Tracking of small-sized air objects

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Abstract. Modern capabilities of tracking air objects are developing at a rapid pace. The article proposes a method for detecting and identifying small-sized air objects during their tracking.

1. Introduction

In recent years, the range of capabilities of general aviation has been significantly expanded. Increasing attention is being paid to the development of methods for the effective tracking of such means. In the context of their widespread use in the national economy, the task of their reliable detection and identification becomes more and more urgent for their control.

The basis for solving this problem can be the analysis of methods for detecting air objects based on several known operating modes of various systems [1]:

1. Pulse-Doppler mode without scanning in elevation [2] provides detection of objects down to the earth’s surface by filtering signals with narrow-band Doppler filters. In this mode, the transmitter emits bursts of radio pulses with a power of \( P_{\text{IDR}} = 500 \text{ kW} \) and a pulse duration of \( T_{\text{ПС}} = 8 \text{ ms} \).

   The pause time between bursts of pulses is within \( \Delta T = 1.3\text{–}2.5 \text{ ms} \); the repetition frequency varies from burst to burst so that \( F_{\Pi} = 25\text{–}30 \text{ kHz} \).

2. Pulse-Doppler mode with scanning in elevation. In this mode, operation of the detection system is similar to its operation in the mode without scanning in elevation. The difference lies in determining the elevation angle of the target using electronic scanning of the directional diagram (DD) in the vertical plane. Due to the high speed of beam movement, several periods of scanning in elevation are carried out during the time DD passes in azimuth through the direction to the target. The position of DD in elevation is controlled by phase shift drivers designed for high conducted power.

   The second group of phase shift drivers in the receiver provides an angular shift of DD antenna, compensating for the time delay between the emitted signal and the received signal reflected from the target, which is at a long range [3].

   In this mode, bursts of radio pulses are emitted with a duration of \( T_{\Pi \text{ var}} = T_{\Pi V} = 1.6 \text{ ms} \). The pause time between bursts is chosen from some considerations. It can be assumed that \( T_{\text{обл}}, T_{\Pi V}, T_{\text{ск}} \) are
related. Within the scanning sector, DD moves abruptly through $\varepsilon_{0.5}$, with $t = T_{\Pi V} + \Delta T(e_1)$ in one position, and $t = T_{\Pi V} + \Delta T(e_2)$ in the next position and the probe pulses are emitted at a different repetition frequency $F_{\Pi}$. 

The irradiation time of a small-sized air object at DD rotation speed $n = 6$ rpm and $\beta_{0.5} = 1^\circ$ is equal to [1]

$$T_{\text{обл}} = \beta_{0.5}/(360 \cdot n) = 0.028 \text{ s}.$$

During this time, the detection station must receive signals on at least 3 frequencies [2]. Whence it follows that

$$T_{\text{ск}} = T_{\text{обл}}/3 = 9.3 \text{ ms}.$$

During scanning period, DD must move through the entire scanning sector and a whole number of pulse bursts must be emitted [1]:

$$N = T_{\text{ск}}/(T_{\Pi V} + \Delta T) \leq 4.$$

Thus, for $T_{\text{ск}}$, DD does not have time to occupy more than four positions; therefore, the scanning sector in elevation is $20^\circ$ ($\varepsilon_{0.5}=5^\circ$) [1, 8]. Since the number of repetition frequencies $F_{\Pi}$, as well as the number of DD positions in elevation equals 4, this makes it possible to predict the law of change of $F_{\Pi}$.

3. Beyond-the-horizon detection.

In this case, the detection system operates in a pulsed mode (the Doppler frequency shift of the reflected signal is not taken into account). This mode provides an increase in the detection range in areas where there is no reflected signal from the earth’s surface, since their sources are beyond the line of sight. Here, the transmitter forms a continuous sequence of linear-frequency-shift keyed radio pulses with the following parameters $T_u=83$ $\mu$s, $F_{\Pi} = 111-118$ Hz, $P_u = 1150$ kW, $P_{\text{ср}} = 10$ W, $\Delta f_c = 1.3$, $T_{\text{ск}} = 0.8$, compression ratio $K = 108$.

4. Operating mode of the oversea detection system.

Detection of ships is provided in a pulsed mode by means of pulse compression and thus obtaining pulses with a short effective duration, at which the level of the reflected signal from the sea surface is significantly reduced. Periodic switching of the detection system operating modes enables an almost simultaneous survey of the airspace and the sea surface.

5. Combined use of detection station modes.

The detection station of the system for detecting and identifying small-sized air objects can simultaneously and separately use the pulse-Doppler mode with scanning in elevation and the beyond-the-horizon detection mode, and, if desired, either or both of them can be active or passive. In this case, the pulse-Doppler mode without scanning in elevation should be used separately or together only with the oversea operating mode.

The power of the direct signal received at point $P_{\Pi}$, emitted along the main lobe of DD of the detection station, for the pulse-Doppler and pulse operating modes, is equal to [4]:

$$P_{\Pi} = \frac{P_{\text{нп}} G_{\lambda}}{4\pi R^2} G_{\text{пр}} \frac{\lambda^2}{4\pi} = 3 - 70 \text{ мВт}.$$

In the calculations, it was assumed that $R = 200$ km is the distance between ‘detection station - receiving point (base)’, $G_{\lambda} = 6000$ is the antenna gain of the detection station, $\lambda = 0.1$ m, $G_{\text{пр}} = 300-6000$ is the gain of the receiver antenna for detection-tracking channels.

From experience, it is usually assumed [1] that the level of the first side lobes is -30 dB, the level of the far side lobes is -50 dB, therefore the power of the direct signal radiated along the near and far lobes of DD antenna and received at point $P_{\Pi}$ is correspondingly less by 3 and 5 orders.
2. Energy and space-time characteristics of signals reflected from small-sized objects

In the pulsed and pulse-Doppler modes without scanning, the exposure time of the object is determined by the width of DD antenna of the detection station in azimuth and the rotation speed of the antenna. Let us assume that $T_{\text{обл}} \approx 30 \text{ ms}$. During this time, in a pulse mode, the object reflects the number of pulses equal to $M_{\Pi} = T_{\text{обл}} \cdot F_{\Pi} = 3$.

In the pulse-Doppler mode without scanning, three bursts of pulses are reflected in $T_{\text{обл}}$: $n = 3$.

Substituting the above values of the parameters, the number of pulses in each burst will be $M_{n} = \frac{T_{\text{обл}}}{T_{\Pi} + \Delta T} \approx \frac{30}{8+2} = 3$.

Thus, the echo from a point object is a set of three bursts of pulses. Each pulse is delayed relative to the moment of receiving a direct signal for a time determined by the difference in the path of the reflected and direct signals:

$$ t_{n} = \frac{R_{\Pi} + R_{\Pi} + R_{\Pi}}{C}, $$

where

- $R_{\Pi}$ – distance from detection station to object;
- $R_{\Pi}$ – distance from object to receiving point;
- $R_{\Pi}$ – distance from detection station to receiving point.

Detection station systems mainly detect objects with large bistatic angles. Under these conditions, the effectiveness of technologies for reducing the visibility is significantly weakened, the radar cross-section (RCS) increases, which ultimately leads to an increase in the detection range of small objects. The effect of increasing the bistatic RCS is described in detail in [4]. It notes that the maximum RCS increment in the forward direction occurs at bistatic angles close to $180^\circ$. The bistatic RCS can be calculated according to the expressions [4]:

$$ \sigma_{dp} = \sigma_{\Pi} (1 + \exp[n \cdot \gamma - 2.4 \cdot n - 1]) ; \quad \gamma = \arccos \left( \frac{R_{\Pi}^{2} + R_{\Pi}^{2} - B^{2}}{2 \cdot R_{\Pi} \cdot R_{\Pi}} \right), $$

where

- $\sigma_{\Pi}$ – RCS of an air object for a combined detection station;
- $\gamma$ - bistatic angle;
- $B$ – base;
- $R_{\Pi}, R_{\Pi}$ – distance from the detection station and the covert location complex to the air object respectively;
- $n$ – propagation factor.

The power of the signal reflected from the air object and received at point $\Pi$ can be calculated using the radar formula for an on-off system [5,6]:

$$ P_{\Pi \text{прот}} = \frac{P_{\Pi} \cdot G_{A}}{4\pi R_{\Pi}^{2}} \cdot \frac{\sigma_{\Pi}}{4\pi R_{\Pi}^{2}} \cdot G_{\Pi} \lambda^{2} \cdot 4\pi. $$

The calculations show that $P_{\Pi \text{прот}}$ is in the range $(10^{-12} - 10^{-15})$ W. In the calculations, it was assumed that $G_{\Pi} = 1000$ is the gain of the receiver antenna, $G_{\Pi} = 6000$ is the gain of the antenna of the detection station, $P_{\Pi} = 500-1150$ kW is the pulse power of the probing signals, $\sigma_{\Pi} = 0.1-1$ m$^{2}$ is RCS of the object, $\lambda = 0.1$ m is wavelength.

Thus, the operation of the spaced detection station is less affected by the signal reflections from the earth’s surface than the operation of the co-located detection station, since the interference pulse is shorter [5, 7, 8], and the exposure time amounts to a few percent of the operation time of the detection station.
Other features of the effect of signal reflections from the earth’s surface include a slight increase in the intensity of interference with an increase in the distance to the reflection area and the dependence of the power of interfering reflections on the angular position of the receiving antenna.

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