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Assessment of the quality of information provided by combined radar airspace surveillance systems

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ABSTRACT

The structure of information support for the airspace control system based on combined radar surveillance systems has been substantiated and investigated. This makes it possible to improve the quality of the detection of air objects, as well as to assess the accuracy of the location of the detected air objects. As a result, this improves the quality of information support for decision-makers in the airspace control system.

Keywords: airspace control system, air traffic control, combined surveillance systems, consumer information support, air object, primary data processing, flight data

1. INTRODUCTION

The main elements of the airspace control system (ACS) [1] and air traffic control (ATC) [2] procedure are air situation analysis and decision making. The decision is made on the basis of analysis of appropriately prepared information data on the state of the air situation in the area of responsibility. The correct decision can be made only when there is sufficiently complete, accurate, reliable and continuous information about the air situation in the control area.

The main sources of information support for ACS and ATC are radar surveillance systems. They are usually combined, i.e. located on one platform, including primary[3] and secondary[4] surveillance radars. The main task of these radar systems is to estimate the location of the air object (AO) with the required quality indicators, to identify the detected AO using the "Friend or Foe" attribute, and also to obtain the flight data (FD) from the air object. All this indicates that the Form of the detected AO is formed after the implementation of the primary data processing[5] in each channel of the combined radar surveillance system. This Form is issued to the decision-maker [6,7].

A sufficient number of works[8,9,10] are devoted to the issues of data fusion of the considered airspace observation systems, in which:

- it is shown that the creation of redundancy of information and software allows to increase the accuracy of tracking air objects and resistance to sensor errors[11,12,13];
- describes a set of algorithms that combine primary radar data and IFF system data;
- algorithms for preliminary data processing are considered[14,15,16]];
- the resistance to unintentional and deliberate interference is assessed.

In the presented work, the quality of information support is assessed when changing the model and method of merging data from primary radar systems and IFF systems[17,18,19]. The aim of the work is to improve the quality of information support for the airspace control system when implementing the weight association of coordinate data of the combined radar surveillance systems.

2. METHOD

The consumer of information of the airspace control system needs the necessary coordinates of the software with the required quality. In practice, the process of automatically measuring coordinates consists of two components: detecting

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AO and measuring their coordinates. In this case, the detection process is nothing more than the measurement of coordinates accurate to the separation elements along the corresponding coordinates, and the measurement process consists only in refined coordinates within the separation elements according to the corresponding coordinates. Detection and measurement of AO coordinates by surveillance radar surveillance systems (including interrogation ones) is carried out on the basis of analysis and processing of received signal packets. It can be argued that the useful signal is a sequence of periodically repeating single received signals (burst of signals). With uniform antenna rotation of observation systems in the viewing space, the number of signals in a burst is determined from the following relation[20, 21]:

$$N = \Delta\phi F_p / \Omega \,, \quad (1)$$

where $\Delta\phi$ the beam width of the antenna directional pattern in the scanning plane, F_p the repetition rate of the SS signals, Ω the angular velocity of the antenna.

It is known that in ACS[1] the following basic information tasks are solved: - conducting continuous radar airspace exploring; assessment of the air situation and detection of violations of the procedure for the use of airspace; issuance of radar data to consumers.

The main information tasks of the primary radar data processing include determination (assessment) of the instantaneous position (coordinates) of the AO in space based on the results of one survey of radar surveillance systems. In the process of this operation, AO is detected by a pack of reflected (emitted) signals, a statistical estimate of the delay time of reflected (emitted) signals relative to the moments of signal emission (statistical estimation of the range to AO relative to the location of radar observation systems), as well as a statistical estimate of the angular coordinates of AO by the angular positions of the antennas of the radar surveillance systems at the moment when the maximum of the radiation pattern passes through the AO. The accuracy of the coordinates estimation AO is generally characterized by the coordinate estimation accuracy matrix.

Therefore, upon completion of the primary data processing, the AO Form is automatically generated [21,22], which includes:

$$\hat{\vec{W}}_p, \vec{C}_p^{-1}, \text{FD}, \text{"friend or foe"}, T_i, \quad (2)$$

where $\hat{\vec{W}}_p$ is current state vector AO, $\vec{C}_p^{-1}$ is matrix of the state vector accuracy, "friend or foe" identification result AO, T_i time of obtaining this measurement.

In particular, for primary data processing, the partial quality indicators of information support can be the probabilities of correct detection of AO by each channel of the joint surveillance radar system $P_i = D_{1i}$, which can be determined from the following dependence

$$D_{1i} = f\left(D_{0i}, F_{0i}, C_i, P_0\right) = f\left(q_{0i}, z_{0i}, C_i, P_0\right), \quad (3)$$

where $z_0(C)$ is analog (digital) signal detection threshold (AO), P_0 is availability of the aircraft transponder that is characteristic for the secondary and IFF surveillance systems.

The availability factor of an aircraft responder is nothing more than the capacity of the latter. The construction of an aircraft transponder based on the principles of a single-channel queuing system with refuses led to its easy paralysis by deliberate emission of request signals of the required intensity, which significantly reduces its throughput and, naturally, the quality of information service.

Consequently, a quality indicator of information support by joint radar systems for observing the airspace as a whole can be the probability of the formation of an information packet, which can be estimated from the following ratio

$$P_{\text{inf}} = D_{11}, D_{12}, D_{13}, P_{per}, P_{obe}, P_{sr1}, P_{sr2}, \quad (4)$$

where D_{1i} is the probability of correct detection of AO by each (primary, secondary and identification) observation system, P_{per} is probability of correct transmission of FD by the secondary observation system, P_{obe} is probability of correct transmission of FD by the secondary observation system, P_{sr1} is the probability of comparing the coordinate data of the primary and secondary surveillance systems, P_{sr2} is probability of comparing the coordinate data of the primary and identification surveillance systems.

Let’s estimate the components of expression (1). With binary signal quantization, which practically exhausts all information about the signal amplitude and the choice of the detection threshold based on the Neumann-Pearson criterion, the probability of detecting a single pulse from AO is:

$$D=\int_{z}^{\infty} x\exp\left(-\frac{x^2+q^2}{2}\right)I_o(qx)dx, \tag{5}$$

where q is voltage signal-to-noise ratio, $z=\sqrt{2\ln(1/F_o)}$ is quantization threshold, selected based on the specified probability of its exceeding by noise (F_0 is probability of a false alarm after the first threshold).

The probabilities of detecting AO can be estimated from the following relation

$$D_{1i}=\sum_{k}^{N} C_N^k D_d^k (1-D_d)^{m-k}, \tag{6}$$

where N is number of received signals from AO, k is digital detection threshold of AO.

It should be noted that the choice of the signal detection threshold completely determines (fixes) the probability of false alarm of AO detection.

When comparing and fusing data from joint radar surveillance systems, which is necessary for the automatic compilation of the AO Form, the criterion can be the quality of measurement of coordinate data, through the probabilities of actions, which include: probability of losing correct FDs; distortion probability FD; the probability of fusing the coordinate and FD by the secondary observation system; the probability of comparing the coordinate data of the primary and identification surveillance systems; the probability of fusing coordinate data and FD by the joint observation system.

Let's consider these probabilities of events in more detail. As a rule[14], to improve the quality of FDs, their interperiod processing is carried out by a scheme according to the k/m criterion. In this case, the probability of losing correct FDs in the data processing device can be estimated based on the following expression

$$P_{pot.p.i}=1-P_{p.i}^k, \tag{7}$$

where $P_{p.i}$ is the probability of issuing FD from the output of the secondary observation system in the first m informational responses.

When using the FD confirmation circuits in the processing device according to the k/m criterion, the FD distortion probability will be:

$$P_{isk.p.i}=\sum_{i=k}^{m} C_m^i P_{isk}^i \left(1-P_{isk}\right)^{m-i}, \tag{8}$$

where P_{isk} is probability of the secondary surveillance system issuing false FDs.

Flight data received through the data transmission channels of the secondary surveillance systems, as a rule, arrives with some delay relative to the AO coordinate data estimated by the secondary surveillance system. In this case, the number of the arrival range element FD can be estimated in accordance with the expression:

$$N_d'=N_d+T\left(KD\right)/r_d, \tag{9}$$

where N_d is the number of the discrete of the arrival of coordinate data; $T\left(KD\right)$ is lag for the secondary observing system, corresponding to the coordinate data code; r_d is the cost of the range element.

Based on the above, it can be argued that the probability of fusing the coordinate data and FD obtained by the secondary observation system can be estimated from the following expression:

$$P_{obe} = \left(1 - P_{pot.p.i}\right)\left(1 - P_{isk.p.i}\right) P\begin{Bmatrix} +N_0' \\ -N_0' \end{Bmatrix}, \quad (10)$$

where $P\begin{Bmatrix} +N_0' \\ -N_0' \end{Bmatrix}$ is conditional probability of arrival of FD in strobe from $+N'$ to $-N'$ relative to AO coordinate data.

It should be noted that the algorithm for combining data in the processing device, as a rule, is constructed so that single marks of the processing channels of the joint observation system are combined if the azimuthal angle between the centers of the received signal packets does not exceed $\Delta\beta$, and the difference in their ranges is Δr .

We will assume that the deviation of packet centers in the primary and secondary radar systems of the combined surveillance system are independent and obey a normal distribution. In this case, the probability of combining information packets in a combined radar system is determined in accordance with the following expression:

$$P_{sr} = \frac{1}{4}\left[1 + F\left(\frac{\Delta\beta}{\sqrt{2}\sqrt{\sigma_{\beta 1}^2 + \sigma_{\beta 2}^2}}\right)\right]\left[1 + F\left(\frac{\Delta r}{\sqrt{2}\sqrt{\sigma_{r1}^2 + \sigma_{r2}^2}}\right)\right], \quad (11)$$

where $F(x)$ is integral of probability, $\sigma_{\beta 1}, \sigma_{\beta 2}; (\sigma_{r1}, \sigma_{r2})$ root-mean-square deviations of azimuths (ranges) of packet centers of primary and secondary (identification) radar surveillance systems.

Thus, the structure of information support for ACS consumers includes channels of primary and secondary surveillance systems.

Therefore, to compile the AO Form in each channel of the combined surveillance system, it is necessary to carry out:

- detection and measurement of parameters of signals from surveillance systems;
- AO detection and measurement of their coordinates.

In addition, FDs must be received and processed by the secondary surveillance system, which requires comparing and combining devices.

In the data processing device, the measurement estimates are merged based on the measurement vectors and the correlation matrix of the measurement accuracy of each of the observation systems. As a result, the resulting measurement vector and accuracy correlation matrix are calculated. And then the resulting measurement vector $\hat{\vec{\alpha}}_p$ and the accuracy correlation matrix $\vec{C}_p^{-1}$, are provided to consumers.

The fusing of the estimates of the measured parameters of the received signals, as a rule, is carried out under the assumption that the estimates of the measurement vector $\hat{\vec{\alpha}}$ are carried out simultaneously in all channels of the combined observation system. We will assume that the estimates of the measurement vector can be approximated by the normal distribution law for each of the components of the measurement vector $\hat{\vec{\alpha}}$. With this formulation of the question, the logarithm of the likelihood ratio can be written in the following form

$$\ln l = \sum_{k=1}^{M} \ln l_k = \sum_{k=1}^{M}\left[-\frac{1}{2}\left(\vec{\alpha} - \hat{\vec{\alpha}}_k\right)^T \vec{C}_k\left(\vec{\alpha} - \hat{\vec{\alpha}}_k\right)\right], \quad (12)$$

where M is the number of combining channels.

Based on expression (12), it can be shown that the logarithm of the likelihood ratio, up to a constant value, can be reduced to the following expression

$$\ln l = -\frac{1}{2}\left(\vec{\alpha} - \hat{\vec{\alpha}}_p\right)^T \vec{C}_p\left(\vec{\alpha} - \hat{\vec{\alpha}}_p\right), \quad (13)$$

where

$$\hat{\vec{\alpha}}_p = \vec{C}_p^{-1}\sum_{k=1}^{M}\vec{C}_k\hat{\vec{\alpha}}_k \;, \quad \vec{C}_p = \sum_{k=1}^{M}\vec{C}_k \; . \quad (14)$$

Thus, based on expression (14), it is possible to estimate the resulting measurement vector and the resulting correlation matrix of accuracy, and, consequently, the resulting correlation matrix of measurement errors.

Based on the foregoing, partial indicators of the quality of information support can be the probabilities of correct detection of AO by each channel of the combined surveillance system, that is, the channels of the primary and requesting surveillance systems.

3. RESULTS

Expression (14) is given for the case of issuing data about an AO that responds to the request signals of the secondary surveillance system. In the case when there are no response signals, a decision is made about the "foe" AO and expression (14) is simplified to the probability of detecting AO by the primary surveillance system.

Calculation of the probability of information provision of consumers with a combined surveillance system as a function

$$P_{\text{inf}} = f\left(k, q, P_0\right), \tag{15}$$

where $k = q_p / q_z$, q_z is signal-to-noise ratio in the channel of the requesting SS, q_p is the signal-to-noise ratio in the channel of the primary observation system when detecting and measuring the coordinates of the AO based on the analysis of the entire packet of received signals and the digital detection threshold AO, which is half of the packet of received signals, are shown in Fig.1-Fig.3. In this case, the continuous curve corresponds to the information support provided by the existing structure of observation systems, and the other curves correspond to the version of information support, which is considered, with different both the availability factors of the aircraft responder and the SNR in the channels of the primary and requesting observation systems.

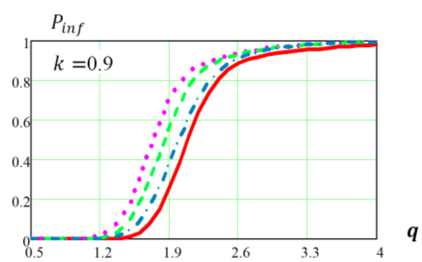

Fig. 1. Dependency $P_{\text{inf}} = f(q, P_0 = 1, k = 0.9)$

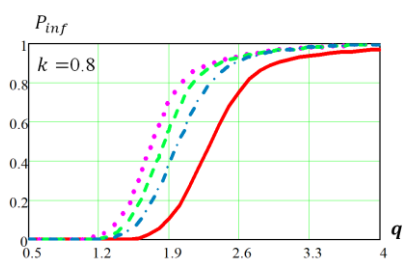

Fig. 2. Dependency $P_{\text{inf}} = f(q, P_0 = 0.9, k = 0.8)$

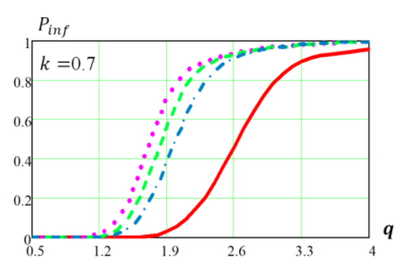

Fig. 3. Dependency $P_{\text{inf}} = f(q, P_0 = 0.8, k = 0.7)$

4. CONCLUSIONS

The above calculations of the user's information support of based on the joint airspace observation system allow us to draw the following conclusions:

- the modernized structure of data fusion in the joint airspace surveillance system improves the quality of information support for users. Thus, the calculations presented in Fig. 1 show that for $q = 3$ the probability of information support by the existing structure is 0.4, and for the proposed structure of information support, regardless of the availability factor of the aircraft transponder, this probability is 0.95;
- there are certain boundaries of both the readiness factor of the aircraft transponder and the difference in the signal-to-noise ratio for the primary and interrogated surveillance systems, above which the effect of modernizing the data processing structure of the surveillance systems is not observed.

The last conclusion requires the imposition of restrictions both on the availability factor of the aircraft responder and the difference in the signal-to-noise ratio at which it is possible to use the considering processing structure, and otherwise – the structure that exists in existing surveillance systems.

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