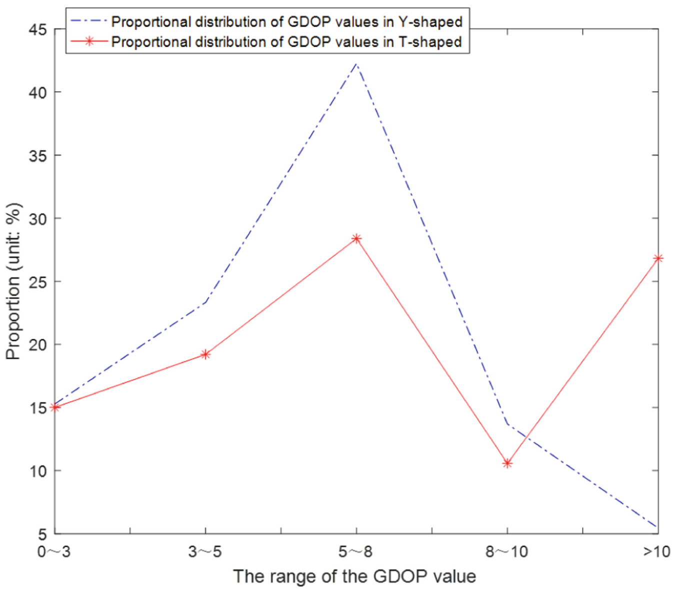

Fig. 10. Proportional distribution of GDOP values in Y-shaped and T-shaped layouts. (Color figure online)

Figure 10 shows the GDOP proportional distribution for the two layouts. The horizontal coordinate represents the range of the GDOP value in the order of 0 to 3, 3 to 5, 5 to 8, 8 to 10, and greater than 10. The blue polyline represents the proportion of the GDOP value of each point in the three-dimensional space in the Y-shaped layout, and the red polyline represents the proportion of the T-shaped layout.

Observing Fig. 10, the ratio of GDOP less than 3 is basically equal in the two layout distribution schemes, and the proportion of GDOP values in the interval of 3 to 8 in the T-shaped layout is significantly smaller than that in the Y-shaped layout, and the proportion of GDOP greater than 10 in the T-shaped layout is relatively large, reflecting the inferiority of this layout scheme. The GDOP values of each point in the Y-shaped layout are concentrated in the interval of 3–8, and the proportion of more than 10 is extremely small, indicating that the pseudo-satellite system in the Y-model has better positioning performance for the user receiver in the three-dimensional space.

It can be seen that in the pseudo-satellite independent positioning system based on the TDOA principle, a better pseudo-satellite layout scheme can significantly reduce the value of geometric dilution of precision(GDOP), thereby achieving more accurate positioning. Different geometric layouts have different advantages and disadvantages, hence it should be designed according to actual needs.

6 Analysis for Factors Affecting Positioning Accuracy

This paper makes assumptions based on the conventional pseudolites placement position height and arrangement spacing, and the four pseudolites positioning system based on TDOA technology is designed.

Next, the influence of the time measurement accuracy and the pseudolites position measurement accuracy on the final user receiver positioning accuracy will be discussed.

Assume that the timie measurement error is increased to 100 ns, the pseudo-satellite position measurement error is not considered, and the GDOP simulation of Y-shaped distribution is obtained as shown in Fig. 12.

Assume that the timie measurement error is still 50 ns, increase the pseudolite position measurement error to 10 m, and obtain the GDOP simulation diagram of Y-shaped distribution as shown in Fig. 11.

Comparing Figs. 11, 12 with Figs. 6, 7, it can be observed that:

(1) After the time measurement error increases from 50 ns to 100 ns, the GDOP increases from 3.7 to 3.9 in the range of -40 to 40 m;
(2) When the pseudolite position error is increased to 10 m, the GDOP positioning accuracy in the same range is increased from 3.7 to 6.8;
(3) The time measurement accuracy and pseudolite position accuracy have a great influence on the final user receiver positioning accuracy.

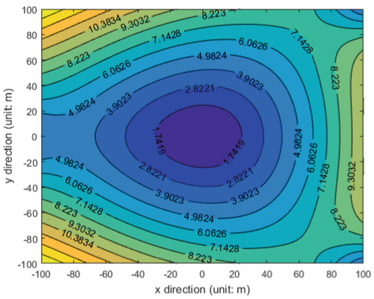

Fig. 11. GDOP contour map after the time measurement accuracy is changed.

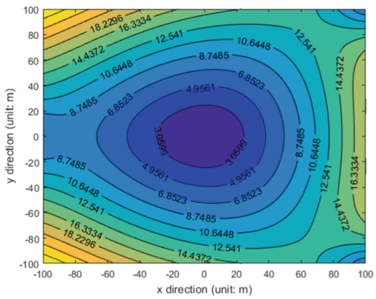

Fig. 12. GDOP contour map after the pseudolite position measurement accuracy is changed.

7 Conclusion

In this paper, an independent pseudolite navigation and positioning system consisting of four pseudolites based on the TDOA principle is proposed in the case that the GNSS satellite signal is interfered and the satellite constellation visibility is affected. This paper introduces the mathematical principle of TDOA, deduces the geometric dilution of precision (GDOP) expression of the positioning system under the TDOA principle, and analyzes the main factors affecting the value of GDOP: time difference measurement accuracy, pseudolite position measurement accuracy and pseudolite geometry layout.

In view of the influence of pseudo-satellite geometric layout on GDOP, two layout schemes, namely Y-shaped and T-shaped, are proposed in this paper, and the distribution of GDOP values under each layout scheme is simulated. After comparing and analyzing the simulation graphs, it is concluded that the Y-shaped geometric layout can significantly reduce the GDOP value compared with the T-shaped layout, and different geometric layouts have advantages and disadvantages. In the subsequent research process, it is possible to consider selecting a larger number of pseudolites for the construction of the positioning system and designing other pseudolite layout schemes to further reduce the positioning error and improve the positioning performance.

References

1. Wang, S.: A pulsed pseudolite signal acquisition method using signal coverage recursion FFT. In: China Automation Society Control Theory Committee. Proceedings of the 36th China Control Conference, p. 6 (2017)
2. Borio, D., Odriscoll, C.: Design of a general pseudolite pulsing scheme. IEEE Trans. Aerosp. Electron. Syst. **50**(1), 2–16 (2014)
3. Shen, J., Cui, X., Lu, M.: Initial frequency refining algorithm for pull-in process with an auxiliary DLL in pseudolite receiver. Electron. Lett. **52**(14), 1257–1259 (2016)

4. Wang, J., Xu, Y., Luo, R.: Synchronisation method for pulsed pseudolite positioning signal under the pulse scheme without slot-permutation. IET Radar Sonar Navig. **11**(12), 1822–1830 (2017)
5. Yang, Y., Gao, W.: An optimal adaptive Kalman filter. J. Geodesy **80**(4), 177–183 (2006). https://doi.org/10.1007/s00190-006-0041-0
6. Shu, F., Yang, S.P., Qin, Y.L.: Approximate analytic quadratic-optimization solution for TDOA-based passive multi-satellite localization with earth constraint. IEEE Access (2016)
7. Foy, W.H.: Position-location solutions by Taylor-series estimation. IEEE Trans. Aerosp. Electron. Syst. **AES-12**(2), 187–194 (1976)
8. Torrieri, D.J.: Statistical theory of passive location systems. IEEE Trans. Aerosp. Electron. Syst. **AES-20**(2), 183–198 (1984)
9. Friedlander, B.: A passive localization algorithm and its accuracy analysis. IEEE J. Ocean. Eng. **12**(1), 234–245 (1987)
10. Huang, Y., Benesty, J., Elko, G., Mersereati, R.: Real-time passive source localization: a practical linear-correction least-squares approach. IEEE Trans. Speech Audio Process. **9**(8), 943–956 (2001)
11. Cheung, K., So, H., Ma, W., Chan, Y.: A constrained least squares approach to mobile positioning: algorithms and optimality. EURASIP J. Adv. Signal Process. **2006**, 020858 (2006). https://doi.org/10.1155/ASP/2006/20858
12. Cho, J.A., Na, H., Kim, S., Ahn, C.: Moving-target tracking based on particle filter with TDOA/FDOA measurements. ETRI J. **34**(2), 260–263 (2012)
13. Meng, C., Ding, Z., Dasgupta, S.: A semidefinite programming approach to source localization in wireless sensor networks. IEEE Signal Process. Lett. **15**, 253–256 (2008)