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A Radiation Source Positioning System Based on GEO Satellites TDOA/FDOA Measurements

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Abstract. Traditional passive satellite positioning systems are facing problems such as construction difficulty, high operation and maintenance costs, and positioning range limits caused by quantity of launched satellites, due to gradually scarce earth's orbit resources. Therefore, a radiation source positioning system design scheme based on quilted GEO communication satellites is proposed to meet with those problems. The proposed positioning system is able to intelligently choose one of three modes (three-satellites TDOA mode, dual-satellites FDOA/TDOA mode, or single-satellite mode), on the basis of searching satellites database, to position unknown radiation source. The positioning result is corrected using a known reference radiation station. To improve signal detection performance, a technology of co-channel interference cancellation is proposed when unknown radiation source signal forwarded by neighboring satellite is interference badly by its communication signal. Results of emulation shows， the proposed system can effectively locate unknown radiation sources within a range of 1000 kilometers, its positioning accuracy can reach 10 kilometers.
Keywords. Satellite positioning system; TDOA/FDOA; Co-channel interference cancellation; Positioning accuracy

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1. Introduction

Passive satellite positioning has received widespread attention because of its unmatched superiority such as all-day all-weather working mode, wide detection coverage, and good concealment features [1]. Passive satellite positioning systems are usually divided into single-satellite, dual-satellites, and three-satellites positioning system based on the number of satellites used. The single satellite positioning system uses one single satellite carrying a two-dimensional interferometer sensor to complete radiation source direction finding and positioning, and its positioning accuracy is relatively low compared to the multi-satellites systems [2-3]. The positioning accuracy of dual-satellites FDOA/TDOA positioning systems is higher than single satellite positioning system, but the positioning error of radiation sources in the sub satellite point area is still large [4-5]. The three-satellites positioning system has higher positioning accuracy, wider reconnaissance range, and smaller positioning blind spots compared to the previous two systems, making it the most widely used in practical applications [6-7]. Among all existing satellite passive positioning systems, the most famous American *White Cloud* series satellites and French *ESSAIM* series satellites both use three LEO satellites formation positioning structure, installing TDOA positioning devices on its satellites to achieve joint positioning of multiple structures [8-9]. However, traditional satellite passive positioning systems are still facing two major problems: Firstly, dedicated reconnaissance satellites are needed to build the system, which bringing a high cost of construction and operation, and with the increasing scarcity of satellite orbital resources, it is difficult to ensure the effectiveness of construction; Secondly, the positioning range is limited by the number of satellites launched, not being able to fully utilize the existing satellite resources. In response to this, a newly designed scheme for an unknown radiation source positioning system based on existing GEO satellite communication systems is proposed. Based on existing satellite communication system and available GEO satellites conditions, the proposed system intelligently select three-satellites TDOA, dual-satellites FDOA/TDOA, or single satellite positioning mode for passive single/multiple satellite positioning of unknown radiation sources. a known position reference sources is used to correct the positioning results. To improve signal detection performance, a technology of co-channel interference cancellation is proposed when unknown radiation source signal forwarded by neighboring satellite is interference badly by its regularly communication signal, so that the positioning accuracy is increased. Results of emulation shows， the proposed system can effectively locate unknown radiation sources within a range of 1000 kilometers, its positioning accuracy can reach 10 kilometers.

2. Principles of the system

2.1. Geography model

A point on or above the earth's surface within a certain height is usually described using a three-dimensional coordinate system of longitude L, latitude B, and height H, which called geodetic coordinates. Meanwhile, it is more convenient to use Cartesian coordinates (X, Y, Z) to describe the position of radiation sources in the situation of satellites TDOA/FDOA measurements. Referring to the WGS-84 ellipsoid model [10], a geodetic coordinates system and a Cartesian coordinates system are established in this paper, as shown in Figure 1, the conversion relationship between two coordinates is

$$\begin{cases} X = (N+H)cosBcosL \\ Y = (N+H)cosBsinL \\ Z = [N(1-e^2)+H]sinB \end{cases} \quad (1)$$

$$\begin{cases} L = arctan\frac{y}{x} \\ B = arctan\frac{z}{\sqrt{x^2+y^2}} \\ H = \sqrt{x^2+y^2+\frac{z^2}{(1-e^2)^2}} - a \end{cases} \quad (2)$$

In the formula, N represents the radius of local prime vertical, $N = \frac{a}{\sqrt{1-e^2 sin^2 B}}$, a represents the long radius of WGS-84 ellipsoid, e represents the first eccentricity ratio of WGS-84 ellipsoid.

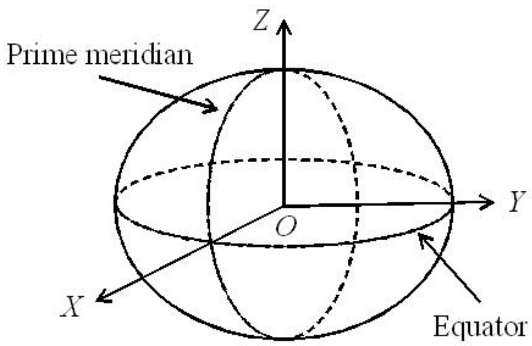

Figure 1. Cartesian coordinates system based on WGS-84 ellipsoid model.

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2.2. Three-satellites TDOA positioning model

A three-satellites TDOA positioning system includes three GEO communication satellites and their ground receiving stations, and an information processing center, as shown in figure 2. The distances from unknown radiation source to three satellites are different, so there is a time difference of arrival (TDOA) of signal received by any two satellites. In a three-satellites TDOA positioning system, the solution that satisfies TDOA forms two hyperboloids in space, combining with the height limit of the radiation source on the earth's surface, the position of the radiation source thus can be determined.

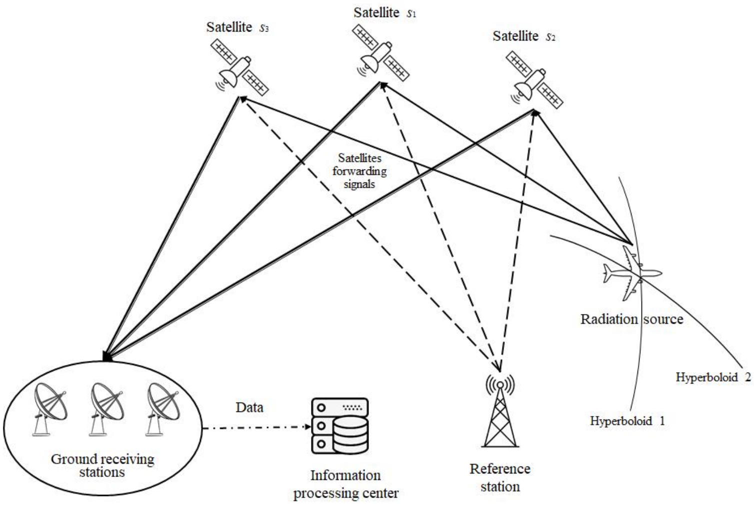

Figure 2. Structure of three-satellites TDOA positioning system.

Assuming the position of the radiation source is $\boldsymbol{u} = (x, y, z)$, three GEO satellites' positions are known, each is $\boldsymbol{s}_i = (x_i, y_i, z_i),\ i = 1,2,3$. Making the distance from unknown radiation source to each satellite is

$$r_i = |\boldsymbol{s}_i - \boldsymbol{u}| = \sqrt{(x_i - x)^2 + (y_i - y)^2 + (z_i - z)^2},\ i = 1,2,3 \quad (3)$$

In the formula (3), $|\cdot|$ represents finding Euclidean distance. When unknown radiation source sends a signal to one of the satellites (major satellite s_1), two other satellites (neighboring satellites s_2 and s_3) receive the same signal. Subtract the time when neighboring satellites receive signals TOA_2 and TOA_3 from the time when major satellite receives signals TOA_1, two sets of TDOA values are obtained.

$$TDOA_{1i} = TOA_1 - TOA_i,\quad i = 2,3 \quad (4)$$

The relationship between TDOAs and the distances from radiation source to satellites is as follow,

$$\begin{cases} TDOA_{12} = TOA_1 - TOA_2 = \frac{r_1 - r_2}{c} \\ TDOA_{13} = TOA_1 - TOA_3 = \frac{r_1 - r_3}{c} \end{cases} \quad (5)$$

In the formula (5), c represents the propagation speed of electromagnetic wave. Compared to GEO satellites, the height of ground or mid to low altitude radiation source target can be ignored, thus

$$x^2 + y^2 + \frac{z^2}{(1-e^2)} = N^2 \quad (6)$$

By solving a joint system of equations consisting of equation (5) and (6), the position of unknown radiation source $\boldsymbol{u}' = (x', y', z')$ can be obtained.

2.3. Dual-satellites TDOA/FDOA positioning model

In the situation where only two GEO communication satellites are available, the system automatically switches to dual-satellites TDOA/FDOA joint positioning mode to locate the radiation source. The structure of dual-satellites TDOA/FDOA positioning system is shown in figure 3. When an unknown radiation source emits signals, due to the differences of distances from it to two satellites and relative directions of motion, the signals received by the satellites have a TDOA and a FDOA. Similar like three-satellites TDOA positioning, the solution that satisfies FDOA also forms a curved surface in space. By combining the constraints of the earth's surface, the location of the radiation source target can be determined.

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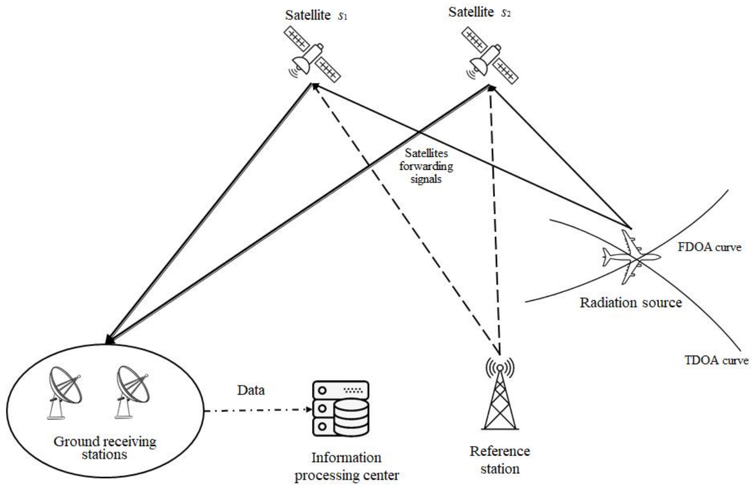

Figure 3 Structure of dual-satellites TDOA/FDOA positioning system.

Assuming the position of the radiation source is $\boldsymbol{u} = (x, y, z)$, two GEO satellites' positions and speeds are known, each is

$$\boldsymbol{s}_i = (x_i, y_i, z_i),\ i = 1,2 \quad (7)$$

$$\boldsymbol{v}_i = \left(v_{xi}, v_{yi}, v_{zi}\right),\ i = 1,2 \quad (8)$$

Making $\boldsymbol{r}_i = \boldsymbol{s}_i - \boldsymbol{u}$ represents vector distance from satellites to radiation source, the TDOA and FDOA of signals emitting from radiation source to two satellites has a relationship as follow

$$TDOA_{12} = \frac{|\boldsymbol{r}_1| - |\boldsymbol{r}_2|}{c} \quad (9)$$

$$FDOA_{12} = \frac{f}{c}\left(\frac{\boldsymbol{v}_1 \cdot \boldsymbol{r}_1}{|\boldsymbol{r}_1|} - \frac{\boldsymbol{v}_2 \cdot \boldsymbol{r}_2}{|\boldsymbol{r}_2|}\right) \quad (10)$$

In the formula (10), *f* represents the frequency of radiation source emitting signal. In WGS-84 ellipsoid model, near the earth's surface target's coordinates meet with the bellowing formula

$$x^2 + y^2 + \frac{z^2}{(1-e^2)} = N^2 \quad (11)$$

By solving a joint system of equations consisting of equation (9), (10) and (11), the position of unknown radiation source $\boldsymbol{u}' = (x', y', z')$ can be obtained.

2.4. Single-satellite Doppler positioning model

When there are no available neighboring satellites near the target communication satellite, the system will use single satellite Doppler positioning mode to locate the radiation source. Figure 4 shows the structure of single satellite positioning system. Single satellite positioning method requires the knowledge of initial position and velocity information of the radiation source, using Doppler frequency changes generated by the movement of the radiation source to calculate the velocity components of the target in the direction and the vertical direction of the satellite connection, estimating the possible position of the target in the next moment, and applying the target tracking algorithm to achieve continuous tracking and positioning of the target. Due to the fact that target tracking algorithms are not the focus of this study, detailed introduction is not to be provided here.

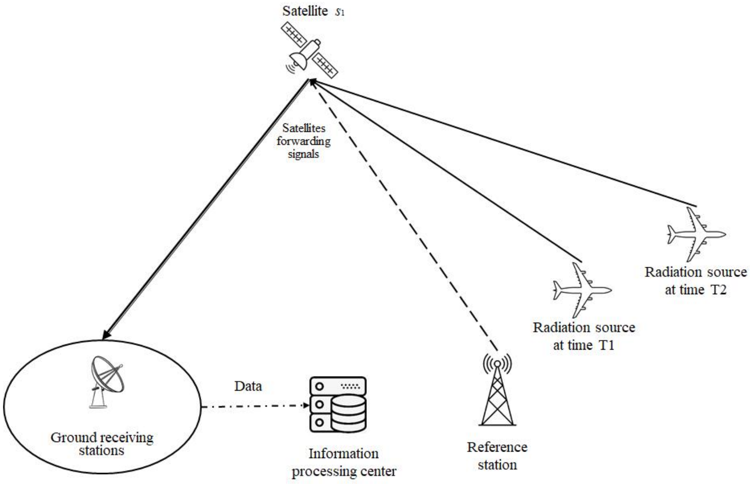

Figure 4 Structure of single-satellite positioning system.

2.5. Method of co-channel interference cancellation

In a multi-satellites positioning system, neighboring satellite receives very weak side lobe signals from the radiation source. If there is a regular communication signal on the same channel, it will further interfere with the radiation source signal. By reconstructing a new signal with equal amplitude and opposite phase to the interference signal, adding to the original interfered signal, co-channel interference signal could be completely cancelled ideally, so that signal detection performance could be highly improved.

The principle of co-channel interference signal cancellation is shown in figure 5, the algorithm process is as follow.

Step 1 receiving and recording signals being co-channel interfered. Assuming that radiation source signals forwarded by neighboring satellites $s_u(t)$ is interferenced by co-channel communication signals $s_I(t)$, the signal received by the receiving terminal is

$$s_r(t) = s_u(t) + s_I(t) + n(t) \quad (12)$$

In the formula (12), $n(t)$ represents Gaussian noise.

Step 2 Analyzing to obtain the information of symbol rate and modulation mode of interference signals. Due to the advantage that $s_I(t)$ is regular communication signal of neighboring satellite, it is possible to obtain symbol rate R_b and modulation mode *MM* of interference signal using digital communication signal modulation mode recognition algorithm.

Step 3 Demodulating interference signals to obtain its bitstream.

Step 4 Re-modulating bitstream with the knowledge of *MM* and R_b, reconstructing interference signal $s'_I(t)$, ideally $s'_I(t) \approx s_I(t)$.

Step 5 Subtracting reconstructing interference signal from original interfered signal,

$$s'_r(\mathrm{t}) = s_r(\mathrm{t}) - s'_I(t) \approx s_u(\mathrm{t}) + \mathrm{n}(\mathrm{t}) \quad (13)$$

So that the aim co-channel interference cancellation could be reached.

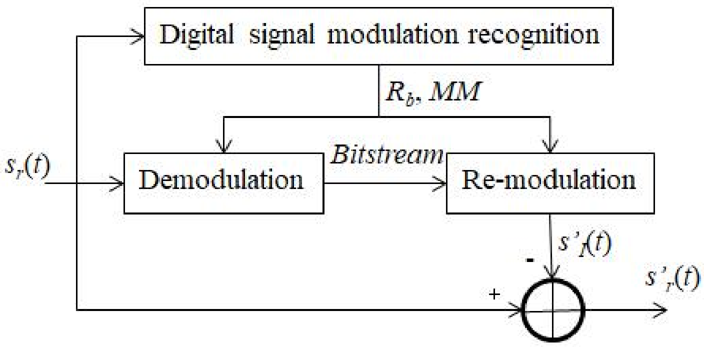

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Figure 5. The principle block diagram of co-channel interference cancellation.

3. The structure and working flow of the system

The structure of the newly designed unknown radiation source positioning system is shown in figure 6, mainly including signals pre-processing, interference signal cancellation, TDOA/FDOA parameter estimation, comprehensive positioning processing, positioning result display, time synchronization and other modules.

a) Signals pre-processing module

Implement the function of RF signals receiving from satellite antenna, recording, and frequency switching, analyzing the receiving signal quality and channel occupying situation of neighboring satellites, and deciding whether to make a co-channel interference cancellation processing.

b) Interference signal cancellation module

If there exists regular communication signal which interferes radiation source signal receiving, using co-channel interference cancellation method to complete cancellation.

c) TDOA/FDOA parameter estimation module

Making parameter estimation of TDOA, FDOA, and Doppler frequency of receiving signals.

d) Comprehensive positioning processing module

Selecting one of three-satellites positioning, dual-satellites positioning, and single-satellite positioning mode, inputting estimated parameters, executing positioning algorithm, outputting positioning results.

e) Time synchronization module

providing high-precision unified time base standards for the positioning system, ensuring the accuracy of TDOA/FDOA parameters estimation.

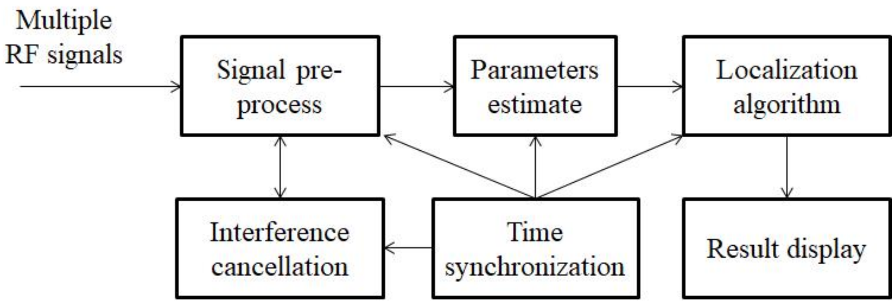

Figure 6. The structure of radiation source positioning system.

The working flow of the system is shown in figure 7. Automatically judging the number of available satellites for positioning based on satellite database, prioritizing three-satellites TDOA positioning mode, secondly adopting dual-satellites TDOA/FDOA positioning or single-satellite Doppler positioning mode.

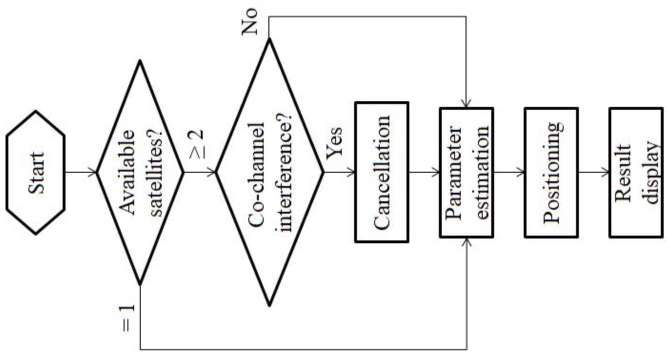

Figure 7. The working flow of radiation source positioning system.

4. Analysis of positioning accuracy

The positioning accuracy of the proposed radiation source positioning system is verified by simulation. Setting satellite ground stations in an east China province, receiving radiation source signals forwarded by satellites. Randomly set a radiation source 1000 kilometers away from the coast of Chinese mainland, between 20° and 80° north latitude. Assuming estimation error of TDOA parameters is 1 μs. Using Geometric Dilution of Precision

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(GDOP) to measure positioning error.

$$GDOP = \sqrt{\sigma_X^2 + \sigma_Y^2 + \sigma_Z^2} \quad (14)$$

In the formula (14), σ represents root mean square (RMS) error of measured values.

The simulation measuring results of positioning error of the proposed radiation source positioning system under different conditions as whether a reference station set up, distance between satellites, and ephemeris errors, is shown in table 1. Figure 8-10 shows GDOP images of positioning error under different conditions.

Table 1. Positioning error under different conditions.

Ephemeris errors (km)	Reference station	Distance between satellites	Positioning error (km)
1	Set	Far (＞15°)	10
20	Set	Far (＞15°)	10
1	Set	Near (＜15°)	20
20	Set	Near (＜15°)	20
1	Not set	Far (＞15°)	50
20	Not set	Far (＞15°)	80
1	Not set	Near (＜15°)	100
20	Not set	Near (＜15°)	＞200

It can be seen obviously from the simulation results.

a) Reference station has the biggest inference on positioning accuracy. Under the condition of having a reference station correction, no matter ephemeris errors or distance between satellites, the positioning accuracy can reach a range 10-20 km. As a comparison it can only reach 50 km without reference station correction. Alas, after multiple simulations, the closer the reference station is to the radiation source, the more accurate the correcting result is, in general a good correction effect can be achieved when the distance between the two is less than 500 km.

b) Far satellites distance (>15°) can improve positioning accuracy to about half of smaller satellites distance (<15°). Under the condition of no reference station, far satellites distance can obviously improve positioning accuracy. However, it should be noted that impractical applications, neighboring satellite too far from main satellite receives very weak radiation source signals, making signal detection much harder, and causing a result of reduction of TDOA parameters estimation.

c) Higher ephemeris accuracy, the more accurate TDOA parameters estimation will be realized theoretically, improving positioning accuracy. Results of simulation shows when a reference station is set, ephemeris errors can be compensated by reference station correction, causing little inference to positioning accuracy. When no reference station set, high ephemeris accuracy can significantly improve system positioning accuracy.

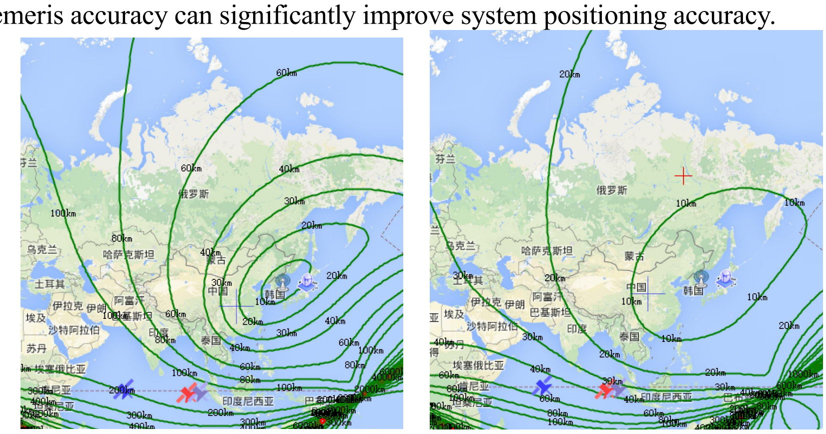

Figure 8. GDOP images of positioning error under the condition of setting a conference station, far satellites distance (left: ephemeris error 1 km, right: ephemeris error 20 km)

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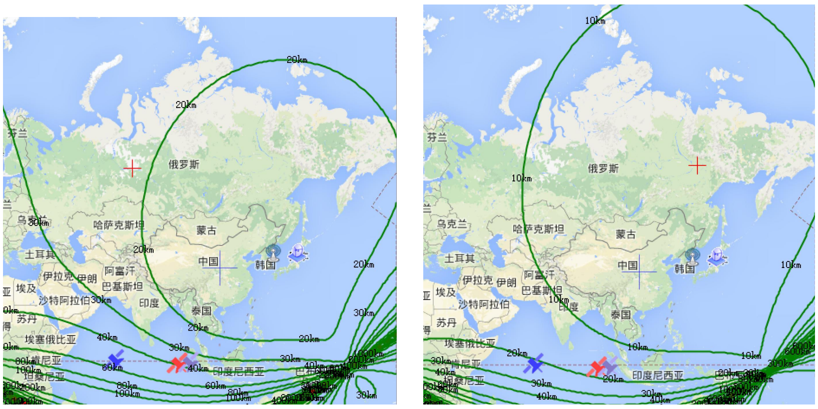

Figure 9. GDOP images of positioning error under the condition of setting a conference station, near satellites distance (left: ephemeris error 1 km, right: ephemeris error 20 km)

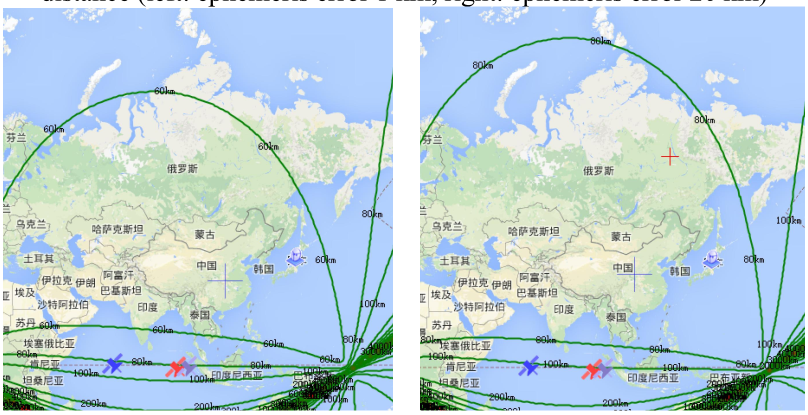

Figure 10. GDOP images of positioning error under the condition of setting no conference station, far satellites distance (left: ephemeris error 1 km, right: ephemeris error 20 km)

5. Real signals positioning

Carrying out positioning processing of satellite communication radiation sources, Implementing data acquisition, co-channel interference cancellation, parameter estimation, positioning processing, error analysis, and other functions of SCPC (Single Channel Per Carrier) communication signals, achieving the goal of satellite communication radiation source target monitoring and positioning, obtaining its trajectory information and analyzing its activity patterns.

On June 3rd 2022, the trajectory of a certain aircraft operating in the East China Sea was obtained through the proposed GEO satellites TDOA positioning system, with a positioning accuracy of better than 10 km.

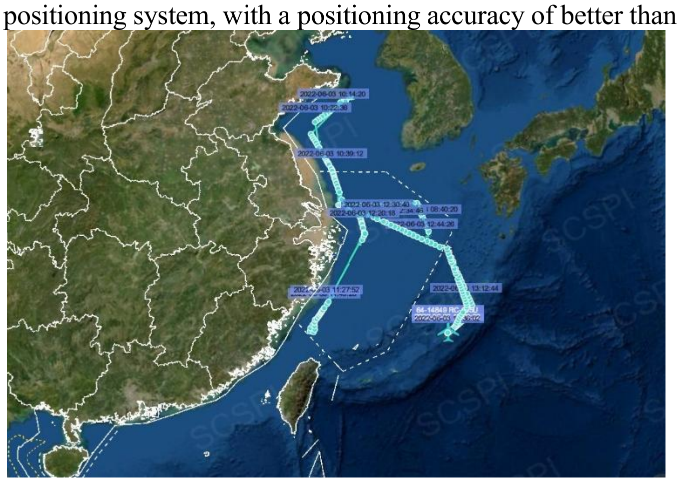

Figure 11. Schematic diagram of a real aircraft's positioning trajectory by TDOA/FDOA measurements

6. Conclusion

A multi-mode integrated passive satellite positioning system based on existing GEO communication satellite is

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proposed in this paper. The system has the ability to automatically choose one of three-satellites TDOA, dual-satellites TDOA/FDOA or single-satellite Doppler modes to position unknown radiation source according to the number of available GEO satellites. Simulation results show that, the positioning system can effectively locate unknown radiation sources on earth's surface within a range of 1000 kilometers, its positioning accuracy can reach 10 kilometers. The positioning accuracy can be improved from 50 km to 10-20 km with a reference station correction, far satellites distance (>15°) can improve the positioning accuracy to about a half of smaller satellites distance (<15°), the positioning accuracy can be obviously improved by higher ephemeris accuracy when there is no reference station correction.

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