The acquisition radar’s detect annulus model of anti-submarine patrol aircraft

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Abstract. Aiming at solving the problem of anti-submarine patrol aircraft (ASPA) detecting different sea-surface and aerial objects, based on the operation performance of acquisition radar, the paper puts forward the concept of detect annulus and establishes the corresponding model, and it gives the manner and method of ASPA detected objects. Through simulation and calculation, it discusses the different pattern of optical axis angle of depression and flight altitude from the width of detect annulus. The paper also provides the basis for the best optical axis angle of depression and flight altitude to meet the operational requirements. At last, the searching method of anti-submarine patrol aircraft using acquisition radar is put forward.

1 Introduction
Acquisition radar is the main load of the ASPA for searching submarine. For anti-submarine patrol, its mechanical scanning antenna mounted is mounted beneath the prow, on all weather conditions, it can take sea and air target searching and tracking. It uses advanced imaging technology to realize the detection and target recognition of the submarine periscope, the exhaust pipe, and various kinds of ship on the surface, and completes sea anti-submarine and matches up weapon fire control system to complete the anti-submarine task. Due to the structural features of the anti-submarine patrol, the baffle area of the backward body won’t emit electromagnetic waves. Before we research how the ASPA uses radar target to search, we must study the effective detection space of the acquisition radar. From the operational use, detect annulus can well describe the problem.

Detect annulus of acquisition radar[1] means that it’s possible for the target in the detect annulus to be detected when mechanical scanning antenna of the ASPA scans the area on the sea (or plane of any height ) for a cycle in a given space. To some extent, the detect annulus of acquisition radar reflects the target search efficiency of anti-submarine patrol aircraft.

2 Basic assumptions
(1) The flight altitude of ASPA is $h$, flight speed is $v$, uniform linear motion;
(2) The angle of acquisition radar beam axis (visual axis) and horizontal plane is $\theta$;
(3) Horizontal beam Angle of acquisition radar is $\theta_a$, vertical beam Angle is $\theta_r$;
(4) Ignore the radar beam side lobe.

3 Build the model of detect annulus
The size of detect annulus is decided by vertical beam Angle of acquisition radar $\theta_r$ and it’s described with the width $\rho$ and the area $S_{\rho}$ of the detect annulus, as shown in figure 1.

![Fig.1 Plan view of detect annulus](image)

Obviously, when the flight height of the anti-submarine patrol aircraft and the optical axis Angle of depression of the radar are determined, the greater the vertical beam Angle, the greater the width of detect annulus. When vertical beam Angle $\theta_r$ is determined, the width of detect annulus is a function of anti-submarine patrol space state, as shown in figure 2. It’s available by the geometric relationship:

$$\rho = h \left[ \cot \left( \theta - \frac{\theta_r}{2} \right) - \cot \left( \theta + \frac{\theta_r}{2} \right) \right]$$

(1)

Consider that $\rho \cdot \sin \theta \approx l_0 \cdot \theta_r$, the width of detect annulus $\rho$ can be nearly described:

$$\rho = \frac{l_0 \cdot \theta_r}{\sin \theta} = \frac{h \cdot \theta_r}{\sin^2 \theta}$$

(2)

And the width of detect annulus $\rho$ can be described with dose the approximate:

$$\rho = \frac{l_0 \cdot \Delta l}{r_0}$$

(3)

If the baffle area of the backward body doesn’t emit ($\pm \alpha$), the area of detect annulus $S_{\rho}$ will be described:

$$S_{\rho} = 2\pi \cdot \left[ h \cdot \cot \left( \theta + \frac{\theta_r}{2} \right) \right] \cdot \left( \frac{h \cdot \theta_r}{\sin^2 \theta} \right) \cdot \left( 1 - \frac{\alpha}{\pi} \right)$$

(4)

As shown in the formula (3). In any search time, the size of detect annulus has nothing to do with the speed of ASPA flight, and the width of detect annulus is proportional to the flying height, and radar optical axis Angle of depression is inversely proportional to the square of the sine function. Vertical beam Angle is determined by the performance of radar. If the radar model is determined, the vertical beam angle will be determined.
Usually, in the view of the conventional radar, high pulse repetition frequency will lead to the distance fuzzy\(^{[2-4]}\), as shown in figure 3. We can see that the distance between target \(P_1\) and antenna is \(l_1\), the time from echo to antenna is \(t_1 = 2l_1/c\) and set \(t_1 < T_r\); the distance between target \(P_1\) and antenna is \(l_1\), the time from echo to antenna is \(t_1 = 2l_1/c\). If pulse repetition frequency is too high can make \(t_1 - t_1 > T_r\). It can result in distance fuzzy.

Therefore, when designing the pulse radar, the choice of the repetition frequency must meet maximum effective distance \(l_{max}\) requirements, pulse repetition frequency \(f_r\) should be \(f_r \leq c/2l_{max} \). If time of maximum distance of target echo to meet in the first repeat cycle, the largest detect annulus width \(\rho_{max}\) is described:

\[
\rho_{max} = \frac{c \cdot l_0}{2r_0 \cdot f_r} \tag{5}
\]

4 Determine the parameter of detect annulus

Set maximum effective distance of search radar \(R_{l_{max}}\), radar range \(R_h\), and target height \(h_t\), the minimum optical axis Angle of depression \(\theta_{max}\) is:

\[
\theta_{min} = \arcsin \left( \frac{h_t - h}{l_{02_{max}}} \right) + \frac{\theta_r}{2} \tag{6}
\]

When radar is in the plan view state, \(l_{02}\) should satisfy:

\[
l_{02} \leq \min(R_{l_{max}}, R_h) \tag{7}
\]

If the optical axis Angle of depression is maximum, the radius of detect annulus is minimum:

\[
\begin{align*}
l_{02_{min}} &= \min \left( R_{l_{max}}, R_h, \frac{(h_t - h)}{\sin(\theta_{max} - 0.5\theta_r)} \right) \\
r_{02_{min}} &= l_{02_{min}} \cdot \cos \left( \theta_{max} - \frac{\theta_r}{2} \right) \\
r_{01_{min}} &= (h_t - h) \cdot \cot \left( \theta_{max} + \frac{\theta_r}{2} \right) \\
R_{l_{max}} &= \left( \frac{P_G G^2 \lambda^2 \sigma_r}{(4\pi)^3 k T_0 F_n L(S/N)B_p} \right)^{\frac{1}{2}}
\end{align*}
\tag{8}
\]

Instruction: \(G\) - antenna gain; \(\lambda\) - radar working wavelength; \(\sigma_r\) - target reflection area; \(k\) - Boltzmann constant; \(T_0\) - 290K; \(F_n\) - system noise factor; \(L\) - system loss; \(S/N\) - signal to noise ratio. Most parameters can be obtained directly, but \(L\) and \(S/N\) should be estimated.

If the optical axis Angle of depression is minimum, the radius of detect annulus is maximum: 3
As shown in the formula (8). The signal to noise ratio is associated with detection probability $P_d$ and false alarm probability $P_{fa}$ \[ S/N = \frac{\ln P_d}{\ln P_{fa}} - 1 \] \[ \ln P_d = \ln P_{fa} + \ln \left[ 1 + \left( \frac{P_{fa}}{P_d} \right) \right] \] \[ \lambda \sigma_\theta = \left( 4\pi \right)^3 kT \left( F - LR \right) B_d \] \[ d_{max} = l_{max} \cdot \cos \left( \frac{\theta_{max} - \theta}{2} \right) \] \[ d_{max} = \left( h - h_r \right) \cdot \cot \left( \frac{\theta_{max} + \theta}{2} \right) \] \[ \theta_{max} = \frac{1}{2} \] \[ \theta_{max} = \frac{1}{2} \] (9)

Where: $P_{fa}$ - average radiation power of radar; $R_s$ - separation distance between anti-submarine patrol aircraft and target.

We can see that the maximum width (or coverage) of detect annulus is different when anti-submarine patrol aircraft detects different targets. When anti-submarine patrol aircraft detects the set targets, it can adjust flight altitude and optical axis angle of depression correspondingly to detect targets earlier.

Flight altitude $h$ must meet the flight constraints:

\[ h_{min} \leq h \leq h_{max} \] (11)

Where: $h_{min}$ - minimum safe flight altitude of anti-submarine patrol; $h_{max}$ - maximum safe flight altitude of anti-submarine patrol.

5 Search method of acquisition radar

Based on the analysis of detect annulus model of acquisition radar, the basic method of anti-submarine patrol aircraft using acquisition radar is parallel flight search and multi-parallel flight search. According to the search manner of radar, the search method of acquisition radar can also be divided into parallel continuous search, parallel discrete search, multi-parallel continuous search and multi-parallel discrete search. The max horizontal detection distance of of anti-submarine patrol aircraft using acquisition radar is $d_a$, the max horizontal detection distance of submarine using radar detection instrument is $d_q$. The situation of anti-submarine patrol aircraft using acquisition radar is shown in figure 4.

According to the problem of multi-aircraft search, if single search can cover the width of the search area, the method of parallel flight search can be choosing, as shown in figure 5(a). The interval of anti-submarine patrol aircraft is $2d_a$, and any anti-submarine patrol aircraft should keep...
synchronization. If single search cannot cover the width of the search area, the method of multi-parallel flight search can be chosen, as shown in figure 5(b). The interval of any parallel flight section is $d_a + d_q$. According to the problem of single-aircraft search, the method of multi-parallel flight search can be chosen, as shown in figure 5(c). The interval of any parallel flight section is $d_a + d_q$.

![Fig.5(a) Parallel flight search](image)

![Fig.5(b) multi-parallel flight search](image)

![Fig.5(c) multi-parallel flight search](image)

No matter radar chooses what kind of the search method, all the methods are adaptive to anti-submarine patrol aircraft. In the actual warfare, we can plan and choose the search method according to the size of search area.

6 Simulation and Analysis
In the same context, aimed at submarine in the surface state and aircraft in the low state, the model of detect annulus can find the varying pattern of optical axis angle of depression and flight altitude from the width of detect annulus. It can determine the best optical axis angle of depression and flight altitude to meet the operational requirements. The simulation results as shown in figure 6-7 and table 1-2.

![Fig.6(a) Sea-surface submarine](image)

![Fig.6(b) Aerial aircraft](image)
The simulation results can show that:

1. The maximum detection range of acquisition radar which detect submarine in the surface state is mainly affected by radar range. Within the scope of ceiling height, the bigger anti-submarine patrol aircraft flight level, the higher maximum detection range. Therefore, anti-submarine patrol aircraft should gain flight altitude for increase detective distance.

2. The optical axis angle of depression has significant influence on the width of detect annulus. The bigger optical axis angle of depression, the smaller width of detect annulus. When detecting the specific low altitude target, the best optical axis angle of depression is $11^\circ \sim 13^\circ$, this moment the

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**Table 1** parameter of detect annulus of sea-surface submarine

| $A_1$ | 1000 | 2000 | 3000 | 4000 | 5000 | 6000 | 7000 |
|-------|------|------|------|------|------|------|------|
| $A_2$ | 89.79| 110.55| 148.71| 177.99| 202.68| 224.43| 244.09|
| $A_3$ | 0.819| 1.403| 2.865| 4.327| 5.789| 7.251| 8.713|
| $A_4$ | 0.7693| 1.3188| 2.0825| 4.0663| 5.4490| 6.8137| 8.1875|

**Table 2** Partial parameter of detect annulus of aerial aircraft

| $A_1$ | 1000 | 2000 | 3000 | 4000 | 5000 | 6000 | 7000 |
|-------|------|------|------|------|------|------|------|
| $A_2$ | 89.79| 110.55| 148.71| 177.99| 202.68| 224.43| 244.09|
| $A_3$ | 0.819| 1.403| 2.865| 4.327| 5.789| 7.251| 8.713|
| $A_4$ | 0.7693| 1.3188| 2.0825| 4.0663| 5.4490| 6.8137| 8.1875|

Where: $A_1$: flight altitude (m); $A_2$: detection range of radar (km); $A_3$: parameter of detect annulus (km); $A_4$: optical axis angle of depression ($^\circ$).
width of detect annulus is largest. It can ensure the targets stay long enough to detect targets more effectively.

7 Conclusion
From the perspective of operational use, this paper aimed at the operation performance of acquisition radar, put forward the concept of detect annulus, combined the flight constraints of anti-submarine patrol aircraft and operational background, established the corresponding model, obtained the best optical axis angle of depression and flight altitude to meet the operational requirements, provided the basis for the manner and method of anti-submarine patrol aircraft detect different sea-surface and aerial objects, and put forward the searching method of anti-submarine patrol aircraft using acquisition radar.

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