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Solution and Optimization of Aircraft Swarm Cooperating Anti-Stealth Formation Configuration

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ABSTRACT There are many problems in present anti-stealth detection technologies, such as small detection range and excessive detection blind zone. Besides, the stealth target is difficult to be detected and tracked with current technology. To solve these problems, this paper presents a novel anti-stealth method that is based on the thought of swarm and makes use of the more flexible airborne platform to generate and change formation configuration. First, the cooperative anti-stealth airspace coverage model of aircraft swarm is established, and an improved airspace coverage solution method is proposed. Second, four evaluation indexes and effective detection airspace are defined, meanwhile, the optimization objective function is obtained by using the weighted sum. Third, based on the study of the one transmitter and one receiver configuration, we optimize the 1TnR spatial configuration by using the rule-searching strategy and particle swarm optimization algorithm. Finally, the effectiveness of the proposed model and the feasibility of the algorithm are verified by simulation examples.

INDEX TERMS Aircraft swarm, anti-stealth, formation configuration, particle swarm optimization.

I. INTRODUCTION

In the future swarm combat, the confrontation between stealth and anti-stealth will be inevitable in the operation. Stealth fighter has already played an important role in several high-tech regional wars. The rapid development of stealth fighter represents a great challenge to the modern and future aerial warfare. Finding out a better way to detect enemy stealth fighter more effectively is crucial to dealing with the threats of stealth fighters. With the rapid development of new material, electronic information and plasma technology, the stealth capability of stealth fighter has been greatly improved. However, the development of anti-stealth early warning detection technology is lagging behind. What's worse, it has many defects, such as the small detection range and excessive detection blind zone. Besides, the stealth fighter is difficult to be detected and tracked with the current technology. To solve these problems, many research teams and scholars have done a lot of significant work. For example, the "Red Team" set out to study the anti-stealth technology and summed up 28 anti-stealth measures [1]. Meanwhile, some scholars have been studying the new technologies to improve the detection performance of radar, such as frequency-agility [2], [3], space time adaptive processing [4], digital filters [5] and broad time width of pulse compression [6], [7]. The above-mentioned technologies can improve the range and anti-jamming capability of radar, and greatly enhance the capacity to deal with stealth targets, e.g.; frequency-agility can quickly shift radar operating frequency to account for atmospheric effects, jamming, mutual interference with friendly sources, or to make it more difficult to locate the radar broadcaster through radio direction finding, and digital filtering technology can process the acquired signal, eliminate all kinds of interference appended to the data, and improve the anti-jamming ability of radar. While they also have flaws: the research takes too long time and is difficult to make a breakthrough in a short time. Afterwards, the rapidly developing of wireless network technology can provide system-level cross-linking information analogous to the single platform for spatially distributed discrete combat platforms, and then; the cross-platform sharing and flexible restructuring of sensors and weapons can be realized. Therefore, researchers began to shift their research efforts form the technical level to the tactical level. In this way, the operational efficiency can be greatly improved through the tactical application of some unconventional sensors. Ordinarily, these tactical methods include multistatic radars [8], [9], passive coherent location radars [10], electronic support measures passive sensors [11], multi-sensor networking detection [12], [13], and etc. The application of some unconventional sensors can help realize the cross-platform share and flexible restructuring of sensors and weapons to enhance the operational effectiveness, so changing the tactic to seek breakthroughs is also an effective measure to deal with the enemy stealth target. Although the above researches mainly focus on ground-based and sea-based radar, rarely involving air-based radar, the key technologies and methods involved in ground-based and sea-based research can provide the necessary theoretical basis and technical support for airborne radar tactical application research. Based on the above analysis, this paper presents a cooperative anti-stealth method for aircraft swarm from the tactical application perspective.

Aircraft swarm cooperating anti-stealth is a novel anti-stealth technology. It takes advantage of the more flexible capacity of airborne platform to generate and change formation configuration. Any members in the aircraft swarm can serve as the transmitter and others are the receivers. Then with the help of space diversity brought by bistatic airborne radar, the enemy stealth targets can be detected effectively by optimizing the spatial distribution of transmitter and receivers. At present, there are many achievements in the research of bistatic/multistatic radar anti-stealth, bistatic radar and optimal deployment of netted radar for reference, e.g., Sobhani [8] proposes a tracking algorithm based on particle filtering for UWB multistatic radars. This paper has illustrated how the proposed algorithm can provide high estimation accuracy even at low signal-to-noise ratios in the presence of either static or dynamic clutter, and how it can track even quite complicated manoeuvring target trajectories. In [14], the stealth target detection based on bistatic balloon-borne radar system is proposed by a novel KA-STAP-FTRAB algorithm to mitigate the heterogeneity of clutter with SN-SWDJ effect. The above two papers mainly focus on algorithm improvement, while the references [15] and [16] focus on specific applications. In [15], how to achieve perimeter barrier coverage with bistatic radar sensors has been studied. Wang *et al.* [16] have found out the minimum cost placement for constructing a belt barrier by bistatic radar sensors. Apart from that, a comprehensive work of stealth target detection based on predicting the real Radar Cross Section (RCS) of target, and TDOA technique is studied in balloon-borne platform with per-defined deployment of platforms [17]. In [18], a bistatic airborne radar system concept and three basic types of maneuver strategies of the swarm aircraft are put forward. The research results show that the detection area and the detection efficiency for stealthy targets can be enhanced by optimizing the geometry of multistatic radar or bistatic airborne radar. However, most of the above researches focus on the ground-based and sea-based radar platform. The position of those platforms is fixed, and few studies involve airborne bistatic radar, especially, the space configuration optimization of airborne bistatic radar. In addition, Mohamed and Peng [14] and Barbary and Zong [17] put forward a method of deploying the receivers on the balloon. This will inevitably lead to poor maneuverability and conversion capacity of spatial configuration despite the low cost. What's worse, it can only complete the single task. However, airborne bistatic radar has more flexible and agile spatial configuration generation and transformation capability. Besides, it can also change the space deployment of bistatic radar dynamically and adaptively according to the moving state of stealth target, which is more conducive to giving play to its capacity. The airborne platform can also participate in the follow-up attack mission. Therefore, it is more practical in battlefield and better than other anti-stealth technologies.

Based on the above discussion, this paper, firstly, reveals the defect that the RCS of the stealth fighter varies greatly in the distribution in different spatial directions, and explores the space configuration design of anti-stealth detection by using its own airborne radar to form a bistatic mode, which expands the detection space by connecting multiple bistatic radars. Then we use the rule-based search strategy and the standard particle swarm optimization algorithm to solve the optimal spatial layout of "*1TnR*". Finally, the effective detection of enemy stealthy target is achieved. The main contribution of this paper lies in the following threefold. (i) A basic conception of aircraft swarm cooperating anti-stealth is proposed, in addition, the cooperative anti-stealth airspace coverage model of aircraft swarm is established, and a modified method of calculating the airspace coverage area is proposed; (ii) Four evaluation indexes and effective detection airspace are defined, meanwhile, the optimization objective function is obtained by using the weighted sum; (iii) An optimization method of formation configuration based on rule-searching strategy is proposed. In this paper, "*1TnR*" is short for "one transmitter and n receivers", where n represents the number of receivers.

The rest of paper is organized as follows: Section II introduces the background and problem. In addition, a basic conception of aircraft swarm cooperating anti-stealth is also proposed in this section. In Section III, we build a space coverage model of aircraft swarm cooperating anti-stealth and present a modified method for calculating the airspace coverage area. Section IV describes the solution of "1*TnR*" formation configuration. The performance of proposed scheme is evaluated via computer simulation in Section V, followed by conclusion in Section VI.

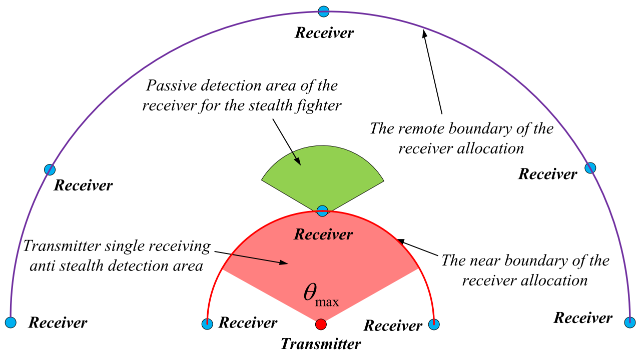


FIGURE 1. **The schematic diagram of the principle of aircraft swarms cooperative anti-stealth.**

II. BACKGROUND ASSUMPTIONS AND PROBLEM DESCRIPTION

A. BACKGROUND ASSUMPTIONS

Based on the literature [18], we make the assumption as follow: When the transmitter of our aircraft swarms boots up, suppose that the enemy stealth fighter can find our transmitter by the passive detection system but the distance between the enemy aircraft and our transmitter is beyond our radar detection range. In order to give full play to its stealth capacity, the enemy aircraft fly in the direction of the radar in our aircraft swarm, which is in the state of power-on, and get ready for missile launching. At the same time, in order to maintain the stealth performance of our aircraft swarm, the fewer radar transmitters in our swarm the better. Besides, in terms of security, the transmitter should be deployed in the rear of our aircraft swarm, and the frontend receiver should be in meditative state.

Based on the above assumption, and considering the maximum scan angle of the airborne radar $\theta_{\max}$, this paper takes the "*1TnR*" formation configuration as example and builds a space detection configuration of which the radar transmitter is situated in the center and the receivers are disposed in the front. The basic idea is shown in Fig.1.

In Fig.1, the red node stands for the transmitter, and the blue nodes are receivers. Any transmitter and receiver can constitute independent airborne bistatic radar, and the combination can be changed dynamically according to the operational situation. Accordingly, the radar system of aircraft swarm has good redundancy and reliability. Apart from that, because the front-end receivers are in meditative state, the bistatic radar system can not only expand the detection area enormously and control its radio frequency, but also protect the transmitter in the aircraft swarm. The red area before the transmitter in Fig.1 is the valid detection area of the radar to the stealth target when the radar is self-sending and self-receiving. The green area represents the detection area of the bistatic radar receiver to the stealth fighter. The radar receiver platform can be disposed in any place from the near boundary by setting the radar transmitter platform as a baseline to the far boundary. The near boundary is the farthest detection distance of the self-sending and self-receiving transmitter to the stealth fighter, which can ensure the expansion of detection range and the continuity of detection domain. The far boundary is defined as the maximum baseline distance when the bistatic radar composed of the transmitter and receiver can work effectively.

B. PROBLEM DESCRIPTION

The problem of aircraft swarm cooperating anti-stealth formation configuration can be summarized as follows: given the number of transmitter and receiver and their performance parameters, the optimal space position of transmitters and receivers is selected to maximize the effective detection efficiency of aircraft swarm radar. To tackle the problem of aircraft swarm cooperating anti-stealth formation configuration, three questions need to be answered: the first is how to calculate the coverage area of detecting airspace with different space layouts of transmitter and receivers; the second is how to define evaluating indicator function and the efficient coverage area of detecting airspace; and the last is how to develop the strategy to optimize the formation configuration of transmitter and receiver. In order to solve the above problems, we have done the following work: Firstly, a cooperative anti-stealth airspace coverage model of aircraft swarm is established and a modified method of calculating the airspace coverage area is proposed. Secondly, four evaluation indexes and the effective detection airspace are defined, and the multi-attribute optimization problem is transformed into the single-attribute problem by using the weighted sum. According to the tactical requirements, different weights are given and the optimization objective function is obtained. Finally, based on the study of the "*1T1R*" configuration, we use the rule-searching strategy and Particle Swarm Optimization algorithm to optimize the "*1TnR*" spatial configuration.

III. MODELING AND SOLUTION

A. THE SPACE COVERAGE MODEL OF AIRCRAFT SWARM COOPERATING ANTI-STEALTH

Without considering the attenuation of radar waves by the atmosphere, the bistatic radar equation is [19]:

$$(R_T R_R)^2_{\max} = \frac{P_T G_T G_R \lambda^2 \sigma_B F_T^2 F_R^2}{(4\pi)^3 P_{R\min}} \tag{1}$$

The constraints conditions of R_T and R_R are:

$$\begin{cases} |R_T - R_R| \le R_L \\ |R_T + R_R| \ge R_L \end{cases} \tag{2}$$

Where, R_T and R_R are the distance from transmitter and receiver to target range respectively, R_L presents the distance between the transmitter and receiver, P_T is the transmitted power, G_T and G_R are the transmit and receive antenna power gain respectively, λ is the transmitted signal wavelength, σ_B is the bistatic radar cross section, F_T and F_R are the transmit and receive propagation factor respectively, $P_{R\min}$ is the minimum detectable signal power. The stealth characteristic of stealth fighter is determined by σ_B; while the other parameters are determined by the airborne bistatic radar system and expressed as $B_{bistatic}$:

$$B_{bistatic} = \frac{P_T G_T G_R \lambda^2 F_T^2 F_R^2}{(4\pi)^3 P_{R\min}} \tag{3}$$

So the bistatic radar equation can be simplified as:

$$(R_T R_R)^2_{\max} = B_{bistatic} \cdot \sigma_B \tag{4}$$

While σ_B is the function of the attitude angles of the two stations [20]:

$$\sigma_B = \sigma(\alpha_T, \varphi_T, \alpha_R, \varphi_R) \tag{5}$$

Where α_T, φ_T, and α_R, φ_R are the azimuthal angle and elevation of transmitter and receiver, respectively.

Under the assumption of the basic concept, we think approximately that the illuminated wave of our airborne radar transmitter incident from the nose cone of the stealth fighter, so $\alpha_T = \varphi_T = 0$. In this case, we just need to get the spatial distribution of the bi-station RCS when the stealth fighter is irradiated by zero degree incident waves, then we can work out the RSC value by using the other prior information and calculation model. After determining the coordinates of transmitter and receiver, we can judge whether the stealth fighter can be detected by calculating the bistatic radar equation and then comparing the value of P_R and $P_{R\min}$.

Where, the power of target signal of the bistatic radar receiver is:

$$P_R = \frac{P_T G_T G_R \lambda^2 \sigma_B F_T^2 F_R^2}{(4\pi)^3 (R_T R_R)^2} \tag{6}$$

If $P_R \geq P_{R\min}$, we think that the enemy stealth fighter is detected, otherwise it is not detected. The detection space of airborne bistatic radar can be calculated by traversing the given airspace.

B. DETERMINATION OF EVALUATION INDEX PARAMETERS

Combining with the actual demand of aircraft swarm combat, S_F, T_{far}, R_{far}, and $W_{\max}$ are designed as the parameters of evaluating indicator. The specific definitions of the parameters are as follow:

Definition 1: $S_F = S_{\det ect} + S_{protect}$. Where, $S_{\det ect}$ is the net total area of the efficient detecting area of the bistatic radar, namely the part is the sum of all the detection area minus the overlap. $S_{protect}$ is the area without danger after examining and distinguishing the blind zone, which is located between the lower edge of the detection area of the connected bistatic radar and the top edge of the detection area of the transmitter. If the whole detection area of the aircraft swarm is regarded as a virtual "macro radar" detection area, since airborne radar moves forward, we can judge that the stealth fighter has been detected and tracked when passing through the detection area and before entering the airspace covered by the rear edge of the detection area. At the same time, in the process of transforming the dense flight configuration into the cooperative anti-stealth configuration, the bistatic radar has detected the airspace covered by the rear edge of the detection area. So the airspace covered by the rear edge boundary of the detection area can also be regarded as an effective anti-stealth protection area of the aircraft swarm radar. By using the boundaries of the detection area and the scanning angle of the radar space, the virtual "macro radar" position and the protected area can be calculated, and the discrimination of detection blind area is mainly determined by the criterion of detecting airspace connectivity.

Definition 2: Criterion of detecting airspace connectivity. If the minimum depth w of the overlapping area of two bistatic radar is $w \geq t_{trance\min} \cdot v_{T\max}$, then we consider the detection airspace is connected. Where, $t_{trance\min}$ is the minimum time needed for the bistatic radar from detecting the stealth fighter to forming steady flight path; $v_{T\max}$ is the maximum speed of the stealth fighter.

Definition 3: T_{far} is the maximum distance from the transmitter to the detection boundary.

Definition 4: R_{far} is the maximum distance from the receiver to the detection boundary.

Definition 5: $W_{\max}$ is the maximum width of the detection area formed by the bistatic radar.

S_F, T_{far}, R_{far}, and $W_{\max}$ have different emphases. Where, the larger S_F, the stronger capacity to defense the stealth fighter effectively. Besides, our capacity to anticipate the enemy can be enhanced. In addition, with the increase of T_{far} and R_{far}, the transmitter and receiver are more difficult to be found and attacked, thus the viability is improved; Meanwhile, the larger $W_{\max}$, the wider the detection barrier of stealth fighters can be formed, which is more conducive to the effective detection of stealth fighters and enhance the detection efficiency.

Definition 6: In order to better measure the optimization effects of aircraft swarm formation configuration, we use aggregative indicators to define detection effect of aircraft swarm to the stealth fighter with the certain formation configuration:

$$\begin{cases} F = \omega_1 \cdot \dfrac{S_F}{S_{all}} + \omega_2 \cdot \dfrac{T_{far}}{L_{all}} + \omega_3 \cdot \dfrac{R_{far}}{L_{all}} + \omega_4 \cdot \dfrac{W_{max}}{X_{max} - X_{min}} \\ S_{all} = (X_{max} - X_{min}) \cdot (Y_{max} - Y_{min}) \\ L_{all} = \sqrt{(X_{max} - X_{min})^2 + (Y_{max} - Y_{min})^2} \end{cases} \tag{7}$$

Where, $\omega_1, \omega_2, \omega_3$, and ω_4 are the proportion of, S_F, T_{far}, R_{far}, and $W_{\max}$ in the integrated effectiveness evaluation of aircraft swarm anti-stealth detection as a whole, besides they satisfy $\sum_{i=1}^{4} \omega_i = 1$, their values are determined by the requirements of specific tactical.

We expect that the detection space formed by n bistatic radars is connected, rather than decentral. Apart from that, it must comply with the practical tactics. For these reasons, this paper defines the effective spatial configuration.

Definition 7: The effective spatial configuration means that, in order to ensure the security of transmitter and receiver, it maximizes the detection efficiency by combining the demand of tactics. Generally speaking, two constraint conditions should be satisfied:

(i) The detection airspace formed by n bistatic radars is connected, and there is no blind zone between them.

(ii) In order to increase the detection probability to the stealth fighter, the detection area should be as large as possible. At the same time, to ensure the security of transmitter and receiver, T_{far}, R_{far}, and $W_{\max}$ must be greater than a critical value. That is:

$$\begin{cases} T_{far} \geq \xi_1 \\ R_{far} \geq \xi_2 \\ W_{max} \geq \xi_3 \end{cases} \tag{8}$$

Where, ξ_1 is determined by the maximum range of the weapons carried by the enemy stealth fighter; while ξ_2 is determined by both the active detection range of the enemy stealth fighter and the weapons it carried. ξ_3 is determined by the maximum active radius when the enemy stealth fighter is maneuvering.

Based on the above analysis, when the detection efficiency of aircraft swarm cooperating to stealth fighter reaches the maximum, the spatial distribution of the transmitter and receivers is optimal, thus the problem of the optimization of "*1TnR*" formation configuration can be described as follow:

$$\begin{aligned} &(P_{T.opt}, P_{R1.opt}, \ldots, P_{Rn.opt}) \\ &\quad = \underset{P_{T.opt}, P_{Tj.opt} \in D}{\arg \max} F \\ &\quad st. \begin{cases} T_{far} \geq \xi_1 \\ R_{far} \geq \xi_2 \\ W_{max} \geq \xi_3 \end{cases}, \quad \sum_{i=1}^{4} \omega_i = 1 \end{aligned} \tag{9}$$

Where, $P_{T.opt}$ and $P_{Rj.opt}$ $(j = 1, 2, \ldots, n)$ stands for the optimal positions of transmitter and receivers. The equation means that: in the area D corresponding to the constraint condition of position, we search for the positions of transmitter and receivers, which maximize the detection efficiency of aircraft swarm cooperating to stealth aircraft. Then the optimized spatial configuration is obtained.

C. FILE FORMATS FOR GRAPHICS

Since the space distribution of bistatic RCS of the enemy stealth fighter is uncertain, the detection airspace is difficult to get with the bistatic radar equation. Therefore, based on the literature [21] and [22], this paper proposes a modified method to calculate the two-dimensional detection aircraft of the bistatic radar. Based on the subdivision grid cutting method, this method takes the problem of determining the spatial connectivity of multiple bistatic radars and the limit to the maximum scanning angle of transmitter radar into account. The specific calculation steps are shown in Fig.2:

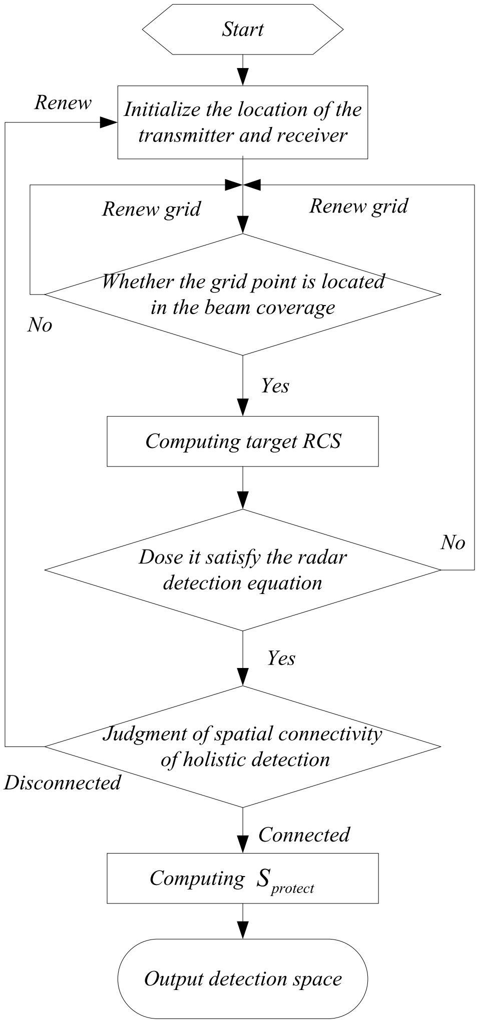


FIGURE 2. Flow chart for detecting space domain.

Suppose the warning airspace is Ω_S, the range is $[X_{min}, X_{max}] \times [Y_{min}, Y_{max}]$, discretize it to the grid cell $\Delta x \times \Delta y$. The area of every cell is denoted by ΔS, the number of the grid in the x and y direction are N_x and N_y. Thus the coordinate Q of the central point in any grid cell is $(X_{\min} + i_x \Delta x + \Delta x/2, Y_{\min} + i_y \Delta y + \Delta y/2)$, where, $0 \leq i_x \leq N_x$, $0 \leq i_y \leq N_y$. Taking the transmitter as origin of coordinate to build a two-dimensional coordinate department, shown as Fig.3 (for the sake of argument, only the graph in the first quadrant is drawn up.), the coordinate of the receiver i is (x_{Ri}, y_{Ri}), the maximum scan angle of the antenna is $\theta_{\max}$ and the minimum receiver's power is $P_{R\min}$.

Step1: Judging whether the target point $Q_k(x_k, y_k)$ is in Ω_1, the coverage area of the beam from the transmitter and receivers.

If $\arctan \frac{x_k}{y_k} \leq \frac{\theta_{max}}{2}$, $\arctan \left| \frac{x_k - x_{Ri}}{y_k - y_{Ri}} \right| \leq \frac{\theta_{max}}{2}$ *and* $y_k > y_{Ri} \geq 0$, *then* $Q_k \in \Omega_1$ *else* $Q_k \notin \Omega_1$.

Step2: calculation of RCS.

Firstly, calculating β_k, the bistatic angle between transmitter and receiver.

$$\beta_k = ar\cos \frac{(x_k^2 + y_k^2) + (x_k - x_{Ri})^2 + (y_k - y_{Ri})^2 - (x_{Ri}^2 + y_{Ri}^2)}{2\sqrt{(x_k^2 + y_k^2)((x_k - x_{Ri})^2 + (y_k - y_{Ri})^2)}} \tag{10}$$

Then, according to the prior information, the stealth fighter model is discriminated, and the RCS value is obtained by

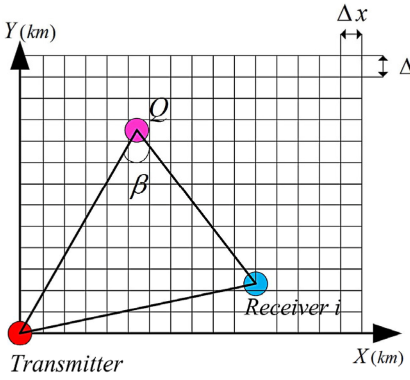


FIGURE 3. Grid division on the bistatic radar plane (the first quadrant in this case).

searching the bistatic radar RCS database based on the value of β_k.

Remark 1: The present analog computation of RCS and the near-field Testing Technology can absolutely support to build the date base of bistatic RCS that corresponds to different models of aircraft, for more details, refer to the literature [23]–[25].

Step3: Judging whether or not the object point $Q_k(x_k, y_k)$ can be detected.

The formula (11) can be obtained combining (6):

$$P_k = \frac{P_T G_T G_R \lambda^2 \sigma_B F_T^2 F_R^2}{(4\pi)^3 (x_k^2 + y_k^2)((x_k - x_{Ri})^2 + (y_k - y_{Ri})^2)} \tag{11}$$

If $P_k \geq P_{R\min}$, then Q_k can be detected and the detection area is $\Delta x \Delta y$.

The connectivity of the detection area can be judged by using the adjacency matrix L. According to Definition 2 and the connectivity criterion of graph, the $1 \times n$ dimension adjacency matrix L formed by the connection relation between two parts in the detection area of "1*TnR*" aircraft radar can be obtained. Let $\Upsilon = \sum_{p=1}^{n-1} L^p$, If all the elements in the matrix Υ are nonzero elements, then, the detection area of swarm is connected. If there is a zero element in the matrix Υ, then the detection area is unconnected.

IV. SOLUTION AND OPTIMIZATION OF FORMATION CONFIGURATION

In essence, the optimization of "*1TnR*" formation configuration can be regarded as the problem of the optimization deployment. Focusing on this issue, scholars have proposed many effective solutions, and the most representative one is using intelligent optimization algorithm. However, the intelligent optimization algorithm has its defects. For instance, its results are unstable and easily trapped in local extreme points. Besides, the algorithm is not suitable for engineering applications. In order to cope with these problems effectively, this paper proposes an optimization method of formation configuration based on rule-searching strategy. Firstly, we use the improved method to calculate the airspace of airborne bistatic radar of "*1TnR*". Secondly, by changing the relative distance and azimuth between the receiver and transmitter, the influence and laws of these two factors on the detection efficiency of stealth fighter is found. Then we sum up the basic configuration rules of the transmitter and receiver. Thirdly, according to the rules, the optimal solution area is screened out. Finally, with the help of particle swarm optimization algorithm, we use the rules as the inducement factor of particle optimization to guide the particle to search for the optimal solution and improve the probability of obtaining the stable optimal solution. In this way, we can realize the optimization of the spatial configuration of the "*1TnR*".

A. OPTIMIZATION RULE EXTRACTION OF "1T1R" FORMATION CONFIGURATION

Based on the above model, we use the improved method to calculate the airspace of airborne bistatic radar of "*1T1R*". At the same time, considering the four indexes of S_F, T_{far}, R_{far}, and $W_{\max}$, we can get the variation trend of each index, when they change with the azimuth of receiver relative to transmitter and the baseline distance between transmitter and receiver. The corresponding figures are Fig.4 (a), Fig.4 (b). The calculation parameters of detection airspace are set as follow: the detection airspace $\Phi = 400km \times 400km$, the performance parameter of bistatic radar $Bi = 3.2552e + 004$, step length of segmentation grid unit is $\Delta x = \Delta y = 2km$, the head-on targets RCS $sigma_0 = 0.0069$, The radius of detection from the nose of transmitter R_S can be estimated by equation as follow:

$$R_S = \sqrt{Bi \times \sqrt{sigma_0}} \approx 52km \tag{12}$$

The data of RCS is from literature [26].

Remark 2: The horizontal ordinate in Fig.4(a) stands for changes of the receiver's azimuth, while that in Fig.4(b) represents the ratio of baseline distance to the detection radius of transmitter when it sends and receives by itself. And the longitudinal coordinate stands for the ratio of each index to the corresponding index of the self-sending and self-receiving transmitter. In addition, S, T, R, W in Fig.4 refer to the ratio of S_F, T_{far}, R_{far}, $W_{\max}$, respectively.

From Fig.4(a): When the baseline distance is constant, S_F, R_{far}, and $W_{\max}$ decrease with the increase of azimuthal angle of the receiver, with T_{far} almost unchanged; however, in Fig.4(b), when the azimuthal angle of receiver is constant, four evaluation indicators increase with the increase of baseline distance. And, when the baseline distance increases to five times, differences have arisen. The most noteworthy feature is that the detection area decreases dramatically. So the anti-stealth detection efficiency can be greatly enhanced by optimizing the layout of transmitter and receiver reasonably. Besides, during the process of optimizing "1*TnR*" formation configuration, we should balance each index and can't go exclusively after the maximum of a certain index at the expense of other indexes. This has also strengthened the rationality of Definition 6. From the analysis of the simulation

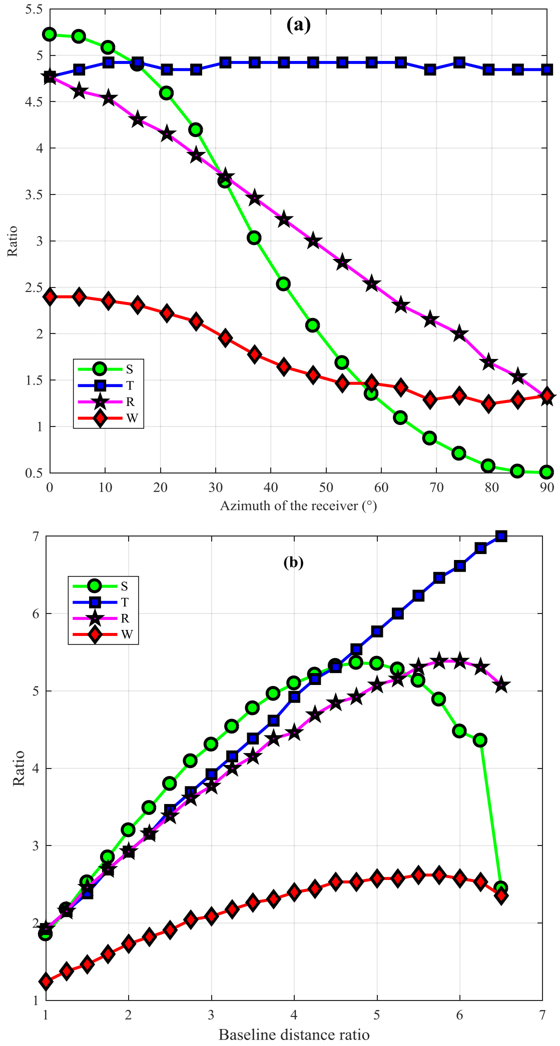


FIGURE 4. The variation tendency of four evaluation indicators.

result, when there is only one transmitter and one receiver in the aircraft swarm, the basic configuration rules of transmitter and receiver are as follow:

Rule 1: The Receiver should be disposed before the transmitter, in order to maximize the swarm detection area, and protect the receiver to defeat enemy anti-stealth fighter.

Rule 2: The receiver should not be in the front area of the transmitter.

Rule 3: The distance between the transmitter and receiver should meet the following constraint:

$$R_S \le R_L \le 6R_S \tag{13}$$

Where, R_S is the detection distance when the transmitter sends and receives by itself.

Rule 4: The receiver should be disposed in, $[0, (\pi - v_{\max})/2)$, $((\pi + v_{\max})/2, \pi]$ of the both wings of transmitter, in order to enlarge the overall detection area of the aircraft swarm, the detection distance and the maximum width of the detection area as much as possible.

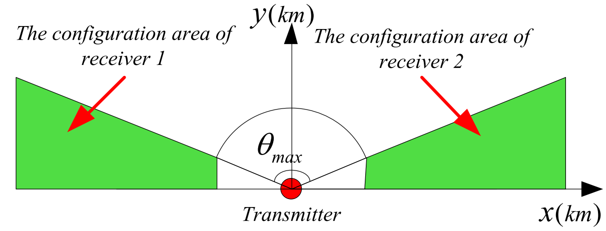


FIGURE 5. Receiver configuration area diagram.

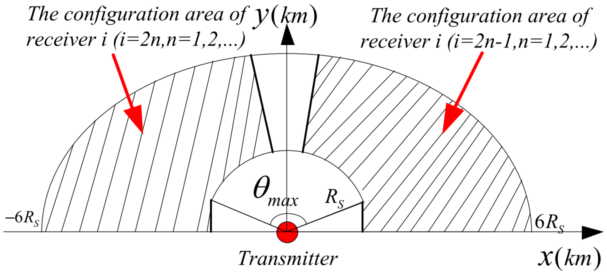


FIGURE 6. Receiver *i* configuration area diagram.

B. SOLUTION AND OPTIMIZATION OF "1T1R" FORMATION CONFIGURATION

Standard particle swarm algorithm [27] is a modified algorithm with inertia weight ω. It can balance global search capability and local search capacity. In order to improve the stability of the algorithm, we propose an improved particle swarm optimization algorithm based on rule search by calculating the airspace of airborne bistatic radar with "*1T1R*". The improved particle swarm optimization algorithm is hereafter referred to as RPSO, and the standard particle swarm algorithm PSO. The solution process of RPSO is shown as follow:

Step1: The number of particles in initialization group is N, particle dimension is D, Maximum Iterations $T_{\max}$, positive constants c_1 and c_2, the maximum value of inertia weight $w_{\max}$ and the minimum value $w_{\min}$, the maximum value of location $L_{\max}$ and the minimum value $L_{\min}$, maximum speed $V_{\max}$ and minimum speed $V_{\min}$.

Step2: Taking Rule 1-4 as basis to determine the spatial range of the particle motion:

(i) When $n = 2$

By taking the transmitter as the origin and building a rectangular coordinate system, we can obtain the area coverage to deploy the two receivers, which is shown in Fig.5:

The constraint of two receivers' configuration area is shown as follow:

$$Receiver1\begin{cases}5\pi/6 \le \theta_1 \le \pi\\ R_s \le r_1 \le 6R_s\\ x_1 = r_1 \cdot \cos\theta_1\\ y_1 = r_1 \cdot \sin\theta_1,\end{cases}\qquad Receiver2\begin{cases}\pi/6 \le \theta_2 \le \pi/2\\ R_s \le r_2 \le 6R_s\\ x_2 = r_2 \cdot \cos\theta_2\\ y_2 = r_2 \cdot \sin\theta_2\end{cases}$$

(ii) When $n > 2$

By taking the transmitter as the origin and building a rectangular coordinate system, we can use the shadow in Fig.6 to show the area to deploy the receiver. Where, the two arcs corresponds with the near boundary (R_S) and the far boundary ($6R_S$) in the basic conception. Then we can guide the different particles to search around the area that the optimum solution is in. So the stability of the algorithm can be improved.

The constraint of receiver i configuration area is as follows:

$$\underset{i=2n-1}{\text{Receiver } i}\begin{cases} 0 \le \theta_i \le 17^{*}\pi/36 \\ R_s \le r_i \le 6R_s \\ x_i = r_i \cdot \cos\theta_i \\ y_i = r_i \cdot \sin\theta_i \end{cases}, \quad n = 1, 2, \ldots$$

$$\underset{i=2n}{\text{Receiver } i}\begin{cases} \dfrac{19^{*}\pi}{36} \le \theta_i \le \dfrac{\pi}{2} \\ R_s \le r_i \le 6R_s \\ x_i = r_i \cdot \cos\theta_i \\ y_i = r_i \cdot \sin\theta_i \end{cases}, \quad n = 1, 2, \ldots$$

Step3: Set adaptive function as F and the particle position and velocity in initialization population as x and v. The optimal position and optimal value of individual particle are p and p_{best}, The optimal position and optimal value of the global particle are g and g_{best}.

Step4: Firstly, update the values of p, p_{best}, g, and g_{best}. Secondly, calculate the dynamic inertia weight ω. Thirdly, update the values of x and v. Finally, deal with the boundary condition. The detailed process is as follows:

Step4.1: Update the values of p and p_{best}, and if the fitness value of particle swarm is superior to p_{best}, then p_{best} is set as the new location and we record the local optimal value $f_{p_{best}}$.

Step4.2: Update the values of g and g_{best}, and if the fitness value of particle swarm is superior to g_{best}, then g_{best} is set as the new location and we record the global optimal value $f_{g_{best}}$.

Step4.3: Calculate the value of $\omega = w_{\max} - \frac{(w_{\max} - w_{\min}) \times t}{T_{\max}}$, where t is the current iterations.

Step4.4: Update the values of x and v according to the formula (14) and (15).

$$v_{id}^{t+1} = wv_{id}^{t} + c_1 rand()(p_{id}^{t} - x_{id}^{t}) + c_2 rand()(p_{gd}^{t} - x_{id}^{t}) \tag{14}$$

$$x_{id}^{t+1} = x_{id}^{t} + v_{id}^{t+1} \tag{15}$$

Step4.5: Deal with the boundary conditions according to the following code:

```
$for\ i = 1 : D$
    $if\ (v(:, i) > V_{\max}(i)) \| (v(:, i) < V_{\min}(i))$
    $v(:, i) = rand^{*}(V_{\max}(i) - V_{\min}(i)) + V_{\min}(i)$
    $end$
    $if\ (x(:, i) > L_{\max}(i)) \| (x(:, i) < L_{\min}(i))$
    $x(:, i) = rand^{*}(L_{\max}(i) - L_{\min}(i)) + L_{\min}(i)$
    $end$
$end$
```

Step5: Judging whether the end condition is satisfied. If $t \ge T_{\max}$, then the search process is finished and we output the global optimum; and if not, then the iterative optimization will continue.

V. THE SIMULATION DESIGN AND ANALYSIS

In order to verify the validity and practicability of the model and algorithm, the following experiments are designed in this paper. Firstly, we use Traversal and RPSO algorithm to optimize the formation configuration of "*1TnR*" to verify the validity and practicability of the model and algorithm we proposed. Then, we proved that RPSO can get a better and more stable solution compared with PSO when solving the spatial configuration of "*1TnR*". The experimental environment and parameters are set as follows:

(i) The experimental environment: All algorithm codes are programmed in M language and run on the Matlab R2017a platform. The physical platform is Lenovo desktop with basic frequency of CPU 2.60GHz, 4G EMS memory, Windows 7 64-bit.

(ii) Initialization of detection airspace calculation parameters is the same as Section 4.1.

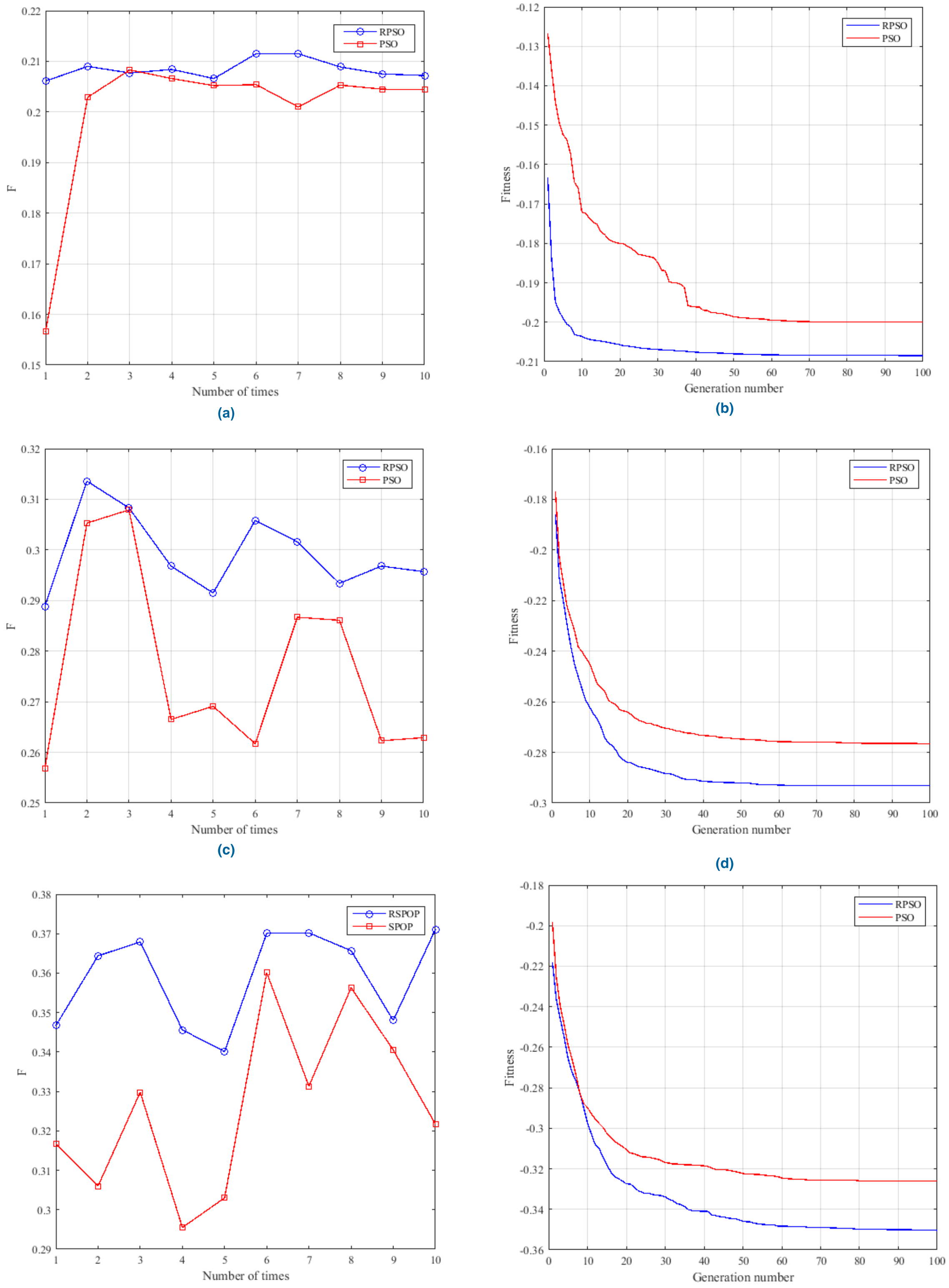
(iii) Parameters setting of RPSO and PSO: Particle number N = 50, particle dimension D = $2m$ (m is the number of receivers), maximum iterations $T_{\max} = 100$, positive constants $c_1 = c_2 = 1.49445$, maximum inertia weight $w_{\max} = 0.8$ and the minimum $w_{\min} = 0.4$, the weight in fitness function F is $\omega_1 = 0.8$, $\omega_2 = \omega_3 = 0.05$, $\omega_4 = 0.1$.

A. EXPERIMENT 1: VERIFY THE EFFECTIVENESS OF THE PROPOSED MODEL AND ALGORITHM

Firstly, we use traversal algorithm to traverse in the area from the near boundary to the far boundary in Fig.1 to determine the optimal formation configuration of "*1TnR*" (this process is recorded as Traversal 1). Then, we use traversal algorithm again to traverse in the limited area in Fig.5 and Fig. 6 to determine to the optimal formation configuration of "*1TnR*" (this process is recorded as Traversal 2). Where, when $n = 2$, Set the step length as: $\Delta r = 10km$, $\Delta\theta = 5°$; When $n > 2$, Set the step length as: $\Delta r = 30km$, $\Delta\theta = 20°$. In addition, we use RPSO algorithm to find the optimal formation configuration of "1*TnR*". The solution result is shown as Table 1.

Remark 3: (, *) stands for the coordinate of the receiver in the two dimensional coordinate system in which sets the transmitter as the origin. F is the object function in (7), Time is the time consumed in computation. In addition, when n > 3, the traversal algorithm takes a long time, so no simulation is carried out.*

From Table 1, Traversal 1 and Traversal 2 have the same optimization results, and Traversal 2 is faster and its efficiency of search is higher. The result proves that the space area of the optimal solution determined by Rule 1-4 is effective, and the rule is valid. In addition, RPSO can take just a little time to get a better solution, which proves the superiority of intelligent algorithm in solving this kind of complex problem. And it also proves the effectiveness of the proposed algorithm.



(a)

(b)

(c)

(d)

(e)

(f)

FIGURE 7. **Comparison diagram of evolutionary curves of objective function and mean fitness. (a) The objective function of "*1T2R*". (b) The average fitness evolution curve of "*1T2R*". (c) The objective function of "*1T3R*". (d) The average fitness evolution curve of "*1T3R*". (e) The objective function of "*1T4R*". (f) The average fitness evolution curve of "*1T4R*".**

B. EXPERIMENT 2: COMPARISON OF RPSO AND PSO

In order to prove that the optimization of intelligent algorithm guided by the rule search strategy is better than that of the ordinary intelligent algorithm when solving the "*1T*n*R*" space configuration, we design the following experiments: Firstly, we use RPSO and PSO to solve the "*1T*n*R*" space

TABLE 1. **The solution result.**

<table>
<tr><th>n</th><th>Algorithm</th><th>Receiver1</th><th>Receiver2</th><th colspan="2">F</th><th>Time</th></tr>
<tr><td rowspan="3">2</td><td>Traversal 1</td><td>(232,0)</td><td>(-232,0)</td><td colspan="2">0.208</td><td>4.735 h</td></tr>
<tr><td>Traversal 2</td><td>(232,0)</td><td>(-232,0)</td><td colspan="2">0.208</td><td>1650 s</td></tr>
<tr><td>RPSO</td><td>(220.914, 16.046)</td><td>(-221.002, 15.990)</td><td colspan="2">0.211</td><td>274 s</td></tr>
<tr><td rowspan="4">3</td><th>Algorithm</th><th>Receiver1</th><th>Receiver2</th><th>Receiver3</th><th>F</th><th>Time</th></tr>
<tr><td>Traversal 1</td><td>(-200.91, 116)</td><td>(29.867, 169.387)</td><td>(274.39, 99.87)</td><td>0.27</td><td>21.45 1 h</td></tr>
<tr><td>Traversal 2</td><td>(29.867, 169.387)</td><td>(-200.91, 116)</td><td>(274.39, 99.87)</td><td>0.27</td><td>2.681 h</td></tr>
<tr><td>RPSO</td><td>(51.674, 180.608)</td><td>(-217.61, 126.981)</td><td>(280.642, 133.76)</td><td>0.31</td><td>289 s</td></tr>
</table>

Remark3：(,*) stands for the coordinate of the receiver in the two dimensional coordinate system in which sets the transmitter as the origin. F is the object function in (7), Time is the time consumed in computation. In addition, when* $n > 3$ *, the traversal algorithm takes a long time, so no simulation is carried out.*

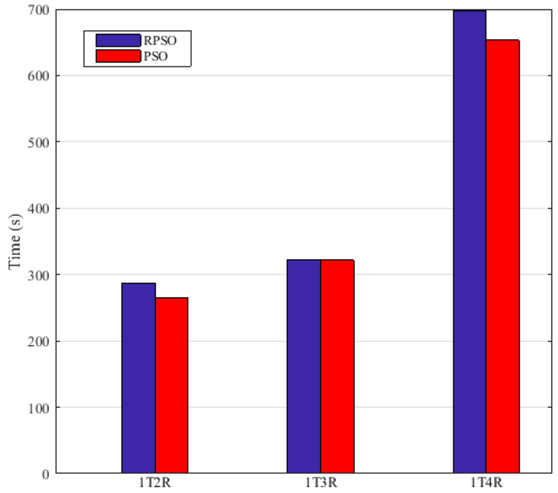


FIGURE 8. **Comparison of average time consumption.**

configuration respectively, and each algorithm runs 10 times. Then, the results are recorded. Finally, we compare and analyze the simulation results through mathematical statistics. Where, Comparison diagram of evolutionary curves of objective function and mean fitness are shown in Fig. 7, and the average time cost in calculation is shown in Fig. 8.

From Fig.7 (a), (c) and (e), we can draw the conclusion that RPSO can get a better object solution. Besides, its fluctuation range of 10 times is smaller, so the stability of RPSO is better. From the comparison of Fig.7 (b), (d) and (f), we find that the convergence rate of RPSO is faster and it begins to converge from the 20th iteration when solving the configuration of "*1T2R*", while, the convergence rates of RPSO and PSO are almost the same when the number of receiver is 3 and 4. From Fig.8: RPSO takes more time than PSO, for the reason that RPSO uses heuristic search based on the rules. So, in the process of searching, RPSO costs more time to handle more boundaries and judge whether the rule could be satisfied; while PSO adopts the random search strategy and the searching process of particle is random and there is no need to judge the rule, so the solution obtained is more

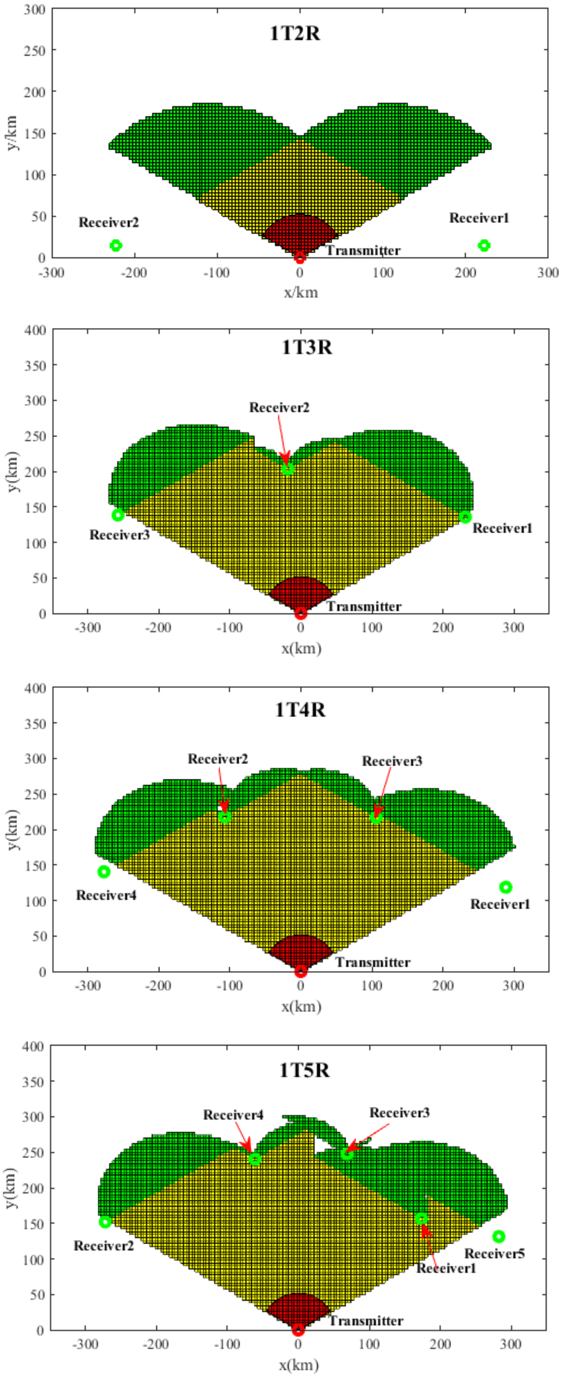


FIGURE 9. **The optimal formation configuration of "*1TnR*".**

random and its stability is poor. In addition, since the main target of this paper is to get the best and most stable formation configuration of "*1TnR*", time consumption is not the key performance indicator, not to mention that the difference in time consumption is only 20s. In summary: the RPSO algorithm proposed in this paper is more stable and better. The result also provides a new idea for the improvement of intelligent algorithm, i.e., starting with solving simple problems, we extract some general rules and further use them

TABLE 2. The simulation result.

1*TnR*	S_F /km^2	T_{far} /km	R_{far} km	$W_{\max}$ /km
n=2	48656	264	324,324	456
n=3	87712	336	216,120,220	508
n=4	102496	352	320,124,132,284	588
n=5	104160	352	240,296,104,104,336	572

Remark5：＊，＊，＊is R_{far} of the receiver i, e.g., 324,324 stands for R_{far} of receiver 1 and receiver 2 are 324km and 324km respectively.

to solve complex problems, so to a certain extent, the defects of poor stability of intelligent algorithm can be overcome. Finally, we use RPSO to get the "*1TnR*" configuration, which is shown in Fig. 9, and the simulation results are shown in Table 2.

Remark 4: The red node represents the transmitter; the red area is the detection range of the "Self-sending and Self-receiving" transmitter; the green node represents the receiver; the green area is the detection range of the bistatic radar composed of transmitter and receiver; and the yellow represents the protected area.

*Remark 5: *, *, * is R_{far} of the receiver i, e.g., 324,324 stands for R_{far} of receiver 1 and receiver 2 are 324km and 324km respectively.*

According to Fig.9 and Table 2, in the design of the aircraft swarm cooperating anti-stealth formation configuration, when the quantity, power and capability are fixed, increasing the number of receivers is conducive to the increase of S_F, T_{far}, R_{far}, and $W_{\max}$. But for aircraft swarm cooperating anti-stealth detection in "*1TnR*", the anti-stealth detection effect tends to be saturated when the number of receivers increases to a certain number. So when the number of transmitters is fixed, the number of cooperative receivers should also be limited. Generally, "*1T4R*" can achieve a better cooperative anti-stealth detection effect.

VI. CONCLUSION

This paper begins with the defect that the RCS of the stealth fighter varies greatly in the distribution in different spatial directions, and explores the space configuration design of anti-stealth detection by using its own airborne radar to form a bistatic mode, which connects the detection space with multiple bistatic radars. Then, we use the rule-based search strategy and the standard particle swarm optimization algorithm to get the optimal spatial layout of "*1TnR*". Finally, the effective detection of enemy stealthy targets is achieved. The simulation results show that:

(1) By optimizing of space configuration of transmitter and receiver, the capability of anti-stealth detection can be greatly improved. Therefore, the rationality of the basic concept of cooperative anti-stealth and the validity of the space coverage model of cooperative anti-stealth are verified.

(2) When the number of transmitters is constant, the number of receivers needed should also be limited. The simulation shows that one transmitter equipped with four receivers can achieve better anti stealth detection capability.

(3) The intelligent optimization algorithm based on rule search strategy can obtain more stable and better solution when optimizing the "*1TnR*" space configuration optimization, which verifies the feasibility and effectiveness of the proposed algorithm.

On the one hand, the research results can provide reference for the demonstration of mission planning, tactical deployment, tactical maneuvering, and determination of the number of transmitters and receivers in the practical application of aircraft swarm; on the other hand, combining with scenario analysis, we can construct the strategy decision bank of anti-stealth tactics to deal with different enemy situations. Besides, the intelligent decision-making of anti-stealth operations can be realized by ECA driving mechanism, which is also one of the key directions of our future work. In addition, on the basis of this paper, we will further explore the "*mTnR*" space configuration optimization, and further enrich and improve the aircraft swarm anti-stealth tactical decision-making rules base.

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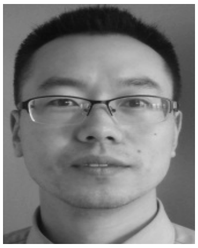

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