Cross-Eye Jamming Effectiveness

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Introduction

Cross-eye jamming is an on-board ECM technique that may potentially be applicable to platform self-protection against missiles that employ fully active radars. This paper explores one aspect of amplitude-modulated cross-eye jamming in missile defense. In this analysis, the seeker in the missile is assumed to contain a monopulse tracking antenna and an exact monopulse processor. It will be seen that the cross-eye technique theoretically has the potential for creating an extremely large missile miss-distance at end game.

Background

Cross-eye jamming is an angle deception ECM technique that employs two spatially separated jamming sources. Each source acts as a repeater-type jammer transmitting the same signal at the same time, and if the two signals arrive at the missile antenna approximately 180° out of phase, wavefront distortion occurs. The missile seeker, presuming that the signal source lies along the normal to the wavefront, tries to re-aligns its antenna at right angles to the distorted wavefront. This antenna re-alignment results in incorrect missile tracking which in turn results in incorrect steering information being passed to the missile autopilot. This may potentially result in a substantial missile miss distance.

The magnitude of the missile miss distance will depend on the characteristics of the induced tracking error. If the missile homes on its target using proportional navigation guidance, then the rate of change of the missile's heading is proportional to the rate of change of the antenna pointing direction. With this type of guidance, the missile will still be able to successfully home on its target even if it is tracking off boresight, as long as the off-boresight track point maintains a constant angular separation from the target line-of-sight. To successfully defend against proportional navigation guidance missiles and ultimately produce a large miss distance, a constantly increasing tracking error needs to be induced into the missile seeker.

In a cross-eye jamming system, a 180° phase relationship between the two jamming sources may be maintained by setting up a retro-reflective transmission system. In this type of system, each of the jamming antennas is acting as the signal source for a repeater-type jammer. However, the signal received by one antenna is transmitted by the other, and vice versa. In this way, the total propagation delay from seeker to receive antenna to transmit antenna and back to seeker is identical for both signal paths and, everything else being equal, the phase of the two signals arriving at the seeker will be identical. A 180° phase shifter is then added to one of the paths to create the wavefront distortion effect.

Static Monopulse Analysis

In the sea-skimming cruise missile scenario analyzed here, the victim seeker is assumed to track only in azimuth and only the responses of the left and right antenna receiver lobes are considered. Under normal, non-jamming tracking conditions the target echo is the primary signal present in the seeker's field of view. The signals from the left and right lobes of the target echo are combined via a monopulse comparator and fed into the Sum and Difference channels of the monopulse processor. The monopulse processor then produces a servo loop error signal by normalizing the Difference signal ***D*** using the Sum signal ***S***.

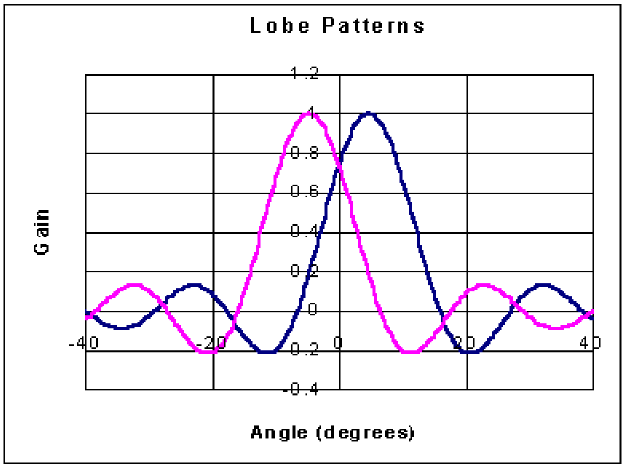

Figure 1a

For purposes of demonstration, representative antenna lobe patterns are graphically depicted in Figure 1a, and the corresponding Sum and Difference patterns as might be produced by an ideal monopulse comparator are shown below in Figure 1b. For these plots, the individual lobes of Figure 1a have a sinx/x shape with a 10° 3 dB beamwidth, and a squint angle of 4.5°. Note that the Sum pattern beamwidth in Figure 1b is approximately 12°, or 1.2 times the beamwidth of the individual lobes of Figure 1a. This is consistent with Sherman [1].

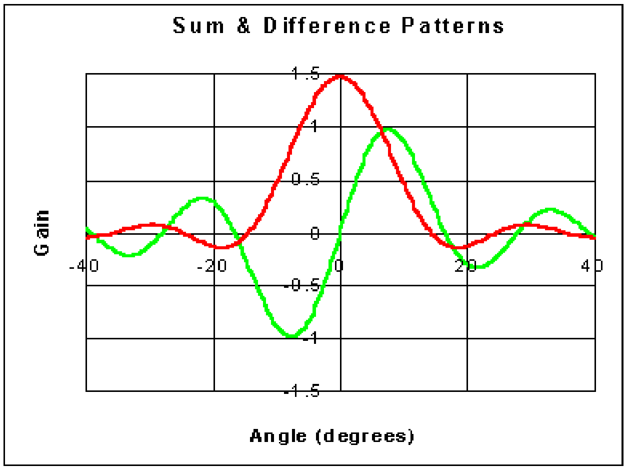

Figure 1b

Also for purposes of demonstration, an exact monopulse processor [1] is assumed. An exact processor is one that normalizes the Difference signal by computing the real part of the complex ratio ***D/S***. The output from such a processor may be expressed as:

$$\mathrm{Re}\left(\frac{\boldsymbol{D}}{\boldsymbol{S}}\right) = \frac{|\boldsymbol{D}|}{|\boldsymbol{S}|}\cdot\cos\delta$$

where δ is the phase of ***D*** relative to ***S***.

The antenna receiver lobe pattern, the monopulse comparator and the monopulse processor together form the discriminator of the missile seeker's angle tracking servo loop. The discriminator measures the difference between the seeker's antenna boresight direction and the line-of-sight bearing to the target. If the antenna boresight is not aligned with the target line-of-sight, the discriminator will generate an error signal proportional to the angular misalignment. The tracking servo will then use the error signal as a forcing function to re-align the boresight over the target.

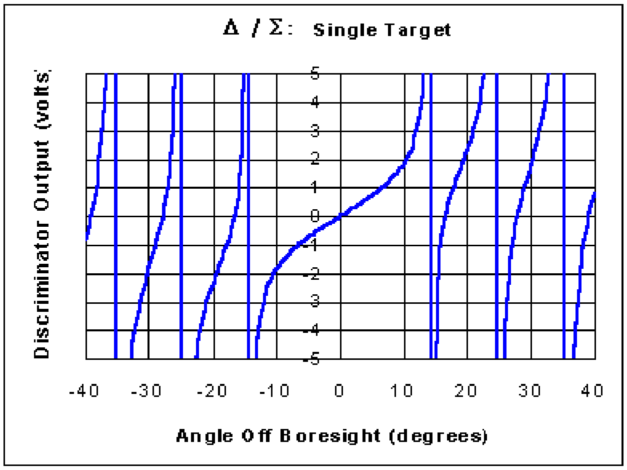

Figure 2

The performance of the monopulse discriminator is characterized by its discriminator curve, an example of which is shown in Figure 2. This curve depicts the discriminator output signal as a function of the target angular distance off boresight, for a two-lobe, single-plane monopulse system. To generate this curve, the following seeker characteristics have been assumed:

- Each receiver lobe has a sinx/x-shaped voltage pattern.
- Each receiver lobe has a 10° 3dB beamwidth.
- The squint angle for each lobe is 4.5°.
- The seeker uses an ideal monopulse comparator.
- The seeker uses an exact monopulse processor.

The discriminator curve of Figure 2 shows a steady-state tracking point at 0°, representing the condition that the target is aligned with the antenna boresight. Note that any point on this curve that crosses the X-axis with positive slope is also a steady-state track point. Therefore, steady-state track points also exist at +/- 16° and +/- 28° off boresight.

Monopulse Response to Cross-Eye Jamming

The response of the missile system to cross-eye jamming may be evaluated by summing the two far-field jamming signals at the seeker antenna and computing the resulting signal for each monopulse antenna lobe. Using this approach, the error signal from the exact monopulse processor may be computed under conditions of cross-eye jamming, at different angular positions for the two jamming sources. By moving the pair of source antennas together in angle across the seeker's boresight and re-computing the error signal for each position, a new "cross-eye" discriminator curve can be plotted. The result is the cross-eye discriminator curve for the case of two equal but anti-phase jamming signals (shown in Figure 3). For this curve, the X-axis is the centroid position of the two jamming sources, and the two sources are assumed to be of equal amplitude and exactly 180° out of phase.

From the plot of Figure 3 it can be seen that there is no longer a steady-state track point at 0° (boresight). The closest steady-state track points to boresight are at +/- 7.5°. This corresponds to 0.63 times the Sum beamwidth, as calculated by Lothes [2]. The next closest steady-state track points are at +/- 22° off boresight.

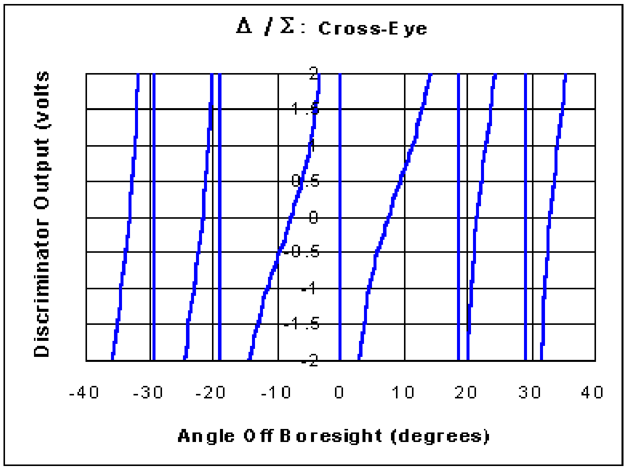

Figure 3

Adding Amplitude Modulation

If the cross-eye jammer operates with only one active source, the other source being initially turned off, the missile seeker will "see" the discriminator curve of Figure 2 and the seeker will be able to center its antenna boresight on the active source. If the second, anti-phase source is now turned on, starting at very low power and gradually increasing until it is equal in power to the first source, the discriminator curve gradually changes to that of Figure 3. The steady-state track point at boresight will move out to 7.5° off boresight and, if the movement of the track point is slow enough, the seeker, under the control of its angle servo, will rotate its antenna to follow.

At the same time as the boresight track point is moving out to 7.5° on one side of the boresight, one of the sidelobe track points, initially at 16° off boresight, is moving in to within 7.5° of the other side of the boresight. In this way, the single target discriminator curve of Figure 2 gradually transforms itself into the cross-eye discriminator curve of Figure 3 as the relative amplitude of the two sources is changed.

After the two jammer sources have equalized in power, the first source is gradually decreased in power until it is off, while the second, anti-phase source maintains its power level. The track point that had initially been forced away from the boresight to the 7.5° position continues to move away, eventually settling at 16° off boresight and becoming a steady-state sidelobe track point. Again, if the movement of the track point is slow enough, the seeker, under control of its angle servo, will rotate its antenna to follow.

As this track point moves away from the boresight, the track point that had originally moved from its sidelobe position towards the boresight continues to move in the same direction and eventually settles directly over the boresight. In this way, the discriminator curve of Figure 3 gradually transforms itself back into the discriminator curve of Figure 2. The result of this amplitude modulation cycle of the two jammer sources is to smoothly slide each steady-state track point over to the position that its neighboring track point had previously occupied. This causes the seeker (if it is in track mode) to rotate its antenna so that it tracks in a sidelobe.

Figure 4 shows a series of discriminator curves as the power ratio of two cross-eye sources, with an angular separation of 1°, gradually changes according to the previously described modulation cycle. The track point that starts at boresight is shown circled in red, and can be seen to move gradually out to the first sidelobe position during the amplitude modulation cycle. The angular position of this particular track point as a function of the power ratio between the two sources has been plotted in Figure 5.

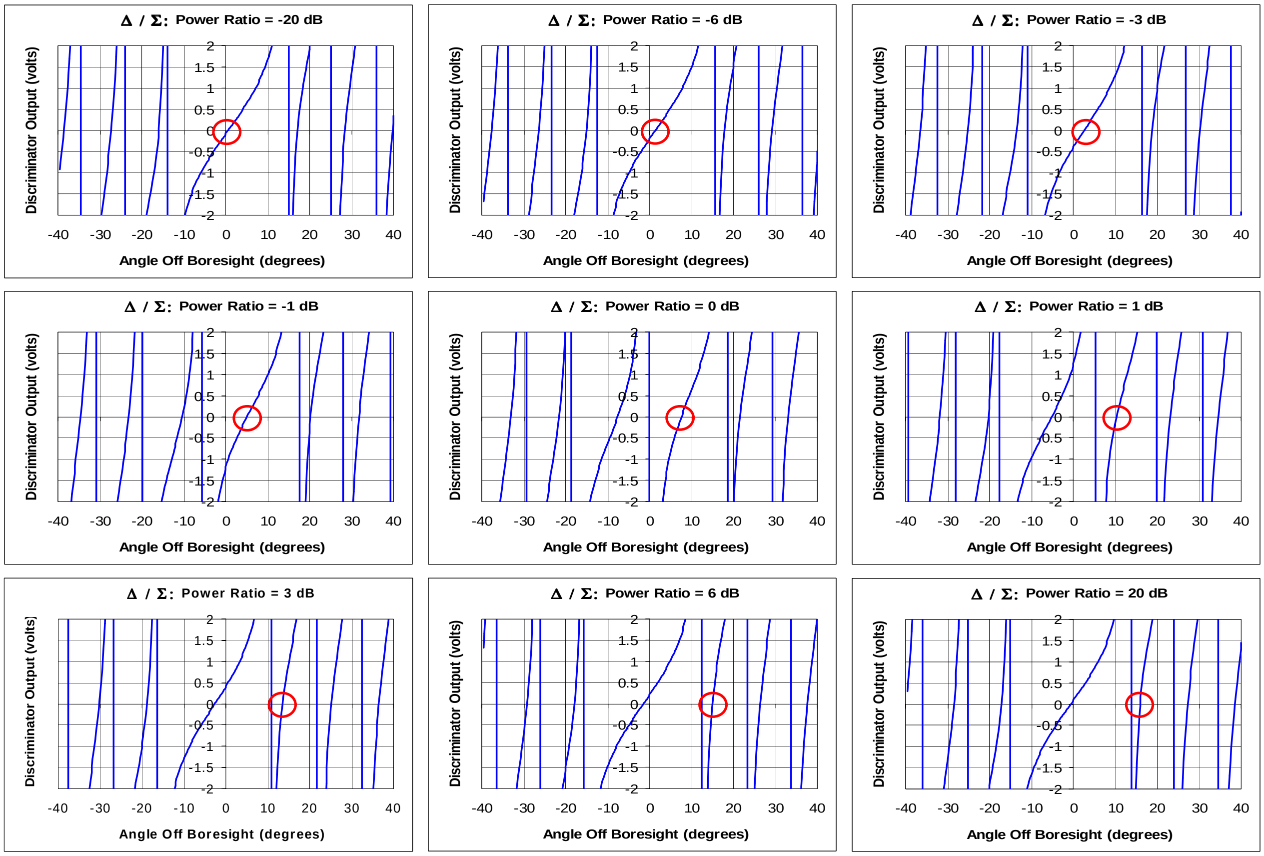

Figure 4

If, after a single amplitude modulation cycle, the first source is suddenly turned back on as the second source is simultaneously turned off, the discriminator curve will not change appreciably, and the seeker will continue to track in its first antenna sidelobe. If the amplitude modulation cycle is now repeated continuously, the result will be to walk the seeker track point off to its second, third, and higher sidelobe positions. These continual movements of the seeker antenna boresight further and further away from the true target line-of-sight will result in substantial and

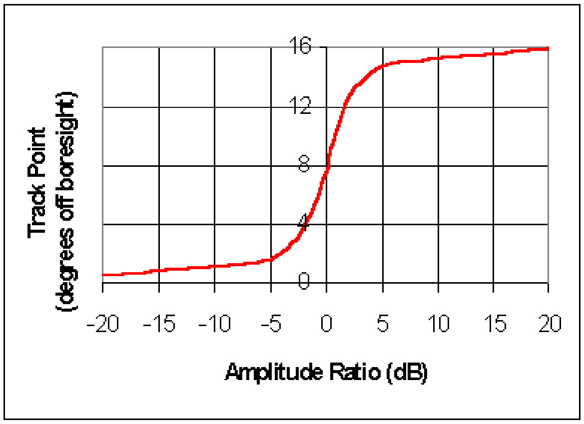

Figure 5

steadily increasing steering errors in a proportional navigation guidance system.

Figure 6 shows a graphical representation of this track point “walk-off” through a number of amplitude modulation cycles. The power ratio between the two jamming sources, expressed logarithmically in dB, is being modulated in a sawtooth fashion between -20 dB and +20 dB with a cycle time of four seconds. After three cycles (12 seconds), the track point that was initially positioned at boresight has been pushed almost 40° off boresight.

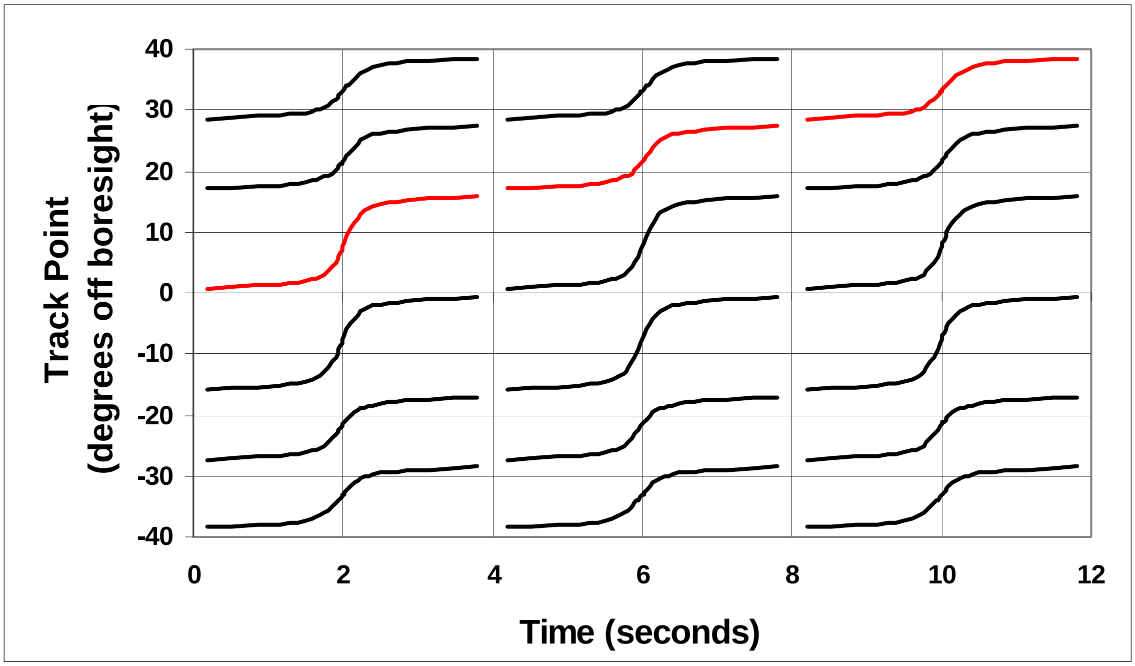

Figure 6

Simulations Using the Tactical Engagement Simulation Suite

To demonstrate the cross-eye effect on a missile system under dynamic missile fly-out conditions, two different simulations were run using the TESS JASCM Simulator (Jamming Effectiveness Simulator: Anti-Ship Cruise Missile) (version 1.4). The first run (Figure 7) shows the effect of cross-eye jamming without amplitude modulation on an incoming missile. The second run (Figure 7) shows the effect of adding amplitude modulation to one of the cross-eye sources.

In the first run, the missile seeker was configured with a 12° (Sum) beamwidth, and the cross-eye jamming antennas on board the ship were set to a separation of 55 meters. The ECM program consisted of a slow, continual range gate pull-off combined with the cross-eye technique. Range gate pull-off was applied so that the ship’s radar echo was no longer in the seeker’s range gate. If the ship's echo were in the gate, this would substantially diminish the cross-eye effect. The power transmitted from the two jamming sources was kept constant and equal throughout the run.

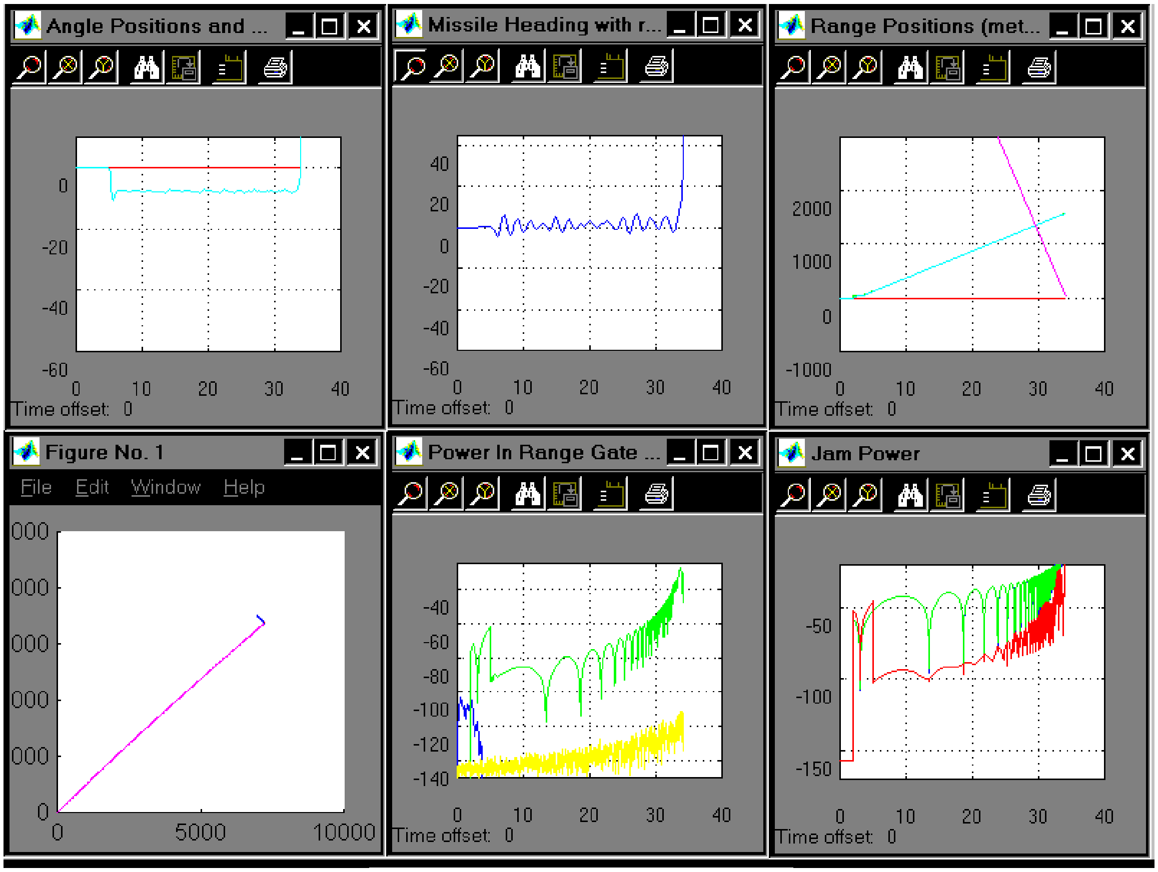

Figure 7

The main events of this run are as follows:

1. At 0 s., the missile is locked on and flying toward the ship.
2. At 2 s., the ship's on-board jammers start transmitting a repeater dwell pulse.
3. At 3 s., range-gate pull-off begins.
4. At 5 s., anti-phase cross-eye jamming begins.
5. At 34 s., the missile reaches its point of closest approach and the simulation stops.

Some of the key performance measures occurring during this run are shown in Figure 7:

- In the lower left corner is an X-Y plot of the missile fly-out. The short dark blue line in the upper right quadrant of the plot shows the path of the ship as it moves along a southeast direction. The purple line is the missile's fly-out trajectory, starting at (0,0) and ending at the closest point of approach to the ship. In this run, the missile missed the center of the ship by only 16 meters.

- In the upper left corner is an Angle Positions scope. The light blue trace shows the azimuth pointing direction of the missile's antenna referenced to the ship line-of-sight (zero line). When cross-eye jamming begins at 5 s., it immediately induces a tracking error of approximately 7° into the seeker. The tracking error remains constant over the rest of the missile's fly-out. This tracking error is consistent with the shift in the steady-state track point as shown in Figure 3, and as discussed by Lothes [2].

- In the upper center position is a Missile Heading scope. The dark blue trace shows the missile heading with respect to the ship line-of-sight (zero line). During the period when cross-eye jamming is active (5 s. to 34 s.), some oscillation in the missile heading can be observed.

- In the upper right corner is a Range Positions scope. The light blue trace shows the range-gate pull-off pulse moving slowly away from the ship range (zero line). The steep purple trace appearing on the right side of the scope display shows the range of the missile relative to the ship rapidly decreasing to zero as the missile approaches the ship.

- In the lower right corner is a Jam Power scope. The green trace shows the individual power densities arriving from each cross-eye source at the missile's antenna. Oscillations observed in this power are a result of multi-path cancellation effects. The red trace shows the combined (difference) cross-eye power arriving at the missile's antenna. When the cross-eye jamming begins (at 5 s.), the power can be seen to drop substantially because of anti-phase cancellation between the two jamming signals.

- In the lower center position is a Power In Range Gate scope. The green trace shows the jamming power in the missile seeker's Sum channel during the time the range gate is on. The dark blue trace, representing the ship echo power, can be seen to quickly leave the range gate after the range-gate-pull-off has begun. The yellow trace shows the level of clutter power in the range gate.

In this simulation run, the missile miss distance was 16 meters from the center of the ship. One of the more important observations from this simulation run is that, despite operating with a substantial angle-tracking error of 7° throughout most of its fly-out, the missile was still able to hit its target. The missile's success was a result of using proportional navigation guidance. In this case the constant tracking error does not result in increasing steering error from the missile's autopilot. The missile heading relative to the ship remains constant throughout the remaining missile flight path and results in negligible miss distance at end game.

In the second simulation run, amplitude modulation was added to the jamming waveform. One cross-eye source (Source A) was configured with variable power and the other (Source B) with constant power. The modulation cycle begins with Source A being 30 dB below the level of Source B and finishes with Source A 6 dB higher than Source B. During the crossover, as the power from Source A approaches and then exceeds that of Source B, the power rate of change is slowed considerably. This prevents the steady-state discriminator track points from shifting too rapidly for the missile's tracking servo to follow. At the end of the cycle, the power out of Source A is rapidly reduce to 30 dB below that of Source B, and the cycle is repeated. For this simulation run, the time for a single amplitude modulation cycle was set to 4.8 s.

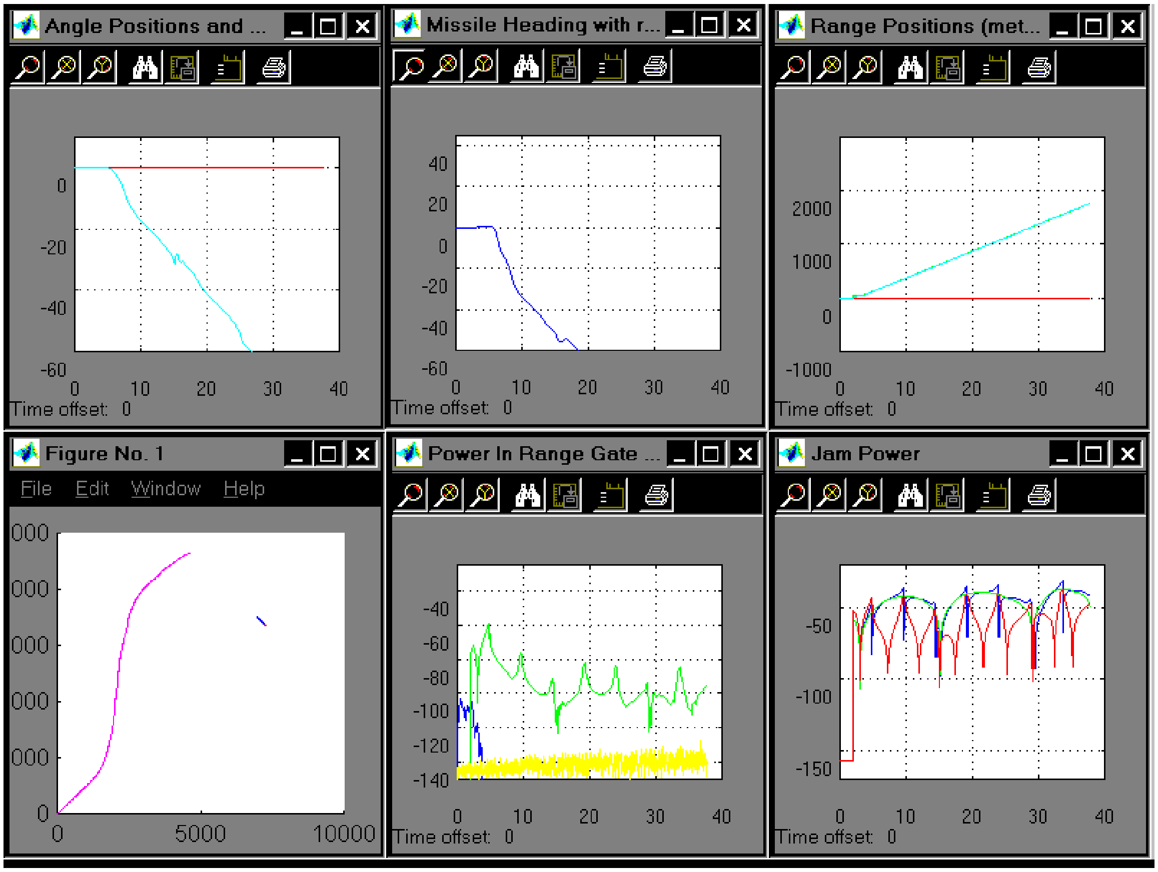

Figure 8

The performance measures for this run are presented in Figure 8. In the X-Y plot (lower left) it can be seen that the missile completely missed the ship, and the miss distance was measured to be in excess of 3 km. This large miss distance can be attributed to the constantly increasing angle tracking error signal, shown in the upper left scope display, resulting in increasing missile heading error which translates into a large missile lateral offset at the point of closest approach

Conclusions

From the above analysis and simulation results it is indicated that large missile miss distances are possible using the cross-eye jamming technique against missiles with fully active seekers. A key ingredient in realizing such large missile miss distance is the use of asymmetric amplitude modulated cross-eye signals of the correct profile and amplitude modulation rate. However, to refine the technique into a specification for an operational ECM system, further consideration of the relationships between key jamming parameters and key missile seeker parameters is of importance. Such relationships include:

1. The relationship between cross-eye phase noise and seeker angle tracking error. If the phase is not kept at 180°, the cross-eye discriminator curve will deteriorate. If it deteriorates sufficiently, it may not be possible to shift the steady-state boresight track point to a sidelobe position. The accuracy required of this phase relationship will very likely depend on the angular separation of the two sources as seen by the missile seeker and system mechanical factors such as the vibration of the cross-eye antennas.

2. The detailed nature of the seeker's angle processor in relation to angle tracking error. Although an exact monopulse processor was assumed for this paper, other types of monopulse processors may be implemented in real-world systems. Also, missile seekers exist which employ angle tracking techniques other than monopulse, such as Lobe-On-Receive-Only, Conical Scan, and Scan-With-Compensation. The different angle tracking processes used within the missile may respond somewhat differently to the application of cross-eye jamming.

3. The relationship of the cross-eye amplitude modulation waveform to the missile's azimuth tracking servo bandwidth. As indicated by Figure 5, the steady-state track point changes by a significantly large number of degrees with a relatively small change in relative amplitudes of the jamming sources (in the region of their being approximately equal). Hence, to allow the angle servo time to respond in this region, the rate of change of amplitude modulation must be fairly small and carefully controlled.

This paper provides a demonstration of the application of TESS dynamic simulations to the identification of a set of very effective cross-eye jamming parameters in a specific electronic combat engagement scenario. The execution of multiple simulation runs involving various jamming and engagement parameter combinations could lead to the identification of regions of effectiveness and to jamming system specifications, including such key jammer parameter requirements as source phase noise.

References

1. S.M. Sherman, "Monopulse Principles and Techniques", Artech House, 1984.

2. R.N. Lothes et al, "Radar Vulnerability to Jamming", Artech House, 1990.