Improving the Reliability of the Information and Measurement System of Aviation Surveillance

A V Eliseev 1

1Department of Radioelectronics, Don State Technical University (DSTU), Rostov-na-Donu, Russia

E-mail: eliseev_av65@mail.ru

Abstract. It is shown that various sensors are used to ensure air traffic control in civil aviation, namely: primary and secondary radars, multilateration surveillance systems, automatic dependent surveillance systems of broadcast and contract types, multistatic radars. Based on the analysis of the main disadvantages of the considered systems, it was concluded that the use of multilateration aircraft surveillance systems (MLAT) is promising. The need to improve the reliability of MLAT is noted. The work proposes a method of structural and informational redundancy of MLAT based on the introduction of an additional receiver into its design. It allows to measure the distance to the aircraft using the energy method. The analysis of increasing the reliability of MLAT at various redundancy rates is carried out.

1. Introduction

To solve the problems of air traffic control in civil aviation, an aircraft surveillance system has been created, which includes primary and secondary radars, multi-position surveillance systems, automatic dependent surveillance systems of broadcast (ADS-B) and contract (ADS-C) types, multistatic radars (MSPSR) [1]. Each of these systems has its own disadvantages: primary radars are characterized by a relatively short range, secondary radars require aircraft to be equipped with transponder equipment, the ADS equipment data are not protected against spoofing [2, 3], MSPSR systems have a limited coverage area which is determined, for example, by the presence of a digital television transmitter of the DVB-T2 standard within the line of sight [4, 5]. Taking this into account, at present time one of the promising directions for improving the aircraft surveillance system is the introduction of multilateration surveillance systems (MLAT) into the system design [1, 6-10]. The principle of operation of such systems is based on the use of the differential-range-finding method for determining the position of an aircraft. It is known that the number of aircraft spatial coordinates determined using MLAT depends on the number of receiving positions. So to determine the spatial position of the aircraft, the minimal required number of receiving positions should be equal to four. Given the significant spatial separation of the receiving positions relative to the processing center, there is a relatively high probability of disruption of one of the communication lines, which will lead to the impossibility to determine all three aircraft coordinates. To prevent such a situation, it is necessary simultaneously to provide redundancy for communication lines, which is not always either physically possible or economically reasonable, and to add possibility to solve the aircraft surveillance problem using MLAT in abnormal situations caused by ground equipment failure [10].

Thus, it is necessary to develop a method for MLAT redundancy, which makes it possible to
increase the probability to solve the problem of aircraft surveillance in the case when information is not received from one of the receiving points, due to the failure of the receiving device or due to the failure of the communication line between the receiving position and the information processing center.

The aim of the work is to improve the reliability of solving the problem of aircraft surveillance based on structural and informational redundancy.

The problem being solved is the development of a method for structural and informational redundancy in a multilateration aircraft surveillance system.

2. Formulation of the problem

We will assume that the MLAT system is used to solve the problem of determining the coordinates of the aircraft (Figure 1), which includes $N_{RS}$ receiving points $\{RS_i, i = 1, N_{RS}\}$, with known location coordinates $X_i = [x_i, y_i, z_i]^T$, $i = 1, N_{RS}$, having non-directional antenna devices, and a computing center (CC) with known coordinates $X_{CC} = [x_{CC}, y_{CC}, z_{CC}]^T$, intended to process the measurements. Each receiving point is connected by a high-speed data link to the computing center. In this case, both fiber-optic communication lines and radio communication lines can be used as communication lines. It is assumed that all receiving points operate on a single time scale, and the times of the signal passing through the data transmission lines from each receiving point to the computing point $\{\tau_{i,CC}, i = 1, N_{RS}\}$ are known [1]. To synchronize the receiving points, as a rule, signals from a satellite navigation system are used.

Let us consider the MLAT operation. If a radio emission source, by which we mean a radio-emitting aircraft $Trg_k, k \in 1, M_{Trg}$, is detected, a signal $S_{i,k}, i = 1, N_{RS}, k \in 1, M_{Trg}$ is received at each receiving position $RS_i, i = 1, N_{RS}$, where $M_{Trg}$ is the number of aircraft located in the MLAT working area.

![Figure 1. Geometric formulation of the problem.](image-url)
The signals $S_{i,k}$ are transmitted via data transmission lines to the computing center $(CC)$, where the time of their reception at the corresponding receiving point $\left(\tau_{i,k}, i = 1, N_{RS}\right)$ is determined in a single time scale. Further, to implement the difference-ranging method, the difference between the times of signal reception from the $k$ - th airborne object at the $i$ - th receiving point $\left(\tau_{i,k}, i = 2, N_{RS}\right)$ and the receiving point taken as a reference, for example, at the first receiving point $\left(\tau_{1,k}\right)$, is calculated: $\Delta\tau_{i,1,k} = \tau_{i,k} - \tau_{1,k}$. The time differences $\Delta\tau_{i,1,k}$, $i = 2, N_{RS}$ correspond to the difference in the distances, passing by the signal from the radio-emitting aircraft to each receiving point:

$$\Delta\tau_{i,1,k} = c\Delta\tau_{i,1,k} = R_{i,k} - R_{i,1,k}, \quad i = 2, N_{RS},$$

where $c$ is the speed of propagation of an electromagnetic wave; $R_{i,k}$ is the distance between the $k$ - th radio-emitting aircraft with coordinates $X_{rg,k} = \left[x_{i,k}, y_{i,k}, z_{i,k}\right]^T$ and the receiving point $R_{S,i}, i \in 1, N_{RS}$:

$$R_{i,k} = \sqrt{\left(x_i - x_{i,k}\right)^2 + \left(y_i - y_{i,k}\right)^2 + \left(z_i - z_{i,k}\right)^2}.$$  

Thus, the vector of measurements of the difference-ranging MLAT contains many measurements of the differences in ranges:

$$Z_k\left(t_j\right) = \left[\Delta r_{2,1,k}, \Delta r_{3,1,k}, \ldots, \Delta r_{\left(N_{rs} - 1\right),1,k}, \Delta r_{N_{rs},1,k}\right]^T,$$

where $Z_k\left(t_j\right)$ is the measurement vector attributed on the basis of the primary identification procedure to the $k$ - th radio-emitting aircraft at times $t_j, j = 1, 2, 3, \ldots$.

It is required: to develop a method for structural and informational redundancy in a multi-position aircraft surveillance system.

### 3. Solution to the problem

As a method of redundancy, we will choose structural and informational redundancy, by which we mean both the simultaneous use of additional measurement information, and the introduction of additional equipment into the MPSN [10]. At the same time, the information redundancy consists in expanding the vector of primary parameters measured by the MPSN: in addition to the difference in the ranges from the aircraft to two adjacent receiving positions, it is proposed to measure the distance to the object at one of the receiving positions using the energy method [11-20]. Structural redundancy consists in the introduction into one of the receiving positions of a device that measures the power of the received signal, as well as special software that allows to calculate the distance to the object based on the several measurements of the power in time.

The implementation of the energy method for measuring range can be performed on the basis of two algorithms [18, 20]. Algorithm [18] assumes the measurement of the received signal power at three points in time at regular intervals. The last condition is mandatory, if it is not met, errors in the range measurement occur. Algorithm [20] assumes power measurements for two different points in time, which reduces the likelihood of an error due to inaccuracy in fixing the moment of measurement. However, this algorithm requires measuring the Doppler frequency of the received signal and determining the moment when it vanishes ($F_{D}\left(t_w\right) = F_{Dw} = 0$). Taking into account these facts, it is advisable to use both of these algorithms with the subsequent calculation of the resulting range estimate.

We will assume that the aircraft moves uniformly and rectilinearly at a fixed altitude, that is, the flight is performed in the horizontal plane [20].
The aircraft movement model is given in the form:

\[ X(t) = X_0 + Vt , \quad t \in [t_0, T] \]  

(4)

where \( X(t) = [x(t), y(t)]^T \) are the Cartesian coordinates of the aircraft, \( X_0 = [x(t_0), y(t_0)]^T \), \( V = [v_x, v_y]^T \) is the vector of the aircraft velocity, the elements of which are the a priori known aircraft velocities along the corresponding coordinates.

Based on our knowledge of \( V = [v_x, v_y]^T \) we can determine the value of the ground speed of the aircraft. \( V_{GS} = \sqrt{v_x^2 + v_y^2} \).

Taking into account (4), the trajectory of the aircraft will be a straight line shown in Figure 1. Then, by analogy with [18], the range at the time \( t_d \) can be found by the formula:

\[ R_d = \left[ 2P_hP_dR_{nh}^2(P_hP_h + P_hP_d - 2P_dP_d)^{-1} \right]^{1/2} \]  

(5)

where \( P_h, P_h, P_d \) are the values of the received signal power at the time \( t_n, t_h, t_d \), respectively, \( \Delta R_{nh} = V_{GS}\Delta t_{nh} = V_{GS}(t_h - t_n) \), \( \Delta R_{nd} = \Delta R_{dh} \).

The indicator of the range measurement accuracy based on (4) is the dispersion of the form [18]:

\[ \sigma_{R_d}^2 = 0.5R_d^2\varepsilon_P^2P_h^2\left( P_h^2 + 4P_n^2 - 2P_nP_h \right) \times \]  

\[ \left( P_nP_h + P_hP_d - 2P_dP_d \right)^{-2} + R_d^2\varepsilon_v^2 \]  

(6)

where \( \varepsilon_P^2 = \sigma_P^2P_n^2 = \sigma_P^2P_h^2 = \sigma_P^2P_d^2 \) is the relative error in power measurement; \( \varepsilon_v^2 = \sigma_v^2V_{GS}^2 \) is relative error in setting ground speed; \( \sigma_P^2, \sigma_v^2 \) are variances of measurements of power and speed, respectively.

Similarly to work [20], in the case when the Doppler frequency \( F_D(t_w) \) is measured at the receiving position, the range at a time \( t_d \) can be found based on the expression

\[ R_d = \Delta R_{wd}(1 - P_dP_w^{-1})^{-0.5} \]  

(7)

where \( P_w \) is the signal power value measured at the time when the Doppler frequency is zero, that is, the aircraft is at the minimum distance \( R_w \) from the receiving position (Figure 1); \( \Delta R_{wd} = V_{GS}\Delta t_{wd} \).

The range measurement error based on (7) can be found based on the expression [20]:

\[ \sigma_{R_d}^2 = \Delta_{dw}^2(1 - P_dP_w^{-1})^{-1}\sigma_{V_{GS,wd}}^2 + \]  

\[ +0.25\left( \Delta_{dw}V_{GS,wd} \right)^2(1 - P_dP_w^{-1})^{-1}P_w^{-2}\left( \sigma_{P_d}^2 + \sigma_{P_w}^2P_w^2\sigma_{V_w}^2 \right) \]  

(8)

where \( \Delta_{dw} = |t_d - t_w| \) is the time interval between the moments of measurements of the power \( P_w, P_d \).

Taking into account (5) - (8), we can form the final weighted estimate of the range at the time \( t_d \)

\[ \tilde{R}_d = \left( \sigma_{R_d}^2R_1 + \sigma_{R_d}^2R_2 \right)^{-1}\left( \sigma_{R_1}^2 + \sigma_{R_2}^2 \right)^{-1} \]  

(9)
where $R_{1d}, \sigma_{1d}^2$ are the estimates of the range and variance of the error found on the basis of (5) and (6), respectively; $R_{2d}, \sigma_{2d}^2$ are estimates of the range and variance of the error found on the basis of (7) and (8), respectively.

Further improvement of the measurement accuracy can be provided on the basis of statistical processing, for example, using filtering algorithms [21, 22].

Thus, as a result of the use of structural and informational redundancy to determine the coordinates of the aircraft, it is necessary to use the system of equations extended with respect to (1):

\[
\Delta r_{i,k} = \sqrt{(x_i - x_{i,k})^2 + (y_i - y_{i,k})^2 + (z_i - z_{i,k})^2 - \\
-\sqrt{(x_i - x_{i,k})^2 + (y_i - y_{i,k})^2 + (z_i - z_{i,k})^2 + \varepsilon_{i1}}, \quad i = 2, N_{RS}, \\
R_{i,k} = \sqrt{(x_i - x_{i,k})^2 + (y_i - y_{i,k})^2 + (z_i - z_{i,k})^2 + \varepsilon_{i}},
\]

(10)

where $\varepsilon_{i1}$ is the random error in measuring the difference in range, which is a white Gaussian noise (WGN) with zero mathematical expectation and known variance; $\varepsilon_{1}$ is a random error in measuring ranges, which is a WGN with zero mathematical expectation and known variance; $x_{i,k}, y_{i,k}, z_{i,k}$ are the coordinates of the $k$-th aircraft, $R_{i,k}$ is the distance from the first receiving position to the aircraft, found on the basis of (9).

Let the probability of failure-free operation $PFFO_{MLAT}$ be used as a reliability indicator of the MLAT. We now estimate how the reliability indicator will change when using structural information redundancy.

Let us consider two cases: MLAT without redundancy, consisting of four main receiving positions $N_{RS} = 4$; MLAT with redundancy, consisting of four main receiving positions $N_{RS} = 4$ and one reserve position $K = 1$, which implements the energy ranging method (9). We will assume that all receiving points are equally reliable and are characterized by the probability of failure-free operation $PFFO_{RS}$. Reliability structural diagrams for these cases are shown in Figures 2 and 3.

![Figure 2](image1.png)  \textbf{Figure 2.} Block diagram of MLAT reliability without redundancy.

![Figure 3](image2.png)  \textbf{Figure 3.} Block diagram of MLAT reliability with fractional redundancy $K = 1$. 


Based on these schemes, we write expressions for calculating the reliability of MLAT without redundancy and with redundancy, respectively:

\[ P_{\text{FFO}}_{\text{MLAT}} = \left( P_{\text{FFO}}_{\text{RS}} \right)^{N_{\text{RS}}}, \]  
\[ P_{\text{FFO}}_{\text{RMLAT}} = \sum_{i=0}^{K} C_{N_{\text{RS}}+K}^{i} \left( 1 - P_{\text{FFO}}_{\text{RS}} \right)^{i} P_{\text{FFO}}_{\text{RS}}^{x_{\text{RS}}^{i}+x_{\text{RS}}^{i-1}}. \]  

The results of calculating the reliability at various redundancy rates are shown in Figure 4. When calculating, it was assumed that \( P_{\text{FFO}}_{\text{RS}} = 0.95 \).

![Figure 4](image)

**Figure 4.** Dependence of the probability of failure-free operation on the number of redundant elements.

Figure 4 shows that the use of redundancy with a rate 4:1 increases the probability of failure-free operation of MLAT from the value \( P_{\text{FFO}}_{\text{MLAT}} = 0.815 \) in the absence of redundancy to the value \( P_{\text{FFO}}_{\text{RMLAT}} = 0.977 \) with the information-structural redundancy. The use of a redundancy with a rate 4:4 provides \( P_{\text{FFO}}_{\text{RMLAT}} = 0.999 \).

However, as follows from Figure 4, the use of redundancy with a rate higher 4:2 is impractical due to the low increase in reliability when each next reserve element is added to the MLAT.

4. **Conclusion**

The work proposes a method for increasing the reliability of MLAT on the basis of structural information redundancy, which differs from the known methods by using additional information about the distance to the aircraft, found on the basis of a weighted combination of the results of two energy algorithms with different accuracy. Application of the proposed method can significantly increase the reliability of MLAT when redundant with multiples 4:2.

5. **References**

[1] Doc 9924 Aeronautical Surveillance Manual (Montreal: ICAO)
[2] Kosyanchuk V V, Selvesyuk N I, Khammatov R R 2019 Overview of the main ways to improve the safety of the AZN-V system Scientific Herald of the Moscow State Technical University T 22 1 pp 40-50
[3] ICAO document A39-WP/2961 TE/125 26/8/16. Surveillance of remotely piloted aircraft and issues of cybersecurity URL: http://www
Advances in Bistatic Radar Ed. by N J Willis, H D Griffiths Raleigh: SciTech Publishing

Eliseev A V 2018 The Calculation of the Working Area of Bistatic Radar 2018 International Multi-Conference on Industrial Engineering and Modern Technologies (FarEastCon) (Vladivostok) pp 1-5 doi: 10.1109/FarEastCon.2018.8602719

Wen H, Li H, Wang Z, Hou X and He K 2019 Application of DDPG-based Collision Avoidance Algorithm in Air Traffic Control 2019 12th International Symposium on Computational Intelligence and Design (ISCID) pp 130-133 doi: 10.1109/ISCID.2019.00036

Lu Y, Wu H and Huang Z 2012 An improved optimization method based on fuzzy clustering in MLAT for A-SMGCS 2012 9th International Conference on Fuzzy Systems and Knowledge Discovery pp 424-428 doi: 10.1109/FSKD.2012.6234128

Chugunov A A, Kulikov R S, Pudlovskiy V B, Petukhov N I and Masalkova N V 2021 Modeling and Comparison of Trajectory Filtering Algorithms in MLAT Systems 2021 Systems of Signals Generating and Processing in the Field of on Board Communications pp 1-6 doi: 10.1109/IEECONF51389.2021.9416117

Eliseev A V 2020 Determining Working Area of Three-Position Passive Radar for Aircraft Surveillance 2020 International Multi-Conference on Industrial Engineering and Modern Technologies (FarEastCon) pp 1-6 doi: 10.1109/FarEastCon50210.2020.9271224

Cheng Y, Zhou Z, Li R, Li J, Wang J and Pei X 2020 Reliability Prediction and Safety Evaluation of ATC Automation System 2020 IEEE 2nd International Conference on Civil Aviation Safety and Information Technology ICCASIT pp 969-972 doi: 10.1109/ICCASIT50869.2020.9368710

Evdokimov Yu F, Medvedev V P 2003 Amplitude system for determining the location of radiation sources using the least squares method and research of its accuracy Telecommunications vol 11 pp 34-37

Ufaev V A, Afanasyev V I, Razinkov S P 2003 Estimation of the coordinates of the radio emission source based on measurements of the amplitude of the electromagnetic field Radiotekhnika vol. 10 pp 71-73

Bulychev Yu G, Mozol A A, Vernigora V N 2010 Operational method for determining the range when direction finding a target with partially known parameters Izv. universities. Aviation technology vol. 1 pp 24-26

Sytenky V D 2011 Passive location based on amplitude measurements Izv. universities. Radio Electronics vol 1 pp 69-75

Bulychev V Yu, Bulychev Yu G, Ivakina S S 2014 Passive location based on angular and power measurements of the direction finder system Izv. RAS. Theory and control systems vol. 1 pp 65-73

Melnikov Yu P, Popov S V 2008 Radio-technical intelligence Methods for assessing the effectiveness of location of radiation sources (Moscow: Radio Engineering) p 432

Bulychev Yu G, Bulychev V Yu, Ivakina S S, Nasenkov I G 2015 Amplitude-geonometric method of non-stationary passive location taking into account partially known parameters of target movement Avtometriya 15 vol. 3 pp 70-79

Bulychev Y G, Ivakina S S, Mozol A A, Nasenkov I G 2016 Analysis of the modification of the energy method of passive ranging Avtometriya 52 vol. 1 pp 37-44

Sturgess B N, Carey F T 1995 Trilateration The Surveying Handbook (N. Y.: Chapman & Hall) 12 pp 234-270

Eliseev A V 2020 Single-Position Method to Measure Range to Mobile Source of Radio Emission 2020 International Multi-Conference on Industrial Engineering and Modern Technologies (FarEastCon) pp 1-5 doi: 10.1109/FarEastCon50210.2020.9271579

Kondratyev V S, Kotov A F, Markov L N 1986 Multi-position radio engineering systems (Moscow: Radio and communications) p 264

Eliseev and Sokolova O 2019 Algorithm of linear discrete filtering with fuzzy modification of
structure" DTS-2019 IOP Conf. Series: Materials Science and Engineering 680 012036
doi:10.1088/1757-899X/680/1/012036