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A Cooperative Algorithm Implementation Improvement MLAT Localization Accuracy

Lin LIN
Civil Aviation Flight University of China , Guanghan City ,Sichuan Province, 618307,China.

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Abstract

MLAT is a proven technology that has been in use for many decades, with high accuracy and update rate, cost-effective of operation and maintenance, anti-fraud and other characteristics by using a method known as Time Difference of Arrival (TDOA). In order to improve positioning accuracy, a high-precision iterative algorithm for initial values of constraints is proposed in this paper, it uses the Chan algorithm to obtain the estimated position of the target and uses this value as the initial guesses of the Taylor algorithm. Both simulation and operation results show that the cooperative algorithm can significantly improve the positioning accuracy of TDOA.

Keywords: *TDOA, MLAT, Chan Algorithm, Tyler Algorithm*

1.INTRODUCTION

Multilateration (MLAT) is a recommended surface surveillance technology that accurately locate aircraft with Mode A/C/S transponder and vehicles with ADS-B(Automatic Dependent Surveillance-Broadcast) transponder in real time by ICAO. MLAT can make full use of the existing airborne transponder without extra modification, its hardware cost is low, and it can meet the requirements of the "cheap and fine" than radar. It is widely used in airport surface, terminal， en route , ADS-B performance verification and other fields.

Like SSR, MLAT is considered to be a co-operative surveillance technique, combining a dependence on target-derived data for identification and altitude with ground based calculation of position. MLAT can achieve a higher update rate than a typical rotating radar, determined by the intervals between aircraft transmissions.

MLAT is based on the measurement of the difference in distance between two stations at known locations by signals at known times. Unlike measurements of absolute distance or angle, measuring the difference in distance between the target and two stations is obtained by algorithm calculating the Time Difference of Arrival (TDOA) between the target signal arrival two stations.

When these possible locations are plotted, they form a hyperbolic curve in 2-Dimensional plane. To locate the exact location along that curve, MLAT relies on multiple measurements: a second measurement taken to a different pair of stations will produce a second curve, which intersects with the first. When the two curves are compared, a small number of possible locations are revealed, producing a "fix point".

In practice，the same situation in three-dimensional space, according to the hyperbolic solution principle, at least 4 stations are needed for the solution of the 3-Dimensional space.

Time Difference of Arrival (TDOA) estimation accuracy of the signal is one of the critical factors which determine target positioning accuracy of MLAT system.

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2.MLAT SYSTEM MODELING

MLAT employs a number of ground stations, which are placed in strategic locations around an airport, its local terminal area or a wider area that covers the larger surrounding airspace.

These stations listen for response, typically to interrogation signals transmitted from a local SSR or a MLAT station. Since individual aircraft will be at different distances from each of the ground stations, their replies will be received by each station at fractionally different times. Using advanced computer processing techniques and positioning algorithm, these individual time differences allow an aircraft's position to be precisely calculated.

The MLAT functional block diagram is shown in Figure 1.

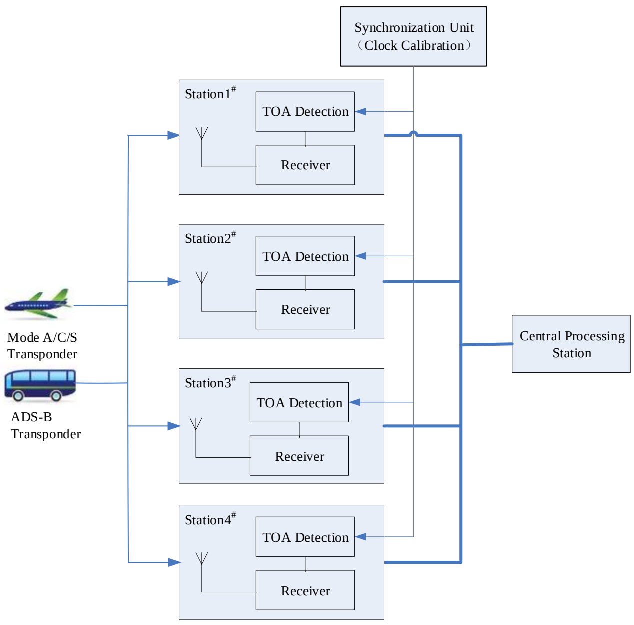

Figure 1.The Operation Principle of MLAT

MLAT requires no additional avionics equipment, as it uses replies from Mode A/C/S transponders, as well as military IFF and ADS-B transponders. Furthermore, while the radar and MLAT "targets" on a controller's screen are identical in appearance, the very high update rate of the MLAT-derived targets makes them instantly recognizable by their smooth movement across the screen. A screen displaying MLAT information can be set to update as fast as every second, compared with the 4–12 second position "jumps" of the radar-derived targets.

Common localization algorithms are implemented based on TOA, TDOA, and TSOA. TOA positioning requires strict clock synchronization between the moving target and all base stations, and the positioning error caused by clock error will be very large. While TDOA positioning converts TOA into TDOA on the premise of setting a reference base station, which overcomes the positioning deviation caused by TOA estimation error to some extent. Therefore, TDOA principle is widely used to realize the positioning function of MLAT system.

3.LOCALIZATION ALGORITHMS FOR TDOA

MLAT uses multiple ground stations to receive and locate the target transponder signals. On the basis of clock calibration for all ground stations by synchronous clock units, the server station calculates the TDOA (Time Difference of Arrival) of the signal transmitted by the location target received by each ground receiving station. Between two MLAT receiving station, the different runtime differences are represented as a group of hyperbolas. Each hyperbola in this group corresponds to exactly one measured runtime difference. This means that at this given runtime difference, the object to be measured may be somewhere on this hyperbola.

The block diagram of the working principle of TDOA is as shown in Fig. 2.

Because the distance is the product of the time and the rate of speed. The time difference is converted to the distance difference between the positioning target and the two selected ground stations, and thus the target is located on the hyperbola focusing on the selected ground station.

Further pairs of receivers also measure a difference in runtime and also get a dedicated hyperbola from their individual group of hyperbolas. The intersection of all

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these selected hyperbolas is the position you are looking for.

Introduction of TDOA, the mobile target, such as aircraft or vehicle, refer to as tag for short, which emits its own signal, and fixed ground receiving station, referred to as anchor, receives Radio-Frequency signal from tag.

According to this hyperbolic positioning method, the location of the tag can be calculated under the condition of selecting a number of anchors.

TDOA location algorithms in MLAT includes WLS (Weighted Least Square) algorithm, Chan algorithm, Taylor algorithm, Friedlander algorithm, SX and SI algorithm. Each algorithm has its limitations. Chan algorithm and Taylor Algorithm is discussed in this paper.

3.1 CHAN Algorithm

Chan algorithm is a positioning algorithm with analytic expression solution, which solves the position coordinates of tag based on the least square method (LS) or weighted least square method (WLS). This algorithm uses non-recursive method to solve hyperbolic equations. The basic idea of Chan algorithm is as follows: firstly, an intermediate variable is used to transform the nonlinear equation into a linear equation. Then according to the position coordinates obtained by rough estimation and other constraints, the weighted least square method is used for the second time to accurately estimate the position coordinates of the mobile target, and the final coordinates can be obtained.

CHAN algorithm is a localization method based on the intersection of hyperbolas, which is applicable to both small range and large range positioning systems.

When the estimation error of TDOA is small, it can be considered as an approximate method of ML (Maximum Likelihood method).

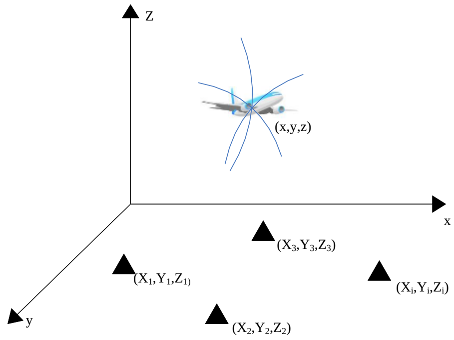

Figure 2. Hyperbolas Positioning Scheme

This algorithm can be discussed in scenarios shown in Figure 2. Assume that there are N anchors and 1 tag, then the signal received by anchor $i^{\#}$ is:

$$u_i(k) = s(k - d_i) + \eta_i(k) \qquad i = 1, 2, ..., N \quad (1)$$

In Eq.(1), Where $s(k)$ represents the signal emitted from the tag, d_i represents the time delay, and $\eta_i(i)$ represents the additive noise. It is assumed that the signal and noise are mutually independent and the noise is zero-mean value gaussian noise.

In order to achieve the purpose of positioning, the TDOA should be estimated first, and then the distance difference between each anchor and the tag should be calculated.

The relative distance between the tag and the anchor $i^{\#}$ is simply given as:

$$R_i = \sqrt{(X_i - x)^2 + (Y_i - y)^2 + (Z_i - z)^2} \qquad (2)$$

In Eq. (2), where (X_i , Y_i , Z_i) i =1,2,3… is the coordinates of the anchor $i^{\#}$, (x , y , z) are the coordinates of the tag.

Distance difference between tag and anchor $i^{\#}$ and $j^{\#}$ is

$$d_{i,j} = d_{i,1} - d_{j,1} \qquad i, j = 1, 2, ..., N \qquad (3)$$

According to the TDOA principle, the difference distance value ($R_{i,1}$)between the between the target aircraft and the station i$^{\#}$ (R_i) and the distance between the target aircraft and the station 1$^{\#}$ (R_1)is:

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$$R_{i,1} = R_i - R_1$$
$$= \sqrt{(X_i - x)^2 + (Y_i - y)^2 + (Z_i - z)^2} - \sqrt{(X_1 - x)^2 + (Y_1 - y)^2 + (Z_1 - z)^2}$$
$$= c \bullet d_{i,1} \tag{4}$$

In Eq.(4),where (X_1, Y_1, Z_1) are the coordinates of the anchor 1#，c is the velocity of light(300000 km/s,) $d_{i,1}$ is the runtime difference between the signal sent by the tag and anchor 1# and anchor i #,usually defined as TDOA of the response, then

$$\begin{aligned} R_i^{\ 2} &= (R_{i,1} + R_1)^2 \\ &= R_{i,1}^{\ 2} + 2R_{i,1}R_1 + R_1^{\ 2} \qquad (5) \\ &= K_i - 2X_i x - 2Y_i y - 2Z_i z + x^2 + y^2 + z^2 \end{aligned}$$

$$R_1^{\ 2} == K_1 - 2X_1 x - 2Y_1 y - 2Z_1 z + x^2 + y^2 + z \tag{6}$$

Where $K_i = X_i^{\ 2} + Y_i^2 + Z_i^{\ 2}$

With Eq. (5)-Eq. (6), finally we get

$$R_{i,1}^{\ \ 2} + 2R_{i,1}R_1 = K_i - 2X_{i,1}x - 2Y_{i,1}y - 2Z_{i,1}z - K_1 \tag{7}$$

Where $X_{i,1} = X_i - X_1, Y_{i,1} = Y_i - Y_1, Z_{i,1} = Z_i - Z_1$

From the Eq.(2) to Eq.(5),the four anchors coordinates are given, equations can be listed and solved, then the coordinates of the tag(x, y, z) can be obtained.

3.2 Taylor Algorithm

Taylor series expansion is a recursive algorithm. The basic idea of the algorithm is as follows: firstly, an initial estimate of the position of the mobile target is required, and then the Taylor series expansion is carried out at that position. The nonlinear equation can be converted into a linear equation by ignoring the quadratic and above terms. Then, the least square method is used for estimation. Each recursive result is used to correct the position of the mobile target, so as to improve the accuracy of estimation and finally make the estimated position close to the real position of the mobile target. Unlike Chan, Taylor series expansion has no expression.

For a set of TDOA measurement values, the first step is to expand Eq. (4) by Taylor series at the initial position of the selected mobile tag(x_0, y_0, z_0), then Eq. (4) can be transformed into:

$$\Psi \approx h - G\delta \tag{8}$$

Where $\delta = \begin{bmatrix} \square x \\ \square y \\ \square z \end{bmatrix}$, $\Psi = \begin{bmatrix} e_1 \\ e_2 \\ e_3 \end{bmatrix}$, $h = \begin{bmatrix} ct_{10} - (\hat{r}_1 - \hat{r}_0) \\ ct_{20} - (\hat{r}_2 - \hat{r}_0) \\ ct_{30} - (\hat{r}_3 - \hat{r}_0) \end{bmatrix}$,

$\hat{r}_i (i = 0,1,2,3)$;

δ represents the error of position estimation, Ψ represents TDOA measuring error, h represents the difference between the true value of the distance difference and the measured value, $\hat{r}_i$ represents the distance between the estimated tag initial value position and each anchor.

$$G = \begin{bmatrix} \frac{\partial \square r_1}{\partial x}\Big|_{(\hat{x},\hat{y},\hat{z})} & \frac{\partial \square r_1}{\partial y}\Big|_{(\hat{x},\hat{y},\hat{z})} & \frac{\partial \square r_1}{\partial z}\Big|_{(\hat{x},\hat{y},\hat{z})} \\ \frac{\partial \square r_2}{\partial x}\Big|_{(\hat{x},\hat{y},\hat{z})} & \frac{\partial \square r_2}{\partial y}\Big|_{(\hat{x},\hat{y},\hat{z})} & \frac{\partial \square r_2}{\partial y}\Big|_{(\hat{x},\hat{y},\hat{z})} \\ \frac{\partial \square r_3}{\partial x}\Big|_{(\hat{x},\hat{y},\hat{z})} & \frac{\partial \square r_3}{\partial z}\Big|_{(\hat{x},\hat{y},\hat{z})} & \frac{\partial \square r_1}{\partial z}\Big|_{(\hat{x},\hat{y},\hat{z})} \end{bmatrix} = \begin{bmatrix} \frac{x_0 - \hat{x}}{\hat{r}_0} - \frac{x_1 - \hat{x}}{\hat{r}_1} - \frac{y_0 - \hat{y}}{\hat{r}_0} - \frac{y_1 - \hat{y}}{\hat{r}_1} - \frac{z_0 - \hat{z}}{\hat{r}_0} - \frac{z_1 - \hat{z}}{\hat{r}_1} \\ \frac{x_0 - \hat{x}}{\hat{r}_0} - \frac{x_2 - \hat{x}}{\hat{r}_1} - \frac{y_0 - \hat{y}}{\hat{r}_0} - \frac{y_2 - \hat{y}}{\hat{r}_1} - \frac{z_0 - \hat{z}}{\hat{r}_0} - \frac{z_2 - \hat{z}}{\hat{r}_1} \\ \frac{x_0 - \hat{x}}{\hat{r}_0} - \frac{x_3 - \hat{x}}{\hat{r}_1} - \frac{y_0 - \hat{y}}{\hat{r}_0} - \frac{y_3 - \hat{y}}{\hat{r}_1} - \frac{z_0 - \hat{z}}{\hat{r}_0} - \frac{z_3 - \hat{z}}{\hat{r}_1} \end{bmatrix}$$

Eq (8) is solved by WLS method to obtain the deviation of position coordinates:

$$\delta = \begin{bmatrix} \square x \\ \square y \\ \square z \end{bmatrix} = (G_t^T Q^{-1} G_t)^{-1} G_t^{-1} Q^{-1} h_t$$

where Q is the covariance matrix of the measurement value.

The $X^1 = X_0 + \Delta X$, $Y^1 = Y_0 + \Delta Y$, $Z^1 = Z_0 + \Delta Z$ as the initial value of the next iteration, repeated iteration, until ΔX , ΔY , ΔZ are small enough, can meet the threshold set by ε , in which $|\Delta X| + |\Delta Y| + |\Delta Z| \le \varepsilon$, after then the output estimate can get the tag coordinates.

Taylor series expansion algorithm can get more accurate results, with high precision, strong stability; However, the algorithm needs an initial estimated position close to the actual position to ensure the convergence of the algorithm.

4.COOPERATIVE ALGORITHM FOR MLAT

The key factor in choosing a TDOA algorithm for MLAT system is the accuracy. The accuracy of the algorithm refers to the proximity of the estimated position to the true position obtained by the algorithm. The closer the estimated position is to the true position, the more accurate the algorithm and the higher the positioning performance.

Taylor series expansion algorithm solves the nonlinear equation in algebra by iterative method. Based on studies of input and output data, a predictive control method of nonlinear model is presented with the linear part of Taylor series expansion of nonlinear system used as predictive model. This method must have an initial guess value and improve the estimation position by solving the local linear Least-squares Solution of the measurement error.

The disadvantage of Taylor algorithm is that it requires initial guesses and does not guarantee the convergence and computational complexity of the algorithm.

Chan algorithm is an optimal output-sensitive algorithm to compute the convex hull of a set of points, in 2- or 3-dimensional space. It is a better non-recursive algorithm for solving hyperbolic equations. This method uses the two-step maximum likelihood estimation to obtain the target position by transforming the TDOA equation into another set of linear equations. The algorithm is characterized by a small amount of calculation and high positioning accuracy in the environment where the noise obeys a Gaussian distribution.

The disadvantage of Chan algorithm is that the positioning accuracy will be significantly reduced in the case of a poor channel environment.

Therefore, a cooperative localization method based on Chan algorithm and Taylor algorithm is proposed. The implementation flow of this method is shown in Fig. 3. Firstly, Chan algorithm is used to locate the measured value of TDOA, and the calculated result is taken as the initial value of Taylor series expansion algorithm. Then, the Taylor series expansion algorithm is used to locate the tag again. In order to avoid the divergence of the positioning results of Taylor algorithm in a few cases, this method proposes to calculate the weighted coefficient based on the positioning results of Chan and Taylor series expansion algorithm, and finally get the final location estimate for tag by processing the position estimates of the two positioning methods based on the weighted coefficient.

In engineering practice, the implementation of the algorithm is required to be as simple as possible and the operation time is short to meet the high refresh rate of the tag surveillance.

In order to overcome the defects of the above two algorithms and maximize the advantage of them, a high-precision iterative algorithm for initial values of constraints is proposed, it uses the Chan algorithm to obtain the estimated position of the target(x_0 , y_0 , z_0) ,and uses this value as the initial guesses value of the Taylor algorithm, and the new algorithm flow is shown in Figure 3.

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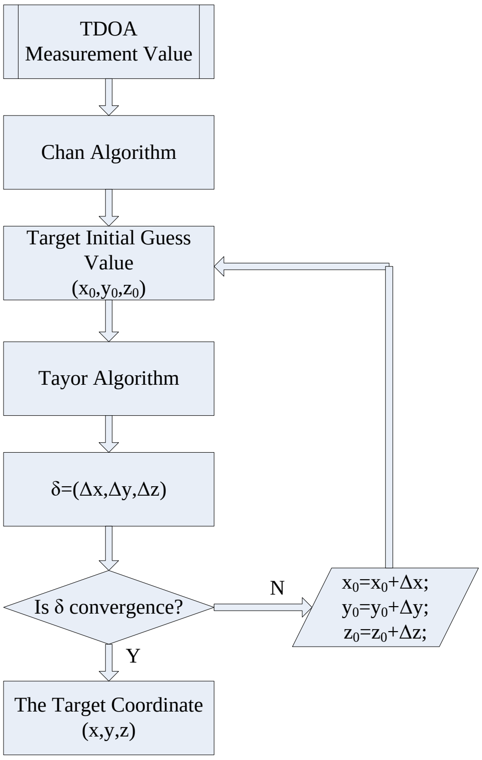

Figure 3. The Cooperative Algorithm Flow

It is proved that the Chan algorithm can provide a higher accuracy initial solution at the general signal-to-noise ratio level. This cooperative algorithm combines the advantages of the two algorithms and overcomes the traditional limitation of the iterative method without initial guess value. This new Cooperative algorithm is called a constrained initial value high precision iterative location algorithm.

5.SIMULATION IMPLEMENTATION

In order to correctly analyze the performance of each location algorithm, indicators are needed to evaluate the accuracy of the algorithm. The commonly used indicators are: Mean Square Error (MSE), Root Mean Square Error (RMSE), and Geometric Dilution Of Precision (GDOP). In this TDOA location algorithm simulation analysis, RMSE is used as an evaluation index of the algorithm.

RMSE is defined as follows Eq.(6),

$$RMSE = \sqrt{(x-\hat{x})^2 + (y-\hat{y})^2 + (z-\hat{z})^2} \quad (9)$$

(x, y, z) are the actual coordinates of target, $(\hat{x}, \hat{y}, \hat{z})$ represents the estimation coordinates obtained by the algorithm.

A large transport airport surface is selected as the simulation environment. Taylor algorithm, Chan algorithm and Cooperative algorithm are used for the initial guess value of the target aircraft respectively, and a comparative simulation is made under the conditions of different stations and different TDOA measurement errors. TDOA's measurement error obeys the ideal Gaussian distribution with a mean of 0 and standard deviations of 10m, 20m, 30m, 40m, and 50m, respectively.

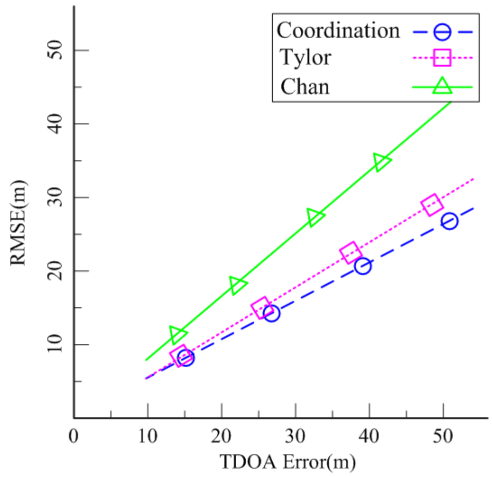

Figure 4. Simulation Results in 7 Stations

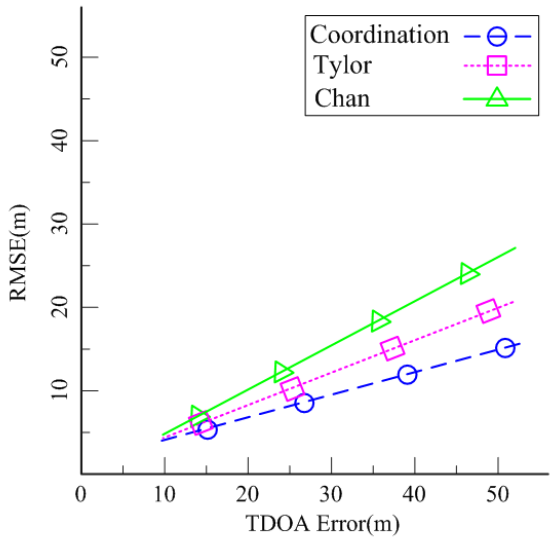

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Figure 5. Simulation Results in 11 Station3

By a large number of such receivers on the airfield measuring errors can be statistically suppressed. Measuring errors occur especially when strong noise or active interference falsify the measurement of the leading edge of the received signal. Furthermore, multiple reflections can affect the measurement of the runtime. The probability of such measurement errors decreases with the reduction of the distance to be measured. Therefore only measurement results from the near range are used for the location determination.

From the simulation results, we can see that each classic TDOA algorithm has its own unique advantages, but it also has some limitations. The high precision iterative target location optimization algorithm and the increase of the number of stations can greatly improve the location accuracy, but from the perspective of cost performance, optimization Cooperative algorithm is more worthy of adoption to improve the location precision of TDOA.

6.ACTUAL OPERATION

This cooperative algorithm is also applied to the location solution of MLAT systemin an airport. The MLAT system with cooperative algorithm is built in an airport and put into actual operation. The actual operation is shown in the following figure.

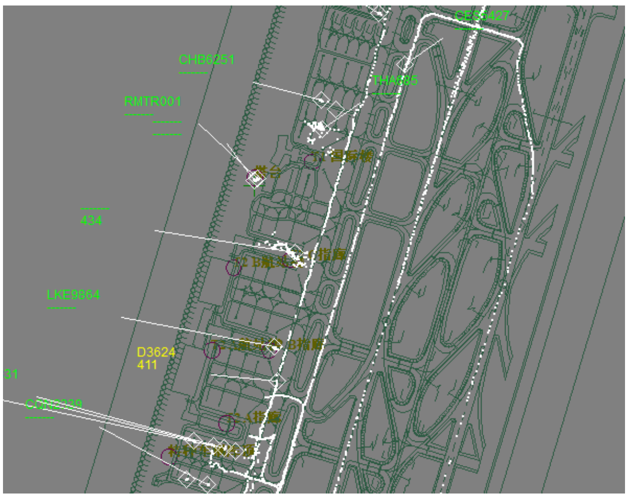

Figure 6. The Actual Operation Picture

According to the position relation between the electronic map of the airport surface and the actual mobile targets, such as aircraft and vehicle, that all moving targets run along the preset trajectory in the map, with the accuracy less than 3 meter compared with the actual situation.

So it can be determined that the cooperative algorithm can improve the positioning accuracy of MLAT to some extent.

7.CONCLUSION

In this article, we present a modified location algorithm which is based on Chan and Taylor. Firstly, this algorithm uses Chan algorithm to estimate the location of mobile station, then the obtained results are optimized by eliminating the contained location results which deviated excessively, the obtained optimized results are acted as the initial value used in Taylor series expansion method to conduct another location operation, finally, the obtained location results using these two algorithms are weighted summed, and the ultimate result is the location coordinate of mobile station. The experiment indicates that in the noise environment, the performance of the proposed algorithm in the article is better than Chan algorithm, which could effectively improve the location precision.

The improved MLAT localization algorithms are designed and tested in both simulation software and realist environment scenario. The test results show that these simple-to-implement and low-computational-load algorithms produce very competitive results, in particular if used as a first step to produce an initial guess for an iterative algorithm in case of MLAT scenario, it can greatly improve positioning accuracy and efficiency in MLAT system .

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