Algorithm for Processing Measurements of a Hybrid Aviation Surveillance System

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Abstract. It is shown that a significant disadvantage of the broadcast-type automatic dependent surveillance system (ADS-B) used to solve the problem of aviation surveillance is its vulnerability to spoofing attempts. To eliminate this disadvantage, it is currently proposed to use the monitoring of ADS-B data using multilateration aviation surveillance systems (MLAT). The work shows the necessity of MLAT modernization to ensure a reliable solution to the problem of aviation surveillance in the event of failure of one or more reception points. To do this, it is proposed to use hybrid methods for assessing the coordinates of an aircraft. It can reduce the number of minimum required receiving positions due to the structural and informational redundancy of the aviation surveillance system. Structures (scenarios) of hybrid multi-position aviation surveillance systems and algorithms for processing their measurements have been developed. The algorithms ensure an increase in the reliability of the formation of estimates of aircraft coordinates.

1. Introduction

It is known that ensuring the safety of civil aviation flights is based on strict following to a given flight level and route, that is, to maintain a given aircraft flight path. To do this, there is a navigation and flight complex on board the aircraft, and there is an aviation surveillance system on the ground designed to provide situational awareness for air traffic control officers. Primary radars (PSR) and secondary radars (SSR) [1] were the base sensors of the aeronautical surveillance system in the beginning. These radars have the following disadvantages: primary radars have a relatively short range, while secondary radars require the aircraft to be equipped with transponder equipment. In addition, PSR and SSR have high manufacturing and operating costs. For this reason, it is not economically reasonable to create a radar network to cover the entire earth’s surface. Expansion of the aviation surveillance zone is possible by using the automatic dependent surveillance systems of broadcast type (ADS-B) and contract type (ADS-C) [1, 2]. The principle of operation of ADS-B is based on the transmission of data about position (latitude and longitude), true altitude, speed, identification index, data quality and other information received from onboard navigation and information management systems from the aircraft to all interested parties. Position data, aircraft speed and associated data quality indicators are usually obtained from GNSS equipment. The aircraft altitude data is usually obtained from the encoder of the barometric altimeter. The advantages of ADS-B are simplicity of equipment and the possibility of creating a global aviation surveillance system based on relaying ADS-B signals through a satellite communication...
system. However, a significant drawback of the ADS-B system is that it does not provide regulated operations to check the reliability of data received by the ADS-B system receivers, which makes the system unprotected against spoofing attempts [2, 3]. To overcome this disadvantage, it is proposed to control the reliability of ADS-B data using multilateration surveillance systems (MLAT) [1, 4-10]. The principle of operation of such systems is based on the use of the differential-ranging method for determining the position of the aircraft, based on the measurement of the time difference of arrival (TDOA) of the radio signal from the aircraft to the receivers located at different points in space. To determine the 3D coordinates of the aircraft, it is necessary to have at least four receiving points synchronized in time and having communication lines with the processing center. These requirements increase the complexity and cost of the MLAT system and reduce its reliability [10].

Thus, it is necessary to modernize the MLAT to provide a reliable solution to the problem of aviation surveillance in the event of failure of one or more receiving points. To do this, it is proposed to use hybrid methods for assessing aircraft coordinates, which will reduce the number of minimum required receiving positions due to structural and informational redundancy of the aviation surveillance system. Particular cases of such a reservation based on the use of information about the range to the aircraft are considered in [11-20].

The aim of the work is to provide reliable control of the reliability of ADS-B data using multilateration aviation surveillance systems that are resistant to failures.

The problem to be solved is the development of structures (scenarios) of hybrid multi-position aviation surveillance systems and algorithms for processing their measurements, which increase the reliability of the formation of estimates of aircraft coordinates.

2. Formulation of the problem

Let us pose the problem for two scenarios: the first scenario: a multi-position surveillance system (MLAT) uses omnidirectional antennas; the second scenario: a two-position surveillance system uses one directional antenna and one omnidirectional antenna.

2.1. Formulation of the problem for the first scenario

Let the MLAT (Figure 1) includes \( N_{RS} - 1 \) stationary receiving points \( \{RS_i, i = 1, \ldots, N_{RS} - 1\} \) with known location coordinates \( X_i = [x_i, y_i, z_i]^T, i = 1, \ldots, N_{RS} - 1 \) and one mobile receiving point located on board an unmanned aerial vehicle (UAV), which coordinates change in time \( t_j, j = 1, 2, 3, \ldots \), \( X_{N_{RS}, j} = [x_{N_{RS}, j}, y_{N_{RS}, j}, z_{N_{RS}, j}]^T \). The MLAT also includes a computer center (CC) for processing measurements with known coordinates \( X_{CC} = [x_{CC}, y_{CC}, z_{CC}]^T \). The computer center can be combined with one of the receiving positions. For example, in Figure 1 it is combined with the first receiving position \( RS_1 \).

![Figure 1. MLAT structure for case \( N_{RS} = 4 \)](image-url)
We assume that at each receiving position $RS_i$, $i = 1, N_{RS}$ a signal $S_{j,k}$, $k = 1, M_{Trg}$ is received. The signal is emitted by the aircraft on-board equipment $Trg_k$, $k = 1, M_{Trg}$, where $M_{Trg}$ is the number of aircrafts located in the MLAT operating area. The signals $S_{j,k}$ are transmitted via data links to the computer center (CC) for the implementation of the difference-ranging method [1]:

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

(1)

where $c$ is the speed of propagation of an electromagnetic wave; $R_{j,k}$ is the distance between the $k$-th radio-emitting aircraft with coordinates $X_{0G,k} = [x_{i,k}, y_{i,k}, z_{i,k}]^T$ and the receiving point $RS_i, i = 1, N_{RS}$

$$R_{j,k} = \left((x_i - x_{i,k})^2 + (y_i - y_{i,k})^2 + (z_i - z_{i,k})^2 \right)^{1/2},$$

(2)

$\Delta t_{i,1,k} = \tau_{i,k} - \tau_{1,k}$ is the time difference of signal reception from the $k$-th air object at the $i$-th receiving point and the reference receiving point.

At the same time, in contrast to the classical MLAT system, an additional receiver is installed at the first point $RS_1$, which implements the energy method for measuring the range to the aircraft [20]:

$$R_j = \Delta R_{0j} \left(1 - P_j P_w^{-1} \right)^{a_j},$$

(3)

where $P_w$ is the value of the signal power 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); $\Delta R_{0j} = V_{GS} \Delta jw$, $V_{GS}$ is the ground speed of the aircraft, $\Delta jw = |j - t_w|$ is the time interval between the moments of power measurements $P_w, P_g$.

Thus, the measurement vector of the MLAT system will have the form:

$$Z_k (j) = Z_{k,j} = Y_{k,j} + N_{z,j},$$

(4)

where $Y_k (t_j) = Y_k (j) = [\Delta \theta_{2,1,k}, \Delta \theta_{3,1,k} \ldots, \Delta \theta_{N_{w,1,k}, 1, 1,k}, R_{0,1,k}]^T$ is vector of measurement noise, characterized by zero mathematical expectations and specified intensities, respectively:

$$M\{N_z (j)\} = 0, \ M\{N_z (j) N_z^T (l)\} = W_z (j) \delta (j - l).$$

It is required to solve the following measurement processing problem: to form the estimates of the motion parameters of the radio-emitting aircraft based on the measurement vector (4).

2.2. Problem statement for the second scenario the hybrid method for the aircraft positioning

Let the aviation surveillance system (Figure 2) include one stationary receiving point $RS_1$ with known location coordinates $X_1 = [x_1, y_1, z_1]^T$ and one mobile receiving point located on board the UAV, which coordinates change in time $t_j, j = 1, 2, 3, \ldots$, $X_{2,j} = [x_{2,j}, y_{2,j}, z_{2,j}]^T$. It is assumed that the movement model and coordinates of the mobile receiving point are known at each moment of time $t_j, j = 1, 2, 3, \ldots$.
Figure 2. The structure of a two-position goniometric-differential-ranging passive aviation surveillance system

Let the stationary receiving point be equipped with a measuring system with a directional antenna that measures the aircraft azimuth $\alpha_j$, $j = 1, 2, 3, \ldots$, the difference in distance $d_j = c\Delta t_j = r_i - r_o$ and range $R_j$ between the radio-emitting aircraft with coordinates $X_{tg,j} = [x_{tg,j}, y_{tg,j}, z_{tg,j}]^T$ and the receiving point $RS_l$ based on the energy method [20], implemented in the form (3).

Thus, the measurement vector of the hybrid aviation surveillance system has the form:

$$Z(t_j) = Z_j = Y_j + N_{z,j},$$

where $Z_j = [z_{j1}, z_{j2}, z_{j3}]^T$ is the vector of observations; $Y_j = [d_j, r_{ij}, \alpha_j]^T$ is the actual values of the observed parameters; $N_{z,j} = [n_{d,j}, n_{r,j}, n_{\alpha,j}]^T$ is the vector of measurement noise, characterized by zero mathematical expectations and specified intensities, respectively:

$$M(N_z(j)) = 0, \quad M\{N_z(j)N_z^T(k)\} = W_z(j)\delta(j - k).$$

It is required: to develop an algorithm for processing trajectory measurements for the two-position aviation surveillance system.

3. Solution to the problem

3.1. Solution to the problem for the first scenario

Further, we will assume that only one aircraft is observed, then the index $k$ can be omitted. Instead we will use below the index $j$ corresponding to the time of observation $t_j$.

As follows from (4), to estimate the aircraft coordinates, it is necessary to solve a system of nonlinear equations of the form (1), (2) taking into account the measurement noise:

$$\Delta r_{i,j} = \left(\left(x_i - x_{tg,j}\right)^2 + \left(y_i - y_{tg,j}\right)^2 + \left(z_i - z_{tg,j}\right)^2\right)^{1/2} -$$

$$\left(\left(x_i - x_{tg,j}\right)^2 + \left(y_i - y_{tg,j}\right)^2 + \left(z_i - z_{tg,j}\right)^2\right)^{1/2},$$

$$i = 2, N_{RS},$$

$$R_j = \left(\left(x_i - x_{tg,j}\right)^2 + \left(y_i - y_{tg,j}\right)^2 + \left(z_i - z_{tg,j}\right)^2\right)^{1/2}. $$

Taking into account the presence of random measurement errors in (4), we solve the system of nonlinear equations (6) using the iterative least squares method (LSM) [21, 22].

Let us write the system of nonlinear equations (6) in generalized form:
\( Z_j = \mathbf{F}(\mathbf{q}_j, \mathbf{Q}_j), \) \tag{7}

where \( Z_j = Z(t_j), \ t_j \in [0, T], \ j = 0, 1, 2 \ldots \) is a vector of measurements of the form (3); \( \mathbf{q}_j = [x_{j,i}, y_{j,i}, z_{j,i}]^T \) is the vector of the true coordinates of the aircraft at time \( t_j; \ \mathbf{Q}_i \) is the matrix of coordinates of the MLAT receiving positions of the form

\[
\mathbf{Q}(t_j) = \mathbf{Q}_i = \begin{bmatrix}
    x_{N_{i}} & y_{N_{i}} & z_{N_{i}} \\
    \vdots & \vdots & \vdots \\
    x_{N_{pi}} & y_{N_{pi}} & z_{N_{pi}}
\end{bmatrix},
\]

To solve equation (7), we apply the iterative LSM algorithm \([21, 22]\):

\[
\mathbf{q}_m(t_j) = \mathbf{q}_{m,m} = \mathbf{q}_{j,m-1} + \left( C_{j,m-1}^T \mathbf{P}_j C_{j,m-1} \right)^{-1} C_{j,m-1}^T \mathbf{P}_j \delta Z_{j,m-1},
\]

\[
\delta Z_{j,m} = Z_j - Z_{j,m-1}\left( \mathbf{q}_{j,m-1} \right)^T
\]

\[
\delta Z_{j,m} = \frac{\partial Z_{j,m-1}(\mathbf{q}_{j,m-1})}{\partial \mathbf{q}_{j,m-1}}.
\]

The elements of the vector \( \delta Z_{j,m} = \left[ \delta \mathbf{r}_{j,i,m-1}, i = \frac{2}{R_{NS}}, \delta \mathbf{r}_{f,j,m-1} \right]^T \) included in (8) are calculated as follows:

\[
\delta \mathbf{r}_{j,i,m-1} = \Delta \mathbf{r}_{j,i,m-1} - \Delta \mathbf{r}_{j,i,m-1}(\mathbf{q}_{j,m-1}), i = \frac{2}{R_{NS}},
\]

\[
\delta \mathbf{r}_{f,j,m-1} = \hat{R}_{j,1,m-1}(\mathbf{q}_{j,m-1}),
\]

Elements of the matrix (8) \( \mathbf{C}_{j,m-1} = \left[ \mathbf{e}_{i,j,m-1}, l = \frac{1}{N_{RS}} \right]^T \) can be determined as follows:

- for \( l = 1, N_{RS} - 1 \)

\[
\mathbf{e}_{i,j,m-1} = \begin{bmatrix}
    (\cos \alpha_{j,i,m-1} - \cos \alpha_{j,i,m-1}) \\
    (\cos \beta_{j,i,m-1} - \cos \beta_{j,i,m-1}) \\
    (\cos \psi_{j,i,m-1} - \cos \psi_{j,i,m-1})
\end{bmatrix},
\]

\[
\mathbf{e}_{i,j,m-1} = \begin{bmatrix}
    (\cos \alpha_{j,i,m-1} - \cos \alpha_{j,i,m-1}) \\
    (\cos \beta_{j,i,m-1} - \cos \beta_{j,i,m-1}) \\
    (\cos \psi_{j,i,m-1} - \cos \psi_{j,i,m-1})
\end{bmatrix},
\]

where \( i = l + 1; \)
point and the reference receiving point.

on the energy method [20].

dispersion of the error in measuring the distance between the first receiving point and the aircraft based on the MLAT, we use the expression for the correlation matrix of the errors of the least squares method:}

\[
\begin{bmatrix}
\sigma^2_{j,1} & \sigma^2_{j,1} & \cdots & \sigma^2_{j,1} & 0 \\
\vdots & \vdots & \ddots & \vdots & \vdots \\
\sigma^2_{j,1} & \sigma^2_{j,1} & \cdots & \sigma^2_{j,1} & 0 \\
0 & 0 & 0 & \cdots & \sigma^2_{j,EM}
\end{bmatrix}
\]

(13)

\(\sigma_{j,1}^2 = \sigma_{j,1}^2 + \sigma_{j,2}^2, \quad \sigma_{j,1}^2, \quad \sigma_{j,2}^2\) is the variance of the error in measuring the difference between the ranges \(\Delta r_{j,1}\) and the range \(R_{j,i}\) at a time \(t_j\) based on the measurement of the signal delay; \(\sigma_{j,EM}^2\) is the dispersion of the error in measuring the distance between the first receiving point and the aircraft based on the energy method [20].

The dispersion value \(\sigma_{j,1}^2\) depends on the value of the dispersion of the error in measuring \(\Delta t_{j,1} = t_{j,1} - t_{j,1}\) the difference in the times of signal reception from the air object at the \(i\)-th receiving point and the reference receiving point.

The value of the variance \(\sigma_{j,EM}^2\) of the ranging error \(R_j\) is determined on the basis of the following expression [20]:

\[
\sigma_{j,EM}^2 = \Delta_{jw}^2 \left(1 - P_j P_w^{-1}\right)^{-1} \sigma_{\phi,0}^2 + 0.25 \left(\Delta_{jw}^2 \cos^2 \theta\right)^2 \left(1 - P_j P_w^{-1}\right)^{-1} P_w^{-2} \left(\sigma_{\phi,0}^2 + P_j^2 P_w^{-2} \sigma_{\phi,0}^2\right),
\]

(14)
where $\sigma_{V_{GS}}^2$, $\sigma_{P_j}^2$, $\sigma_{P_N}^2$ are the variance of the parameter measurement errors $V_{GS}, P_j, P_N$, respectively.

3.2. Solution to the problem for the second scenario (Figure 2)
In this scenario, the actual values of the observed parameters in expression (5) are:

$$
Y_j = \begin{bmatrix}
\frac{d_j}{R_j} \\
\frac{\alpha_j}{\text{arctg} \left( \frac{y_{t,j}}{x_{t,j}} \right)}
\end{bmatrix},
$$

(15)

where

$$
n_{n,j} = \left( (x_{1,j})^2 + (y_{1,j})^2 + (z_{1,j})^2 \right)^{1/2},
$$

$$
n_{2,j} = \left( (x_{2,j} - x_{1,j})^2 + (y_{2,j} - y_{1,j})^2 + (z_{2,j} - z_{1,j})^2 \right)^{1/2},
$$

$(x_{t,j}, y_{t,j}, z_{t,j})$ are the aircraft coordinates.

To find the estimate of the aircraft coordinates $\tilde{q}_j = [\tilde{x}_{t,j}, \tilde{y}_{t,j}, \tilde{z}_{t,j}]^T$, we use the algorithm (8), in which the matrix of partial derivatives $C_{i,m-1} = [e_{i,j,m-1}, i = 1, 3]^T$ contains the following elements, similar to (10), (11), and taking into account (15):

$$
e_{1,j,m-1} = \begin{bmatrix}
\cos \alpha_{j,2,m-1} - \cos \alpha_{j,l,m-1} \\
\cos \beta_{j,2,m-1} - \cos \beta_{j,l,m-1} \\
\cos \gamma_{j,2,m-1} - \cos \gamma_{j,l,m-1}
\end{bmatrix}^T,
$$

$$
e_{2,j,m-1} = \begin{bmatrix}
\cos \beta_{j,1,m-1} \\
\cos \gamma_{j,1,m-1}
\end{bmatrix}^T,
$$

$$
e_{3,j,m-1} = \begin{bmatrix}
\tilde{x}_{i,j,m-1} - \tilde{x}_{k,j,m-1} \\
\tilde{y}_{i,j,m-1} - \tilde{y}_{k,j,m-1} \\
0
\end{bmatrix},
$$

where $\tilde{r}_{2D,j,m-1} = \left( (\tilde{x}_{i,j,m-1})^2 + (\tilde{y}_{i,j,m-1})^2 \right)^{1/2}$. 

To assess the accuracy of determining the aircraft coordinates vector $\tilde{q}_{j,m}$, we can use an expression of the form (12), in which

$$
W_{z,j} = \begin{bmatrix}
\sigma_{j,1,2}^2 & 0 & 0 \\
0 & \sigma_{j,R}^2 & 0 \\
0 & 0 & \sigma_{j,a}^2
\end{bmatrix},
$$

where $\sigma_{j,1,2}^2 = \sigma_{j,1}^2 + \sigma_{j,2}^2$ is the variance of the error in measuring the difference of the ranges $\Delta r_{j,1,2}$, $\sigma_{j,R}^2$ is the variance of the error in measuring the distance between the first receiving point and the aircraft based on the energy method, determined similarly to (14), $\sigma_{j,a}^2$ is the variance of the error in measuring the azimuth of the aircraft.

It should be noted that the estimates of aircraft coordinates obtained on the basis of (8) can be improved using dynamic filtering algorithms, for example, the Kalman filter [22, 23].

4. Simulation results
The simulation considers a uniform linear motion of the aircraft on a plane, that is, with a fixed flight
altitude. The aircraft moved with ground speed \( V_{GS} = 111 \text{ m/s} \) and heading \( C_{aircraft} = 45^\circ \) (Figure 3). We assume that the speed of the aircraft is known a priori. The MLAT structure included four receiving points \( \{RS_i, i = 1,4\} \) for the implementation of TDOA (Figure 3). At the receiving point \( RS_i \), the aircraft range was measured based on the energy method [20]. Simulation was performed over a time interval \( t_i \in [t_0, T] = [0, 100], i = 0, N \). For each time, we measure the power of the signal received from the aircraft \( P(t_i) = P_i, t_i \in [0, 100], c = 0, N \) with a relative error \( \delta P = 1\% \). An airborne transponder of an aircraft transmitting ADS-B signals was considered as a signal source.

Algorithm (8), (12) was used to estimate the aircraft coordinates. The simulation shows that for the aircraft movement trajectory shown in Figure 3, the mean square error of aircraft coordinates estimation does not exceed 15 meters. It meets the requirements for aviation surveillance systems. In addition, the use of a hybrid method based both on the use of TDOA measurements and on the measurement of the range to the aircraft by the energy method allowed to increase the reliability of the MLAT by 22% due to the use of structural information redundancy.

5. Conclusion
The work proposes algorithms for processing measurements of hybrid aviation surveillance systems based on the iterative least squares method, which in contrast to the known algorithms use the additional information about the range to the aircraft, found on the basis of the energy method, implemented at one of the receiving positions of the MLAT system. The use of the hybrid measurements allows to increase the reliability of the MLAT by 22% due to the introduced structural and informational redundancy.

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