

# Research on Course Planning for Multi-AEW Cooperative Detection based on Real-time Detection Area

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**Abstract.** This paper presents a concept of stable coverage degree and its quantitative formula, and two kind of cooperative detection modes was put forward, which was defined as Mode A and Mode B. On the basis of estimation models including the model for real-time detection area, the model for cross coverage area, and the model for course planning, the decision-making model for multi-AEW optimal deployment was given. Finally, the contrastive analysis on two models was provided by simulation computing, its results showed the Mode B surpass Mode A, and various internal and external factors were considered into estimation models, which can offers the applied basis for multi-AEW course planning.

## 1. Introduction

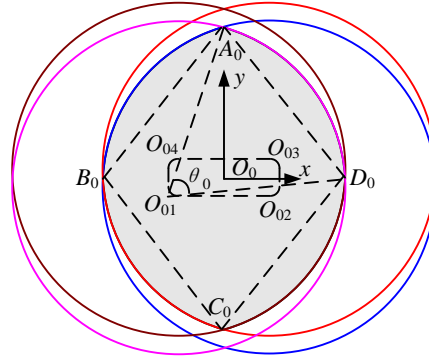
When multi-AEW take on aerial defense early warning mission in responsible area, two kinds of cooperative deployment mode was adopted, including Mode A and Mode B. In Mode A way, each AEW take on aerial mission of sub-responsible area independently, can't hand over mission transversely across areas, target information can't be syncretized and shared, which was used commonly. In Mode B way, by contrast, each AEW not only hand over mission transversely across areas, but also target information can be syncretized and shared by superior intelligence fusion center of an appointed AEW. Mode B is much better than Mode A. For the moment, mode A was researched mostly. For example, the concept of real-time coverage was put forward, and the calculation case of a single AEW was presented[1]. The concept of serial-parallel cooperative mode for multi-AEW was put forward, indicating that unstable coverage was caused by serial mode with numbered AEW, and easy to form blind zone[2]. The instantaneous coverage rate in way of parallel line and transverse-8 line was discussed[3]. The concept of high-efficiency and low-efficiency area was put forward, based on relative location and velocity between target and AEW, and detection efficiency was simulated[4]. The strategy of AEW used number was put forward, which discuss the skyway planning of a single AEW[5]. How to optimize deployment for multi-AEW was discussed while active jamming, based on radar self-defense jamming equation[6]. Information fusion and intelligence sharing for multi-AEW were not involved above literatures.

Two coverage estimation model of AEW real-time detection was established, the concept of stable coverage degree was defined and a quantitative equation was given. The decision-model of multi-AEW optimal deployment was given while multi-AEW deployment was discussed. Simulation results showed that Mode B surpass Mode A. With en-lengthen of responsible area  $L$  and higher coverage degree, Mode B superior to Mode A evidently. And major factors were considered in models, so the results is valuable.



## 2. Real-time detection area

The area that target can be detected effectively on altitude layer H with detection probability ( $P_d$ ) and false alarm rate ( $P_f$ ), was called real-time detection area. Usually, take parallel line as examples, as shown in Figure1,  $O_0$  is the coordinate origin of parallel line.  $O_{01}(-m_1, -n_1)$ ,  $O_{02}(m_1, -n_1)$ ,  $O_{03}(m_1, n_1)$  and  $O_{04}(-m_1, n_1)$  are four turning points of parallel line.  $R_1$  is the maximum detection range of airborne radar.  $S_0$  is the real-time detection area of an AEW which is the shadow in Figure1.



**Figure1.** Real-time detection area on parallel line

$S_0$  can be calculated as[5]

$$S_0 = 4 \times (S_{AOD} + S_{ADarc}) \quad (1)$$

$$\begin{cases} S_{AOD} = 0.5 \times (\sqrt{R_0^2 - m_0^2} - n_0) (\sqrt{R_0^2 - n_0^2} - m_0) \\ S_{ADarc} = 0.5 \times (R_0^2 \theta_0 - |AB| \times \sqrt{R_0^2 - 0.25 \times |AB|^2}) \\ \theta_0 = 2 \arcsin \left( \frac{\sqrt{2} |AB|}{2R_0} \right) \\ |AB| = \sqrt{R_0^2 - m_0^2} \sqrt{R_0^2 - n_0^2} - n_0 \sqrt{R_0^2 - m_0^2} \end{cases} \quad (2)$$

Where  $m_0 \in [20, 50]$  and  $n_0 \in [10, 20]$  with unit km[7]. If  $R_1 = 400\text{km}$ ,  $S_{10} = 457\text{km}^2$ . According to equation (1) and (2), the size of real-time detection area was determined by the size of parallel line and maximum detection range.  $R_0$  is generally determined by target cross section  $\sigma$ , pulse accumulation  $m$ , signal to noise ratio SNR, weather attenuation coefficient  $\delta$ , weather attenuation distance  $d_p$ , insertion loss  $L$ ,  $R_0$  can be calculated as

$$R_0 = \left[ \frac{P_t G^2 \lambda^2 \sigma e^{-0.115 \delta d_p}}{(4\pi)^3 k T_0 B_n F_n (S/N)_m L} \right]^{1/4} \quad (3)$$

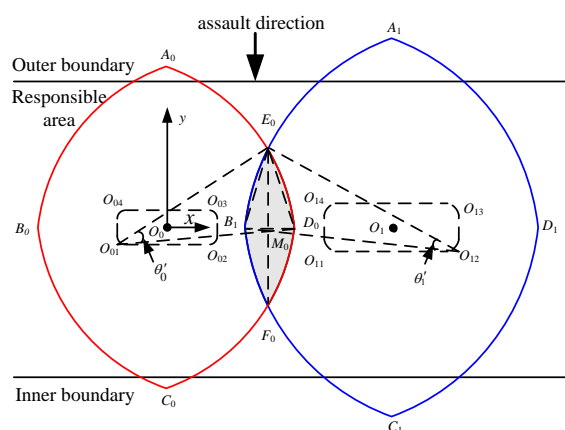
For air-defense early-warning, air-guidance, low-slow-small target detection mission, the detection probability index is 0.5, 0.8, 0.9, and  $R_0(P_d=0.5) > R_0(P_d=0.8) > R_0(P_d=0.9)$  with false alarm rate is  $P_f = 10^{-6}$ .

## 3. Cross coverage area of multi-AEW

As Figure2 shows that ribbon responsible area is divided by inner and outer parallels.  $O_0$  is the center point of the first course with its length  $2m_0$  and width  $2n_0$ , which is the coordinate origin.  $O_1$  is the

Assuming that  $R_0$  is maximum range of the first course,  $R_1$  is maximum range of the second course, the coordinate of cross point  $E_0$  is expressed by  $\overrightarrow{O_0E_0} = (x_{E_0}, y_{E_0})$ , it can be calculated as

$$\left\{ \begin{array}{l} \left| \overrightarrow{O_{01}E_0} \right| = \left| \overrightarrow{O_{01}O_0} + \overrightarrow{O_0E_0} \right| \\ R_0 = \left| m_0 + n_0 j + x_{E_0} + y_{E_0} j \right| \\ \left| \overrightarrow{O_{12}E_0} \right| = \left| \overrightarrow{O_{12}O_1} + \overrightarrow{O_1E_0} \right| \\ R_1 = \left| -m_1 - n_1 j + x_{E_0} - d + y_{E_0} j \right| \end{array} \right. \quad (4)$$



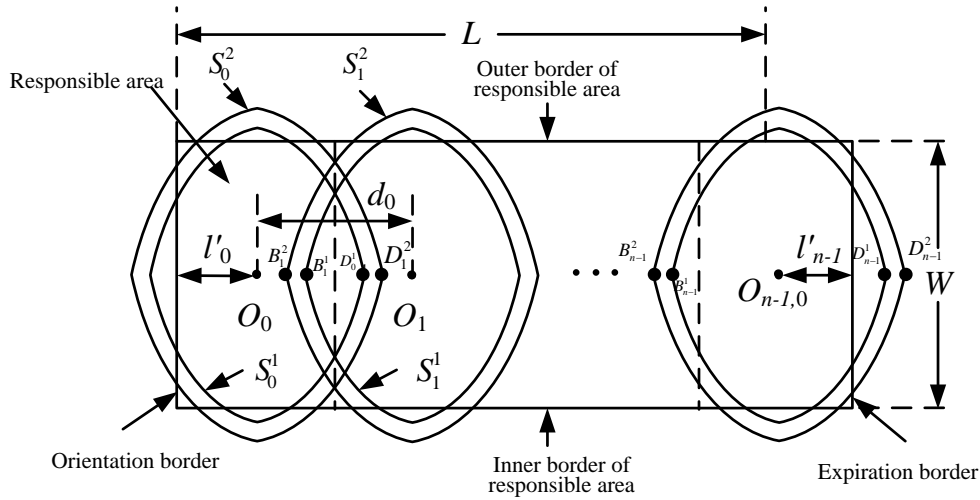
**Figure 2.** Real-time cross coverage of two AEW

The real-time cross coverage area  $S_{cross}$  can be calculated as

$$S_{\text{cross}} = S_{E_0 B_1 F_0 D_0} + 4S_{E_0 D_0 g} \quad (5)$$

$$\left\{ \begin{array}{l} S_{E_0 E_1 F_0 D_0} = \left| \overrightarrow{E_0 F_0} \right| \cdot \left| \overrightarrow{B_1 D_0} \right| \\ \left| \overrightarrow{E_0 F_0} \right| = 2 y_{E_0} \\ \left| \overrightarrow{B_1 D_0} \right| = R_0 - m_0 - (d_0 + m_1 - R_1) \\ S_{E_0 D_0 g} = \frac{1}{2} R_0^2 \theta'_0 - \frac{1}{2} \left| \overrightarrow{E_0 D_0} \right| \cdot \sqrt{R_0^2 - \left( \frac{1}{2} \left| \overrightarrow{E_0 D_0} \right| \right)^2} \\ \left| \overrightarrow{E_0 D_0} \right| = \sqrt{\left( -m_0 + \sqrt{R_0^2 - n_0^2} - x_{E_0} \right)^2 + y_{E_0}^2} \\ \theta'_0 = 2 \arcsin \frac{\left| \overrightarrow{E_0 D_0} \right|}{2 R_0} \end{array} \right. \quad (6)$$

Obviously, Real-time cross coverage area of two AEW was mostly determined by planning course and radar max detection range.



**Figure 3.** Real-time detection area of multi-AEW

As showed in Figure3, the ribbon responsible area is composed of length  $L$  and width  $W$ , which it is deployed by  $N$  AEW. If the center coordinate of the first course is assumed as origin, then the center coordinate of all courses are expressed by  $\{(0,0),(0,d_1)\dots,(0,d_{N-1})\}$ .  $l'_0$  is the length between  $O_0$  and origination border, and  $l'_{n-1}$  is the length between  $O_{n-1}$  and expiration border. Ordinarily,  $S_i^1$  is real-time detection area of  $i$ th AEW with  $P_{di}^0$ ,  $S_i^2$  is real-time detection area of  $i$ th AEW with  $P_{di}^1$ .  $S_i^1 \cap S_{i+1}^1$ ,  $S_i^2 \cap S_{i+1}^2$ ,  $S_i^1 \cap S_{i+1}^2$  and  $S_i^2 \cap S_{i+1}^1$  are cross area of  $S_i^1$  and  $S_i^2$ , while  $i = 0, 1, \dots, N-1$ ,  $P_{di}^0 > P_{di}^1$ . Detection probability of cross coverage area  $P_{dcross}$  can be calculated as

$$P_{dcross} = \begin{cases} \max \{P_{di}^j\} = P_d, & \text{Model} \\ 1 - \prod_{i=0}^{N-1} (1 - P_{di}^j), & \text{Mode2} \end{cases}, i = 0, 1, \dots, N-1, j = 0, 1 \quad (7)$$

$P_{dcross} \geq P_d$  can be obtained by choosing  $S_i^2$  properly. Cross coverage area of multi-AEW  $S_{sum}$  can be calculated as

$$S_{sum} = \begin{cases} S_0^1 + \sum_{i=1}^{N-1} [S_i^1 - (S_{i-1}^1 \cap S_i^1)] & , \text{Model} \\ S_0^1 + \sum_{i=1}^{N-1} [S_i^1 + (S_{i-1}^2 \cap S_i^2) - (S_{i-1}^1 \cap S_i^2) - (S_{i-1}^2 \cap S_i^1)] & , \text{Mode2} \end{cases} \quad (8)$$

#### 4. Multi-AEW course planning

For long ribbon responsible detection area, Multi-AEW course planning is decision-making question with many constrained conditions. The ultimate purpose is to get stable coverage in specified responsible area. The key parameter is interval distance between one course and another course. Constrained conditions are stable coverage degree, distance between inner border and outer border of responsible area, cooperative model, max detection range of an AEW, real-time coverage area of an AEW, and cross real-time coverage area of multi-AEW. Stable coverage degree  $\eta_c$  can be calculated as

$$\eta_c = \frac{S_{sum} \cap S_0}{S_0} \quad (9)$$

If the outer border coordinate is expressed by  $y_{D\_out}$ , then the purpose of multi-AEW course planning is to get optimal interval distance between courses with constrained conditions, that is

$$\begin{aligned} \{d_0, d_1, \dots, d_{N-1}\} &= \text{opt} \{d_{0j}, d_{1j}, \dots, d_{N-1j}\}_{j=0,1,\dots} \\ s.t. \left\{ \begin{aligned} \eta_C &\geq \eta_C^{\text{need}} \\ y_{D\_out} &\leq \frac{W}{2} \\ L - l'_0 - l'_{N-1} &\leq \sum_{i=1}^{N-1} \max d_i \\ \max d_1 &\geq \max d_2 \dots \geq \max d_{N-1} \\ |O_i D_i^1| + |O_{i+1} B_{i+1}^1| - \beta T_{\text{search}} v_{TH} &\geq \max d_{i+1} > 0, \text{Model1} \\ |O_i D_i^1| + |B_{i+1}^2 D_i^2| - |B_{i+1}^2 O_{i+1}| &\geq \max d_{i+1} > 0, \text{Mode2} \\ i &= 1, 2, \dots, N-1 \end{aligned} \right. \end{aligned} \quad (10)$$

where  $\eta_C^{\text{need}}$  is prospective stable coverage degree.  $T_{\text{search}}$  is radar scan period.  $\beta$  is plot number required in intelligence handover for Mode A.  $v_{TH}$  is target velocity. Condition 5 assures interval distance  $\beta T_{\text{search}} v_{TH}$  required for intelligence handover, while  $\max d_i$  satisfied the demand of continuous detection area. Condition 6 assures that cross area with  $P_{di}^1$  overlap detection area with  $P_{di}^0$ , to make the target detected incessantly.  $\max d_i$  is constrained with condition 1 and 2.

## 5. Simulation and analysis

### 5.1. Contrastive analysis on two models

In order to contrastive analysis the operation efficiency of the two modes, the benefit of stable coverage area  $\eta_G$  can be defined as

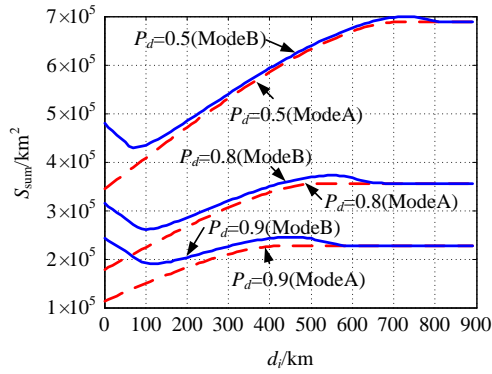
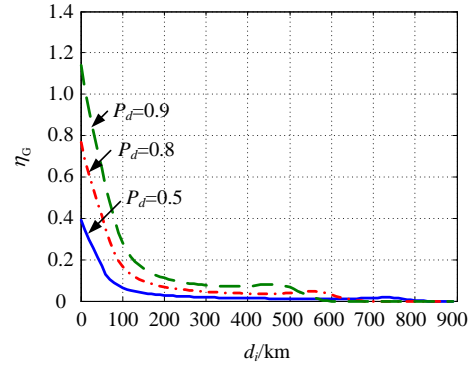
$$\eta_G = \left( \frac{S_{\text{sum\_mode2}}}{S_{\text{sum\_mode1}}} - 1 \right) \times 100\% \quad (11)$$

It is assumed that two AEW with same type are on early warning mission on a fine day,  $m = 50\text{km}$  and  $n = 10\text{km}$  with  $\min S_{i0}$ ,  $R_{\text{max}} = 400\text{km}$  with Swerling I target and  $RCS = 5\text{m}^2$ . With the equation from literature 8,  $R'_{\text{max}}$  is got with any  $P_d$ . The relation of  $d_i$  and  $S_{\text{sum}}$  is shown in Figure4. The relation of  $d_i$  and  $\eta_G$  is shown in Figure5. The conclusions are as follows:

First, the smaller of  $P_d$ , the bigger of cooperative detection area  $S_{\text{sum}}$  for two AEW, the bigger of  $d_i$  critical value. That is to say, the smaller of  $P_d$  working with, the bigger of effective detection area, in which continuous target intelligence can be offered.

Second, When  $d_i$  is smaller than critical value, the bigger of detection probability, the bigger of  $\eta_G$  value, That is to say, Mode B surpass Mode A obviously when  $P_d$  need to be bigger.

Third, When  $S_{\text{sum}}$  is a fixed value, critical value of Mode B exceeds Mode A with any  $P_d$ . Results indicates that Mode B can obtain enough cross coverage area with bigger  $d_i$ , so that to handover target intelligence reliably between adjacent two AEW.

Figure 4. Relation of  $d_i$  and  $S_{su}$ Figure 5. Relation of  $d_i$  and  $\eta_G$ 

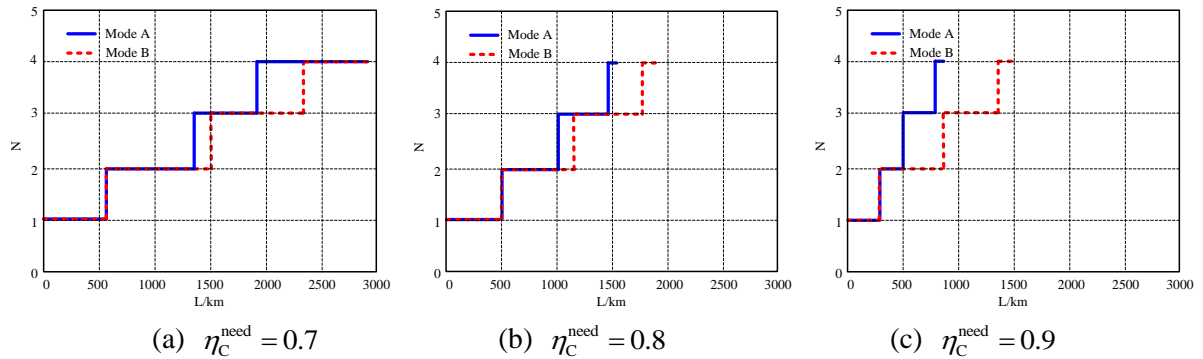
### 5.2. Analysis on value of $L$ and $N$

It is assumed that each AEW with same  $R_{\max}$ , then  $l'_0 = l'_{N-1} = l$ ,  $\max d_1 = \max d_2 \cdots = \max d_{N-1} = d$ .

$$\min N = \left\lceil \frac{L - 2l}{d} + 1 \right\rceil \quad (12)$$

Where  $\lceil \cdot \rceil$  is a symbol that round up to an integer.

It is assumed that width of responsible area  $W = 700\text{km}$ ,  $P_d = 0.5$ ,  $\beta = 5$ ,  $T_{\text{search}} = 10\text{s}$ ,  $v_{\text{TH}} = 380\text{m/s}$ ,  $\eta_c^{\text{need}} = \{0.7, 0.8, 0.9\}$ , and other parameters are the same as 5.1 section. The relation of  $L$  and  $N$  is shown in Figure 6.

Figure 6. Relation of  $L$  and  $N$ 

In view of the different  $\eta_c^{\text{need}}$ , the  $L$  value of cross coverage area is shown in Table 1 where four AEW are deployed.

The conclusions are as follows: Fewer AEW are need with growing  $L$  on mode B; cooperative mode B surpass mode A with growing  $\eta_c^{\text{need}}$ .

Table 1. Relation of  $d_i$  and  $L$  with  $S_{\text{cross}}=0$ 

$\eta_c^{\text{need}}$	Cooperative mode	$L(\text{km})$			
		1	2	3	4
0.7	Mode B	588	1490	2310	2894
	Mode A	588	1290	1901	2400
0.8	Mode B	497	1242	1737	1912
	Mode A	497	991	1477	1500
0.9	Mode B	315	817	1319	1438
	Mode A	315	505	789	859

## 6. Conclusion

In view of the problem of course planning for multi-AEW, two kinds of cooperative mode were given, four models were established, including estimating model for real-time detection area, the model for cross coverage area, the model for course planning, and decision-making model for multi-AEW. Lots of influence factor are considered to ensure practicability value of four models, thereby the next study is a step towards the application, how can these models be used into various early warning surveillance mission.

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