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Static Decoy for Countering Anti-Radiation Missiles Against Ship-Borne Radars

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***Abstract*— This paper proposes an efficient decoy system structure designed to protect air-defense radar systems. In the past, decoy systems required an extensive surface area for deployment, and worked by diverting anti-radiation missiles to their location by creating greater energy density. In this way, in old models the decoy sacrificed itself to save the radar site. The evolution of decoy systems made it possible for them to protect themselves through the use of multiple decoys. However, an extensive area is still required to deploy these systems, leading to many restrictions on applications that require deployment within a smaller surface area (naval applications on ships are one example of this). The model proposed in this article diverts anti-radiation missiles into the safe range of an air-defense site, by controlling phase and amplitude of the received signal and using angular error on a mono-pulse missile tracker created by glint phenomena. This method allows for reduction of the land surface area required for decoy system deployment. The effectiveness of the proposed method is approved and evaluated using theoretical relations and simulation results**

Keywords—Radar; Decoy; Anti-radiate missile; Ship; Glint

I. INTRODUCTION

The best way to counter the attack of air targets is through the use of radar systems, which are the foundation of air defense. On the other hand, the attacking targets commonly use techniques such as reduction of radar cross-sections, jamming, and deceptive techniques to evade the radar. Anti-radiation missiles are the most lethal offensive armament against a radar system, and pose a serious threat to defense systems. Therefore, an effective method to divert anti-radiation missiles from radar sites is necessary to protect equipment related to the radar systems.

In related literature, various methods (e.g., the use of bait decoy, self-guarding decoy systems) have been proposed for countering anti-radiation missiles.

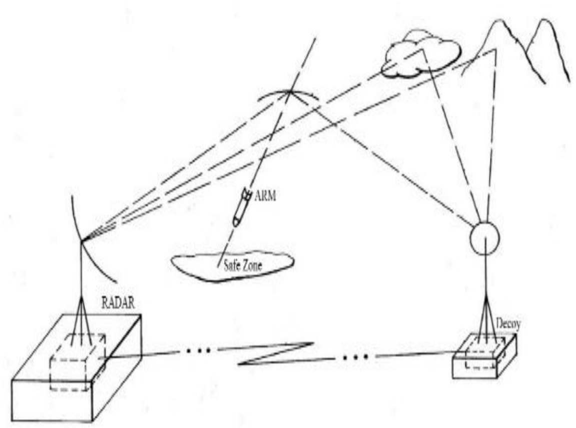

Fig 1. Survival Decoy System

Each of these methods has their weaknesses; therefore, the need exists to develop a more-complete decoy system that is more reliable than the previous ones. In this paper, phase control and a double-loop amplitude system are proposed to precisely control the phase and amplitude of the signal. After controlling the phase and amplitude of the signal, the use of glint phenomena is suggested to create the most-effective error in the mono-pulse receiver of anti-radiation missiles to disable them [1,2]. This satisfactorily divert anti-radiation missiles to areas outside the radar and decoy site. The simulation results depict the efficiency of this method.

II. TWO-LOOP PHASE DIFFERENCE MEASUREMENT ALGORITHM [6]

The system devised in this article consists of coherent radar and decoy and assumes that radar and decoy have transmitters capable of controlling their phases and amplitudes. Furthermore, radar and decoy have the same antenna pattern, carrier frequency, and pulse repetition frequency (PRF) [3,4].

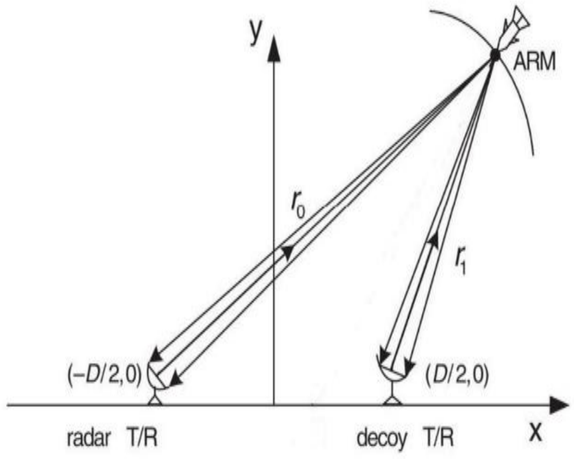

Fig 2. Coherent decoy and radar system [6]

r_0 :Distance between anti-radiation missile and radar

r_1 :Distance between anti-radiation missile and decoy

Received signals in radar have phases proportional to $2r_0$ and $r_0 + r_1$

Received signals in decoy have phases proportional to $2r_1$ and $r_0 + r_1$

Assuming that the emitted intermediate frequency (IF) signal from radar is $\cos(\omega t + \varphi_0)$ decoy is $\beta\cos(\omega t)$, and φ_0 is the phase difference between them.

IF signals received by radar and decoy are S_0 and S_1

$$S_0 = E_0\beta\cos\left(\omega t - \frac{2\pi(r_0 + r_1)}{\lambda}\right) + E_0\cos\left(\omega t - \frac{2\pi \times 2r_0}{\lambda} + \varphi_0\right) = E_0(\beta\cos(\omega t + \varphi_1) + cos(\omega t + \varphi_2)) \quad (1)$$

$$S_1 = E_1\cos\left(\omega t - \frac{2\pi(r_0 + r_1)}{\lambda} + \varphi_0\right) + E_1\beta\cos\left(\omega t - \frac{2\pi \times 2r_1}{\lambda}\right) = E_1(\cos(\omega t + \varphi_1') + \beta\, cos(\omega t + \varphi_2')) \quad (2)$$

Phase difference of $\Delta\varphi = \varphi_1 - \varphi_2$ measured in the radar or decoy receiver is equal to the phase difference in anti-radiation missile PRS[1].

The output signals of radar and decoy, S_0 and S_1 are mixed with a controllable local oscillator signal, namely S, defined as:

$$S = E\cos(\omega t + \varphi) \quad (3)$$

[1] PRS: passive radar seeker.

In the next step, these signals pass through a low-pass filter; the results are shown in Fig 3 and by changing phase signal of local oscillator φ, we find maximum value of output signal from low-pass filter, then we have φ_{1max} from maximum of $S_0 \times S$ and φ_{2max} from maximum of $S_1 \times S$ then value of phase difference is $\Delta\varphi = \varphi_{1max} - \varphi_{2max} - \varphi_0$ this shown in Fig 4.

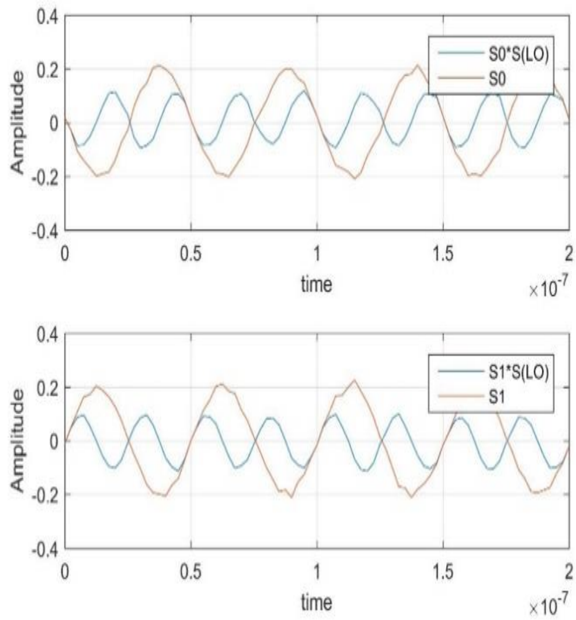

Fig 3. Received signal in radar and decoy

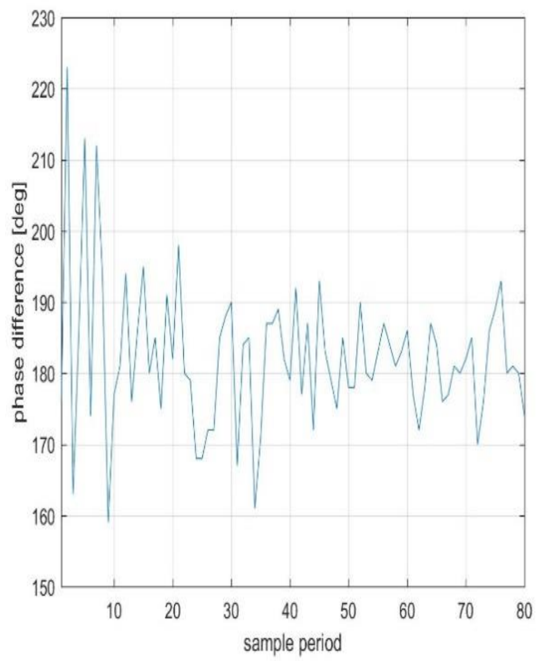

Fig 4. Estimations of average phase difference

III. Proposed Method for Inducing Effective Error with Glint Phenomena

In the single-target case, the sum and difference voltages s and d are in phase, and the normalized difference signal $d/_s$ is real [5]. In the case of unresolved targets, however, s and d may have any relative phase, and their ratio is therefore complex. To demonstrate this fundamental point in a simple way [6, 7], consider two unresolved targets at different angles within the beam. Considering each of two angular coordinates, this introduces a glint-related error in the monopulse system [11].

In the phase diagram shown in Figure 5, s_a and d_a are the monopulse sum and difference signals from the first target, and s_b and $d_b$the corresponding signals from the other. Although both targets are in the same range resolution cell, in general their ranges are not exactly the same. This leads to a degree of phase difference between s_a and s_b. Even if the ranges are equal, there may be a phase difference because of different backscatter phase characteristics of the two targets. The resultant s is the sum of two signals. . Suppose, for illustration, that the two targets are on opposite sides of the beam axis, with the first target on the side that causes d_a to be in phase with s_a ; in this scenario, d_b is in opposite phase of s_b . The total difference signal d is the resultant difference of d_a and d_b.

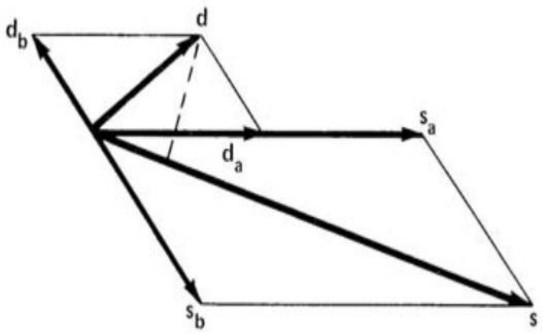

Fig 5. Phase diagram of two target

It is clear from Fig 5 that, in general, d has a quadrature component with respect to s, shown by the dashed line, as well as an in-phase component. In other words, the ratio d/s is complex. It is also easy to see that if s_a and s_b are 180° out of phase and nearly equal in magnitude, the ratio $d/_s$ can become very large.

To express the result mathematically, let θ_a and θ_b be the angular displacements of the two targets from the axis in the selected coordinate. Relation between sum and difference components for each target is:

$$\overrightarrow{d_a} = k_m \overrightarrow{S_a} \tag{4}$$

$$\overrightarrow{d_b} = k_m \overrightarrow{S_b} \tag{5}$$

The resultant indicated angle is

$$\theta_i = \frac{1}{k_m} d/_s \tag{6}$$

$$\theta_i = \frac{1}{k_m} \frac{\overrightarrow{d_a} + \overrightarrow{d_b}}{\overrightarrow{S_a} + \overrightarrow{S_b}} = \frac{\theta_a \overrightarrow{S_a} + \theta_b \overrightarrow{S_b}}{\overrightarrow{S_a} + \overrightarrow{S_b}} \tag{7}$$

Eq. (7) states that the indicated angle θ_i is a weighted average of the actual angles of the targets, with weightings proportional to their respective sum-signal contributions. However, the weighting is complex, since s_a and s_b in general have different phases, and the result is not clear without further analysis [7, 8].

This equation can also be written in another form that equates the indicated angle to the true angle of the first target, θ_a, plus an error term; this form is convenient for determining the error in measuring the angle of a particular target:

$$\theta_i = \theta_a + \Delta\theta \frac{pe^{j\phi}}{1 + pe^{j\phi}} \tag{8}$$

The quantity θ_i on the left-hand side of (8) has been named the complex indicated angle, or, simply, the complex angle [9]. The indicated angle equals the geometric angle, regardless of the amplitudes and phases of the two targets. However, in general the indicated angle is a complex quantity. The monopulse processor is normally designed to extract only the real part of the indicated angle. Real part of the indicated angle can be written as:

$$\theta_i^{real} = \theta_a + \Delta\theta \times Real\left\{\frac{pe^{j\phi}}{1 + pe^{j\phi}}\right\} \tag{9}$$

Given that $e^{\pm j\phi} = cos\phi \pm jsin\phi$, we have:

$$Real\left\{\frac{pe^{j\phi}}{1 + pe^{j\phi}}\right\} = Real\{\frac{pe^{j\phi}}{1 + pe^{j\phi}} \times \frac{1 + pe^{-j\phi}}{1 + pe^{-j\phi}}\} \tag{10}$$

$$\frac{pcos\phi + p^2cos^2\phi + p^2sin^2\phi}{1 + 2pcos\phi + p^2} = \frac{pcos\phi + p^2}{1 + 2pcos\phi + p^2} \tag{11}$$

By substituting $\Delta\theta = \theta_a - \theta_b$ in (9), we have:

$$\frac{\theta_i^{real} - \theta_a}{\theta_a - \theta_b} = \frac{pcos\phi + p^2}{1 + 2pcos\phi + p^2} \tag{12}$$

It can be seen from fig. 6 that $\theta_a - \theta_b$ and $\theta_i - \theta_a$ are respectively equal to θ_D and $\Delta\theta_e$. So:

$$\frac{\Delta\theta_e}{\theta_D} = \frac{p cos\phi + p^2}{1 + 2p cos\phi + p^2} \quad (13)$$

Where $\Delta\theta_e$ is the amount of angular error, and θ_D is view angle in PRS between radar and decoy line of sights. p and ϕ are the amplitude ratio and phase difference between two targets, respectively.

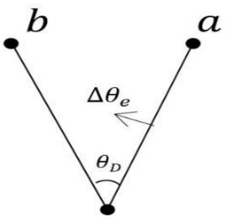

Fig 6. *Two-target model [10]*

IV. SIMULATION RESULTS

Equation (13) can be used to calculate the amount of angular error created in an anti-radiation missile monopulse tracker system during simulation. Suppose that p = 0.6, 0.7, 0.8, and $\theta_D = 6°$. The resulted angular errors are shown in Figure 7. Now suppose that the amplitude ratio is equal to 0.8. Curves of $\Delta\theta_e$ for values of 2, 4, and 6 degree of θ_D are represented in Fig 8.

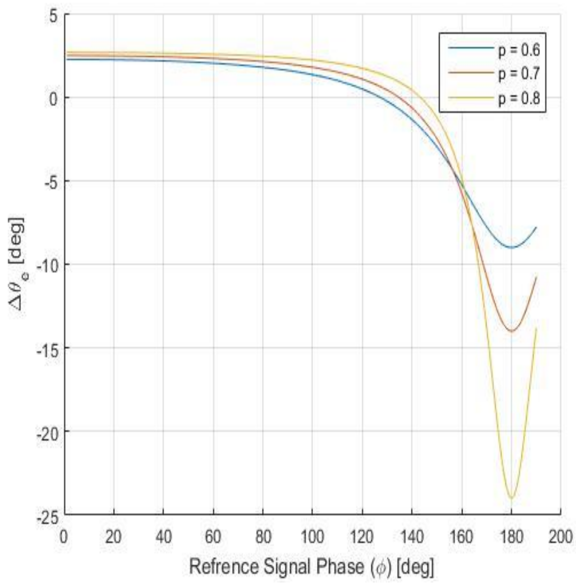

Fig 7. *Angular Errors with different amplitude ratios*

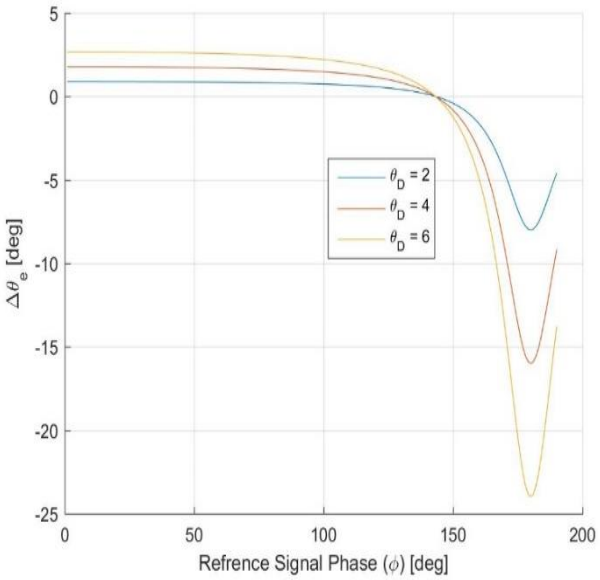

Fig 8. *Error angular with different θD*

When the angular error has a negative value in the monopulse seeker of the anti-radiation missile, the missile is led to a zone beyond the area between the radar and the decoy systems. This phenomena can be used in radar systems of ships and warships, to guide the ARMs outward the ship/warship. Ships generally counter anti-radiation missiles with decoy systems based on rockets, such that a rocket is launched from the deck of the ship after detection of anti-radiation missile. This system causes serious constraints, for example, in the seating location of the rocket launcher and with reduction in the number of rockets that can be carried.

The proposed system avoids these issues by providing a surviving decoy that guides the missile outside the area of concern. To our knowledge, the current literature on decoys and decoy systems has not mentioned the concept of the ability of decoy to guide anti-radiation missiles out of the radar-decoy area. The concept can be proved via scenarios that imagine its use with a fleet.

Consider a ship with a length of 100 m and an anti-radiation missile that is 2 km far from it. Setting ϕ = 170°, the decoy and radar systems cause an error angle of about 6.5 degrees in the monopulse system tracker, causing the intercept site to be 159 m outside of the area occupied by the ship.

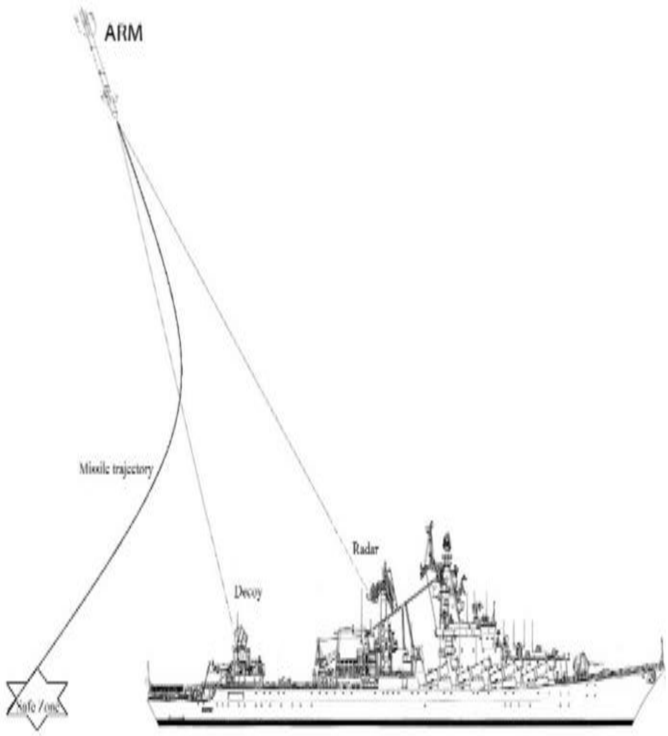

Fig 9. Schematic of the proposed system

CONCLUSION

In this article, a novel method was proposed that uses survival decoys against anti-radiation missiles. In this method, the controlled phase and amplitude of the transmitted signal can counter the monopulse tracker system of anti-radiation missiles and guide them to a safe zone outside of the radar-decoy area. This method is specifically useful for naval applications;, because the radar and the decoy are both located on the ship and the missile should not be guided to a point between them. Simulations show that this method can move the intercept point of anti-radiation missiles outside of the zone between the radar and the decoy systems. In the previous methods, the missiles impact the area between the radar and the decoy, with subsequent decreases in the reliability of its performance against anti-radiation missiles.

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