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Issues of Optimizing Detection of Stealth Aircraft Using Group of Satellites Flying at Different Altitudes

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The article is devoted to the optimization of the detection of stealth aircraft using a group of satellites flying at different altitudes and equipped with an infrared reproducing system. The main sources for the formation of the infrared signature of stealth aircraft are the heating of the aircraft casing during flight and the high-temperature plume emanating from the nozzle of the aircraft engine. The necessity of calculating the infrared signature of stealth aircraft is noted. The infrared signature of such aircraft is usually calculated in wide ranges of IR waves. At the same time, there are works according to which it is advisable to use narrow spectral wavelengths for these purposes. A push-pull method of detecting stealth aircraft using satellites flying in a group at different orbital altitudes has been developed. The proposed method makes it possible to increase the signal-to-noise ratio in the resulting informative signal, which is the difference between the signal from the aircraft itself and the background signal within the frame. It is shown that the introduction of a binary control signal depending on the spatial resolution of the distance to the satellites allows minimizing the total background signal coming from a group of satellites. At the same time, an increasing version of this function applied to the sum of signals from the background under a given restrictive condition ultimately increases the signal-to-noise ratio in the system, and also increases the probability of detecting a stealth aircraft using spectrometric devices installed on satellites.

Keywords: stealth aircraft; detection; group flight; optimization; control function; target functionality

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Introduction

Currently, the detection of stealth aircraft using space means encounters a number of difficulties. Such interfering factors as Earth radiation, atmospheric attenuation and the small size of the infrared signature of such aircraft seriously limit the possibility of their detection from an orbital altitude [1, 2].

The main sources for the formation of the infrared signature of stealth aircraft are the heating of the aircraft casing during flight and the high-temperature plume emanating from the nozzle of the aircraft engine [3–5]. A large number of papers have been devoted to the issue of calculating the infrared signature of stealth aircraft (see for example [6–10]). A number of studies have noted the need to calculate the infrared signature of stealth aircraft in wide ranges of IR waves, such as (1.8-2.4 microns); (2.5-3.57 microns); (4-4.76 microns) [11,12]. At the same time, it was shown in [13] that for these purposes it is advisable to use narrow spectral wavelengths (4.14-4.18 microns), (4.56-4.65 microns). In relation to the space detection systems of stealth aircraft, the use of ranges (2.65-2.90 microns) and (4.25-4.50 microns) is proposed in [15]. The ideas presented in [15] were further developed in [16], in which the analysis also included such indicators as aircraft speed, flight altitude, atmospheric attenuation, the influence of Earth radiation, etc. At the same time, the issue of detecting a stealth aircraft from an orbital altitude in [16] was considered in relation to one satellite equipped with IR recording equipment. In this paper, this issue is considered in relation to a group of orbiting satellites performing a joint flight at different altitudes above the atmosphere. To solve this problem, we will use some of the research results presented in [16].

1 Materials and methods

The main indicator of the ability to detect stealth aircraft in the IR range using a group of satellites flying at different altitudes is the signal-to-noise ratio (SNR), defined according to [16] as

$$SNR = \frac{N_{TD} - N_{BD}}{N_n}, \qquad (1)$$

where N_{TD} is the signal power of the IR detector detecting the target, i.e. the signal coming from the aircraft; N_n is the noise power in the system.

According to [16]:

$$N_{TD} = \frac{(L_{q.back}(S^2 - A_{aircr}) + I_{q.aircr}PVF) \cdot A_{opt}\tau_{opt}\eta T_{int}}{R^2} + \frac{T_{int}I_{dark}}{q}, \tag{2}$$

where A_{opt} is the area of the input aperture; τ_{opt} is the optical transmission; η is the quantum efficiency of the photodetector; I_{dark} is the dark current of the detector; q is the electric charge, $q = 1{,}6 \cdot 10^{-19}$C; A_{aircr} is the projection area of the aircraft in the imaging system (including the image of the casing and plume); S is the spatial resolution of the imaging system, defined as

$$S = \frac{(Pix) \cdot R}{f}, \tag{3}$$

where R is the distance to the object; f is the focal length; Pix is the pixel size; $L_{q.back}$ is the total background radiation; $I_{q.aircr}$ is the radiation intensity of the aircraft at the input aperture; PVF is the point visibility coefficient; T_{int} is the integration time on the photodetector.

In formula (1), N_{BD} is the signal strength of the detector receiving the signal from the entire plot of Land in the image frame. According to [16], N_{BD} is defined as

$$N_{BD} = \frac{L_{q.back}S^2 \cdot A_{opt}\tau_{opt}\eta T_{int}}{R^2} + \frac{T_{int} \cdot I_{dark}}{q}. \tag{4}$$

The method we propose is to use a group of satellites in the number n; which should fly on trajectories of height R_i; $i = \overline{1,n}$. At the same time, there are many

$$R = \{R_i\} \tag{5}$$

contains the elements of R_i, which are ordered as follows

$$R_i = R_{i-1} + \Delta R; \;\; \Delta R = const,$$

where R_0 is the lower orbital height; R_n is the upper orbital height.

It is assumed that the satellites are equipped with IR spectroradiometers, the focal length of which is adjustable, which according to (3) leads to a change in the resolution S (Fig. 1).

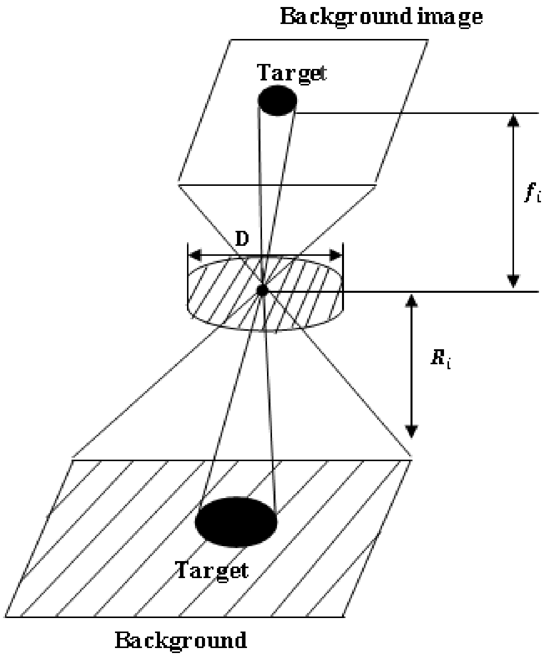

Fig. 1. Schematic representation of the formation of IR images in one satellite from a group located at altitude R_i, equipped with a spectroradiometer with a focal length f_i

Next, we consider the case when $R_i \gg h$, where h is the altitude of the aircraft. Our proposed method of detecting stealth aircraft involves a push-pull implementation of the detection process using signals from all satellites in orbit. In this case, two sums are formed:

$$\alpha_1 = \sum_{i=1}^{n} N_{TD_i}, \tag{6}$$

$$\alpha_2 = \sum_{i=1}^{n} N_{BD_i}. \tag{7}$$

Therefore, the signal-to-noise ratio, by analogy with (1), is determined by the formula

$$SNR = \frac{\sum_{i=1}^{n} N_{TD_i} - \sum_{i=1}^{n} N_{BD_i}}{\sum_{i=1}^{n} N_i}, \tag{8}$$

where N_i is the noise power in the system of the i-th satellite.

The push-pull implementation of the detection procedure aims to achieve the maximum value of the SNR by calculating $\sum_{i=1}^{n} N_{TD_i}$ in the first clock cycle and minimizing $\sum_{i=1}^{n} N_{BD_i}$ in the second clock cycle. The formation of these amounts is carried out in a controlled mode. The control function $S = f(R)$ is introduced into the system, the type of which is selected from the following criteria:

When measuring the sum of $\sum_{i=1}^{n} N_{TD_i}$ the form of the function $f(R)$ should ensure the immutability of this sum;

When measuring the sum of $\sum_{i=1}^{n} N_{BD_i}$ the form of the function $f(R)$ should provide a minimum of this sum. Thus, such an order of calculation of these amounts in two cycles will allow achieving a high SNR value when conducting group satellite measurements. A block diagram of the algorithm for implementing the proposed method is shown in Fig. 2.

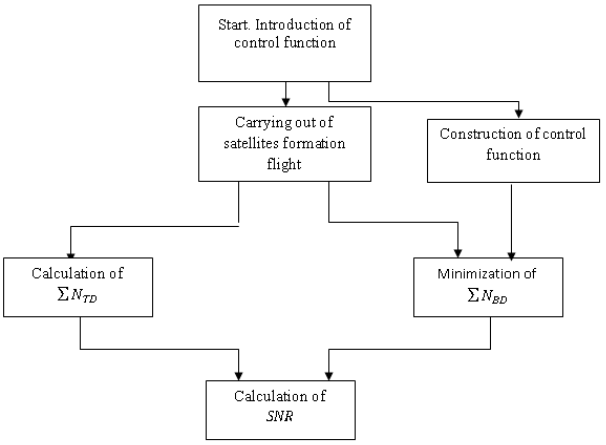

Fig. 2. A block diagram of the algorithm for implementing the proposed method

Let's form the control criteria specified in the flowchart shown in Fig. 2. As noted above, the control function uses the functional dependence $S = f(R)$ in binary form, the general form of which is shown in Fig. 3.

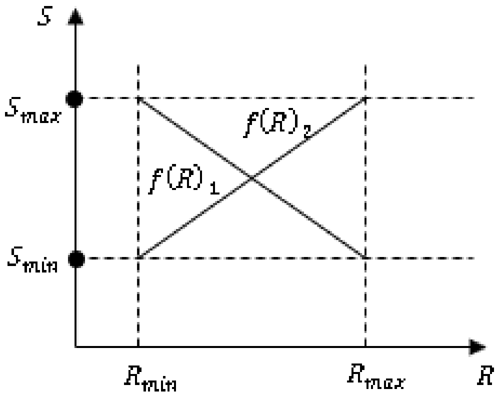

Fig. 3. The general form of the binary function $f(R)_i$, $i = 1, 2$; where $f(R)_1$ is an increasing function; $f(R)_2$ – decreasing function

In order to optimize the procedure of stealth aircraft identification we need to adopt following limiting condition concerning total value of spatial resolutions of all acting satellites. In first approximation the total value of spatial resolutions is equivalent to total initial information to be processed. So that condition (9) is necessary for required optimization

$$\int_{R_{min}}^{R_{max}} f(R)_1 dR = \int_{R_{min}}^{R_{max}} f(R)_2 dR = C; \quad C = const. \tag{9}$$

The technical realization of condition (9) should be carried out by changing the focal length of optics depending on distance as far as stealth aircraft.

The shown variants of the functions $f(R)_1$ and $f(R)_2$ allow us to impose restrictive condition (9) on them. To clarify the order of selection of criteria for applying the functions $f(R)_1$ and $f(R)_2$ to calculate the sums of $\sum_{i=1}^{n} N_{TD_i}$ and $\sum_{i=1}^{n} N_{BD_i}$ expressions (2) and (4) are represented in the following form

$$N_{TD} = \frac{[a_1(S^2 - a_2) + a_3] \cdot a_4}{R^2} + a_5, \tag{10}$$

$$N_{BD} = \frac{a_1 \cdot S^2 a_4}{R^2} + a_5, \tag{11}$$

where:

$$\left.\begin{array}{l} a_1 = L_{q.back}; \;\; a_2 = A_{aircr}; \;\; a_3 = I_{q.aircr} PVF; \\ a_4 = A_{opt} \tau_{opt} \eta T_{int}; \;\; a_5 = \dfrac{T_{int} \cdot I_{dark}}{q}. \end{array}\right\} \tag{12}$$

At the same time, we assume that $a_i = const$; $i = (1, 5)$.

If the sums in (6) and (7) are conditionally changed to integrals, then taking into account (10), the following functional can be formed

$$F_1 = \int_{R_{min}}^{R_{max}} \left[\frac{[a_1(S^2 - a_2) + a_3] \cdot a_4}{R^2} + a_5 \right] dR. \tag{13}$$

Similarly, taking into account (11), we form the following functional

$$F_2 = \int_{R_{min}}^{R_{max}} \left[\frac{a_1 \cdot S^2 a_4}{R^2} + a_5 \right] dR. \tag{14}$$

Taking into account (9) and (14), we form the following target functional of unconditional variational optimization

$$F_3 = \int_{R_{min}}^{R_{max}} \left[\frac{a_1 \cdot S^2 a_4}{R^2} + a_5 \right] dR + \lambda \left[\int_{R_{min}}^{R_{max}} S(R) dR - C \right]. \tag{15}$$

The analysis based on the Euler-Lagrange equation [17] allows us to conclude that the minimum F_3 appears when the condition is met

$$\frac{2a_1 a_4 S(R)}{R^2} + \lambda = 0. \tag{16}$$

From (16) we find:

$$S(R) = \frac{-\lambda R^2}{2a_1a_4}. \tag{17}$$

Taking into account (9) and (17), we obtain

$$-\int_{R_{min}}^{R_{max}} \frac{-\lambda R^2}{2a_1a_4} dR = C. \tag{18}$$

From (18) we find

$$\lambda = -\frac{C}{\frac{R^3_{max} - R^3_{min}}{6a_1a_4}}. \tag{19}$$

Taking into account (17) and (19), we obtain

$$S(R) = \frac{3CR^2}{(R^3_{max} - R^3_{min})}. \tag{20}$$

Thus, when solving (20), the functional F_4 reaches a minimum, since the derivative (16) with respect to $S(R)$ turns out to be a positive value.

Consequently, the application of control (20) to the functional F_3 can lead to an increase in the signal-to-noise ratio calculated by the formula (8).

Let's estimate the gain in the signal-to-noise ratio when using control (20) to calculate F_3. If there is no such control, we estimate the difference $\Delta F = F_1 - F_2$ as

$$\Delta F = \int_{R_{min}}^{R_{max}} \frac{a_3a_4 - a_1a_2a_4}{R^2} dR. \tag{21}$$

The corresponding difference in the proposed method is defined as

$$\Delta F_{pr} = \int_{R_{min}}^{R_{max}} \frac{a_1 S(R)^2 a_4 - a_1a_2a_4 + a_3a_4}{R^2} dR - \int_{R_{min}}^{R_{max}} \frac{a_1a_4}{R^2} \cdot \frac{9C^2R^4}{(R^3_{max} - R^3_{min})^2} dR. \tag{22}$$

Taking into account (21) and (22), the gain in the proposed method δ is defined as

$$\delta = \Delta F_{pr} - \Delta F = a_1a_4 \times \times \left[\int_{R_{min}}^{R_{max}} \frac{S(R)^2}{R^2} dR - \int_{R_{min}}^{R_{max}} \frac{9C^2R^4}{(R^3_{max} - R^3_{min})^2 R^2} dR \right]. \tag{23}$$

From (23) we obtain the following winning condition

$$S(R) > \frac{3CR^2}{R^3_{max} - R^3_{min}}. \tag{24}$$

Therefore, based on conditions (23) and (24), it can be concluded that in the proposed method of push-pull measurements of stealth aircraft using a group of satellites located at different altitudes, a real gain in the value of the signal-to-noise ratio is possible.

We will conduct model studies to calculate the threshold value of spatial resolution, when exceeded, there is a gain in the signal/noise ratio. Calculate the values of the constant C.

According to (9) we have

$$C = (R_{min} \div R_{max}) \cdot \left[S_{min} + \frac{(S_{max} - S_{min})}{2} \right]. \tag{25}$$

We conditionally assume

$$R_{max} - R_{min} = 100\,\text{km} = 100 \cdot 10^3\,\text{m},$$

$$S_{min} + \frac{(S_{max} - S_{min})}{2} = 1\,\text{m}.$$

In this case we get

$$C = 100 \cdot 10^3\,\text{m}.$$

Take:

$$R_{max} = 200\,\text{km}; \; R_{min} = 100\,\text{km}. \tag{26}$$

For $R = 150\,\text{km}$ we get

$$S(R) > \frac{3C \cdot 2,25 \cdot 10^4 \cdot 10^3}{R^3_{max} - R^3_{min}}. \tag{27}$$

Taking into account (26) and (27) we get

$$S(R) > \frac{3 \cdot 100 \cdot 10^3 \cdot 2,25 \cdot 10^7}{(8 \cdot 10^6 - 10^6) \cdot 10^9} = = \frac{3 \cdot 100 \cdot 2,25 \cdot 10^{10}}{7 \cdot 10^{15}} = \frac{0,7 \cdot 10^{13}}{7 \cdot 10^{15}}\,\text{m} \approx 0,1\,\text{cm}.$$

Thus, even with a spatial resolution of more than 0.1 cm, a gain in increasing the signal-to-noise ratio is possible.

Conclusion

A push-pull method of detecting stealth aircraft using a group of satellites flying at different orbital altitudes is proposed. The purpose of the proposed method is to increase the signal-to-noise ratio when calculating an informative signal, which is the difference between the signal from the aircraft itself within the frame and the background signal within the frame. It is shown that the introduction of a binary control signal ensuring the constancy of spatial resolution in the range of the distance to the satellites ($R_{min} \div R_{max}$) allows minimizing the total background signal coming from a group of satellites. In this case, the control function has a binary character and can have both a decreasing and an increasing type. An increasing version of this function applied to the sum of signals from the background under a given restrictive condition leads to a decrease in the total background signal, which ultimately increases the signal-to-noise ratio in the system, and also increases the probability of detecting an aircraft using spectroscopic radiometric devices installed on satellites.

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Питання оптимізації виявлення стелс літаків із використанням групи орбітальних супутників

Агаєв Ф. Г., Асадов Х. Г., Алієва Г. В.

Стаття присвячена питанням оптимізації виявлення стелс літаків з використанням групи супутників, що знаходяться на різних висотах. Зазначено необхідність обчислення інфрачервоної сигнатури стелс. Основними джерелами формування інфрачервоної сигнатури стелс літаків є нагрівання кожуха літака при польоті та високотемпературний шлейф, що виходить із сопла двигуна. Інфрачервона сигнатура таких літаків зазвичай обчислюється у широких діапазонах ІЧ хвиль. Разом з тим, існують роботи, згідно з якими з цією метою доцільно використовувати вузькоспектральні довжини хвиль. Розроблено двотактовий метод виявлення стелс літаків за допомогою супутників, що знаходяться у групі на різних орбітальних висотах. Пропонований метод дозволяє збільшити відношення сигнал/шум в результуючому різницевому інформативному сигналі, отриманому з урахуванням сигналу від літака і фонового сигналу в межах кадру. Запропоновано бінарну функцію управління, яка є залежністю просторового дозволу зображувальної системи супутників від відстані між літаком і супутниками. Розглядається випадок, коли на цю функцію накладено певне інтегральне обмеження. Показано, що введення бінарного керуючого сигналу залежності просторового дозволу від відстані до супутників дозволяє мінімізувати сумарний фоновий сигнал, що надходить від групи супутників. При цьому зростаючий варіант цієї функції, що застосовується до суми сигналів від фону, підвищує відношення сигнал/шум в системі та ймовірність виявлення стелс літака за допомогою спектрометричних пристроїв, встановлених на супутниках.

Ключові слова: стелс літак; виявлення; груповий політ; оптимізація; функція контролю; цільова функціональність