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# The Assessment Method for Multi-Azimuth and Multi-Frequency Dynamic Integrated Stealth Performance of Aircraft

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## 1. Introduction

Stealth technology of aircraft, known as one of the three technological revolutions together with high-energy laser weapons and cruise missiles in the development history of military science since 1980s, has become the third milestone after jet engines and swept wings technology in modern aviation history. Stealth aircraft has been also considered as one of the ten greatest inventions of the U.S. ADARPA (Defense Advance Research Project Agency). Nowadays, stealth technology has become one key technology. The countries all over the world have paid great attention and strived to develop the stealth technology. Reasonable assessment method for stealth performance plays a crucial role in the development of advanced stealth technology. For example, the result of the stealth performance assessment of aircraft can provide reference for modifying the aircraft's stealth design to achieve a higher stealth performance. Meanwhile, it can also provide reference for making some specific strategies to increase the probability of successful tasks by reducing the detecting probability of the radar or radar network. Nowadays, the electronic battlefield is becoming more complex and it is urgent to build up a new method to analyze the multi-azimuth and multi-frequency dynamic integrated stealth performance of aircraft, under the complex electronic environment.

The existing stealth performance assessment methods include two types. One is the static stealth performance assessment method, the other is the stealth assessment method based on the effectiveness of combat simulation. The former just uses the average RCS value of target circumferential area, or that of some critical radar detecting areas, under some important radar frequencies as the basis. And the latter uses aircraft's survival probability (including detection probability, hitting probability and damage probability) in specific combat tasks as the basis to assess the stealth performance of aircraft. Each method can reflect the characteristics of the target's stealth performance well. However, there are still some limitations such as: the results based on the two methods can't reflect the impact on aircraft stealth performance caused by different target scattering characteristics. As not taking the certain combat task and detecting environment into consideration, the results also fail to reflect the dynamic characteristics of stealth performance, which happens in the entire

proceeding of different combat tasks of aircraft, and the multi-azimuth and multi-frequency integrated stealth performance under complex electronic environment. According to the above, the development of modern stealth technology urgently requires a new type of stealth performance assessment method to provide the reliable basis.

In this paper, a new type assessment method for multi-azimuth and multi-frequency dynamic integrated stealth performance of aircraft was established by building the multi-azimuth and multi-frequency dynamic integrated stealth performance assessment models and the series of assessment criteria. With these efforts, on the one hand, a more reasonable analysis result of stealth performance based on the multi-azimuth and multi-frequency dynamic detecting environment can be provided, on the other hand, the limitations of the existing stealth performance assessment methods can be overcome.

## **2. The existing stealth performance assessment method**

Although lots of countries home and abroad started researches about the stealth technology early, there are just only a few assessment methods for stealth performance of aircraft. One of the two main existing methods is static stealth performance assessment method, the other is the stealth performance assessment method based on the effectiveness of combat.

### **2.1 The static stealth performance assessment method**

#### **2.1.1 The theory of the static stealth performance assessment**

The classical static stealth performance assessment method includes two aspects: one is the static testing assessment method and the other is theoretical calculation assessment method. The American scholar Knott E.F has made a number of deep studies into the radar cross section calculation and testing technologies. Chinese scholars, such as Ruanying Zheng, Kao Zhang, Dongli Ma and so on, also have done researches on radar cross section calculation and testing, they propose the concept of critical RCS reduction region of aircraft, which has been widely used. At present, the radar cross section testing technology home and abroad has been used widely. The static radar cross section testing is a method, by doing the outfield or laboratory RCS testing on made full-scale models or reduce-scale models to get a basic understanding of the target scattering characteristics. The existing methods of the radar cross section theoretical calculation mainly include three types and they are the high frequency approximation, finite difference time domain and finite difference time domain.

The detailed steps of static stealth performance assessment are as follows: First of all, obtaining the RCS curve of the target under different radar detecting frequencies through static testing method or theoretical calculation method, then analyzing the stealth performance of aircraft, according to the average RCS of target circumferential area, or that of some critical radar detecting area, or the RCS value of certain radar detecting azimuth, under some important radar frequencies.

The assessment criteria of the static stealth performance assessment method is that the lower the average RCS of target circumferential area, or that of some critical radar detecting area, or the RCS of specific azimuth, under some important radar frequencies, the better the stealth performance of aircraft has. Technology flow chart of the static stealth performance assessment method is shown as Fig.1.

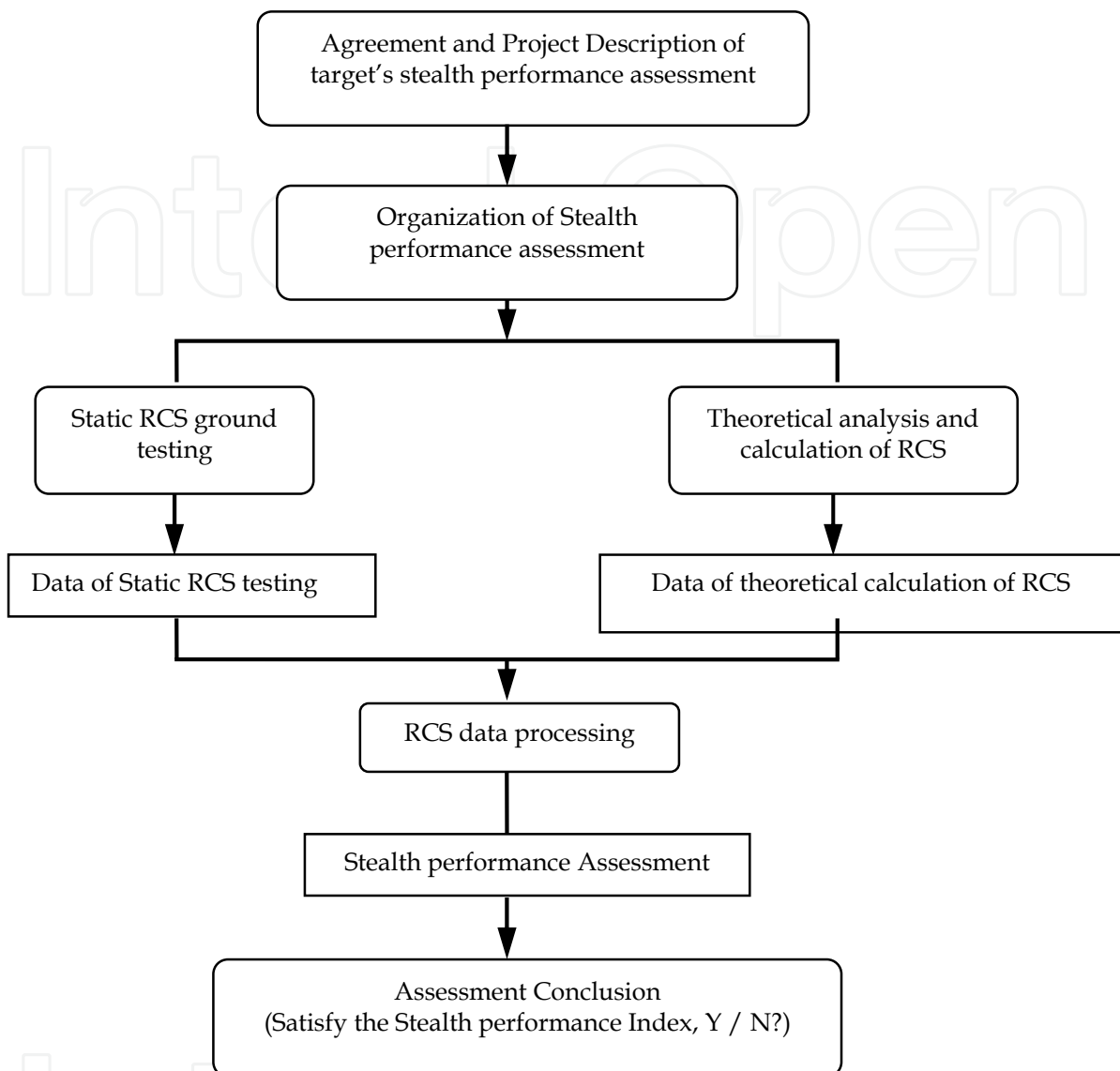


Fig. 1. Flow Chart of Static Stealth performance Assessment Method

The overall average RCS of both model one and model two is  $0.5\text{m}^2$ . There are three RCS curve peaks at  $\pm 30^\circ$  and  $180^\circ$  azimuth for model one. The maximum value of RCS curve peak is  $10\text{ m}^2$  and the azimuth-width is  $4^\circ$ . There are four RCS curve peaks at  $\pm 45^\circ$ ,  $135^\circ$  and  $225^\circ$  azimuth. The maximum value of RCS curve peak is  $20\text{m}^2$  and its peak azimuth takes up  $4^\circ$  as well.

A penetration testing is carried out in this section. The locations of every single radar in the radar network and the penetration destination are shown in Table 1, where GR means single radar and Basement stands for the penetration destination. The penetration testing angle is set from  $-60^\circ$  to  $+60^\circ$  and the interval angles is  $5^\circ$ .

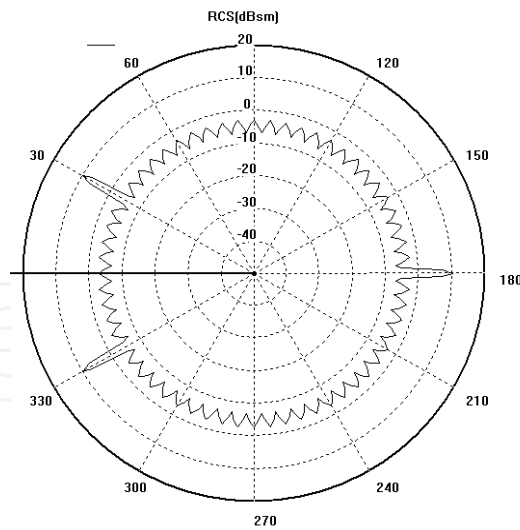


Fig. 2. Circumferential scattering distributions of model one

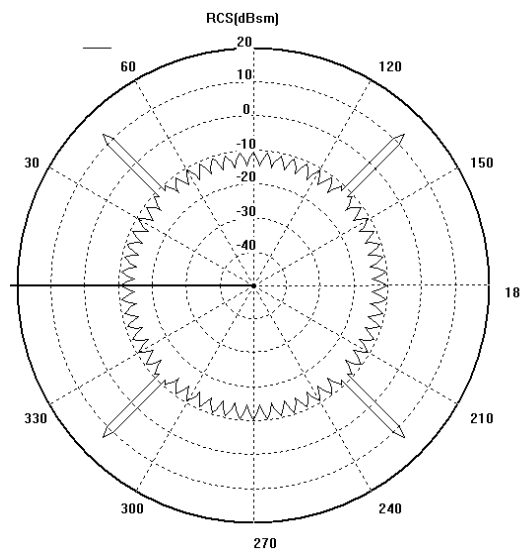


Fig. 3. Circumferential scattering distributions of model two

Name	GR1	GR2	GR3	GR4	GR5	GR6	GR7	Basement
Longitude	119.6330	121.550	120.4830	121.5330	121.6170	121.05	121.9667	121.5
Latitude	23.5667	24.0667	22.70	25.0330	24.0167	25.0667	24.8	25.0

Table 1. Locations of Each Single Radar and the Penetration Destination

Fig.4 to Fig.7 just show several simulation results of these two models. The Y axis of the testing diagram the FoundValue stands for the radar network detection results. When FoundValue is equal to 0, it means that no target has been found by radar network. When FoundValue is equal to 1, it means the target has been found. The X axis of the diagram the Time stands for the time length of the penetration testing process. Fig (a) is the radar detection results of simulation model one and Fig (b) is the radar detection results of simulation model two.

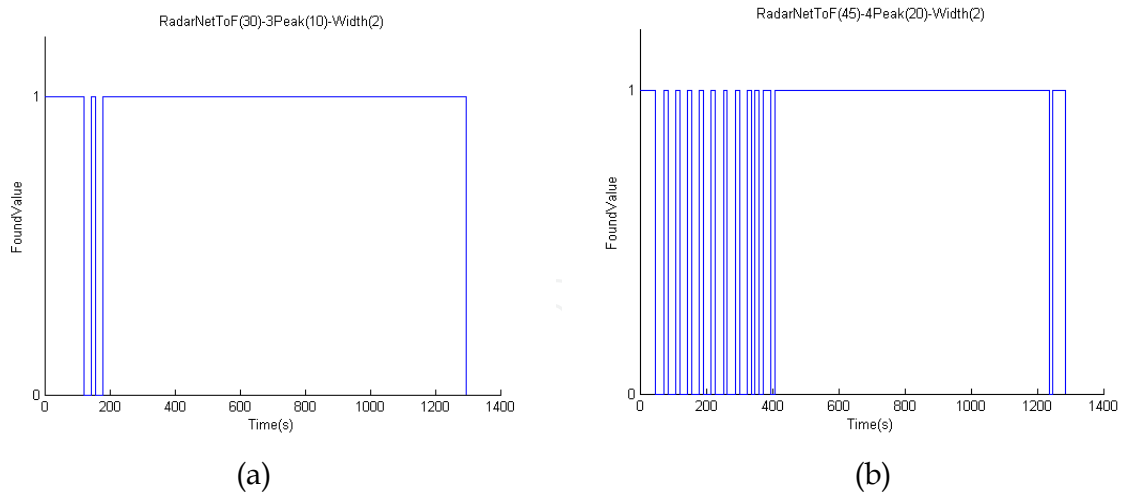


Fig. 4. Simulation results comparison of model one and model two (penetration angle  $-60^\circ$ )

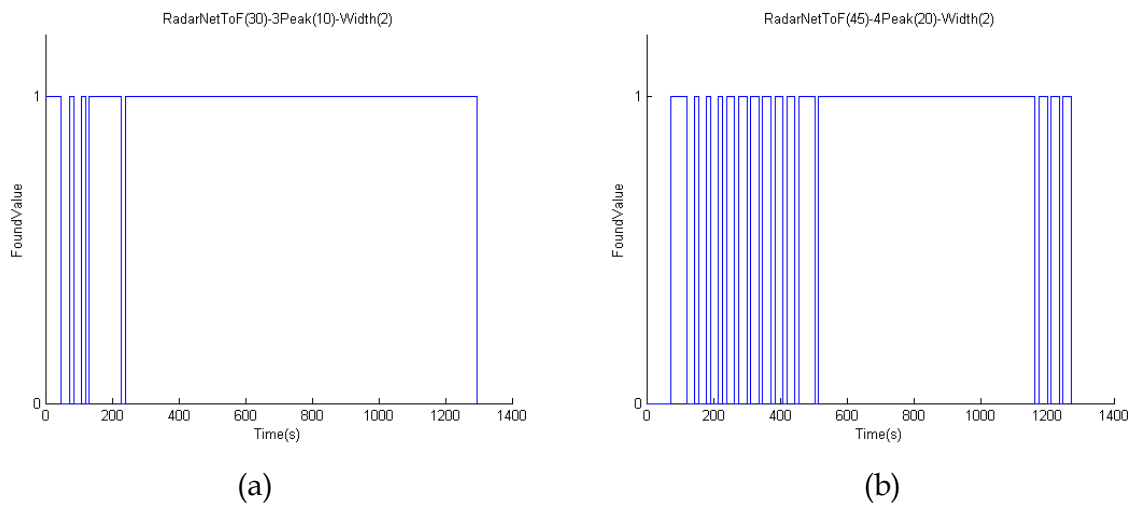


Fig. 5. Simulation results comparison of model one and model two (penetration angle  $-45^\circ$ )

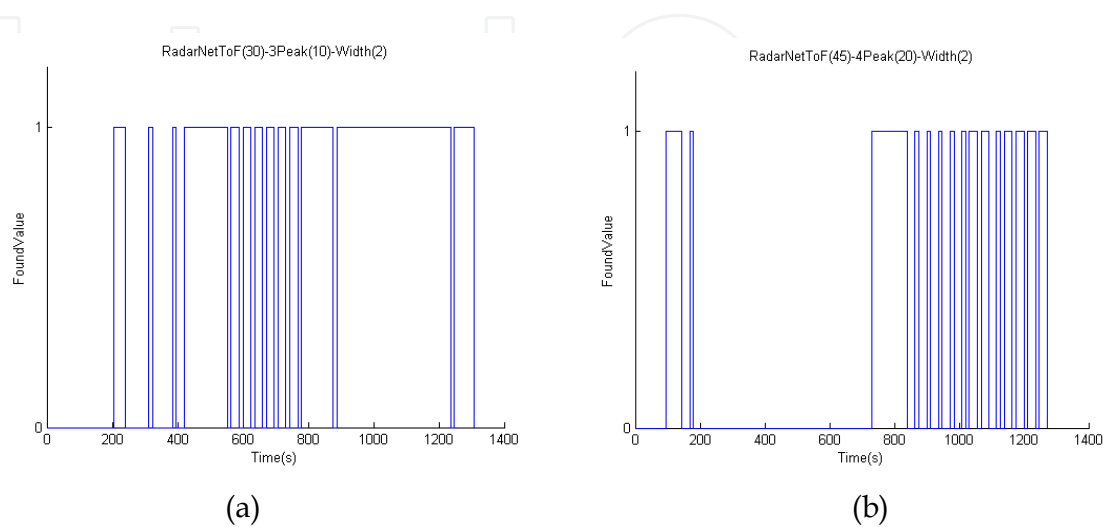


Fig. 6. Simulation results comparison of model one and model two (penetration angle  $0^\circ$ )

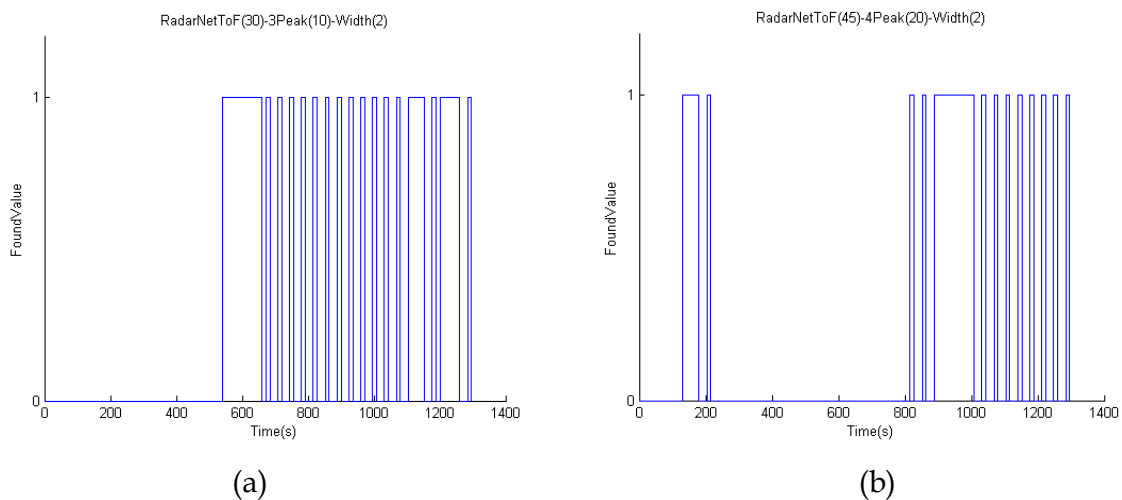


Fig. 7. Simulation results comparison of model one and model two (penetration angle  $15^\circ$ )

It can be seen from the results that although the overall average RCS of the two simulation models is  $0.5\text{m}^2$ , the dynamic stealth performance of these two models differs much from each other. Such as it is shown in Fig.6 and Fig.7, the simulation model two would be discovered earlier by radar network than the model one at the same penetration angle. After the model two was discovered for the first time, it was lost by the radar network for a long time, while the model one was detected continuously by radar network after its first being found.

Above all, the static stealth performance assessment method still has some limitations. Conclusions drawn from the tests are listed as follows:

1. Different circumferential scattering distribution can makes the aircraft has absolutely different stealth performance, even if they have the same circumferential average RCS;
2. According to the stealth performance of aircraft with different circumferential scattering distribution, the average RCS of aircraft requirement could be appropriately relaxed.

### 2.3 The assessment method based on the effectiveness of combat

Based on the radar simulation and target signal simulation technology, the steps of assessment method based on the effectiveness of combat are listed: first of all, calculating the aircraft survival probability during the whole combat mission, then summarizing the effects of RCS characteristic on aircraft survivability and evaluating the stealth performance of aircraft. The rules of this method are the aircraft with higher survivability has better stealth performance. The assessment method based on aircraft effectiveness of combat has been investigated early abroad. Ball R E made deep studies into the RCS reducing technology which would improve the survivability of aircraft greatly. At the same time, some software corporations abroad developed many kinds of analysis software that were applied for analyzing survivability and vulnerability of aircraft. For example, several kinds of software developed by SURVIAC center could quantitatively and comprehensively evaluate the survivability and vulnerability of aircraft in the situation of one to one air battle. In China there are a great deal of research about the effects of aircraft RCS on its survivability have been done. For example, Zhang Kao and Ma Dongli proposed the method of calculating the survivability of stealth aircraft that carries out given mission. Aimed at analyzing the effects of reducing aircraft RCS on survivability of aircraft.

Assessment method based on the effectiveness of combat reflects the stealth performance of aircraft carrying out the given mission, but still has some limitations: firstly, this method couldn't reflect the process and dynamic character of the stealth performance of aircraft during the whole mission. For example, the target 'flashing signal' caused by the different distributions of strong scattering source. Secondly, the assessment method based on the survivability could not reflect the character of multi-azimuth and multi-frequency dynamic comprehensive stealth performance of aircraft, and it also ignores characters of the multi-azimuth and multi-frequency electronic detecting environment.

### **3. The multi-azimuth and multi-frequency dynamic integrated stealth performance assessment method**

Because of the limitations of the existing assessment method told in chapter 2, it should build up a new assessment method for stealth performance of aircraft. This method could evaluate the multi-azimuth and multi-frequency dynamic comprehensive stealth performance of aircrafts, not just gives the evaluation conclusions based on the average RCS of target circumferential area, or that of some critical radar detecting areas. The aircraft with different scattering characteristic could meet requirements of different missions. In order to evaluate the multi-azimuth and multi-frequency dynamic comprehensive stealth performance of aircraft, it should build up the RCS scattering model and the multi-azimuth and multi-frequency dynamic detecting environment model when the aircraft carries the given mission, then make the assessment rules for analyzing the multi-azimuth and multi-frequency dynamic comprehensive stealth performance of aircraft.

#### **3.1 The multi-azimuth and multi-frequency dynamic comprehensive assessment models**

This section describes the building steps of the multi-azimuth and multi-frequency dynamic comprehensive assessment models in detail, the assessment model includes the typical complex dynamic detecting environment simulation model based on the given mission and the RCS scattering model of aircraft.

##### **3.1.1 The RCS scattering model of aircraft**

In order to build a model that could reflect the RCS scattering character of aircraft and use this model to analyze the stealth performance, we need to guarantee the accuracy of the model.

Aircrafts executing different missions will encounter different detecting threat at different azimuths from land, sea, air and space. And even if using the same detector with the same working mode, the signal of aircraft the radar detected may still changes at any moment in the mission. So the method of building reduced-scale model of aircraft and doing experiments is considered. We can acquire the corresponding data for building up the scattering model of aircraft. The RCS database should include the data of aircraft RCS at different azimuths, under different frequencies. It is impossible to meet the needs of building the database by the way of building model and testing it because of the limitation of experiment condition. So the feasible way is to combine the data from both experiment and theoretical calculating. Fig 8 shows the detailed steps.



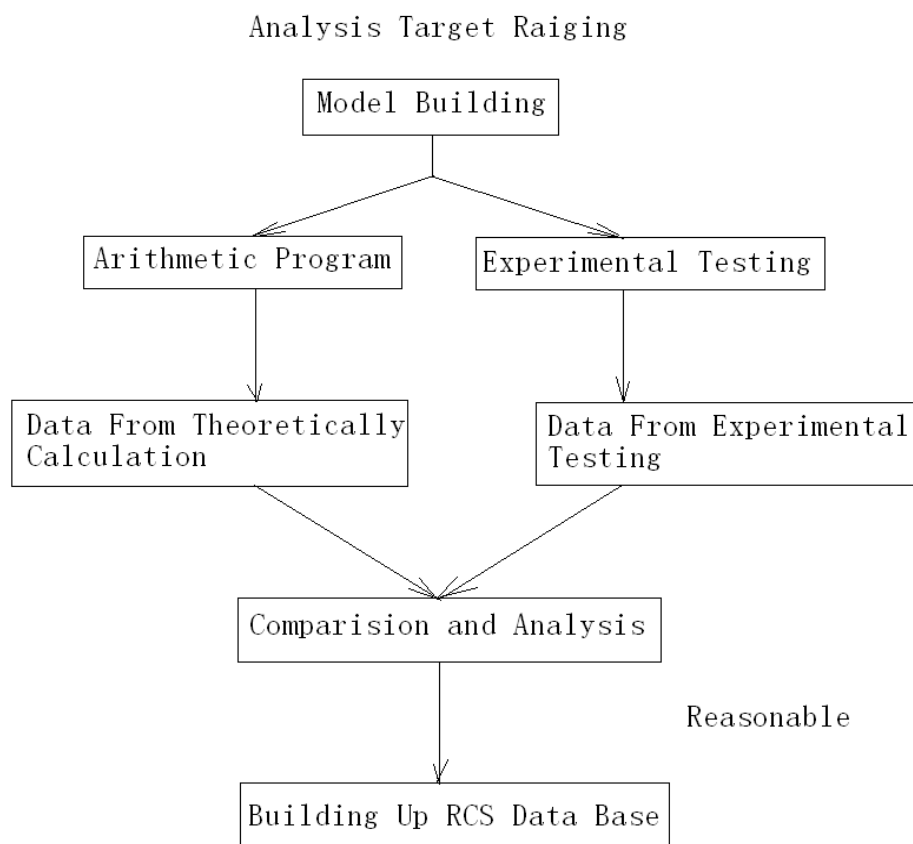


Fig. 8. Flow chart of building the RCS database

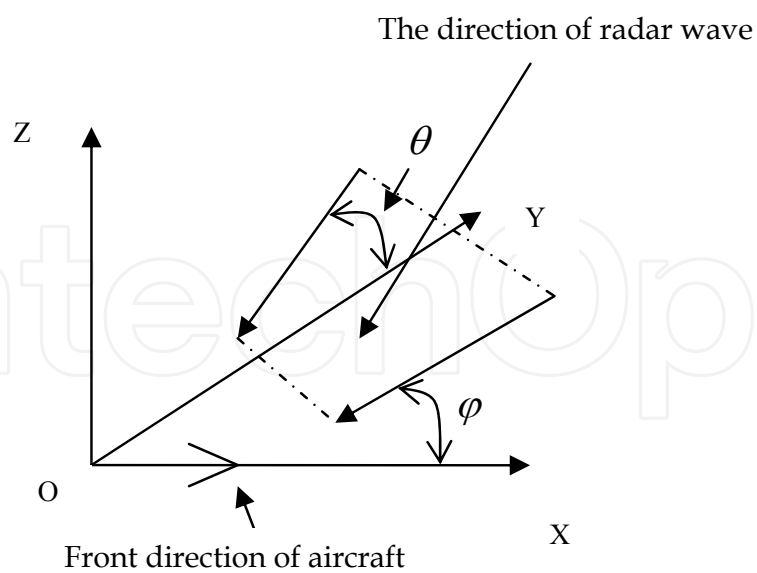


Fig. 9. Schematic illustration of the aircraft scattering model

The aircraft scattering model can be built up based on the adequate RCS data. The detailed steps of building up the aircraft scattering model are showed as Fig.9. The coordinate system in Fig.9 is defined just the same as aircraft body axes coordinate system for building

up equation of motion, which follows the right-handed screw rule.  $\theta$  and  $\varphi$  are two parameters of radar detecting wave.  $\varphi$  is defined as the angle between the project of radar wave on the XOY plane and the X-axes.  $\theta$  is defined as the angle between the project of radar wave on the YOZ plane and the Y-axes.  $\theta$  and  $\varphi$  together decide the location of radar wave in aircraft body axes coordinate system.

The planform of one aircraft scattering model is shown as Fig10. Fig11 shows the test RCS curve of this model. We can see from the two figures that the model's RCS scattering character is consistent with experiment result which looks like a butterfly. This building method of the RCS scattering model is feasible. The method of building a scattering model is an innovation, which accurately reflects the RCS scattering character of the aircraft under different frequencies. This method could be applied for analyzing different kinds of stealth aircraft.

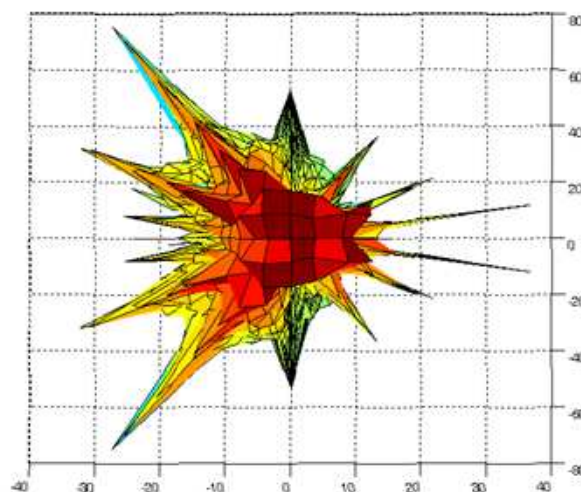


Fig. 10. Planform of the Aircraft Scattering Model

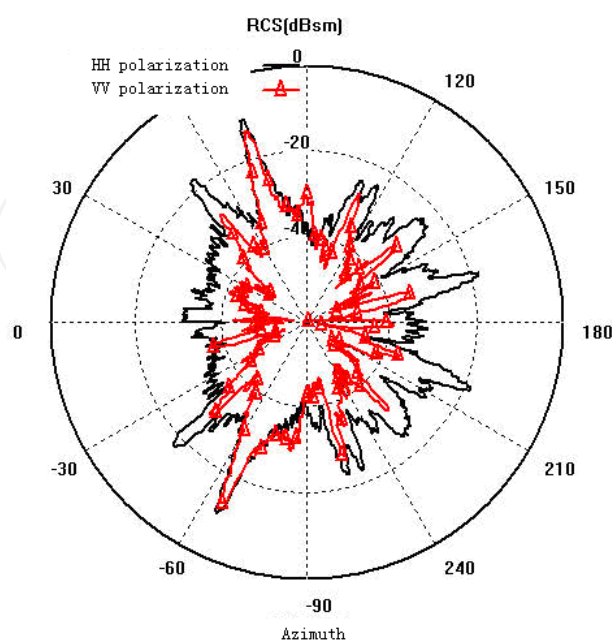


Fig. 11. Circumferential Test RCS curve of Aircraft

### 3.1.2 The typical complex dynamic detecting environment model

The typical detecting environment is different when the aircraft executes different missions. So if we want to evaluate the multi-azimuth and multi-frequency dynamic comprehensive stealth performance of aircraft, we must consider the typical complex detecting environment. For example, when an aircraft is executing a penetration mission, the main radar detecting thread is from the head or tail direction of aircraft.

The detection environment of warfare is becoming more complex, so it is extremely difficult to describe it completely and accurately. By studying the performance of radar detection systems, we can summarize the typical detection environment. Here are the main elements to describe the typical complex and dynamic detection environmental model including two types, one is the main tactical applications, such as (1) characters of the two sides of combat. (2) Threat which the opposing sides may meet. (3) Interference and anti-interference measures of the opposing sides. The other is the related information of electronic equipment in typical detection environment, such as: (1) Number of detectors. (2) Spatial distribution of detectors. (3) Density of the detectors (time domain). (4) Parameters of the detector's signal. (5) Frequency and scope of the detector's signal. (6) The power of detector. (7) Working mode of detector. Using these model parameters above, we can accurately describe the typical complex dynamic detection environment when aircraft carries a specific mission.

### 3.2 The multi-azimuth and multi-frequency dynamic comprehensive stealth assessment rules

As mentioned above, the existing assessments method is based on the average RCS of aircraft. In order to make sure that the aircraft stealth performance assessments conclusions are applicable, which can be used to guide the new type of stealth aircraft design and stealth performance analysis, we should consider the specific tasks the aircraft carries. When performing different tasks, the aircraft may encounter different typical detection environment. So it is not reasonable to use the same stealth performance assessment rules. Therefore, this section will establish the multi-azimuth and multi-frequency dynamic integrated stealth performance assessment rules based on the given mission. Based on specific combat mission, the assessment rules should be built up by analyzing various types of detection threat the aircraft may encounter and the influence of the aircraft scattering characteristic. Based on the conclusions got from the assessment rules above, we can compare and analyze the stealth performance of different aircrafts which perform the same task. The task-based aircraft multi-azimuth and multi-frequency dynamic integrated stealth performance assessment rules should satisfy two conditions:

1. Assessment rules should reflect the character of specific tasks carried by aircraft. For example, the stealth performance assessment rules for penetration aircraft should reflect the character of penetration task firstly. In different stages of penetration task, the influence of the aircraft survivability and successful mission probability is different. For example, the first time when penetration aircraft is found by radar (or radar network) decides how many times the aircraft would probably be attacked by enemy firepower. When penetration aircraft was first discovered by radar network, the distance from the penetration destination determines whether the plane could use the remote attack weapon. Therefore, the establishment of penetration stealth performance assessment rules should be combined with the penetration characters, so that the evaluation conclusions reflect the differences of stealth performance among different aircraft when executing penetration.

2. The conclusion got from the assessment rules should be able to reflect the scattering character of aircraft. For example, during the process of penetration, aircraft mainly get detecting threat from its front azimuth by various types of detectors in the enemy air defense. If the aircraft goes through the first line of air defense system undetected and continues to fly to the enemy's air defense system, it may also be detected by radars at its two side azimuths. Therefore, when establishing stealth performance assessment rules, we should focus on the stealth performance of the front and two side azimuths of aircraft. The stealth performance of penetration aircraft is changing all the time. Therefore, the assessment rules should not only combine with combat characteristics of the penetration mission, but also need to consider the dynamic scattering character of penetration aircraft.

#### 4. The effects of different aircraft circumferential RCS scattering characters

The aircrafts with different circumferential scattering characters is suitable for different combat missions, caused by various configuration design parameters. The stealth performance evaluation conclusions of aircraft with different circumferential RCS scattering characters can provide reference for a reasonable layout design of new type of aircraft. This section will combine the multi-azimuth and multi-frequency dynamic comprehensive assessment rules developed in chapter 3 to analyze and evaluate the aircrafts with different circumferential RCS scattering characters.

##### 4.1 The new target integrated circumferential RCS scattering model

###### 4.1.1 The relevant model parameters

There are several requirements which the model should meet for the new analysis method: 1) quantified the overall and partial RCS scattering characters of target; 2) setting up the relations between each different radar detecting areas; 3) controlling the RCS scattering changing trends of model through inducing several model RCS scattering control parameters. Considering that the RCS value can reflect the quantified target scattering characters and the differences between the RCS values may up to the magnitude order for the different target azimuth, the average RCS value of target circumferential area is introduced as one of the RCS scattering characteristic parameters of model and the unit is dBsm, and its symbol is  $\delta_{ave}$ .

The existing analysis method does not take the effects of the changing relations between different important radar detecting region on the target stealth ability into account. For example, the aircraft could be excellent in depth penetration mission, if it has lower RCS value at the front azimuth and higher RCS values at other azimuths. Moreover, if the stealth aircraft has lower RCS value at its two side azimuths compared with that for the rest azimuths, it can carry out penetration mission with a smaller horizontal distance arriving at the enemy bases. In order to build up the relations between different target important detecting areas, the new analysis method uses the average RCS value of target front important radar detect area as the basis. Furthermore, the average RCS values of another radar detecting areas are introduced into the model as the target local RCS scattering characteristic parameters and the corresponding symbols are  $\bar{\delta}_i$  ( $i=0,1,\dots$ ). The subscript  $i$  represents the sequence of radar detecting areas. For describing the relations between the

target front and other direction important radar detecting areas, the new model defines a set of relational parameters. Their symbols are  $k_{\delta_i}$  ( $i = 0, 1, \dots$ ) and can be written as:

$$k_{\delta_i} = \bar{\delta}_i / \bar{\delta}_0 \quad (1)$$

where  $\bar{\delta}_0$  represents the average RCS value of the target front important radar detecting area.

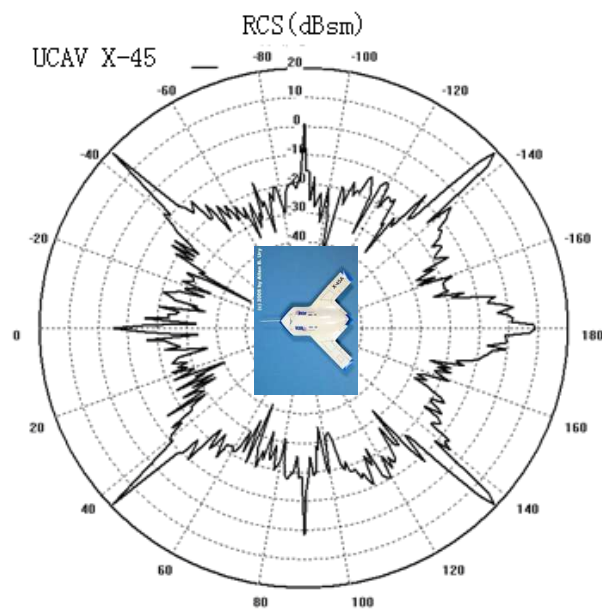


Fig. 12. RCS curve corresponding to one type of stealth aircraft (Under the S wave band).

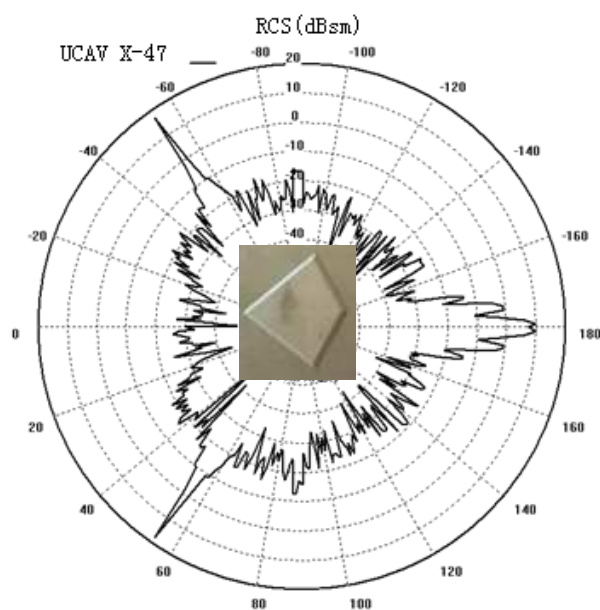


Fig. 13. RCS curve corresponding to one type of aircraft (Under the S wave band).

Due to different stealth design parameters the UCAV X-45 and X-47 have, so they have completely different RCS scattering characters. Their RCS curves differ much from each other, as shown in Fig.12 and Fig.13. So the same set of RCS scattering controlling parameters can not be used to describe the dissimilar RCS curve patterns and control the RCS scattering changing trends of various new models well. There are two requirements for the RCS scattering control parameters: one is that it is not advisable to introduce too many RCS scattering control parameters, the other is the model can satisfy all kinds of stealth ability analysis requirements. For example, building up the target circumferential RCS scattering model with triangle pattern character as shown in Fig.2 needs two RCS scattering control parameters, which can meet the requirements of controlling RCS scattering changing trends and conducting target integrated stealth performance analysis. These parameters are  $K_L$  and  $K_A$  respectively,  $K_L$  and  $K_A$  can be expressed as:

$$K_L = L_a / L_b \tag{2}$$

$$K_A = A_F / 360 \tag{3}$$

where  $L_a$  and  $L_b$  are the side lengths of model with triangle circumferential RCS scattering character. The parameter  $K_L$  can control the RCS scattering changing trends of target head and tail areas. By this way, it can satisfy the analysis requirements about the effects of different target head and tail stealth performance on its integrated stealth performance.  $A_F$  represents the angular region of target front important radar detecting area. Likewise, the models with different  $A_F$  values can meet the analysis requirements about the effects of different front important radar detecting areas on target integrated stealth performance.

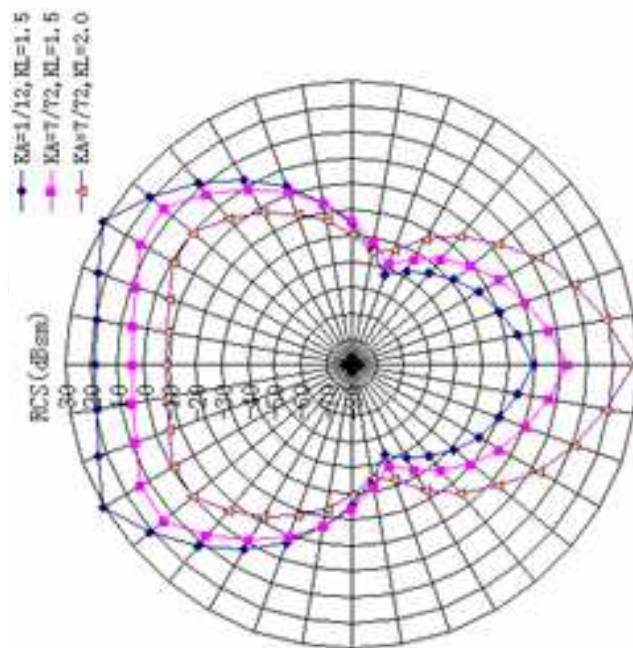


Fig. 14. RCS curves of different target RCS scattering models.

Fig.14 shows the models with various target circumferential RCS scattering characters and being built up by changing the values of  $K_L$  and  $K_A$ , when  $\delta_{ave}$  is equal to -10dBsm.

#### 4.1.2 The model building method

According to Fig.12, the detailed building steps of the new model are described in this section. First of all, defining the suitable target whole and local RCS scattering characteristic parameters and introducing several model RCS scattering controlling parameters according to the different target RCS scattering characters are necessary. So as it is shown from Fig.1, the average RCS value of target circumferential area and the heading direction within the angular region of  $-30^0$  to  $+30^0$  are introduced as the target entire and local RCS scattering characteristic parameters respectively. Their corresponding symbols are  $\delta_{ave}$  and  $\delta_0$ .  $K_L$  represents the ratio between long side and short side lengths. Secondly, different functions are used to describe the RCS curves of different radar detecting regions. The variable of curve function is angle value  $\varphi$ , its corresponding function value is length value R. But in the target RCS curve, the corresponding value of angle  $\varphi$  is the target RCS value. Therefore, a transform between the coordinate length value R and the target RCS value is needed. Based on this transform, RCS value in any direction of the target can be expressed by:

$$\delta_{(\varphi)} = \delta_{ave} + (R_{(\varphi)} - \frac{1}{N} \sum_{i=1}^N R_i) \times \frac{\delta_{ave} + \delta_{min}}{\frac{1}{N} \sum_{i=1}^N R_i} \quad (4)$$

where  $R_{(\varphi)}$  denotes the R value in any target azimuth,  $R_i$  is one of the series values of R in any target important radar detecting areas and subscript i represents the sequence of these R values,  $\delta_{ave}$  is the average RCS value of target circumferential area or local radar detecting areas and  $\delta_{min}$  represents the RCS value of the coordinate origin. The stealth analysis about the target local RCS scattering character should be included in the conclusions of target integrated stealth performance analysis. So the last step is dividing the target RCS curve into several parts according to the target RCS scattering characters, then using different functions to describe these parts respectively. By this way, the analysis conclusion about how the target local stealth performance affects its integrated stealth ability can be reached. All the functions for every part of the curve can be written as:

$$\delta_{(\varphi)} = R_{(\varphi)} \times \frac{(\delta_{ave} + \delta_{min})}{\frac{1}{N} \sum_{i=1}^N R_i} - \delta_{min} \quad (5)$$

where  $\delta_{i(\varphi)}$  and  $R_{i(\varphi)}$  are the target RCS values and R values respectively and corresponding to the target azimuth of  $\varphi$ . The subscript i represents the sequence of target important radar detecting areas.

The functions corresponding to Fig.12 can be expressed as:

$$\delta_{i(\varphi)} = \begin{cases} (\delta_{ave} + \delta_{min}) \times \frac{K_L}{2 \times \cos \varphi} \times \frac{91}{Sum} - \delta_{min} \\ 0 \leq \varphi \leq \varphi_{Limit} \\ or(180 - \varphi_{Limit}) \leq \varphi \leq (180 + \varphi_{Limit}) \\ or(360 - \varphi_{Limit}) \leq \varphi < 360 \end{cases} \quad (6)$$

$$\begin{cases} (\delta_{ave} + \delta_{min}) \times \frac{1}{2 \times \sin \varphi} \times \frac{91}{Sum} - \delta_{min} \\ (180 + \varphi_{Limit}) < \varphi < (360 - \varphi_{Limit}) \\ or(360 - \varphi_{Limit}) \leq \varphi < 360 \end{cases}$$

$$Sum = \sum_{\alpha=0}^{\varphi_{Limit}} \left| \frac{K_L}{2 \times \cos \alpha} \right| + \sum_{\alpha=\varphi_{Limit}+1}^{90} \left| \frac{1}{2 \times \sin \alpha} \right|$$

where  $\delta_{ave}$  is the average RCS value of target circumferential area,  $\delta_{min}$  represents the RCS value of the coordinate origin,  $\alpha$  is the radar detect angle and  $K_L$  is the model RCS scattering controlling parameter.

#### 4.2 Examples and discussions

In this section, the new kind of target circumferential RCS scattering models will be built according to Fig.12 and Fig.13. Before that, disposing several radars in different azimuths of enemy base. Combing relevant dynamic models and integrated stealth analysis rules can give the detailed integrated stealth analysis conclusions. In these examples, aircraft flight altitude is 1000m and flight velocity is 500m/s. The aircraft carries out the penetration mission along a straight flight course at the azimuth of 90 degrees. The azimuths of these radars are 0, 30, 45, 60, 90, 120, 135 and 180 degrees respectively. A comparison is made between the integrated stealth performance of these two serial models are given blow.

##### 4.2.1 Rectangular RCS scattering models

Combining the new modeling methods described in Section 4.1.2 and the relevant stealth performance analysis requirements, the serial models with absolutely different RCS scattering characters are modeled.

The values of relevant model RCS scattering parameters are  $\delta_{ave} = -10\text{dBsm}$  and  $0\text{dBsm}$  and  $K_L = 0.5, 1.0$  and  $2.0$  respectively. Fig.15 and Fig.16 compare the average radar detecting probability of these serial models. Fig.15 shows that when  $\delta_{ave}$  is equal to  $-10\text{dBsm}$ , the RCS scattering characters of these three models differs much from each other. Among these models, the one corresponding to  $K_L = 0.5$  has the highest average radar detecting probability. When  $K_L = 1.0$ , the corresponding model will have much lower average radar detecting probability. When  $K_L = 0.5$ , the radars located in the two sides of the enemy base will have much higher detecting probability than that for  $K_L = 1.0$ . So when  $\delta_{ave}$  is around  $-10\text{dBsm}$ , the condition of  $K_L = 1.0$  can make the penetration aircraft with rectangular RCS scattering character have excellent sidewise stealth ability. Then the aircraft can carry out



the penetration mission with a small transverse distance arriving at enemy base. The average radar detecting probability rises remarkably, when  $\delta_{ave}$  goes up to 0dBsm.

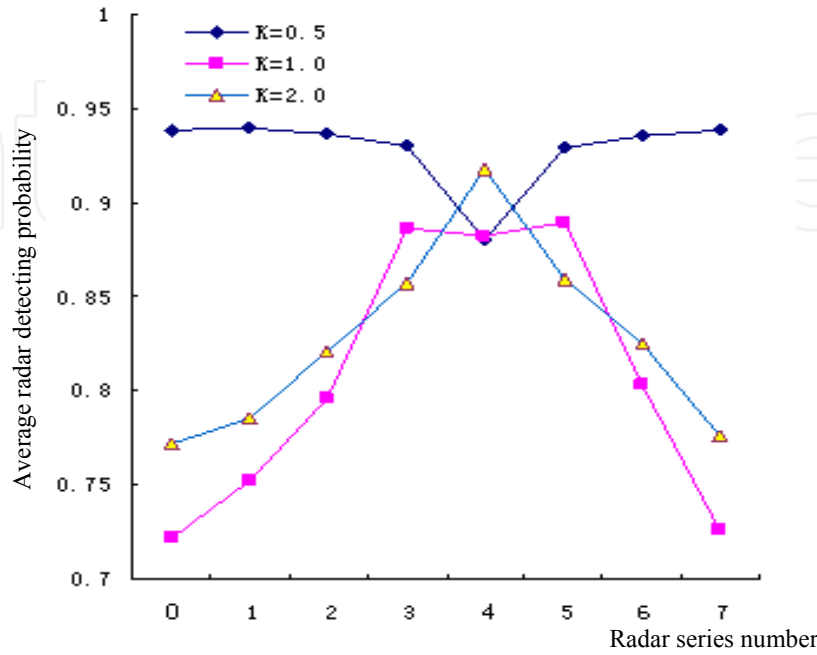


Fig. 15. Comparison of radar detecting probability corresponding to serial models ( $\delta_{ave} = -10\text{dBsm}$ ).

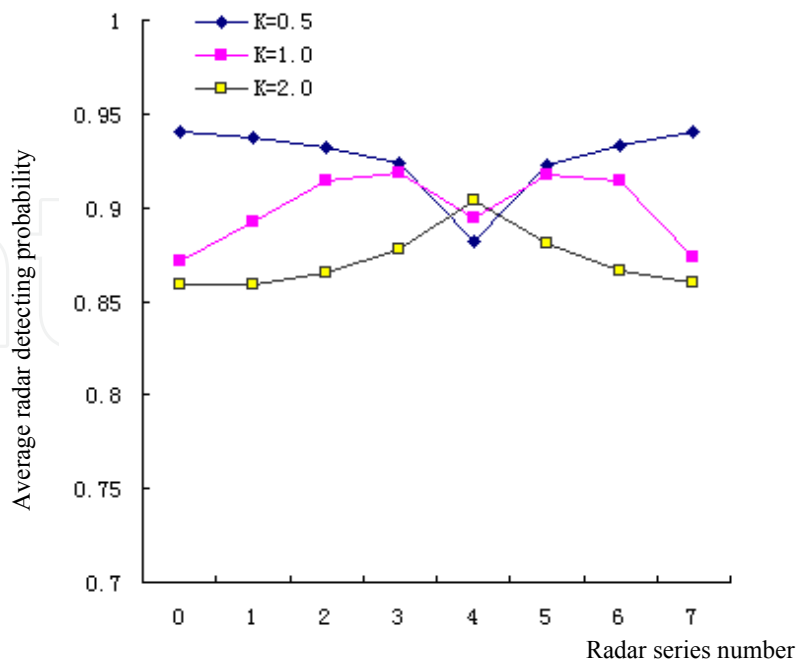


Fig. 16. Comparison of radar detecting probability corresponding to serial models ( $\delta_{ave} = 0\text{dBsm}$ ).

$K_L$	Radar series number	Lost target number	$T_{First}$	Stable tracking number	Tracking duration (s)
0.5	0	1	289	1	315
0.5	1	1	201	1	291
0.5	2	1	174	1	263
0.5	3	1	161	1	225
0.5	4	1	167	1	159
0.5	5	1	162	1	223
0.5	6	1	175	1	261
0.5	7	1	290	1	313
1.0	0	2	194	1	139
				2	139
1.0	1	2	110	1	174
				2	174
1.0	2	1	87	1	436
1.0	3	1	79	1	389
1.0	4	1	89	1	315
1.0	5	1	81	1	385
1.0	6	1	89	1	433
1.0	7	2	196	1	141
				2	142
2.0	0	2	1	1	142
				2	300
2.0	1	2	1	1	105
				2	346
2.0	2	2	1	1	137
				2	399
2.0	3	2	1	1	197
				2	469
2.0	4	1	1	1	765
2.0	5	2	1	1	202
				2	474
2.0	6	2	1	1	142
				2	402
2.0	7	2	1	1	147
				2	304

Table 2. Relevant radar detecting data of serial models ( $\delta_{ave} = -10\text{dBsm}$ )

Table 2 lists the radar detecting data of this serial models. The data shows that when  $\delta_{ave} = -10\text{dBsm}$ , the lost target number will increase and  $T_{First}$  will decrease with the increase of  $K_L$ . Suppose that the aircraft will counter the threat of enemy firepower only when it is continuously found by radar more than a certain time threshold and the corresponding notation is  $T_{Limit}$ . If the time threshold is 200 seconds, when  $K_L = 0.5, 1.0$  and  $2.0$ , the

corresponding valid stable track number are 7, 5 and 8 respectively. So when  $K_L=1.0$ , the model has the least chances of meeting with enemy firepower.

$K_L$	Radar series number	Lost target number	$T_{First}$	Stable tracking number	Tracking duration
0.5	0	1	242	1	409
0.5	1	1	156	1	381
0.5	2	1	132	1	347
0.5	3	1	122	1	303
0.5	4	1	131	1	231
0.5	5	1	123	1	301
0.5	6	1	133	1	344
0.5	7	1	244	1	406
1.0	0	1	86	1	721
1.0	1	1	4	1	685
1.0	2	1	1	1	626
1.0	3	1	1	1	569
1.0	4	1	1	1	509
1.0	5	1	1	1	568
1.0	6	1	1	1	625
1.0	7	1	88	1	717
2.0	0	2	1	1	250
				2	966
2.0	1	2	1	1	201
				2	1003
2.0	2	1	1	1	221
				2	1049
2.0	3	1	1	1	1390
2.0	4	1	1	1	1347
2.0	5	1	1	1	1389
2.0	6	2	1	1	255
				2	1053
2.0	7	2	1	1	255
				2	970

Table 3. Relevant radar detecting data of serial models ( $\delta_{ave} = 0\text{dBsm}$ )

The data in Table 3 shows that when  $\delta_{ave} = 0\text{dBsm}$ , the duration of aircraft being stable tracked rises obviously and the valid stable tracking number also increases. It is also learned from the data that the time of models first being found by radar corresponding to  $K_L=1.0$  and 2.0 will be much earlier. Therefore, the data shows that the RCS scattering controlling parameter  $\delta_{ave}$  has big effects on the integrated stealth performance of serial models.

#### 4.2.2 Triangular RCS scattering models

The serial models with triangular RCS scattering characters are established according to the methods described in section 4.1.1. The meanings of  $\delta_{ave}$ ,  $K_L$  and  $K_A$  have been told in

section 4.1.1. The values of  $K_L$  and  $K_A$  are taken as  $K_L=1.5$ , 2.0 and  $K_A = 1/12, 7/72$  and  $1/9$  respectively. Fig.6 and Fig.7 show the comparison of average radar detecting probability between these serial models.

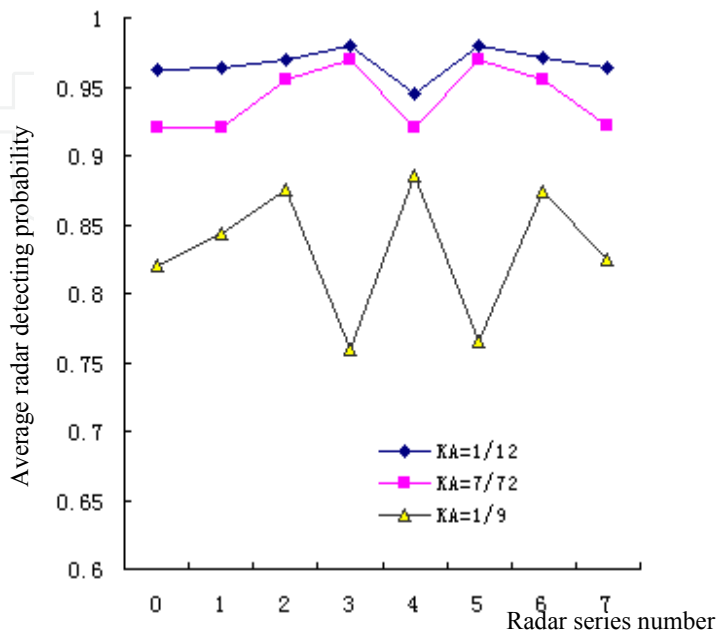


Fig. 17. Comparison of radar detecting probability of serial models ( $\delta_{ave}=-10\text{dBsm}$ ,  $K_L=1.5$ ).

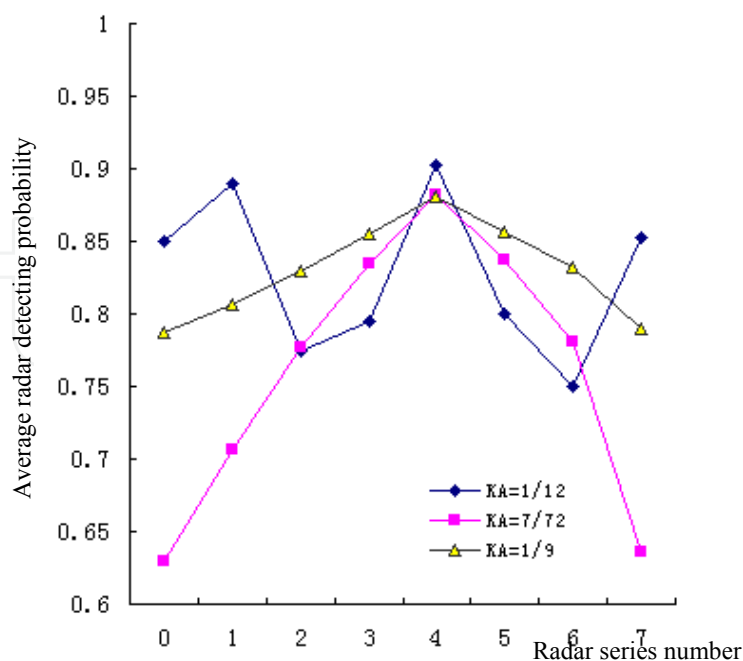


Fig. 18. Comparison of radar detecting probability of serial models ( $\delta_{ave}=-10\text{dBsm}$ ,  $K_L=2.0$ ).

Fig.17 shows that when  $\delta_{ave} = -10\text{dBsm}$  and  $K_L = 1.5$ , the model with RCS scattering parameters  $K_A = 1/9$  has lower radar detecting probability than both the models for  $K_A = 1/12$  and  $7/72$  respectively. The radar detecting probability curves in Fig.18 show that when  $K_L = 2.0$  and  $K_A$  adopts different values, the average radar detecting probability of all these serial models are decreased. Especially for the situation of  $K_A = 7/72$ , the decreasing range is the maximum one. Both the two models corresponding to  $K_A = 7/72$  and  $1/9$  respectively have lower radar detecting probability in their two sides than that in their heading direction. Especially when the RCS scattering controlling parameter  $K_A = 7/72$ .

$K_L$	Radar series number	Lost target number	$T_{First}$	Stable tracking number	Tracking duration
1.5	0	1	1	1	378
1.5	1	1	1	1	299
1.5	2	1	1	1	279
1.5	3	1	1	1	269
1.5	4	1	1	1	684
1.5	5	1	1	1	270
1.5	6	1	1	1	281
1.5	7	1	1	1	380
2.0	0	2	120	1	161
				2	773
2.0	1	2	37	1	197
				2	1020
2.0	2	2	16	1	224
				2	1244
2.0	3	2	9	1	243
				2	1476
2.0	4	1	17	1	2097
2.0	5	2	10	1	243
				2	1489
2.0	6	2	17	1	226
				2	1259
2.0	7	2	121	1	165
				2	799

Table 4. Relevant radar detecting data of series models ( $\delta_{ave} = -10\text{dBsm}$ ,  $K_A = 7/72$ )

Table 4 lists the relevant radar detecting data corresponding to the situation for the RCS scattering controlling parameters  $\delta_{ave} = -10\text{dBsm}$  and  $K_A = 7/72$  and  $K_L$  adopts different values.

The data in Table 4 shows that when  $\delta_{ave} = -10\text{ dBsm}$ , the models with RCS scattering parameter  $K_L = 2.0$  will have more chances of being tracked by radar and the duration of radar stable tracking will be longer than the models corresponding to  $K_L = 1.5$ .

## 5. The effects of different aircraft RCS curve peak characters

Analyzing rules about effects of the aircraft RCS curve peaks with different shape on penetration stealth performance reasonably, is meaningful. These rules could be references for both the concept penetration aircraft's stealth configuration design and making effective aircraft RCS reduction plans.

### 5.1 The target RCS curve peak numerical simulation model

#### 5.1.1 The relevant model parameters

The RCS curve peaks on the target circumferential RCS curve are formed by the total RCS of aircraft scattering sources, which are located in different radar detecting directions. The RCS curve peaks with different shape would cause different effects on the aircraft penetration stealth performance.

There are two requirements for the target RCS curve peak numerical simulation model: (1) The changing trends of RCS curve peak scattering characteristic can be controlled (2) The analysis requirements about effects on penetration dynamic stealth ability, which are caused by kinds of RCS curve peak scattering characteristic changes, can be satisfied.

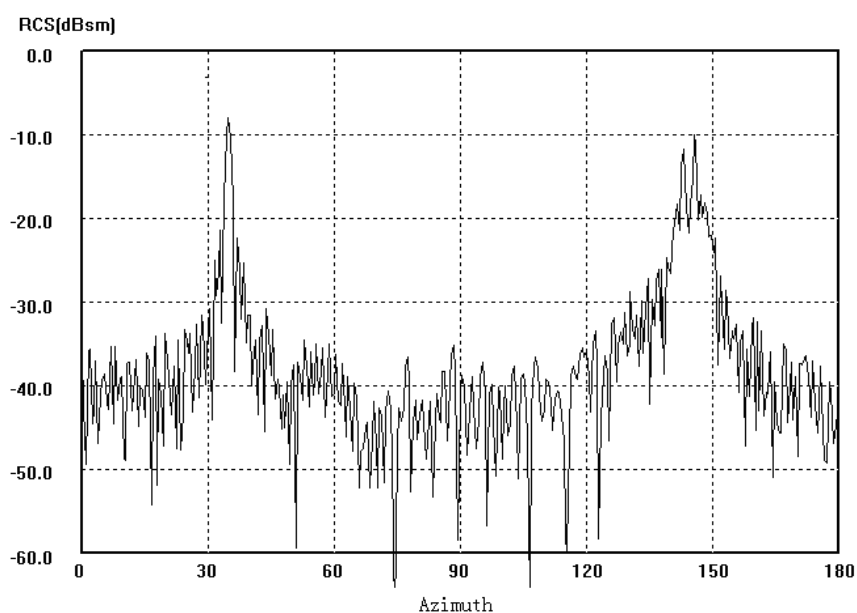


Fig. 19. The RCS curve peaks with different shape

The two RCS curve peaks with different shape in Fig19 show that RCS curve peak value and RCS curve peak azimuth-width are the main factors, which control the changing trends of RCS curve peaks. Changing the number or azimuth of aircraft scattering sources both can alter the RCS curve peak value or RCS curve peak azimuth-width. Rules about effects on the penetration dynamic stealth ability, which are caused by changes of the RCS curve peak value and RCS curve peak azimuth-width, could be references for reasonable stealth configuration design. As mentioned above, it defines two target RCS curve peak numerical simulation model parameters to control the changing trends of model's scattering characteristic, one is the peak value controlling parameter, the symbol is  $\delta_{Max}$ . The other is the peak azimuth-width controlling parameter, the sign is  $\varphi_{Width}$ . This article also defines a

set of RCS curve peak location parameters, corresponding signs are  $\varphi_i$  ( $i=0,1, 2\dots$ ), the subscript  $i$  represents the sequence of RCS curve peaks, which are located on the target circumferential RCS curve. As analyzing the rules about effects on aircraft penetration stealth ability, which are caused by changes of RCS curve peak scattering characteristic, influences of target scattering characteristic in another aircraft azimuth, should be eliminated. This article sets the RCS value in another model azimuth, as a constant value and less than the RCS peak value. As mentioned above, this article introduces the scattering characteristic controlling parameter, which is corresponding to another model azimuth, the symbol is  $\delta_\varphi$ .

### 5.1.2 The model building method

Defining the model parameters according to section 5.1.1, the detailed model building method is told as below: (1) Defining the variable model parameters, according to the analysis requirements about influences on the aircraft penetration stealth ability, which are caused by different RCS curve peak scattering characteristic. For example, the RCS curve peak value would be reduced by the decrease of aircraft scattering sources. For analyzing the corresponding effects on the penetration stealth ability, it can build up a series of models with different RCS curve peak value, by changing the RCS curve peak value controlling parameters  $\delta_{(i)Max}$  ( $i=0,1,2\dots$ ), the subscript  $i$  represents the sequence of RCS curve peaks on the target circumferential RCS curve. Therefore, it can define  $\delta_{(i)Max}$  as the variable model parameters. (2) Introducing the scattering characteristic controlling parameters and RCS curve peak location parameters into the model, then determining the value of these parameters. For example, according to the case that there are two RCS curve peaks with  $6^\circ$  azimuth-width, which are located on  $-30^\circ$  and  $30^\circ$  azimuth of aircraft front area respectively, it can define the RCS curve peak azimuth-width controlling parameter:  $\varphi_{(i)Width} = 6^\circ$  ( $i=0,1$ ) and the RCS curve peak location parameters:  $\varphi_i$  ( $i=0,1$ ),  $\varphi_0 = 30^\circ$ ,  $\varphi_1 = -30^\circ$ . (3) Fixing up the value of scattering characteristic controlling parameter ( $\delta_\varphi$ ), which is corresponding to another model azimuth.

## 5.2 Examples and discussion

This section builds up a series of target RCS curve peak numerical simulation models with different peak value or azimuth-width. By testing and analyzing these models, influences of RCS curve peak value or RCS curve peak azimuth-width on the dynamic stealth ability are generalized.

### 5.2.1 Influences of RCS curve peak characters

For evaluating effects on the integrated stealth performance of penetration aircraft, caused by different target RCS curve peak characters. According to Fig.19, this section builds up series of models, with same circumferential RCS characters, but different RCS curve peak characters. The circumferential RCS character controlling parameters of these models are:  $\delta_{ave} = -10\text{dBsm}$ ,  $K_L = 1.0$ , and the RCS curve peak azimuth-location parameters are:  $\varphi_0 = 45^\circ$ ,  $\varphi_1 = 135^\circ$ ,  $\varphi_2 = 225^\circ$  and  $\varphi_3 = 315^\circ$ . Table 1 lists another RCS curve peak character controlling factors.

	$\delta_{j(Max)} \quad (j=0,1,2,3)$	$\varphi_{j(Width)} \quad (j=0,1,2,3)$
Model 1	10 dBsm	2°
Model 2	10 dBsm	4°
Model 3	10 dBsm	6°
Model 4	20 dBsm	2°
Model 5	20 dBsm	4°
Model 6	20 dBsm	6°
Model 7	30 dBsm	2°
Model 8	30 dBsm	4°
Model 9	30 dBsm	6°

Table 5. The RCS curve peak controlling factors

Simulation conditions of this example are:

flight condition: flight altitude H=1000 m; flight velocity V=200 m/s, flight azimuth (relative to enemy base)  $\varphi_f = -40, -20, 0, 20$  and 40 degrees; distance to penetration destination L=400Km.

condition of radar network : Table 2 lists positions of every ground to air radar (GR) in the network and location of the penetration destination (Basement).

Name	Longitude	Latitude
GR1	119.6330	23.5667
GR2	121.550	24.0667
GR3	120.4830	22.7
GR4	121.5330	25.0330
GR5	121.6170	24.0167
GR6	121.05	25.0667
GR7	121.9667	24.8
Basement	121.5	25.0

Table 6. Positions of radar and destination

Table7 lists the radar network detecting results of this serial models, corresponding to  $\varphi_f = -20$  degree.

From Table7 we find that,  $\varphi_{Width}$  and  $\delta_{Max}$  have different effects on the integrated stealth performance of penetration aircraft. Firstly, if  $\varphi_{Width}$  takes a fixed value, with the rise of  $\delta_{Max}$ ,  $T_{First}$  will decrease and target "flashing signal" will weaken ( $T_{f(Find)}$  increases and  $T_{(l)Lose}$  decreases). Furthermore, when  $\varphi_{Width}$  has a bigger fixed value, effects caused by increase of  $\delta_{Max}$  would be more obvious. Adversely, if  $\varphi_{Width}$  takes a small value, namely, the azimuth-width of target RCS curve peak is narrow,  $\delta_{Max}$  has little effect on the integrated stealth performance of penetration aircraft. Secondly, if  $\delta_{Max}$  takes a fixed value,



$T_{First}$  will decrease and the target "flashing signal" will weaken, with increase of  $\varphi_{Width}$ . Similarly, when  $\delta_{Max}$  has a bigger fixed value, effects caused by increase of  $\varphi_{Width}$  would be more obvious. Lastly, when one of  $\delta_{Max}$  and  $\varphi_{Width}$  takes a big fixed value, the other increases, effect on putting off  $T_{First}$ , caused by increase of  $\varphi_{Width}$  is more obvious.

	$T_{First}$	$N_{(f)Find}$	$T_{f(Find)}$	$N_{(l)Lose}$	$T_{(l)Lose}$
Model 1	209.4	1	150.5	1	559.1
		2	281		
Model 2	173.6	1	222.3	1	523.1
		2	281		
Model 3	173.6	1	258.3	1	475.1
		2	293		
Model 4	209.4	1	186.5	1	523.1
		2	281		
Model 5	173.6	1	258.3	1	487.1
		2	281		
Model 6	137.7	1	330.2	1	427.1
		2	305		
Model 7	209.4	1	186.5	1	523.1
		2	281		
Model 8	137.7	1	294.2	1	487.1
		2	281		
Model 9	101.8	1	366.1	1	427.1
		2	305		

Table 7. Radar network detecting results of serial models

The rules for reducing aircraft scattering sources and improving integrated stealth performance of penetration aircraft can be got from above conclusions:

1. reducing  $\delta_{Max}$  firstly for putting off  $T_{First}$ .
2. plan about strengthening target "flashing signal" is: it should reduce  $\delta_{Max}$  firstly and  $\varphi_{Width}$  secondly, when  $\delta_{Max}$  takes a big value. However, when  $\delta_{Max}$  is small, it should reduce  $\varphi_{Width}$  firstly.
3. there is no need to reduce  $\delta_{Max}$  too much, if azimuth-width of RCS curve peak is narrow.

### 5.2.2 Influences of superposing RCS curve peaks

Because of the stealth design plan: "parallel leading-edge" and "parallel trailing-edge", the RCS curve peaks created by wing edges, could be located on the same azimuth. For evaluating effects of the plan, this section builds up two models, corresponding to "before superposing" and "after superposing" respectively (see Fig.10 and Fig.11). Circumferential RCS controlling parameters of these two models are:  $\delta_{Max} = -20\text{dBsm}$ ,  $K_L = 1.0$ , and the RCS curve peak controlling factors are:

model one:  $\varphi_0 = 57^0$ ,  $\varphi_1 = 63^0$ ,  $\varphi_2 = 180^0$ ,  $\varphi_3 = 297^0$ ,

$\varphi_4 = 303^0$ ;  $\varphi_{j(Width)} = 2^0$ ;  $\delta_{j(Max)} = 10\text{dBsm}$ , ( $j=0,1,2,3,4$ )

model two:  $\varphi_0 = 60^0$ ,  $\varphi_1 = 180^0$ ,  $\varphi_2 = 300^0$ ;  $\delta_{1(Max)} = 10\text{dBsm}$ ,  $\delta_{0(Max)} = \delta_{2(Max)} = 13.01\text{dBsm}$ ;

$\varphi_{j(Width)} = 2^0$  ( $j=0,1,2$ ).

Simulation conditions are the same as the example in section 5.2.1

Table 8 lists the radar network detecting results corresponding to  $\varphi_f = -20^0$ ,  $0^0$  and  $20^0$ , respectively. These results show that, due to superposing RCS curve peaks, not only  $T_{First}$  is reduced a little, but also the target "flashing signal" is strengthened. Namely, the integrated stealth performance of penetration aircraft can be enhanced by superposing RCS curve peaks.

$\varphi_f$		$T_{First}$	$N_{(f)Find}$	$T_{f(Find)}$	$N_{(l)Lose}$	$T_{(l)Lose}$
$-20^0$	Model 1	742.4	1	197.8	1	202.1
			2	57.7		
	Model 2	740	1	195.9	1	243.9
			2	20.2		
$0^0$	Model 1	284.2	1	435.7	1	67.9
			2	196.1	2	92.3
			3	123.8		
	Model 2	230.2	1	363.5	1	218
			2	172.2	2	92.3
			3	123.8		
$20^0$	Model 1	250.1	1	325.8	1	57.5
			2	566.6		
	Model 2	250.1	1	325.8	1	57.5
			2	566.6		

Table 8. Radar network detecting results of two models

## 6. Conclusions

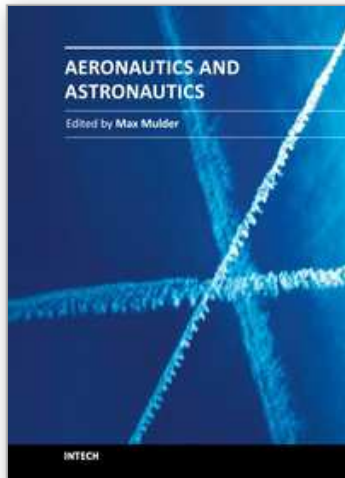
The conclusions about integrated stealth performance of penetration aircraft, based on a reasonable assessment method, are meaningful for both new type of stealth penetration aircraft design and efficient penetration tactics making. This paper proposes a new integrated stealth performance assessment method for penetration aircraft, which constitutes of the target RCS numerical simulation model and dynamic assessment model. This method can assesses effects on the integrated stealth performance of penetration aircraft, caused by different target circumferential RCS characters and RCS curve peak characters. As a fruit, three examples in this article show that:

1. The target RCS numerical simulation models, performing different circumferential RCS characters or RCS curve peak characters, could satisfy various assessment requirements for the integrated stealth performance of aircraft.
2. Better configurations, which can improve integrated stealth performance of penetration aircraft, could be got from the laws for effects of different target RCS characters.

As a new method, it can be applied in the integrated stealth performance of aircraft assessment field. To get more credible assessment conclusions, the more accurate target RCS numerical simulation model and dynamic assessment model should be introduced.

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