Evaluating Airliner MANPADS Protection

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Introduction

In 2004 the AOC released a Position Statement[1] which "advocates and urges that the federal government rapidly research, develop, purchase and install a surface-to-air missile detection and deterrent system for the American commercial airline fleet". This AOC position was taken following 9/11/2001, and after MANPADS attacks on commercial airliners in Mombasa in November 2002, Baghdad in November 2003, and some 33 or more additional reported MANPADS attacks on civil aircraft over the last 25 years.

Much has been written about potential terrorist threats to commercial airliners, not only MANPADS threat systems but also RPGs and some larger caliber guns. Also much has been written about the various means potentially applicable to protecting such aircraft, using not only on-board countermeasure systems but also area defensive and escort systems. An extensive MANPADS bibliography is provided by the AOC web site[2] that offers an excellent guide to the open literature on the subject. The literature includes numerous analysis and position papers from various interested agencies such as the Congressional Research Service[3], the Air Line Pilots Association[4], the CREATE Homeland Security Center at USC[5] and the Rand Corporation[6], which include not only on-board countermeasure protection against IR–guided MANPADS threats, but also threat proliferation prevention measures, aircraft hardening measures and tactical and training measures. An issue of continuing concern in many such documents is the cost of each of the various options and the relative effectiveness of the options[6,7].

The Issue of Effectiveness

While the estimated cost of various protection options for commercial airliners is discussed widely in the open literature the issue of the effectiveness of these options is left relatively unaddressed. The effectiveness of countermeasure protection measures against attacking missiles has historically been a military-only type of issue and military organizations have addressed it using classified data analyzed by cleared and knowledgeable staff operating in secured facilities using extensive simulation and testing facilities. The consequent limited availability of system effectiveness information is mandated by the need to control nationally sensitive data, beginning with the detailed technical analysis and characterization of threat missile systems. It extends to the characteristics, programming and tactical employment of protective systems. For jamming systems it is openly recognized[8] that "for each IR missile type there is an optimum set of jamming algorithms." Further, if the countermeasure system can't identify specific missiles, "it uses generic jamming algorithms or else sequences through a catalog of specific jamming codes. The IR tracker measures the effectiveness of the jamming as it tracks the incoming missile. Through trial and error it determines which algorithms work – all in as little as 3 seconds".

The roles of modeling and simulation in the identification of jamming algorithms and the determination of their effect on various classes of missiles are well established and reported in the open literature. For example, the AOC has prepared two joint government/industry study reports on this subject[9,10]. Also numerous textbooks[11,12,13,14,15] and handbooks[16,17] outline the underpinning physics models and their use in the simulation of dynamic threat and countermeasure engagements for the evaluation of countermeasure effectiveness. Many information sources, such as Jane's Information Group[18] and the Federation of American Scientists[19] describe the open characteristics of specific threat weapons.

The analytic processes required for evaluating countermeasure effectiveness and optimizing countermeasures in relation to specific threat weapons is left largely unaddressed in the literature. Such processes and the required knowledge base, however, will inevitably become an integral part of the infrastructure required to support and re-program any countermeasure systems operationally deployed on commercial aircraft. This paper intends to be a contribution toward the development of such infrastructure.

Tactical Engagement Simulation

Here we demonstrate an approach to evaluating the effectiveness of both jamming and flare protection applied against several classes of MANPADS threats, based on the open literature characterization of the threats and countermeasures. This approach is supported with the use of open source Tactical Engagement Simulation Software[20]. It should be noted that the open source threat and countermeasure characterizations used limit the results described in this paper to being qualitative and demonstrative in nature and are not system specific. However, actual system parameter characteristics could also be entered into the simulation software and the same analytic processes applied to the evaluation of countermeasure effectiveness in relation to specific missiles.

In discussing countermeasure effectiveness it is necessary first to define what constitutes an effective countermeasure. We assume that if the MANPADS misses the body of the aircraft by a distance comparable to a half wing span, then the missile will not impact the aircraft, and with an assumed impact fuse, the warhead does not detonate. In this circumstance the probability of missile kill will equal the probably of hit which would be zero. Hence the countermeasure is taken to be effective if the missile miss distance exceeds the half wing span and hence misses the aircraft.

It is then necessary to define the basic sample engagement scenario to be used in executing the effectiveness evaluation simulations. The scenario used assumed the aircraft was a four engine turbo-jet with a half wing span of 20 meters. The engines were located under the wings 7 meters and 14 meters from the body of the aircraft. The aircraft was climbing from take-off at a 10 degree climb rate. In each simulation run the missile was fired from a range of 1.2 to 1.4 Km and had a terminal velocity of between 580 and 640 meters per second. The aircraft velocity was between 100 and 125 meters per second at an altitude of between 250 and 500 meters at the time the missile was fired. Batch simulation runs were executed in which 20 missiles were fired at each 10 degree increment around the aircraft with the Monte Carlo random selection of the above parameters within the identified parameter ranges. The missile's miss distance was recorded for each of the individual simulation runs. Finally polar plots were generated which showed the number of missiles out of the 20 fired at each angle that missed the body of the aircraft by greater than 20 meters. The resulting "probably of adequate miss" metric was taken to be the primary measure used for comparing the effectiveness of flare and jamming countermeasures against both first generation and third generation MANPADS weapons. A first generation missile seeker has been described[6] as a reticle scan or spin scan tracker in the class of SA-7, whereas a third generation missile has been described[6] as a pseudo-imaging tracker in the class of SA-18. One example of a pseudo-image tracker is described[17] as a rosette tracker.

A First and Third Generation IR Seekers

The mechanism used by a first generation spin scan IR tracker to steer the missile to its target is demonstrated in Figure 1.

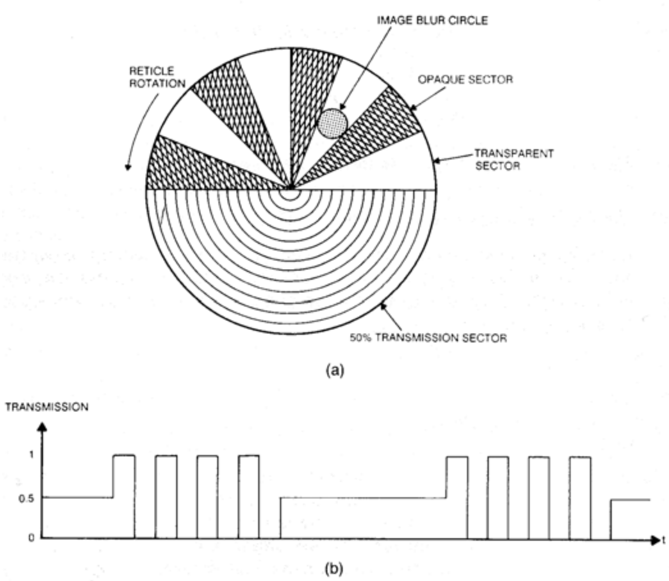

Figure 1. Illustration of a spin-scan reticle (a) rising-sun reticle pattern (b) reticle modulation function (From the IR/EO Handbook[16], Volume 7.)

A spin scan tracker possesses a spinning reticle, typically similar to that shown in Figure 1(a) which chops the IR signal from the tracked target, producing a signal modulation pattern as shown in Figure 1(b). This chopped IR signal is detected and then smoothed with a narrow filter centered on the reticle rotation frequency. The resulting filtered detected signal contains only the fundamental (rotation rate) frequency and this is compared in phase to the rotation reference signal of the reticle. The phase difference between the detected signal and the reference signal is a measure of the angle to steer the optics and missile in order to home on the target.

By way of comparison the mechanism used in a third generation pseudo-imaging seeker might typically be with the use of a track-while-scan rosette pattern as shown in Figure 2(a). Such a rosette pattern might be generated using counter-rotation mirrors or prisms which possess different rotation frequencies. Track is established using a narrow instantaneous seeker field-of-view which scans with the rosette pattern while the tracking function is performed, perhaps using digital extraction techniques. The periodic detected pulse train as shown in Figure 2(b) occurs only in the special case of the target being at the center of the rosette and, hence, is detected within the instantaneous field-of-view in each and every petal period. When the target is offset from the center of the rosette, the detected pulse pattern is periodic only at the rate of the entire rosette scan and is non-periodic within a single rosette scan period. If the instantaneous field-of-view is less than the spatial extent of the target, then the target may be detected in several petal scans of the rosette, leading to a pseudo-imaging capability.
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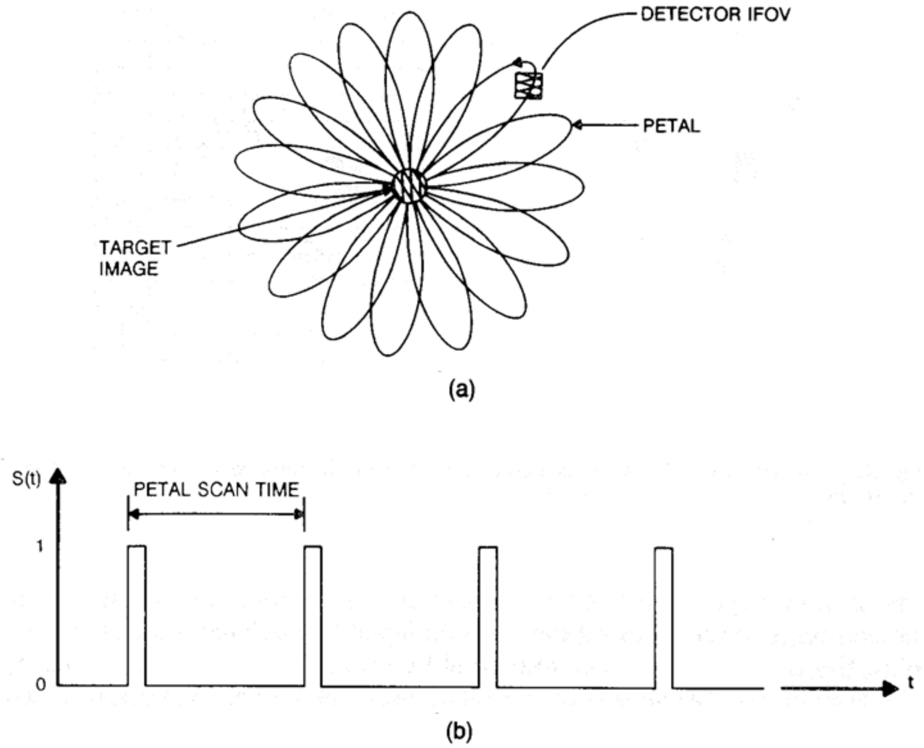


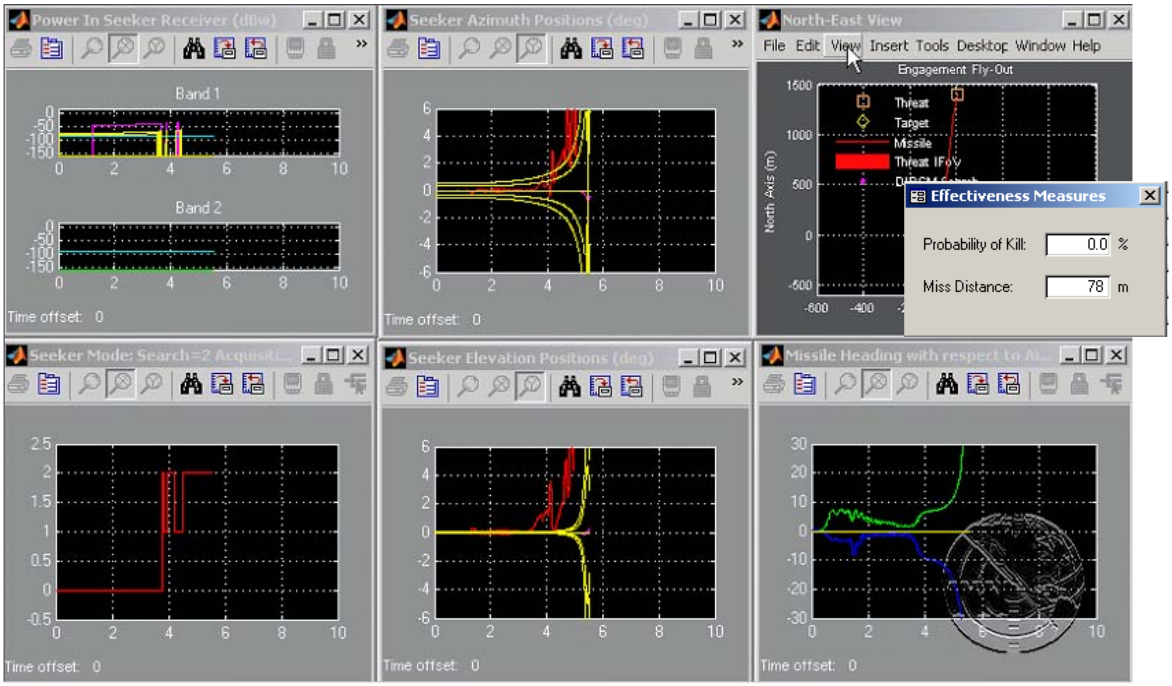
Figure 2. Rosette Scanning Pattern and (b) normalized signal pulse sequence for on-axis image. (From the IR/EO Handbook[16], Volume 7.)

Jamming a Spin Scan IR Seeker

Before reviewing the results of dynamic engagement simulations involving the active jamming of first generation spin scan seekers it is worthwhile reviewing the fundamental physics involved in the interaction between the jamming signal and the spin scan tracking mechanism. Starting with the non-jamming situation, when the target is being ideally tracked the target signal is positioned in the center of the spinning reticle. The detected signal is then at the same phase as the scan reference signal and no angle error drive signal is generated, hence the target remains in the center of the tracking reticle. If the target moves off-boresight, then a phase difference between the detected target signal and the reference develops and this is of an appropriate sign that the optics, under servo loop control, are steered in the direction that re-centers the target signal.

To cause a substantial missile miss distance the jammer must create an angular offset of the missile from the target through generation of an angle track error that is either sufficient to cause a track break-lock or to cause a continuing increase in tracking error as the missile's flight progresses. One mechanism that the jammer may use to generate an angle track error is to illuminate the seeker with a jamming signal that is amplitude modulated (typically with about a 50% duty cycle) with a phase that is 180 degrees off-set from the reticle scan reference signal. However, there are difficulties for the jammer in its establishing the optimum frequency and phase for the amplitude modulated jamming signal. First, the frequency of the seeker's scan reference must be known reasonably accurately, normally through intelligence exploitation. An additional complexity is that if the reticle is spun-up initially and then slowly decays the scan reference frequency will change during the missile's flight. A second difficulty is in adjusting the phase of the jamming modulation to be opposite that of the scan reference (which is not directly measurable by the jammer). The uncertainty in the frequency and phase of the seeker's scan reference is typically addressed by sweeping the jammer's amplitude modulation frequency around or near that of the scan reference. Because phase is the integral of frequency the jammer's frequency modulation causes the phase of the jamming AM signal to vary and a linear frequency excursion gives rise to a parabolic phase excursion. Hence, it is possible to walk the phase of the jamming signal through the 180 degree anti-phase condition that is associated with the creation of angle track error. An additional complication in optimizing the jammer's frequency modulation pattern is the difficulty of ensuring that the 180 degree anti-phase condition is maintained for a sufficiently long period of time that the seeker's angle tracking servo loop has time to respond. With enough jamming power and with the anti-phase relationship being maintained for a time that is longer than the angle servo response time then a track break-lock condition is possible. The DIRCM jammer with its focused beam can direct substantially more jammer power on the missile seeker than can an omni-directional conventional IR jammer; hence can potentially create more angle tracking error more quickly.

The execution of a single typical engagement simulation of a spin scan missile attacking a four engine turbo-jet aircraft, produces results for a typical engagement as shown in Figure 3.



Probability of Kill: 0.0 %

Miss Distance: 78 m

Figure 3 Typical Simulation Results for a Swept Amplitude Modulated Jammer vs Spin Scan Missile Engagement

Figure 3 contains five scopes showing the responses of various key measurement points in the missile and one plan view graphic of the engagement. In this engagement the swept AM jamming was successful in causing a seeker track break-lock, giving rise to a miss distance of 78 meters and a probability of kill of zero. In the plan view graphic (which is in the top right position of Figure 3), the trajectory of the missile is shown by the red line while that of the target aircraft is shown by the yellow line with the yellow diamond being the target aircraft icon.

The scopes shown in Figure 3 can be used to analyze the sequence of events that occurred in the engagement. The top left scope shows the jammer's power (magenta) within the seeker's field of view exceeded that of the aircraft (yellow) by approximately 30 dB. It also shows that the jammer turned on one second into the engagement and that at about four seconds the seeker lost power from both the jammer and the aircraft. It might be noted that this missile was assumed to be a single band (color) system and hence there was target and jamming signals in Band 1 only. The bottom left scope shows the seeker's mode, which for the first about 4 seconds after the engagement's start, was in a track or locked-on mode, with a mode logic value of 0. After about 4 seconds (coincident with the loss of aircraft and jammer power) and with a mode logic value of 2 the seeker was unlocked and remained unlocked for the remaining about 1.5 seconds of the engagement. During this final 1.5 seconds the missile would have been flying without guidance in a ballistic trajectory.

The middle two scopes show the azimuth and elevation track positions (red) of the missile seeker relative to that of the aircraft (yellow). There are 5 separate yellow traces that represent the four hot-spot engines and the fifth being the body of the aircraft at a relative angle of zero. Note that the angular positions of the engines separate as seen by the seeker as the missile approaches the aircraft toward end game. In these two middle scopes it is seen that the seeker's track point diverges from that of the aircraft body at about 4 seconds and this is consistent with the missile's losing signal from the aircraft and switching into an unguided mode. Finally the bottom right scope shows the missile's heading diverges in angle (both azimuth and elevation) from the aircraft in the last 1.5 seconds of missile flight.

It is of some interest to evaluate the effectiveness of the same technique when the missile is launched from various aspect angles around the aircraft and when the launch range, missile terminal speed, aircraft speed and aircraft altitude at missile launch are all randomly varied over the parameter ranges described above. Figure 4 shows the polar plot results of a batch run for the above conditions. Of the 20 missiles launched from the 320 degree aspect of the aircraft, the miss distance for 15 of the 20 missiles (75%) exceeded 20 meters, while 5 or 25% of the 20 missiles were within a miss distance of 20 meters. In total, this batch run contained 720 individual simulated engagements.

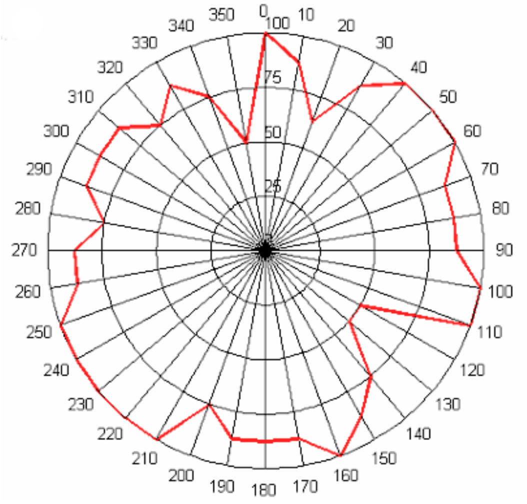


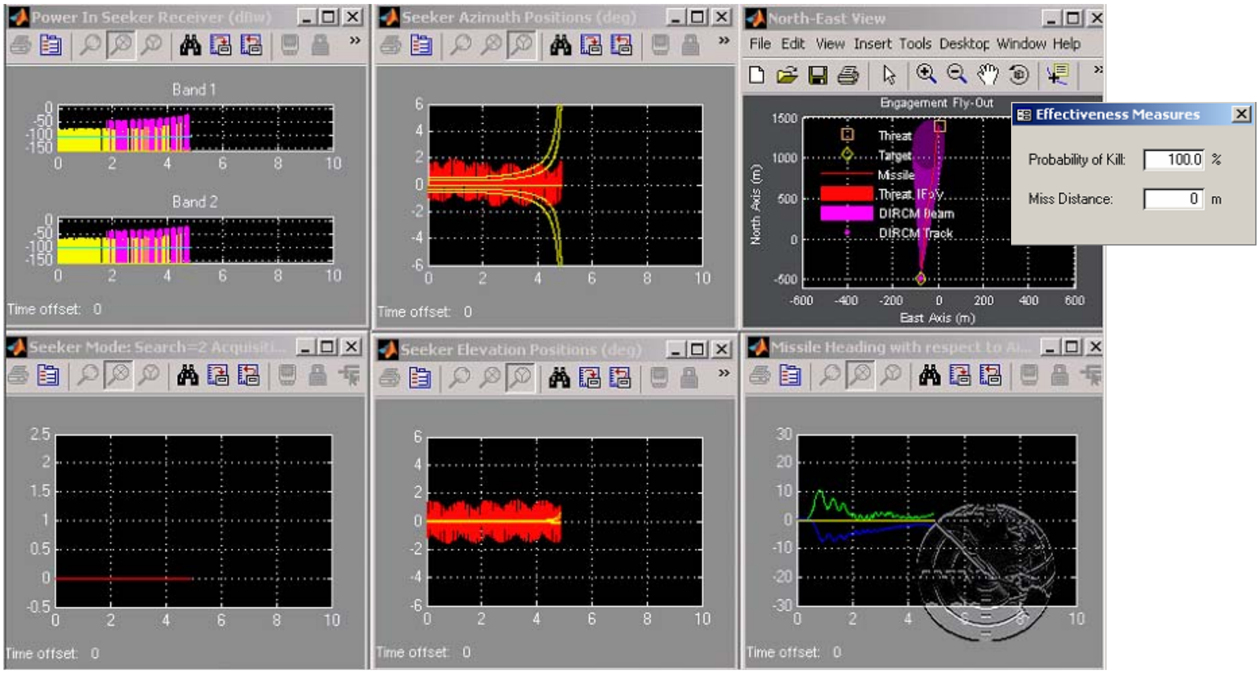
Figure 4. Polar Plot Showing the Percentage Of All Spin Scan Missiles Launched At An

AM Jammer Protected Aircraft (Launched At 10 Degree Increments) That Missed The Target Aircraft By Greater Than 20 Meters When Missile Launch Range, Missile Terminal Velocity, Aircraft Speed And Aircraft Altitude At Missile Launch Were Monte Carlo Selected.

Jamming a Rosette IR Seeker

While the principles of creating angle track error using amplitude modulated jamming in a rosette tracker are similar to those for jamming the spin scan tracker, the conditions of ensuring that the jamming pulse pattern is synchronized to both the rosette and the petal periods is substantially more difficult.

Figure 5 shows an engagement similar to that shown in Figure 3, except now the seeker uses a rosette tracker and the jammer's amplitude modulation center frequency and sweep are relatively optimized to the rosette's dual frequencies. Even with that the miss distance was zero meters (a missile hit on the body of the aircraft)



Probability of Kill: 100.0 %

Miss Distance: 0 m

Figure 5 Typical Simulation Results for a Swept Amplitude Modulated Jammer vs Rosette Missile Engagement

The scopes and graphic shown in Figure 5 for the rosette tracker are as those shown in Figure 3 for the spin scan tracker. There are however a number of significant differences that are apparent. The first is that in the Seeker Azimuth and Elevation scopes it is seen that the instantaneous pointing direction of the seeker scans around the aircraft body position through-out the engagement but the center of that scan remains fixed on the body of the aircraft (no angle error is apparent). The other apparent difference is that the seeker mode, as shown in the bottom left scope, stays firmly fixed in track mode (zero logic value) for the entire engagement. In other words the amplitude modulated jammer (based on a DIRCM steered beam with a 30 dB jam to signal ratio) did not create a break-lock in the rosette's track at any point in the engagement.

Figure 6 shows the results of a batch simulation run for an AM jammer engaging a rosette tracking missile and uses input parameter ranges like those used in the analogous AM jammer engaging a spin scan tracker as shown in Figure 4.

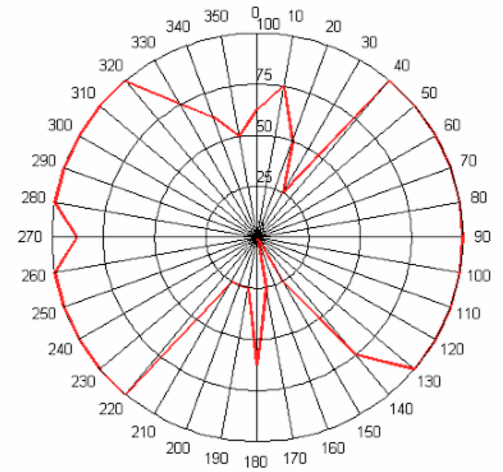


Figure 6. Polar Plot Showing the Percentage Of All Rosette Missiles Launched At An AM Jammer Protected Aircraft (Launched At 10 Degree Increments) That Missed The Target Aircraft By Greater Than 20 Meters When Missile Launch Range, Missile Terminal Velocity, Aircraft Speed And Aircraft Altitude At Missile Launch Were Monte Carlo Selected.

A comparison of the batch run polar plots of Figures 4 and 6 indicates that the AM jammer provided more protection against the spin scan missile than the rosette missile. The rosette tracker is more difficult to amplitude modulate jam because, put simply, the probability of being able to synchronize the amplitude modulation signal's frequency and phase to both the petal and rosette frequencies, where there may be only a few dozen rosette periods in one entire engagement is much less than for a spin scan tracker for which there are probably many hundreds of spin scan cycles in the course of an engagement.

Flare Protection against Spin Scan and Rosette Trackers

It is of interest to compare the effectiveness of flares against spin scan and rosette tracking missiles. Batch runs analogous to those shown for AM jamming of these two classes of missiles flare engagements were also run using similar scenario conditions. In each engagement the same flare pattern was used, a total of six flares were ejected in pairs at one second intervals. Each ejection consisted of the flares being ejected at right angles to the direction of flight of the aircraft, one to the right side, and the other to the left. Each was ejected with a downward component of 15 degrees.

The results of these batch runs are shown in Figures 7 and 8 (flares vs spin scan and flares vs rosette respectively).

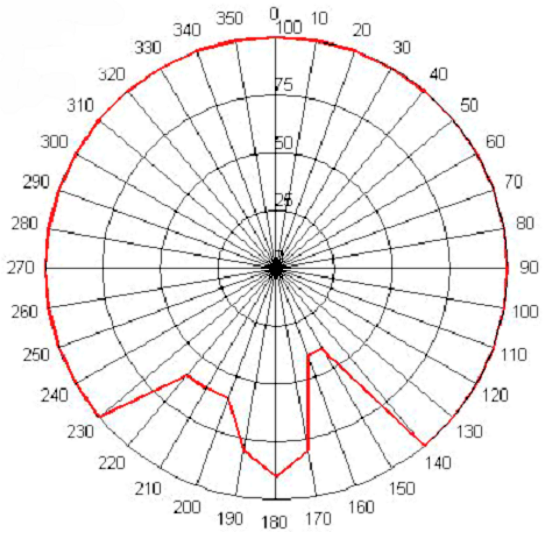


Figure 7. Polar Plot Showing the Percentage

Of All Spin Scan Missiles Launched At A Flare Protected Aircraft (Launched At 10 Degree Increments) That Missed The Target Aircraft By Greater Than 20 Meters When Missile Launch Range, Missile Terminal Velocity, Aircraft Speed And Aircraft Altitude At Missile Launch Were Monte Carlo Selected.

It is noticeable in Figure 7 that there are two notches in the flare protection pattern both associated with missile firings from behind the aircraft and slightly offset from the centerline of the aircraft. Individual simulation runs at those specific angles indicates that the flares were successful in capturing the seeker's tracker, however the engagement geometry was such that in about 50% of the missile launches the threat-side launched flares captured the seeker and the missile flew into the aircraft after passing through the flares.

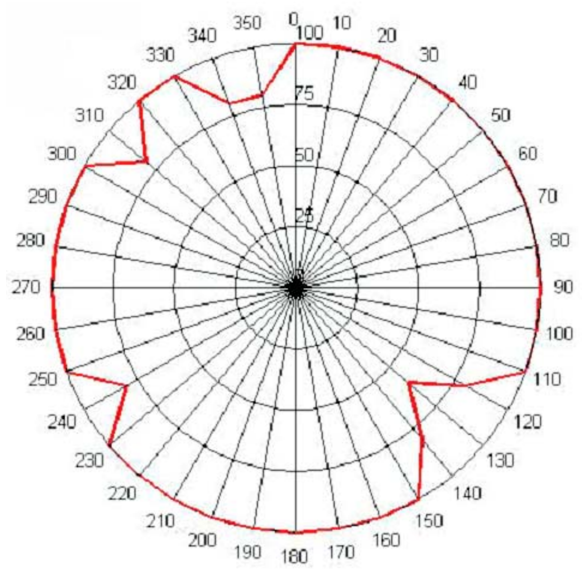


Figure 8. Polar Plot Showing the Percentage of All Rosette Missiles Launched At a Flare Protected Aircraft (Launched At 10 Degree Increments) That Missed the Target Aircraft by Greater Than 20 Meters When Missile Launch Range, Missile Terminal Velocity, Aircraft Speed and Aircraft Altitude at Missile Launch Were Monte Carlo Selected.

Comparative Results and Observations

In comparing the four batch run results shown above it is apparent that the combination of an AM jammer used against a rosette missile was less effective in providing aircraft protection than for any of the other three combinations. It should be noted that the use of other engagement geometries, flare deployment sequences and jammer amplitude modulation schemes would almost inevitably give rise to different effectiveness results.

The purpose of this paper was to describe an approach and a process using modeling and simulation, for evaluating commercial airliner MANPADS protection. The approach and process described here identified a means whereby the various factors which influence countermeasure effectiveness and aircraft survivability can be evaluated and results in a common framework. It is a framework in which the classified characteristics of threats and countermeasures can be inserted in place of the open characteristics and then new results generated. It should also be noted that the few sample engagements used here, are just that, samples. To determine the most robust and optimal protection measures many, many more batch runs involving many other combinations of countermeasure and threat parameters, particularly those associated with specific systems, would need to be executed.

Finally, it is probably important to emphasize that the jamming modulation waveforms used against the two types of missiles were quite different from one another and also that a substantial amount of information about the missile seeker was needed to establish these modulation patterns. Such critical missile information included the reticle and mirror/prism rotation rates and the seeker's angle tracking loop servo bandwidths. Such detailed missile characteristics are not as critical for the evaluation of the effectiveness of flares. Sensitivity analysis, which is made necessary by the number of non-linearities in the countermeasure/seeker interaction, shows clearly that AM jammer performance is a sensitive function of its amplitude modulation parameters, while flare performance is not as sensitive a function of flare deployment sequences. In the context of commercial airliner applications, particularly international applications, the required detailed missile knowledge and evaluation processes may represent not only technical challenges but also security, system and information control challenges.

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