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ANGLE DECEPTION OF INSTANTANEOUS AMPLITUDE-COMPARISON RADAR TRACKING SYSTEMS BY PHASE FRONT DISTORTION

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ABSTRACT

In spite that different techniques have been developed to create errors or instabilities in modern angle trackers based on Instantaneous Amplitude Comparison, no practical results of their application have yet been published.

In this paper a typical ***IAC*** angle tracker is simulated and its characteristics are evaluated without jamming and under the effect of ***Phase Front Distortion*** jamming technique. The main parameters of the technique have been optimized for maximum possible effectiveness.

KEY WORDS

tracker, basic coordinate tracking, angular tracking, gate stealing, angle deception, sequential comparison, Instantaneous Amplitude Comparison (IAC), antenna boresight, Sequential Lobing, Conical Scan, Phase Front Distortion jamming.

NOMENCLATURE

BW = Beam Width
G_m = the maximum antenna gain, G_T, transmitting antenna gain, G_R and G_L are the Right and Left receiving antenna gains, respectively.
P_T = transmitted power
IAC = Instantaneous Amplitude Comparison
β_s = squint angle ≈ BW/2
Θ = azimuth angle; referred to the antenna axis of symmetry
σ_T = Target crossection

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λ = wavelength
φ = phase difference between the two jamming sources
d = distance between the two jamming antennas
R_{TM} = Target to Missile Range
$\Delta\beta$ = jamming induced angle tracking error

JAMMING TECHNIQUES VERSUS TRACKING TECHNIQUES

In order to destroy a target its direction must be tracked. To track the direction of a certain target it has to be resolved from other targets by using a selective time-domain or frequency-domain gate. By tracking the basic coordinate (range or relative speed) additional information is gained that helps the guidance process itself. The range information increases the accuracy of command missile guidance, and the relative speed information is a basic factor of every guidance command in proportional navigation homing systems. **Fig. 1** shows a simplified functional diagram of a general missile guidance system.

The main mission of a self protection jammer is to minimize the accuracy of missile guidance systems by inducing certain errors in their angular tracking. If the jammer degrades only the *basic coordinate tracking* sub-system; the missile may continue its successful operation by tracking the direction of the jammer, which is the same target direction. On the other hand; if the jammer aims only at deceiving the angle measurement subsystem without suppressing the target return signal by *gate stealing* or by *obscuration* techniques; the existence of the real target return would degrade the effectiveness of *angle deception* [1].

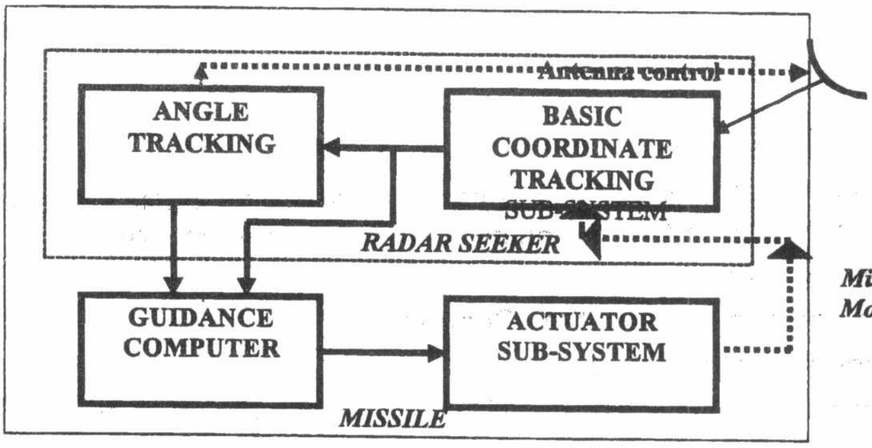


Fig. 1. A Simplified Functional Diagram of A Homing Guidance System

Old angle tracking techniques were based on ***sequential comparison*** of the target return signal amplitudes received from two consecutive positions of the same antenna. The ***antenna boresight*** was considered *aimed* at the correct target direction when the two signal amplitudes were equal. Those old techniques; such as ***Sequential Lobing*** and ***Conical Scan*** were sensitive to signal amplitude fluctuations. Moreover, specialized techniques based on well-studied amplitude modulated jamming signals succeeded to deceive them and, in some cases, to cause instabilities in the angle tracking sub-system [1]. Almost all existing self-protection jammers have inherent AM-based angle deception techniques capable of effectively deceiving different types of sequential comparison angle trackers.

Modern angle tracking systems apply more jamming -immune techniques based on the ***instantaneous comparison*** of the return signal amplitudes (or phases) received from two identical ***receiving channels*** (UP-DOWN and/or RIGHT-LEFT) with independent antennas. Since the system refers the difference between the two channels to their sum; any signal amplitude fluctuations or modulations will be canceled out and; consequently, have no effect on the tracking performance. Therefore; all traditional AM-based angle deception techniques applicable to sequential comparison tracking systems have no effect. In order to deceive such a tracking system there are three main approaches; to utilize some deficiencies in the tracking system design, to create instabilities in the tracking control loop, or to create physical deformation in the phase front of the jamming wave. The third approach has been selected for this study; since it is independent of the tracking system design parameters. A mathematical simulation model has been built for a typical IAC angle tracker; on which the deception technique has been applied and analyzed.

AN IAC ANGLE TRACKING MODEL WITHOUT JAMMING

In an Instantaneous Amplitude Comparison angle tracking system, the outputs of two identical receiving channels are summed and subtracted. The sum is taken as a reference signal while the difference is multiplied by the sum to form the output error voltage to be used for antenna boresight control [2]. The tracking characteristic is the relation between the output error voltage and the corresponding angle β. The gain of each antenna can be assumed to follow one of the following angular functions:

a. exponential without side lobes:

$$G(\Theta) = G_m \cdot e^{\{-(\Theta/k)^2\}}$$

$$\text{where} \quad k = 0.6 * BW \qquad (1)$$

b. of the form sin(x)/x with -13 dB side lobes:

$$G(\Theta) = G_m \cdot \sin(x)/x$$

where $x = 2.783\Theta/BW$ (2)

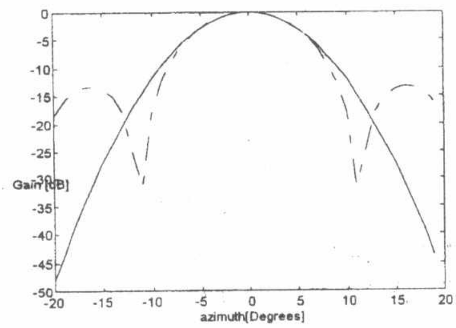
The right and left antennae are squinted by an angle Δβ to the right and to the left, respectively, with respect to the boresight. The effective gain angles of the Right and Left antennae(with respect to the antenna maximum) will be:

$$\Theta_R = (\beta_s - \beta) \quad (3a)$$

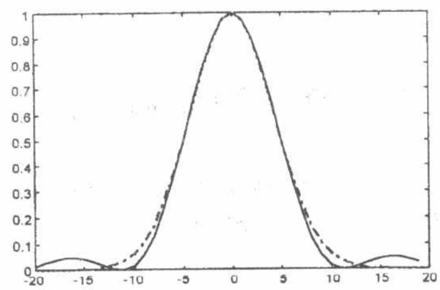
and

$$\Theta_L = (\beta_s + \beta) \quad (3b)$$

We can get the gains of the Right and Left antennae by substituting (3a) and (3b) in (1) or in (2) according to the assumed gain function. The antenna coverage diagram for both gain functions are drawn in **Fig.2**. A 20° BW and a 10° squint angle have been assumed; leading to a 40° total coverage; which is an appropriate value for a homing guided missile seeker.



a. Logarithmic Scale



b. Linear Scale

Fig.2. Assumed Antenna Characteristics

——— exponential

-·-·-·-· sin(x)/(x)

The signal powers received from the Right and Left antennas are given by :

$$S_R = G_R.P_T.G_T.\sigma_T.\lambda^2/[(4\pi)^3 * R^4] \quad (4a)$$

$$S_L = G_L.P_T.G_T.\sigma_T.\lambda^2/[(4\pi)^3 * R^4] \quad (4b)$$

For a 50[Ω] input impedance the Right and Left signal amplitudes are given by:

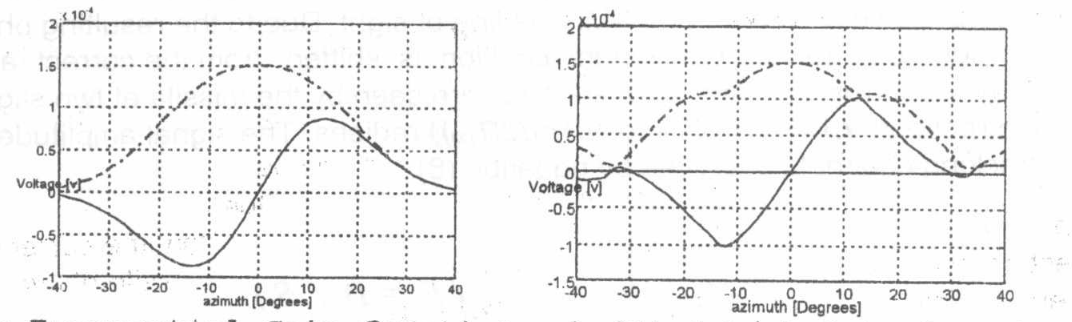
$$A_R = 10 \,.\, (S_R)^{1/2} \tag{5a}$$
$$A_L = 10 \,.\, (S_L)^{1/2} \tag{5b}$$

The sum and difference outputs are:

$$S = A_R + A_L \tag{6a}$$
$$D = A_R - A_L \tag{6b}$$

Assuming a 200 [w] CW transmitted power at 10 [GHz], a 10 [dB] antenna gain, a 10 [km] range between the illuminator and a 4 [m^2] target; the corresponding sum and difference patterns are given in **Fig.3** for the two assumed gain functions. The distortion effect of side lobes on the sum and difference outputs is evident in the second gain function. The output error voltage is

$$E = S \,.\, D = (A_R + A_L) \,.\, (A_R - A_L) \tag{7}$$



a. Exponential Gain function   b. [Sin(x)/x] Gain function

———— *Sum*   ———— *Difference*

Fig.3. Sum and Difference Outputs of the IAC Angle Tracking System

Fig.4 shows the output error voltage as a function of the error angle for both gain functions. The two gain functions show similar output characteristics without jamming. Note that the output decreases with the increase of R_{TM}.

However, it may be useful to consider another model in which the output error voltage is given by the ratio between the sum and difference outputs. The tracking characteristic of this second model without jamming is shown in **Fig.5** for both gain functions. For the [sin(x)/x] case; the side lobes have shown irregularities in the tracking characteristics with two additional stable equilibrium positions (at ±34°) and other two additional unstable equilibrium positions (at ±30°). Therefore; only the exponential gain function will be assumed. This model has two advantages; the output voltage is much higher and independent of R_{TM}. It needs much less receiver gain and no AGC.

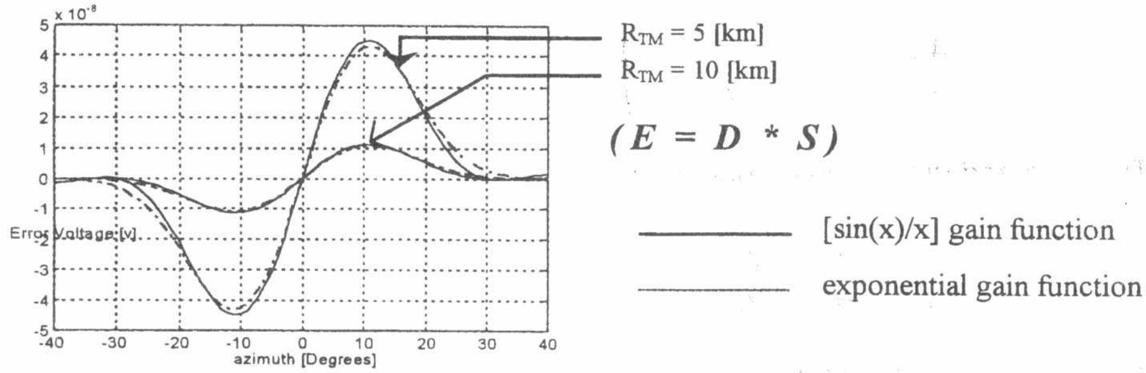


Fig.4. Angle Tracking Characteristics : First Model

PHASE FRONT DISTORTION TECHNIQUE

The idea of this technique is to utilize two coherent jamming sources of equal amplitudes, shifted in phase by an angle φ and in space by a distance d in the direction perpendicular to the Target-Missile line of sight. Due to the resulting phase front distortion; the tracker equilibrium position is shifted from the correct target direction by an error $\Delta\beta$. The two sources are seen by the missile at two slightly different directions $\{\beta-d/(2R_{TM})\}$ and $\{\beta+d/(2R_{TM})\}$ radians. The signal amplitudes at the two tracking channels are given by equation (8).

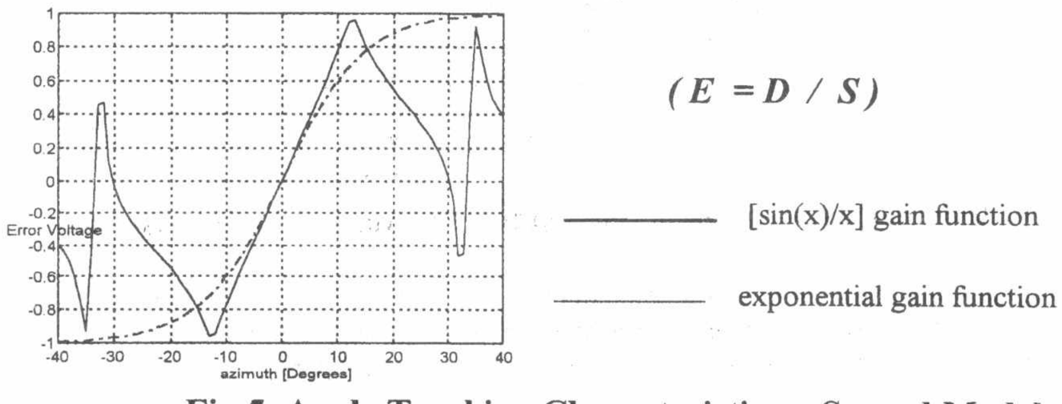


Fig.5. Angle Tracking Characteristics : Second Model

$$
\begin{aligned}
A_{RJ1} &= 10 * (J_{1R})^{1/2} \\
A_{RJ2} &= 10 * (J_{2R})^{1/2} * \cos(\varphi) \\
A_{LJ1} &= 10 * (J_{1L})^{1/2} \\
A_{LJ2} &= 10 * (J_{2L})^{1/2} * \cos(\varphi) \qquad (8)
\end{aligned}
$$

where J_{1R} and J_{2R} are the jamming powers received by the Right antenna from the two jammers, respectively.

J_{1L} and J_{2L} are the jamming powers received by the Left antenna from the two jammers, respectively.

In case of a successful velocity gate stealing; no return signal is received and the Right and Left tracking channels get the following signal amplitudes:

$$A_R = A_{RJ1} + A_{RJ2}$$
$$A_L = A_{LJ1} + A_{LJ2} \quad (9)$$

It is worth noting that as φ approaches 180° the resulting amplitudes of equation (9) decrease substantially; since the signals received from the two jamming sources become out of phase when φ = 180°. If no gate stealing succeeds; the target return signal is added to the jamming signals and the amplitudes become:

$$A_R = A_{RJ1} + A_{RJ2} + A_{RS}$$
$$A_L = A_{LJ1} + A_{LJ2} + A_{LS} \quad (10)$$

where A_{RS} and A_{LS} are the return signal amplitudes received by the Right and the Left antennas, respectively. The target return signal has a negligible effect at relatively long distances. Its effect increases with the decrease of R_{TM}.

JAMMING SIMULATION RESULTS

Fig.6. shows the output error voltages for the first model under the effect of a phase front distorted jamming with different values of φ, assuming a 50 [w] jamming power, a successful velocity gate stealing and d = 5 [m]. In this figure we can notice the following:

- The output error voltage substantially decreases as φ approaches 180° and arrives at its minimum for φ = 180°.
- The system behavior is the same for φ = (180 ± δ)°, where δ is any angle.
- The results are nearly equal for the two assumed functions for antenna gain.
- The most important result is that the stable equilibrium position of the tracking system is shifted to the left of the boresight by an angle Δβ. An additional stable equilibrium position lies to the right of the boresight, but since a positive error voltage causes the antenna to move left; it is more likely that the tracking system rests at the left equilibrium point. The tracking error *Δβ* increases as φ approaches 180° and arrives at its maximum for φ = 180°.

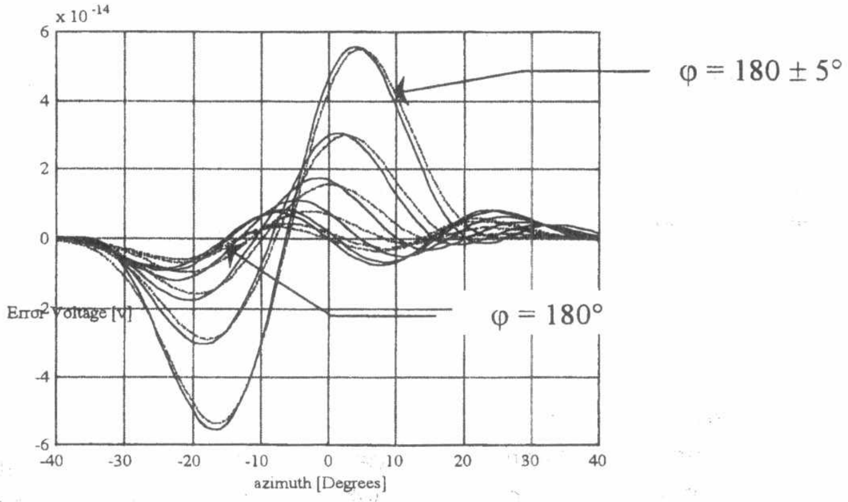


Fig.6. Tracking Characteristics of the First Model Under the Jamming Effect

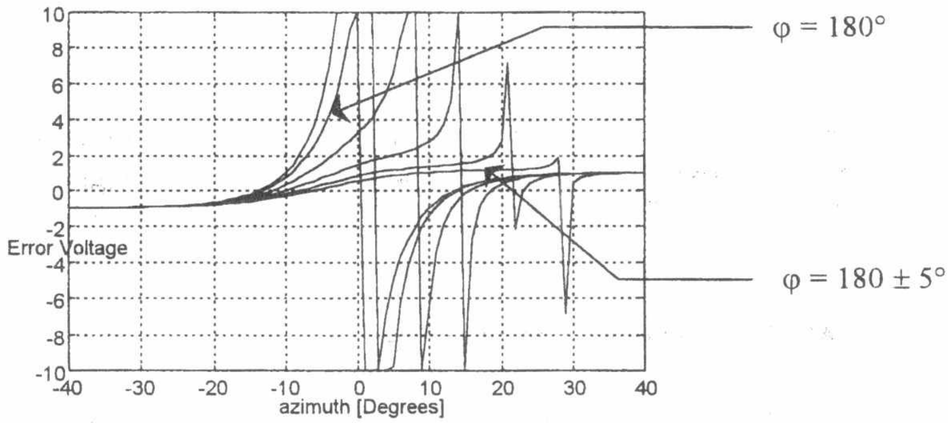


Fig.7. Tracking Characteristics of the Second Model Under the Jamming Effect

Fig.7. shows the simulated results for the second model with different values of φ. In this figure we can notice the following:

- The system behaviour is the same for $\varphi = (180 \pm \delta)°$, where δ is any angle. An additional stable equilibrium position to the right of the boresight starts to appear for $\delta = 4°$ and $5°$, but since a positive error voltage causes the antenna to move left; it is more likely that the tracking system rests at the left equilibrium point.
- The output error voltage gets a large positive peak for $\delta < 5°$; causing the system to go faster to its new stable equilibrium position at the error angle $\Delta\beta$ off the boresight (to the left). The value of this peak increases as φ approaches 180° and arrives at its maximum for $\varphi = 180°$.

- The most important note is that the jamming induced angle tracking error $\Delta\beta$ gets the same values in the two models for the same values of φ.

A recursive loop has been simulated to determine the stable equilibrium position of the tracking system (first model) under the effect of this technique and compute the value of $\Delta\beta$ corresponding to each phase shift φ. Fig.8. shows the results of this simulation for different Missile-Target ranges.

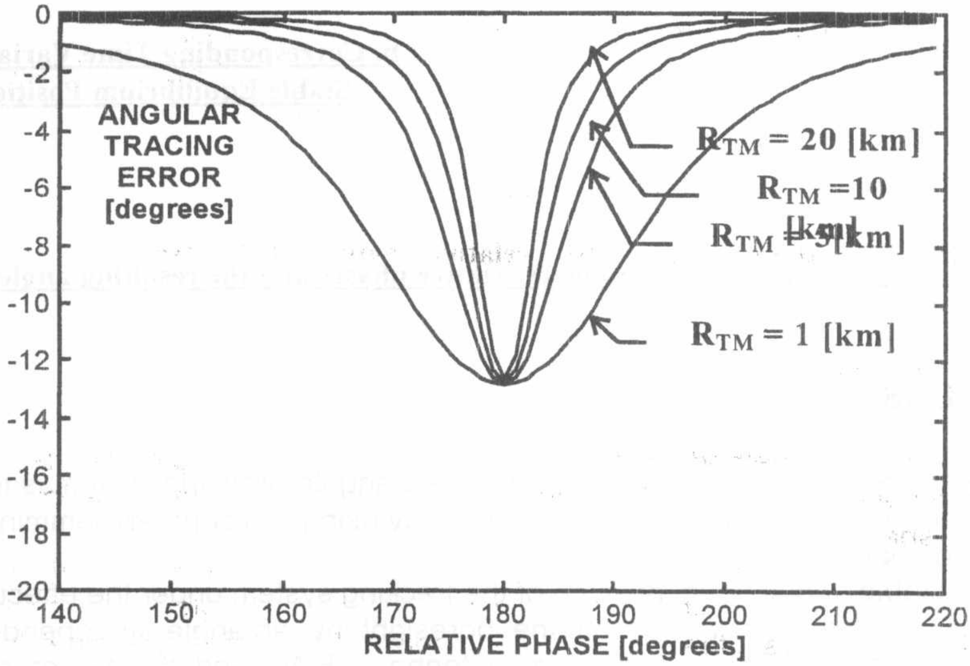
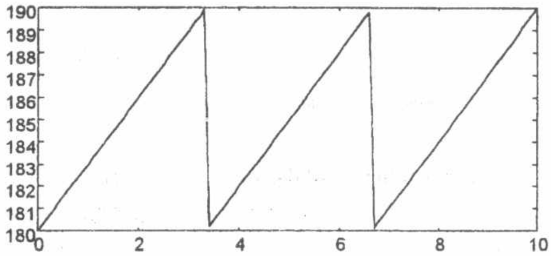


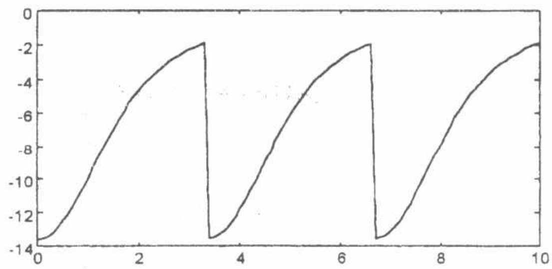
Fig.8. Jamming Induced Angular Error for Different Values of φ and R_{TM}

It is evident that the maximum value of $\Delta\beta$ corresponding to a 180° phase shift is independent of R_{TM} and of the signal amplitude. As R_{TM} decreases the rate of change of $\Delta\beta$ with respect to φ around 180° decreases and we can get a wider zone of possible phase variation within which we can still induce relatively high tracking errors. With the decrease of R_{TM} the relative viewing angle between the two jamming sources $\{d/(R_{TM})\}$ increases; which increases the induced angle tracking error corresponding to the same phase shift. The maximum value can not increase; since it is limited by ≈ 0.6 BW (≈12° in our case) [3, 4].

Using the same simulation programs; we have simulated a time sweep of φ near 180° and obtained the corresponding time variation of the equilibrium position angle $\Delta\beta$. The resulting waveform, which is very similar to the input sawtooth waveform controlling the phase φ, is shown in Fig.9.



a. Time Variation of the Phase Shift between the Two Jamming Sources $\varphi(t)$



b. Corresponding Time Variation of the Stable Equilibrium Position $\beta(t)$

Fig.9. Time Variations of the jammers relative phases and the resulting angle error

CONCLUSION

1. One of the best methods to deceive an IAC angular tracking system is to create a real deformation in the jamming wave front; by using two coherent jamming sources shifted in space and in phase.
2. The stable equilibrium position of the tracking system under the effect of such a jamming technique is shifted off the boresight by an angle $\Delta\beta$ dependent on the jamming parameters, the tracking antenna BW and the target range and independent of the tracking system design.
3. It is possible to vary the jamming induced angular error with time according to a corresponding time variation of the jammers phase difference.

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