A correction method for radar detection range evaluation in interference environment

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Abstract. Effective evaluation of radar detection range in jamming environment is crucial to the grasp of battlefield situation. The equation widely used in engineering ignores the influence of system noise, and this is easily to cause the distortion of radar range evaluation in weak electromagnetic environment and may even lead to a situation that the detection distance in jamming environment is greater than that without interference. To solve the problem, this paper performed a detailed derivation of the radar detection range evaluation in different situations, before and after taking anti-jamming measures in main-lobe and side-lobe jamming environment. Correction method to the traditional calculation is proposed, closed-form expressions are given correspondingly as well. Simulation shows that the correction method has considerable universality and can effectively avoid the distortion of radar range evaluation in weak jamming environment, which is of great significance to the analysis and evaluation of radar detection range under different jamming environment.

Keywords: Interference environment, Radar detection distance, Self-defense distance, Side-lobe Jamming, Main-lobe Jamming.

1 Introduction

With the development of electromagnetic technology, the environment faced by modern radar is increasingly terrible. The radar detection range will be affected to varying degrees while faced with different jamming environment. The effective evaluation for the changes of radar detection range in jamming environment is quite important to fully grasp the battlefield situation and make better use of radar performance.

The equation to calculate radar self-defence distance widely used in engineering usually ignores the influence of system noise. In this way, the change of radar range in strong electromagnetic environment can be evaluated relatively accurate. But when the interference is getting weaker, the distortion of radar range evaluation will appear, sometimes even occurs the circumstances that the radar detection range under jamming environment is greater than that without jamming. This will bring trouble to the evaluation and analysis of the radar detection range under jamming environment.

To solve the problem, this paper deeply analyses the change of radar detection range under different interference environment, makes modification to the traditional calculation

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and gives closed-formed expressions correspondingly as well.

2 Engineering calculation method for radar self-defense distance

In this chapter, the widely used engineering equations to calculate radar detection range in different situations will be discussed, such as the self-defence distance in main-lobe jamming environment, the self-defence distance in side-lobe jamming environment as well as the maximum detection distance without jamming. The detailed analysis is as follows.

2.1 Maximum detection distance in ideal space

Regardless of clutter factors, the maximum detection distance of radar in a non-interference environment is mainly affected by thermal noise.

At this time, the maximum detection distance of radar $R_{\max}$ can be expressed as:

$$R^4{}_{\max} = \frac{P_t \tau G_t G_r \sigma \lambda^2}{(4\pi)^3 k T_s D_0 L_s} \tag{1}$$

Where P_t represents the radar transmitting power, τ represents the pulse width of radar transmitting signal, G_t represents the gain of radar transmitting antenna, G_r represents the gain of radar receiving antenna, σ represents target radar cross section (RCS), λ represents radar operating wavelength, k represents Boltzmann constant, T_s represents system noise temperature, D_0 represents detection factor, L_s represents system loss.

Equation (1) is the radar detection range equation in ideal space, in this paper the maximum detection distance at this time is denoted as $R_{\max 0}$.

2.2 Radar self-defense distance in active suppression jamming environment

When exposed to active suppression jamming environment, the radar detection range will be reduced to some degree. According to the different incident direction, the jamming is usually divided into main-lobe jamming and side-lobe jamming. Typically, long-range support jamming enters from the side-lobe of radar receiving beam and it is classified as side-lobe jamming, while self-defence jamming and team support jamming enter from the main-lobe, which are classified as main-lobe jamming.

In engineering calculation, the jamming is usually considered strong enough that the system noise can be ignored.

Assuming that the distance between the jammer and the radar is R_{j}, the polarization of the jammer's antenna is the same as that of the radar's antenna. Ignoring the transmission loss, then the jamming power spectral density entering the radar receiver can be expressed as:

$$P_{\mathrm{rj}} = \frac{P_{\mathrm{j}} G_{\mathrm{j}}}{B_{\mathrm{j}}} \times \frac{1}{4\pi R_{\mathrm{j}}^2} \times \frac{G_{\mathrm{rs}} \lambda^2}{4\pi} \tag{2}$$

where P_{j} is the transmitting power of the jammer, G_{j} is the gain of the jammer's antenna, B_{j} is the effective bandwidth of the jammer, and G_{rs} is the receiving gain of the radar antenna in the jamming direction. In Equation (2), The first polynomial represents the equivalent jamming power spectral density, the second polynomial represents the jamming divergence at the radar antenna, and the third polynomial is the effective receiving area of radar.

Thus, the radar self-defence distance in strong electromagnetic jamming environment can be described as:

$$R^4{}_{\max} = \frac{P_t \tau G_t G_r \sigma \lambda^2}{(4\pi)^3 P_{rj} D_0 L_s} \tag{3}$$

2.2.1 Main lobe self-defence distance

When the jamming comes from the main lobe of the radar receiving beam, the receiving gain of the radar in the jamming direction is close to the main lobe receiving gain, i.e., $G_{rs} \approx G_r$. At the same time, since the location of the jammer is close to the target aircraft in main lobe jamming scenario, the jammer distance can be considered equal to the protected target distance, i.e., $R_\mathrm{j} \approx R$.

Substituting $R_\mathrm{j} \approx R$, $G_{rs} \approx G_r$ into Equation (2), the jamming power spectral density received by the radar in main lobe jamming scenario can be described as:

$$P_\mathrm{rj} = \frac{P_\mathrm{j} G_\mathrm{j} G_\mathrm{r} \lambda^2}{(4\pi)^2 R^2 B_\mathrm{j}} \tag{4}$$

Substituting Equation (4) into Equation (3), the radar self-defence distance in main lobe jamming environment can be obtained as follows:

$$R^2{}_{\max} = \frac{P_t \tau G_t \sigma}{4\pi (P_j / B_j) G_j D_0 L_s} \tag{5}$$

In Equation (5), $(P_j / B_j)G_j$ is the transmitting power spectral density of the jammer,the meaning of the rest parameters is the same as Equation (1).

Equation (5) is the engineering calculation formula of self-defence distance in main lobe jamming environment, in this paper the main lobe self-defence distance here is denoted as $R_{\max 11}$.

2.2.2 Side lobe self-defence distance

When the jamming comes from the sidelobe of the radar receiving beam, the receiving gain of the radar in the jamming direction can no longer be considered equal to the receiving gain of the main lobe, i.e., $G_{rs} \neq G_r$. The jammer distance is no longer close to the target distance either, i.e., $R_\mathrm{j} \neq R$.

Therefore, in the side-lobe jamming scenario, the jamming power spectral density received by the radar can be described as.

$$P_\mathrm{rj} = \frac{P_\mathrm{j} G_\mathrm{j} G_\mathrm{rs} \lambda^2}{(4\pi)^2 R_\mathrm{j}^2 B_\mathrm{j}} \tag{6}$$

Substitute Equation (6) into Equation (3), the radar self-defence distance in sidelobe jamming environment can be obtained as follows:

Where G_{sl} is the ratio of the radar's receiving gain in the target direction to the radar's receiving gain in the jamming direction, i.e., $G_{sl} = G_r / \mathrm{G_{rs}}$. $(P_j / B_j)G_j$ is the transmitting power spectral density of the jammer. R_j is the distance between the jammer and the radar, the rest parameters represent the same as those in Equation (1).

$$R^4{}_{\max} = \frac{P_t \tau G_t G_{sl} \sigma R_j{}^2}{4\pi (P_j / B_j) G_j D_0 L_s} \tag{7}$$

In Equation (7) is engineering calculation formula of self-defense distance in side-lobe jamming environment, in this paper the side lobe self-defense distance here is denoted as $R_{\max 21}$.

3 Corrected method to calculate self-defense distance

The commonly used Equation to calculate self-defence distance derived in previous section is obtained under the precondition that the jamming is strong enough that the system noise can be ignored. However, in practical applications, the interference power received by the radar is not always stronger than the internal radar receiver noise. In this situation, deviations will be brought while estimating the radar self-defence distance according to the traditional equation, sometimes even occurs the situation that the radar self-defence distance in jamming environment is greater than that without jamming. Obviously, this is unreasonable and inaccurate.

In order to avoid the error caused by the traditional calculation formula in radar self-defence distance evaluation under weak jamming environment, a correction method is proposed to make the equation more universal and practical in this section. The details are as follows.

Since the effect of active suppression jamming imposed on radar detection performance is like that of "antenna noise" in nature, equivalent noise temperature can be introduced to describe interference.

For the interference with power spectral density P_{rj} at the radar receiving end, the equivalent noise temperature T_j it brought to the radar receiver can be expressed as:

$$T_j = \frac{P_{rj}}{k} = \frac{P_j G_j G_{rs} \lambda^2}{(4\pi)^2 R_j^2 k B_j} \tag{8}$$

For a radar with internal system noise temperature of T_s, its equivalent system noise temperature T_s' in jamming environment can be expressed as:

$$T_s' = T_s + T_j \tag{9}$$

Thus, the maximum detection distance of the radar in jamming environment can be expressed as:

$$R^4{}_{\max} = \frac{P_t \tau G_t G_r \sigma \lambda^2}{(4\pi)^3 k T_s' D_0 L_s} \tag{10}$$

Considered that the influence of receiver noise cannot be ignored in weak electromagnetic interference environment, substitute equation (9) into equation (10), and take the reciprocal of equation (10), it can be obtained that:

$$\frac{1}{R^4{}_{\max}} = \frac{(4\pi)^3 k T_s D_0 L_s}{P_t \tau G_t G_r \sigma \lambda^2} + \frac{(4\pi)^3 k T_j D_0 L_s}{P_t \tau G_t G_r \sigma \lambda^2} \tag{11}$$

3.1 Corrected calculation of main lobe self-defense distance

In main lobe jamming scenario, substituting Equation (8) into Equation (11), and considering $G_{rs} \approx G_r$, Equation (11) can be transformed to:

$$\frac{1}{R^4{}_{\max}} = \frac{(4\pi)^3 kT_s D_0 L_s}{P_t \tau G_t G_r \sigma \lambda^2} + \frac{(4\pi)(\mathrm{P_j}/\mathrm{B_j})\mathrm{G_j} D_0 L_s}{P_t \tau G_t \sigma} \bullet \frac{1}{\mathrm{R_j}^2} \tag{12}$$

The first polynomial on the right side of Equation (12) is the reciprocal of the radar equation in ideal space, and the first factor of the second polynomial is the reciprocal of the traditional equation of the radar main lobe self-defence distance where the influence of system noise is ignored.

Substituting Equation (1) and Equation (5) into Equation (12), and considering $R_{\mathrm{j}} \approx R_{\max}$ in main lobe jamming scenario, it can be obtained that:

$$\frac{1}{R^4{}_{\max}} = \frac{1}{R^4{}_{\max 0}} + \frac{1}{R^2{}_{\max 11}} \bullet \frac{1}{R^2{}_{\max}} \tag{13}$$

Taking the main lobe self-defence distance here as $R_{\max 12}$, and solving Equation (13), it can be obtained that:

$$R^2{}_{\max 12} = \frac{R^4_{\max 0}}{2R^2_{\max 11}}\left(\sqrt{1+4\frac{R^4_{\max 11}}{R^4_{\max 0}}} - 1\right) \tag{14}$$

Equation (14) is the modified formula to calculate main lobe self-defence distance. It can be seen from Equation (14) that the corrected radar main lobe self-defence distance can be obtained from the maximum radar distance in ideal space and the radar main lobe self-defence distance calculated by when noise is ignored.

3.2 Corrected calculation of side lobe self-defense distance

In sidelobe jamming scenario, substituting Equation (8) into Equation (11), and considering $G_{rs} \neq G_r$, $R_{\mathrm{j}} \neq R$, Equation (11) can be expressed as:

$$\frac{1}{R^4{}_{\max}} = \frac{(4\pi)^3 kT_s D_0 L_s}{P_t \tau G_t G_r \sigma \lambda^2} + \frac{4\pi (P_{\mathrm{j}} / B_{\mathrm{j}}) G_{\mathrm{j}} D_0 L_s}{P_t \tau G_t G_{sl} \sigma R_{\mathrm{j}}^2} \tag{15}$$

The first polynomial on the right side of equation (15) is the reciprocal of the radar detection range equation under no-interference conditions, and the second polynomial is the reciprocal of the radar sidelobe self-defence distance calculation equation when the influence of system noise is ignored.

Substituting equations (1) and (7) into the above equations, it can be obtained that:

$$\frac{1}{R^4{}_{\max}} = \frac{1}{R^4{}_{\max 0}} + \frac{1}{R^4{}_{\max 21}} \tag{16}$$

Taking the radar sidelobe self-defence distance here as $R_{\max 22}$, and solving Equation (16), it can be obtained that:

$$R_{\max 22} = \frac{R_{\max 0} R_{\max 21}}{\sqrt[4]{R^4{}_{\max 0} + R^4{}_{\max 21}}} \tag{17}$$

Equation (17) is the modified formula to calculate sidelobe self-defence distance. It can be seen from the above formula that the corrected radar sidelobe self-defence distance can be calculated from the maximum radar distance without interference and the radar sidelobe self-defence distance when system noise is ignored.

By further decomposing the radar detection range equation (10) under jamming environment, it can be obtained that:

$$R^4{}_{\max} = \frac{P_t \tau G_t G_r \sigma \lambda^2}{(4\pi)^3 kT_s D_0 L_s} \times \frac{kT_s}{(kT_s + kT_j)} \tag{18}$$

Substituting Equation (1) into the above equation, and taking into account that $P_{rj} = kT_j$, we can get:

$$R^4{}_{\max} = R^4{}_{\max 0} \times \frac{1}{(1 + P_{rj} / kT_s)} \tag{19}$$

In equation (19), P_{rj} / kT_s is the ratio of the interference power spectral density to the noise power spectral density, that is, the interference-to-noise ratio INR. Therefore, the radar sidelobe self-defence distance can also be expressed as:

$$R^{'}_{\max 22} = R_{\max 0} \times \frac{1}{\sqrt[4]{1 + INR}} \tag{20}$$

Another evaluation method for sidelobe self-defence distance is given in Equation (20). When the interference-to-noise ratio and the radar detection distance in ideal space are known, the radar sidelobe self-defence distance can be obtained according to this formula.

From Equation (14) and Equation (17), it can be seen that corrected self-defence distance calculation formula is a function of the radar maximum detection distance when only considering system noise and the self-defence distance when only considering interference. It is reasonable because when we derived the modified radar self-defence distance the effects of system noise and interference are taking into account jointly.

According to the above formula, the corrected radar self-defence distance can be calculated from the radar maximum detection distance when there is no interference and the self-defence distance obtained by the commonly used engineering calculation, so as to solve the error caused by ignoring internal noise.

3.3 Evaluation of radar detection distance after taking anti-jamming measures

In order to improve the radar detection performance in jamming environment, anti-jamming measures are usually taken while encountered with active suppression interference. For example, side lobe cancellation (SLC) technique is often used to suppress sidelobe jamming while blind source separation method is generally adopted to suppress main lobe jamming.

Assuming that the interference suppression ratio is JCR, then the interference power spectral density after taking anti-jamming measures can be expressed as follows:

$$P^{'}_{rj} = P_{rj} / JCR \tag{21}$$

3.3.1 Maximum distance calculation before correction

Substituting Equation (21) into Equation (3), the radar detection distance after taking anti-jamming measures while ignoring the influence of noise can be obtained as follows.

$$R^4{}_{\max} = \frac{P_t \tau G_t G_r \sigma \lambda^2}{(4\pi)^3 P_{rj} D_0 L_s} \bullet JCR \tag{22}$$

For main lobe jamming scenario, the maximum detection distance after taking anti-jamming measures while ignoring the influence of noise will be:

$$R^2_{\max} = R^2_{\max 11} \cdot JCR \tag{23}$$

In equation (23), $R_{\max 11}$ is the main lobe self-defence distance before correction. Equation (23) is the engineering calculation formula of the maximum radar detection distance after taking anti-jamming measures in main lobe jamming scenario, where the influence of system noise is ignored. Taking the maximum radar detection distance here as $R_{\max 13}$.

For sidelobe jamming scenario, the maximum detection distance after taking anti-jamming measures while ignoring the influence of noise will be:

$$R^4_{\max} = R^4_{\max 21} \cdot JCR \tag{24}$$

In equation (24), $R_{\max 21}$ is the radar side lobe self-defence distance before correction. Equation (24) is the engineering calculation formula of the maximum radar detection distance after taking anti-jamming measures in sidelobe jamming scenario, where the influence of system noise is ignored. Taking the maximum radar detection distance here as $R_{\max 23}$.

3.3.2 Maximum distance calculation after correction

Substituting Equation (21) into Equation (10), the corrected equation to calculate radar detection distance after taking anti-jamming measures can be obtained, where the influence of noise and interference are taking into account can jointly:

$$R^4{}_{\max} = \frac{P_t \tau G_t G_r \sigma \lambda^2}{(4\pi)^3 (kT_s + P_{rj} / JCR) D_0 L_s} \tag{25}$$

Main lobe jamming scenario

In main lobe jamming scenario, take the reciprocal of equation (25) and substitute equation (4) into it, it can be obtained that:

$$\frac{1}{R^4{}_{\max}} = \frac{(4\pi)^3 kT_s D_0 L_s}{P_t \tau G_t G_r \sigma \lambda^2} + \frac{4\pi (P_\mathrm{j} / B_\mathrm{j}) G_\mathrm{j} D_0 L_s}{P_t \tau G_t \sigma} \cdot \frac{1}{R_j^2} \cdot \frac{1}{JCR} \tag{26}$$

The first polynomial on the right side of equation (26) is the reciprocal of the radar maximum detection range equation under no-interference conditions, and the first factor of the second polynomial is the reciprocal of the radar main lobe self-defence distance equation ignoring system noise.

Substituting equations (1) and (5) into the above equations, and considering $R_\mathrm{j} \approx R_{\max}$ in the main lobe interference scenario, it can be obtained that:

$$\frac{1}{R^4{}_{\max}} = \frac{1}{R^4{}_{\max 0}} + \frac{1}{R^2{}_{\max 11}} \cdot \frac{1}{R^2{}_{\max}} \cdot \frac{1}{JCR} \tag{27}$$

From formula (23), $R^2_{\max 13}=R^2_{\max 11}\cdot JCR$, thus the above formula can also be expressed as:

$$\frac{1}{R^4{}_{\max}}=\frac{1}{R^4{}_{\max 0}}+\frac{1}{R^2{}_{\max 13}}\cdot\frac{1}{R^2{}_{\max}} \tag{28}$$

Taking the maximum radar detection distance here as $R_{\max 14}$, and solving Equation (28),it can be obtained that:

$$R^2{}_{\max 14}=\frac{R^4_{\max 0}}{2R^2_{\max 13}}\left(\sqrt{1+4\frac{R^4_{\max 13}}{R^4_{\max 0}}}-1\right) \tag{29}$$

Equation (29) is the corrected formula to calculate the maximum radar detection distance after taking anti-jamming measures in main lobe jamming scenario. It can be seen from Equation (29) that the corrected maximum radar detection distance can be obtained from the maximum radar detection distance without interference and the maximum radar detection distance before the correction.

Side lobe jamming scenario

In sidelobe jamming scenario, take the reciprocal of equation (25) and substitute equation (6) into it, it can be obtained that:

$$\frac{1}{R^4{}_{\max}}=\frac{(4\pi)^3 kT_s D_0 L_s}{P_t\tau G_t G_r\sigma\lambda^2}+\frac{4\pi(P_{\mathrm{j}}/B_{\mathrm{j}})G_{\mathrm{j}}D_0 L_s}{P_t\tau G_t G_{sl}\sigma R_j^2}\cdot\frac{1}{JCR} \tag{30}$$

The first polynomial on the right side of Equation (30) is the reciprocal of the radar detection range equation under no-interference conditions, and the first factor of the second polynomial is the reciprocal of the radar sidelobe self-defence distance equation ignoring system noise.

Substituting equations (1) and (7) into the above equations, it can be obtained that:

$$\frac{1}{R^4{}_{\max}}=\frac{1}{R^4{}_{\max 0}}+\frac{1}{R^4{}_{\max 21}}\cdot\frac{1}{JCR} \tag{31}$$

From formula (24), $R^4_{\max 23}=R^4_{\max 21}\cdot JCR$, thus the above formula can also be expressed as:

$$\frac{1}{R^4{}_{\max}}=\frac{1}{R^4{}_{\max 0}}+\frac{1}{R^4{}_{\max 23}} \tag{32}$$

Taking the maximum radar detection distance of the radar here as $R_{\max 24}$, and solving Equation (28), it can be obtained that:

$$R_{\max 24}=\frac{R_{\max 0}R_{\max 23}}{\sqrt[4]{R^4{}_{\max 0}+R^4{}_{\max 23}}} \tag{33}$$

Equation (33) is the corrected formula to calculate the maximum radar detection distance after taking anti-jamming measures in the sidelobe jamming scenario. It can be seen from the above formula that the corrected maximum radar detection distance can be calculated by the maximum radar detection distance without interference and the maximum radar detection distance before the correction.

So far, we have obtained the maximum detection distance correction formula before and after the anti-jamming measures are taken in the main lobe and side lobe active suppression jamming scenarios, while taking into account the interference and noise effects jointly.

Comparing Equation (14), Equation (17) with Equation (29) and Equation (33), it is not difficult to find that the modified radar detection distance calculation formulas before and after anti-jamming measures are similar. The only difference is that the self-defence distance used in ignoring the influence of noise is replaced by the self-defence distance before taking anti-jamming measures to the maximum detection distance after taking anti-jamming measures.

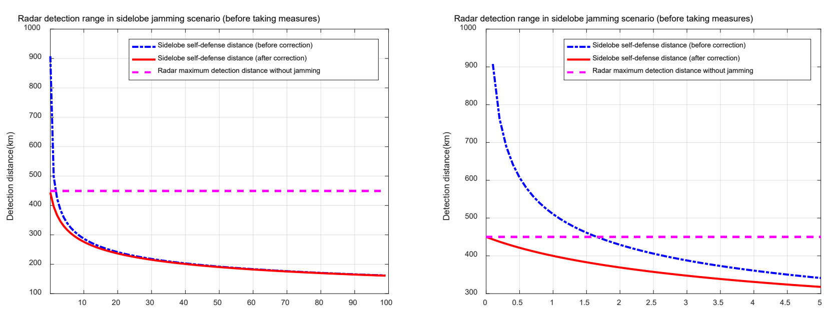
4 Simulations

To verify the accuracy and effectiveness of the corrected method, a radar model is established in this paper. The specific parameters are set as follows: radar transmit peak power $P_t = 100kW$, antenna transmit gain $G_t = 35dB$, antenna receive gain $G_r = 40dB$, pulse width $\tau = 500us$, target radar cross section $\sigma = 10m^2$, radar operating frequency $f = 3GHz$, detection factor $D_0 = 13.7dB$, system loss $L_s = 10dB$. According to the above parameter settings, the radar maximum detection distance is $R_{\max 0} = 450km$ when there is no interference.

4.1 Simulations of side lobe jamming scenario

4.1.1 Analysis of detection distance before taking anti-jamming measures

Assuming that the interference comes from the radar side lobe, the polarization mode of the jamming antenna is the same as that of the radar main antenna. The jammer is 200 kilometres away from the radar, and the ratio between the main lobe and side lobe of radar antenna receive gain is $G_{sl} = 35dB$. When the interference power spectral density increases from 0.1W/MHz to 100W/MHz, the comparison of the radar sidelobe self-defence distance curves before and after the correction are shown in the following figure.



(a) Overall view (b) Left partial enlarged view

Fig. 1. Comparison of radar sidelobe self-defense distance curves.

The blue dotted line in the figure is the radar sidelobe self-defense distance curve before correction, the red solid line is the radar sidelobe self-defense distance curve after correction, and the purple dotted line is the maximum radar detection distance without interference.

It can be seen from Figure 1 that when the interference power is strong, the radar sidelobe self-defence distance calculated by ignoring the system noise is basically the same as the sidelobe self-defence distance calculated by jointly considering the system noise and interference effects; as the interference power decreases, the radar sidelobe self-defence distance calculated by ignoring system noise gradually deviates from the corrected sidelobe self-defence distance.

Table 1 selects several typical interference power spectral densities, and compares the radar sidelobe self-defence distance before and after correction as well as the radar detection distance without interference, as shown below:

Table 1. Comparison of the radar sidelobe self-defence distance before and after correction.

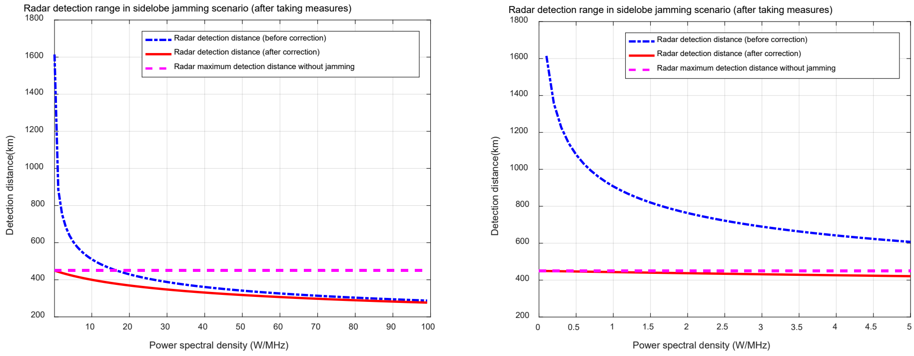
Prj W/MHz	INR /dB	Distance before correction/km	Distance after correction/km	Distance without interference/km
0.1	-12	907	443	450
1	-2	510	399	450
5	4.8	341	317	450
10	7.8	287	276	450
100	17.8	161	160	450

It can be seen from Table 1 that when the interference power is small, for example, the interference-to-noise ratio is less than 10dB, there exists deviation in the sidelobe self-defense distance before and after the correction; When the interference power gets weaker to an interference-to-noise ratio less than 0dB, the sidelobe self-defense distance before correction will be greater than the radar detection distance without interference, resulting in distortion phenomenon. However, the corrected radar sidelobe self-defense distance keeps undistorted, which can evaluate the change of radar detection distance in jamming environment more accurately.

4.1.2 Analysis of detection distance after taking anti-jamming measures

The setting of sidelobe interference parameters remains the same as the previous section, and the radar interference suppression ratio is set to 10dB after taking anti-jamming measures.

When the interference power spectral density increases from 0.1W/MHz to 100W/MHz, the comparison of the radar detection distance curves before and after the correction are shown in the following figure:



(a) Verall view (b) Left partial enlarged view

Fig. 2. Comparison of radar detection distance curves after taking anti-jamming measures.

Table 2 shows the comparison of radar detection distance before and after correction under different interference power spectral densities:

Table 2. Comparison of the radar detection distance after taking anti-jamming measures.

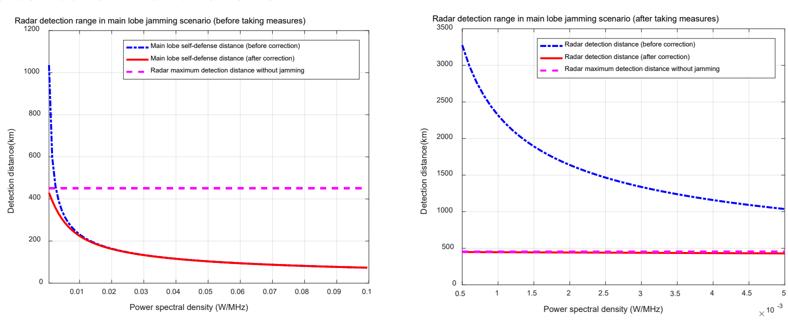
Prj W/MHz	INR /dB	Distance before correction/km	Distance after correction/km	Distance without interference/km
0.1	-12	1614	449	450
1	-2	907	443	450
5	4.8	607	421	450
10	7.8	510	399	450
100	17.8	287	276	450

It can be seen from Table 2 that since the interference power is greatly suppressed after anti-jamming measures are taken, the radar detection distance before correction is more easily to get distorted. Even when the interference is strong, the radar detection distance after taking measures will be affected to a certain degree while ignoring the system noise. At this time, it is particularly necessary to make correction to the radar detection distance after taking measures.

4.2 Simulations of main lobe jamming scenario

4.2.1 Analysis of detection distance before taking anti-jamming measures

Assuming that the interference enters from the radar main lobe, the location of the jammer and the target aircraft is close, and the polarization of the jammer is the same as that of the radar. When the interference power spectral density increases from 0.0005W/MHz to 0.1W/MHz, the comparison of the radar main lobe self-defense distance curves before and after the correction are as follows:



(a) Overall view. (b) Left partial enlarged view.

Fig. 2. Comparison of radar mainlobe self-defense distance curves.

Table 3 shows the comparison of the radar main lobe self-defence distance before and after the correction under different interference power spectral densities:

It can be seen from the above that in the main lobe interference scenario, even if the interference power is very weak, the interference-to-noise ratio imposing on the radar receiver will be rather high due to the huge radar receive gain.

Similar to the sidelobe interference scenario, when the interference-to-noise ratio is high, the main lobe self-defence distance before and after the correction is basically the same; as the interference power decreases, the main-lobe self-defence distance before and after the correction gradually deviates; when the interference-to-noise ratio is less than 0dB, the phenomenon that the radar self-defence distance in jamming environment is greater than the radar detection distance without interference appears. However, the modified radar main lobe self-defence distance is always kept within the range of the radar's maximum detection distance without interference, which can evaluate the change of the radar detection distance after being interfered more accurately.

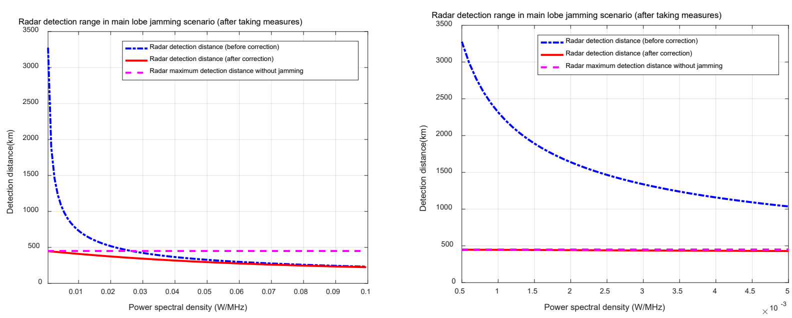
Table 3. Comparison of the radar main lobe self-defence distance before and after correction.

Prj W/MHz	INR /dB	Distance before correction/km	Distance after correction/km	Distance without interference/km
0.0005	-6.8	1036	429	450
0.001	-3.4	732.62	409.81	450
0.005	6.4	327.63	295.60	450
0.01	11.8	231.67	224.40	450
0.05	25.5	103.60	103.46	450
0.1	31.5	73.26	73.23	450

4.2.2 Analysis of detection distance after taking anti-jamming measures

The setting of main lobe interference parameters remains the same as the previous section, and the radar interference suppression ratio is set to 10dB after taking anti-jamming measures.

When the interference power spectral density increases from 0.0005W/MHz to 0.1W/MHz, the comparison of the maximum radar detection distance curves before and after the correction are as follows:



(a) Overall view. (b) Left partial enlarged view.

Fig. 4. Comparison of radar detection distance curves after taking anti-jamming measures.

Table 4 shows the comparison of radar detection distance before and after correction under different interference power spectral densities:

Table 4. Comparison of the radar main lobe self-defence distance after taking anti-jamming measures.

Prj W/MHz	INR /dB	Distance before correction/km	Distance after correction/km	Distance without interference/km
0.0005	-6.8	3276.4	448	450
0.001	-3.4	2316	445	450
0.005	6.4	1036	429	450
0.01	11.8	732.62	409.81	450
0.05	25.5	327.63	295.60	450
0.1	31.5	231.67	224.40	450

It can be seen from the above that since the interference power is greatly suppressed after the radar adopts anti-jamming measures, the radar detection distance calculated by ignoring the influence of the system noise is more prone to be distorted, which the correction is particularly necessary.

Simulations show that the corrected formula can accurately analyse and evaluate the change of radar detection distance before and after taking anti-jamming measures in different interference intensity scenarios, avoiding the distortion problem of radar range evaluation in weak interference environments. The correction method proposed in this paper is helpful to evaluate the change of radar detection distance quickly and accurately in the active suppression jamming scenario.

5 Conclusion

To solve the distortion problem of engineering calculation formula of radar detection distance in weak electromagnetic environment, this paper derives correction method of calculating radar detection distance in different interference scenarios in detail, and the closed-form expression of radar detection range is proposed where the influence of system noise and interference is jointly considered. Simulation shows that the modified formula can accurately analyze and evaluate the change of the radar detection range before and after taking anti-jamming measures under different jamming strengths, which is of great significance for effectively evaluating the operational performance of the radar.

References

1. CHEN Gantao, XU Jia, GAO Xiao, LIU Minglu, QU Junliang and NIE Mingxin. *Analysis and Calculation of Radar Detection Range with Active Blanket Jamming* [J]. Radar Science and Technology, 2011, 9 (1):13-17.
2. MA Hao, RUAN Zengmiao, ZHAO Chunguang and TANG Zhiqun. *Model Modification and Analysisi of Radar Detection Range for Anti-jamming* [J]. Information and Electronic Engineering, 2010, 8 (1):1-6.
3. WANG Xiaomo, KUANG Yongsheng and CHEN Zhongxian. *Surveillance Radar Technology* [M]. Beijing: Publishing House of Electronics Industry, 2008.
4. DING Lufei and GENG Fulu. *Radar Principle* [M]. Publishing House of XIDIAN University.
5. LI Shanshan. *Study on Target Detection Power and Anti-jamming Performance of Radar System*. Xi'an: XIDIAN University.
6. LI Zenghui, LIU Xiao, SHI Haitian and ZHANG Xinsheng. *Specifications and test evaluation methods of radar anti-jamming ability* [J]. Modern Radar, 2018, 40 (7):5-9.
7. HU Jin, LI Jianxun and LIU Xiao. *The Quantitative Analysis on the anti-active jamming ability for land-based intelligence radar* [J]. Modern Radar, 2015, 37 (10):5-10.
8. Skolnik M. *Radar Handbook* [M].2nd ed., New York: McGraw-Hill, 1990.
9. MARIA G, FULVIO G and AL FONSO F. *Radar Detection and Classification of Jamming Signals Belonging to a Cone Class* [C]. IEEE Transactions on Signal Processing, 2008, 56 (5):1987-1993.
10. HARVEY D H and WOOD T L. *Designs for Sidelobe Blanking Systems*[C]. IEEE International Radar Conference. Washington D.C.: IEEE Press, 1980: 410-416.