JOURNAL OF GUIDANCE, CONTROL, AND DYNAMICS
Vol. 18, No. 6, November–December 1995

Terminal Homing Performance of Semiactive Missiles Against Multitarget Raids

Craig Phillips*
U.S. Naval Surface Warfare Center, Dahlgren, Virginia 22448-5100

The effects of low altitude multitarget raids against surface ships with command midcourse/semiactive rf terminal homing defensive missiles are investigated in terms of terminal homing miss distance. The scenario presently considered is that several defensive missiles are fired with each assigned a target to engage. A missile must engage its designated target for a successful intercept, and the miss distance is measured relative to the designated target. Raid geometry and the approach angle of the interceptor relative to the raid scintillation axis were found to be important parameters in determining miss distance. The stream raid and the closely spaced stacked raid had resolution ranges so short as to be practically unresolvable. Reasonable variations in the heading and seeker pointing errors had little effect on terminal miss distance for these unresolvable scenarios. For larger stacked raid separations, which are just resolved at handover, the handover errors can cause a loss of resolution and poor homing performance. Thus, a highly accurate handover is of use only for a band of separation spacings for the stacked raid and has little benefit against the stream raid. A method to counter the stream raid is to control the missile handover aspect angle through midcourse trajectory shaping so as to approach antiparallel to the raid velocity. For stacked raids, minimizing the handover range while using the midcourse guidance to bias the handover heading error allows more tightly spaced raids to be successfully engaged.

Nomenclature

a_i = sum channel gain aimed at the individual target
ϵ_i = boresight angle to the individual target
ϕ_i = relative phase angle of the individual target signal

Introduction

THE requirement to discriminate and track targets in the presence of multiple signals has existed since the creation of radar homing systems. The multiple signals can come from both man-made and environmental sources. Additional signals may come from multipath signals arising from surface reflections, jamming, decoys, secondary targets, and target-like debris.

When semiactive rf missiles engage targets at low altitudes, surface multipath effects present a significant problem. At low altitudes, signal multipath is caused by the sea surface reflection of rf energy so that signals arrive at the same point via two paths. A perfectly smooth sea surface would reflect rf energy coherently at a single reflection point. For an agitated sea surface condition, a transmitted signal is reflected diffusely over an extended area of the sea which produces many small, randomly phased reflections.

In a semiactive rf missile system, there are two dominant types of surface multipath: 1) forward and 2) back. Forward multipath refers to the existence of two signal transmission paths from the illuminator to the target or the missile receiver. Forward multipath to the target can lead to fading of the target in addition to the natural fading of complex targets. Clutter is yet another form of forward multipath involving transmission from the illuminator to the missile main receiver antenna and is created by diffuse reflections over a relatively wide area. For antiparallel intercepts, the signal arriving along this path may be removed by narrow-band Doppler filtering.

Back multipath, on the other hand, refers to the situation where the reflected illuminator energy from the target follows two paths back to the missile receiver. Multipath reflections induce additional fading effects, noise, and false signals to the tracking process, which disrupt the guidance loop and lead to greater miss distances.

Received Sept. 22, 1994; revision received April 15, 1995; accepted for publication April 20, 1995.

*Senior Aerospace Engineer, Dahlgren Division, 17320 Dahlgren Road. Member AIAA.

Electronic countermeasures such as jamming can also degrade the angular tracking. The use of a separate vehicle to carry a jammer is stand-off jamming. The jamming aircraft usually is positioned outside of the missile defense range and, thus, must broadcast into the missile sidelobes. A jammer carried by the attacking vehicle is self-screening jamming. Broadband jammers produce incoherent radiation over a wide bandwidth to lower the interceptor receiver signal-to-noise ratio and degrade the angle tracking of the target. To deal with the self-screening jammer, the semiactive missile may switch to a passive mode and home on the jammer broadcast. Jamming techniques and countermeasures can become quite involved, and a discussion which does justice to the subject is beyond the scope of this paper.

Decoys, secondary targets, and target associated debris all are examples of scenarios of multiple target-like signals. For re-entry vehicles, decoys are relatively easy to deploy at high altitudes where atmospheric density is insufficient to strip away decoys with incorrect dynamics. Multiobject raids may be produced at the higher altitudes by target debris that follows the target and for sea-skimming missiles by decoys or secondary targets, which fly in a coordinated fashion. In the presence of multiobject raids, the track radar will track a composite target and will glint strongly until resolution through some type of discrimination. The glinting can be caused by the fading effects of the complex targets or by interference of the signals from the multiobjects. This glinting can disrupt the homing process before resolution and lead to heading errors at resolution greater than the separation of the objects in the raid. When defending against a multitarget raid, a weapon control system may fire a volley of interceptors, each of which is assigned a particular target for engagement. In this scenario, the glinting before resolution may disrupt the interceptor/target assignment process, and the missile may engage the incorrect target. Should this happen, one target may be engaged by several missiles, and some targets may be not engaged. So engagement of the correct target is an important measure of performance and, as such, the miss distance will be measured relative to the designated target.

To provide discrimination and tracking, the first missile seekers depended on conical scan techniques to provide angle discrimination. In this method, the antenna pattern produces a narrow pencil-like beam which is rapidly scanned about an imaginary cone. The difference in received signals from the subsequent dwells is proportional to the angle of the target off of the scan centerline. Then the scan centerline may be moved to track the measured target position.

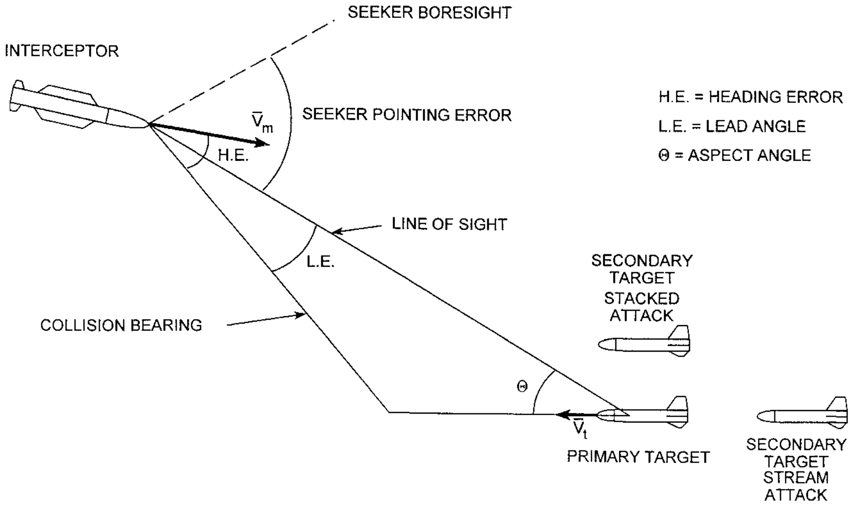

Fig. 1 Scenario definition.

The conical scan system is vulnerable to electronic countermeasures and by the 1970s was being supplanted by monopulse systems.

In a monopulse system, the two beams (per tracking plane) are generated simultaneously through the antenna pattern. Thus, the angle measurement of the perceived target off of the antenna boresight may be determined in a single dwell. The monopulse system most often discussed is the amplitude comparison monopulse where the amplitude from four receiving horns in the antenna are processed to estimate the target off-boresight angle. In practice the phase comparison monopulse is often used because it reduces the amount of signal processing hardware. In this approach, an interferometric antenna senses the phase of the received signal on each of the quadrants of the antenna. These may be combined to produce the voltages proportional to the angular offset of the perceived target relative to the boresight. From a practical hardware implementation, the phase-comparison monopulse is much simpler, but from a system-level analysis perspective the two methods are very similar.

This paper seeks to determine the multitarget effects on miss distance in the following problem. The basic scenario at handover is shown in Fig. 1. The ship system has resolved the raid and designated one of the targets as the primary target. Two target stacked and stream raids are considered. The designated target for the stream raid is the front target. For the stacked raid, the designated target is the lower target. The missile has acquired the designated target with its continuous-wave seeker through shipboard illumination. Measurement errors of the target position and velocity by the ship system may lead to seeker pointing and heading errors as defined in Fig. 1. The measure of effectiveness is the miss distance relative to the primary target.

The terminal homing of guided missiles against single targets has been extensively studied. The miss distances of missiles guided by proportional navigation due to target maneuvers, heading errors from midcourse phase navigation errors, receiver noise, and radome aberrations have been presented.[1–5] These efforts have yielded both numerical and closed-form solutions. Sources in the literature have typically decoupled the terminal analysis from nonlinear models of the signal processing and the environment. Such effects have typically been included as noise sources added via superposition to the true line-of-sight measurements. A coupled analysis of the guidance and signal processing for semiactive rf guided missiles in clutter has been presented in Ref. 6. A similar analysis on the effects of back specular multipath on the return from the target to the interceptor has been presented in Ref. 7.

Reference 8 has presented very useful results for two target engagements, which may be used to answer fundamental questions concerning terminal guidance. Signal processing is represented in that study as the having the missile seeker track the power centroid and achieving resolution at a parameterized time to go. The results of that study are most applicable to infrared focal plane seekers which provide very fine discrete angular resolution. Angular track performance and angular resolution in radar seekers do not exhibit the definite resolution that characterizes the infrared seeker. The ability to resolve multiple objects is affected by monopulse difference channel antenna patterns, the geometry dependent radar cross section of the objects, the target fading characteristics, and signal processing algorithms. Angular resolution may be enhanced via the application of angle-editing schemes. The relatively wide beamwidths of smaller diameter missile-borne rf seekers further compound the multitarget tracking problem. For radar seekers, the presence of multiple targets continues to degrade the track accuracy over relatively wide angular separations, and as the missile and targets close, the missile track will glint between the targets. For radar seekers, very definite discrimination may be provided in Doppler frequency. If the effective Doppler resolution frequency cell is sufficiently small, then radar seekers may be able to achieve very definite discrimination and prevent corruption of the track. Reference 8 does not consider the gradual degradation of the track accuracy, Doppler search and acquisition, or the association problem.

At handover and when the Doppler tracks of the two targets separate from the same frequency cell, the missile must associate one of the tracks with the designated ship system track or the previous track before the resolution was lost. Because of the interceptor dynamics during the terminal homing phase, it is possible for previously resolved targets to coalesce into a single Doppler track cell and the association problem may have to be solved several times. Jockeying of the targets may also lead to coalescing of the Doppler frequencies of previously resolved targets. Each opportunity to solve the association problem is also an opportunity for the incorrect target to be chosen for homing. The new element of the present study is that it combines guidance and dynamics with considerations of the monopulse angle tracking, association algorithms, and multiple targets. The influence of raid geometries will be considered as will missile guidance parameters and midcourse trajectory shaping.

Problem Definition

This paper makes the following assumptions.

1) The analysis begins at handover from command midcourse to semiactive homing.

2) The missile has acquired the target or the composite raid.

3) There are two targets in the raid.

4) The ship system has resolved the multitarget raid and has designated the correct target. For the stream raid, this is the lead target. For the stacked raid, this is the lower target.

5) The targets fly in a fixed formation with the front or lower target at an altitude of 30 ft and a constant speed of 3000 fps.

6) The missile has a speed at handover of 3800 fps. The nominal missile noise filter time constant is 0.15 s. The nominal seeker loop and autopilot/airframe time constants are 0.25 and 0.15 s, respectively.

7) At handover, the ship system has directed the missile seeker to point at the measured or estimated position of the designated target.

8) The midcourse guidance has guided the missile to zero deterministic heading error in the case of the perfect handover. When heading errors are assumed, they may be due to ship system measurement errors or intentional as part of the midcourse trajectory design.

9) All heading errors, seeker pointing errors, and miss distance values are measured relative to the primary target.

10) The missile has sufficient maneuverability to steer out the heading errors considered when flying with the same heading error against the single target raid.

11) Except when the acquisition range is being studied, acquisition range to go is assumed to be 8.5 n mile, which provides more than 10 time constants of homing.

12) Radio frequency multipath and clutter effects are neglected, as are Earth curvature and low-altitude propogration effects.

13) The intercept is far from the ship-based illumination system in that the Doppler shift between the two targets on the illuminator-to-target leg is negligible.

14) The targets are modeled as simple reflectors.

The missile is assumed to have the following characteristics: 1) rf continuous wave semiactive terminal homing, 2) monopulse tracking in angle during terminal homing, 3) Doppler search and tracking during terminal homing, and 4) a prediction of the primary target Doppler frequency is received from the ship system at start search and handover.

The airframe parameters used in this study are typical of the class of short range missiles with tail control and a significant portion of the lift achieved off of the missile body. The missile is assumed burned out during the terminal homing phase.

Analysis Approach

This study analyzes the stacked and the stream raids in a parameterized fashion to determine the miss relative to the primary target. The effects of target separation and handover errors are considered for each case. Also elements that are possibly under the system designer's discretion are analyzed including the range to go, at which terminal homing is initiated, and the approach or aspect angle at handover.

Analysis Model

The terminal homing model overview is shown in Fig. 2. The basic simulation uses point mass dynamics with three cascaded lags. The response of the autopilot/airframe system to acceleration commands is determined by a first-order lag model, which is followed by acceleration limiting. The acceleration commands are generated with an onboard proportional navigation law using the filtered seeker head rates as inputs. A digital first-order filter is implemented to smooth the measured head rates. The seeker track loop is modeled as a first-order system, which attempts to null the measured target off-boresight angle. The resulting head rates then drive the guidance algorithm.

For many cases, the miss distance is sensitive to the parameters of the problem including the separation of the targets. To counteract this effect, the miss distances presented are averaged over five samples uniformly distributed over 0.25-ft band about the specified target separation.

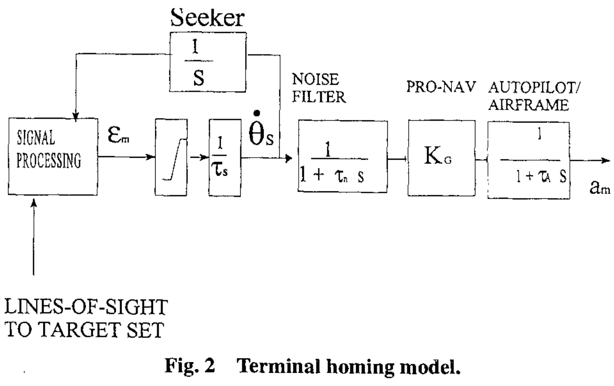

Fig. 2 Terminal homing model.

Monopulse Signal Processing Model

As shown in Fig. 2, the signal processing produces a measured off-boresight angle which the seeker track loop tries to null. Because of interference effects between the target returns, this measured off-boresight angle can be significantly different from the true angle to any of the targets.

An overview of the monopulse angle tracking signal processing model is now presented. At each 50-Hz update, the rf seeker conducts a new Doppler search centered at the previous designated target Doppler track frequency. The search covers 40 Doppler bins of a nominal bin bandwidth of 50 Hz. During periods of high dynamics, such as near the intercept, it is possible for the target Doppler to shift more than the width of the Doppler search. In this case, the width of each cell is doubled and a new search conducted. The assumption is made that the Doppler search time is negligible. The Doppler search is illustrated in Figs. 3 and 4. The Doppler shift of each of the targets is computed, and the targets are sorted into the appropriate Doppler bins. The signals in each bin are summed, and the bin with the greatest rms power is then selected as the designated cell. For the particular guidance update, all Doppler discrimination is done relative to the center frequency of the cell designated as containing the target. At handover, the designated Doppler cell is centered perfectly on the target Doppler frequency. This implies that the ship system has resolved the primary target and uplinked a perfect Doppler frequency prediction.

Only the signals in the designated cell pass through the Doppler discrimination to be used by the monopulse angle tracking signal processing. These sum channel and difference channel returns from all of the targets returns in the designated cell are combined by phasor arithmetic. Then the measured off-boresight angle ϵ_m, at which the seeker measures the perceived target to be, is given by the real component of the ratio of the weighted difference channel signal to the sum channel signal. This equation is given by

$$\epsilon_m = Re\left(\sum_{i=1}^{n} \epsilon_i a_i e^{j\phi_i} \bigg/ \sum_{i=1}^{n} a_i e^{j\phi_i}\right)$$

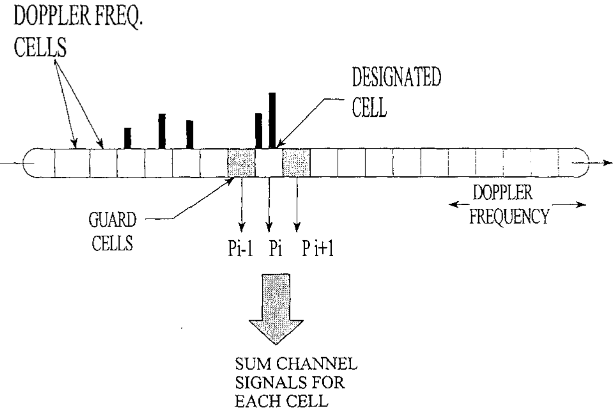

Fig. 3 Doppler discrimination.

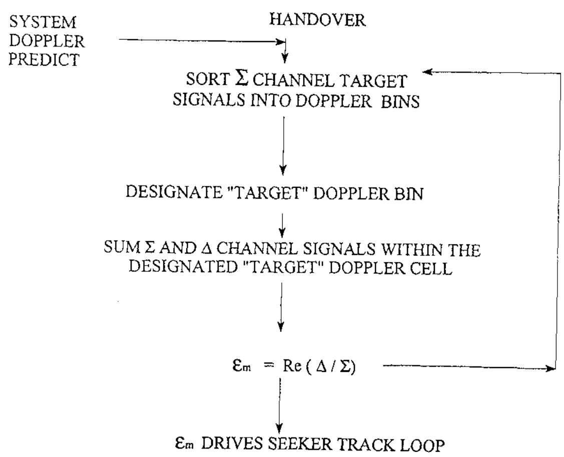

Fig. 4 Monopulse angle tracking with Doppler search.

Because of interference effects of the multiple returns, the sum channel signal can become small. This results in large errors in the measured boresight angle producing extremely erratic behavior that can not be tolerated in a practical system and that is difficult to simulate accurately. To counter the large angular errors during periods of sum channel fading, angle editing schemes are typically employed. In this study, the estimate of the seeker boresight error is set to zero when the sum channel signal drops below a specified threshold in a technique known as seeker track loop coasting. Zeroing of the measured boresight errors has the effect of zeroing the commanded seeker track loop head rates. The acceleration commands are eventually affected through the filtering of the measured head rates. The selection of the threshold is based on the angular error induced as a function of the reduction in the sum channel signal. The errors tend to remain relatively small as the sum channel signal is reduced until a breakpoint is reached, at which the errors in the measured boresight angle rapidly diverge as the sum channel is reduced beyond this point. The value of the sum channel fading at which the breakpoint occurs is a function of the target separation and intercept geometry. The threshold for coasting the track loop is set to cover the expected variations in the breakpoint. Should the sum channel exhibit a fading of −14 dB relative to the estimated peak signal, the coasting is activated until the signal is recovered.

Results

Stacked Attack

The first scenario considered is the head-on intercept against a stacked attack. The resultant image of the two targets will oscillate along the vertical line that connects them, defined as the scintillation axis. For this scenario, the missile is flying horizontally and is at the same altitude as the lower target. Figure 5 shows the miss distance relative to the primary target as function of the variation in the target altitude separation for a perfect handover with no heading or seeker pointing error. In this case the missile seeker is looking normal to the scintillation axis of the raid. Thus, there is a large amount of angular glinting between the targets. Even though the seeker is perfectly aimed, the secondary target is within the beamwidth of the missile and immediately drives the seeker off the line of sight to the primary target for altitude separations less than 1400 ft. For target raid separations greater than 1400 ft, the targets are resolved in Doppler at the 8.5-n mile missile-to-target range at handover. Thus, the signals from the second target do not corrupt the tracking of the primary target. Since the handover is perfect, the trajectory is benign and the Doppler track of the primary target is never lost. For separations slightly less than 1400 ft, Doppler resolution along the original trajectory would occur shortly after handover; however, the tracking corruption from the second target is sufficient to disrupt the homing. Once the homing is corrupted, the response of the missile through the proportional navigation to the bad tracks destroys the guarantee of Doppler resolution of the primary target at some point along the original path. This arises from the contribution of the interceptor's own velocity on the Doppler shift of the target signals.

The erratic guidance commands can modify the relative geometry to cause the two target Doppler frequencies to join in the same resolution cell after the initial resolution. For such situations, the

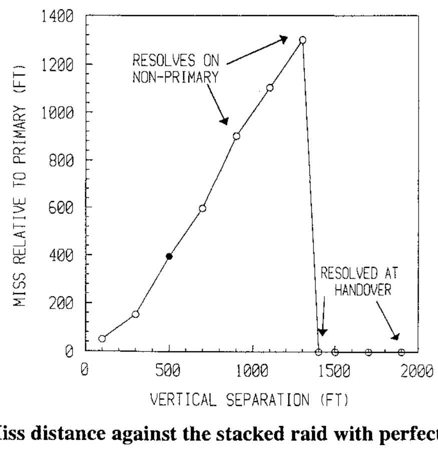

Fig. 5 Miss distance against the stacked raid with perfect handover.

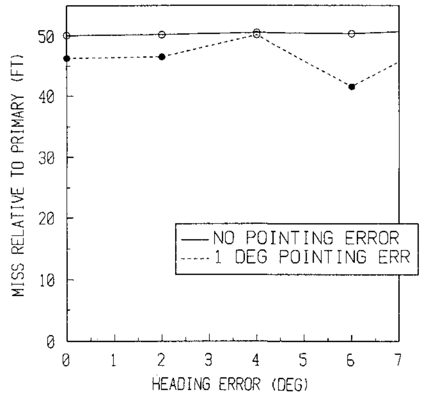

Fig. 6 Effect of handover errors on miss for 100-ft stacked raid.

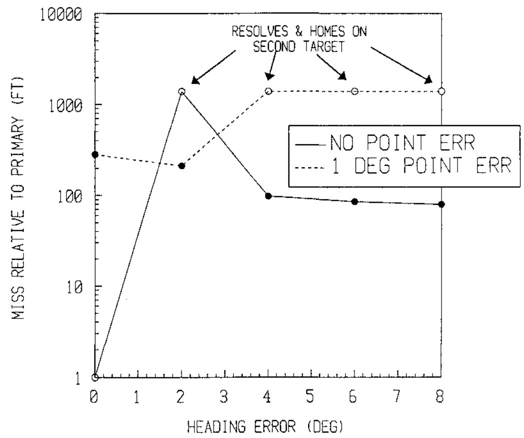

Fig. 7 Effect of handover errors on miss for 1400-ft stacked raid.

association problem must be dealt with repeatedly when the tracks diverge out of the Doppler cell, just as for the initial resolution. The possibility of the incorrect solution to this problem exists, and the missile may begin to track the second target.

For separations of 1000 ft and greater, the interceptor consistently resolved on the second target. Between 400 and 800 ft, the interceptor homes on the primary target, but miss distance is induced by the heading errors caused by the multiple targets. For intercept less than 400 ft, practical resolution never occurs, and the interceptor tends to fly between the two targets.

In the results presented here, should the interceptor trajectory pass through the surface it is continued with extrapolated atmospheric properties. The dark symbols represent such trajectories in the figures that follow. The purpose of this approach is to maintain the curve shapes and to preserve the maximum amount of information that would be lost if those intercepts were simply listed as splashed.

This same scenario is now considered including the effect of handover errors. These include heading error of the missile and seeker pointing error. Figure 6 shows the effect of varying the heading error for 0- and 1-deg seeker pointing errors for the 100-ft target separation. Intercepts against this target separation do not achieve Doppler separation until just before intercept. For such largely unresolvable intercepts, the miss distance is not a function of the heading error. A small heading error does not imply good miss distance performance. There is no clear benefit to controlling the pointing error. Thus, reducing the heading error and seeker error does not have much effect on the miss distance against the unresolvable multitarget raid.

The effects of handover accuracies on the stacked raid that is just resolved at handover (1400-ft vertical separation) are now considered. Figure 7 shows the miss resulting for various heading errors for seeker pointing errors of 0 and 1 deg. For the perfect handover, the miss is practically zero, so that the existence of heading and seeker pointing errors does reduce performance for this case. The heading error reduces the Doppler separation of the two targets and prevents resolution at handover leading to corrupted terminal guidance. The seeker pointing error does not disrupt the initial Doppler

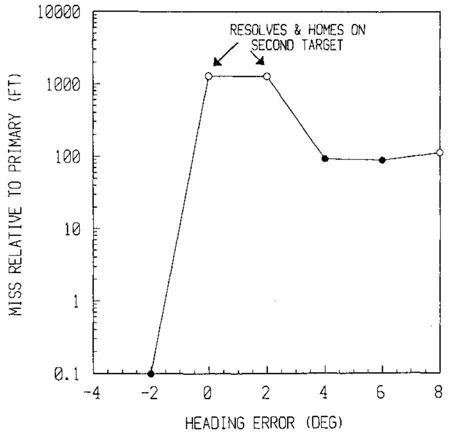

Fig. 8 Effect of heading error on miss for 1300-ft stacked raid.

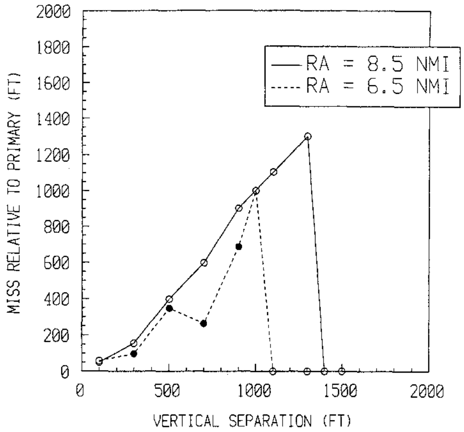

Fig. 9 Effect of handover missile-to-target range (RA) on stacked raid miss.

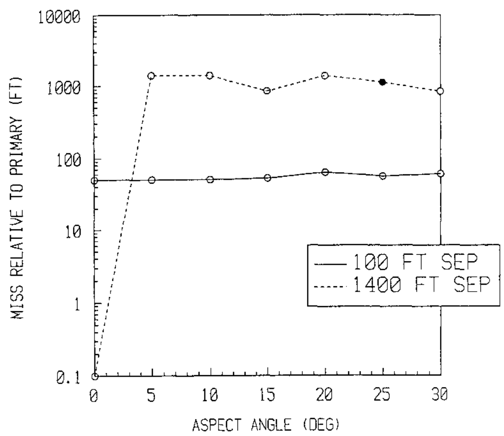

Fig. 10 Effect of handover aspect angle for stacked raids.

resolution but does lead to an initial trajectory perturbation as the seeker attempts to null the initial boresight error. This disruption of the trajectory may also lead to the loss of the resolution between the two targets. In fact, the 1-deg seeker pointing error for the 4- and 8-deg heading errors causes trajectories where the missile homes on the second target for the last portion of the flight, leading to large miss distances. For these geometries where the raid is on the edge of resolution, the handover accuracies of less than a degree for both heading and seeker pointing errors seems beneficial.

To further illustrate the effects of handover geometry on the resolution, the 1300-ft intercept is also investigated. For the perfect handover, this separation produced intercepts where the interceptor resolved on the nonprimary target at some point after handover producing a large miss relative to the primary target. The initial Doppler frequency separation of the targets is a function of the heading errors. Large heading errors increase the separation with heading errors that bias the trajectory away from the raid providing the greatest separation. This effect is reflected in Fig. 8, which shows the negative heading errors giving good resolution and homing performance. The negative heading errors are those which pull the interceptor velocity down relative to the perfect bearing. Thus, the result suggests that one possible countermeasure to the stacked raid is the use of midcourse trajectory shaping to purposely bias the heading error at handover downward. The use of a downward heading angle at handover against low-altitude raids requires the use of a diving trajectory to provide altitude above the surface for the resulting interceptor maneuver. For high-altitude engagements this is not a concern, and the interceptor heading error should be biased away from the raid to maximize initial Doppler frequency separation. If the designated target is the upper target, then the handover heading error should be biased upward away from the raid. In the case of the upward bias, then the requirement for the diving angle is removed.

For altitude separations greater than 2000 ft, the Doppler separation is great enough that the heading and seeker pointing errors considered in this study do not disrupt the homing process. Thus, the benefit of controlling the handover errors seems to be useful only over a small transition region for raid spacings that produce Doppler resolution ranges that are near the handover missile-to-target range. Reducing the handover missile-to-target range to significantly less than the range for resolution will eliminate the requirement for an accurate handover to maintain resolution but must be balanced against the subsequent increased handover accuracy requirement associated with shorter homing times.

Next, the benefits of controlling the missile-to-target range at handover to terminal guidance is considered. The assumption in this analysis is that an algorithm is available to control the initiation of terminal guidance and that the missile acquires the raid immediately and can begin homing. Before this time, the missile may be flying midcourse guidance or some type of trajectory hold in the vertical plane. The miss distance for the perfect handover for two handover missile-to-target range-to-go values as a function of the separation of the stacked attack is shown in Fig. 9. For the 8.5-n mile handover range, the interference effects on the guidance modifies the trajectory sufficiently to disrupt the association process and may allow the interceptor to select the nonprimary target as the designated target. The shorter range of 6.5 n mile is the minimum distance for this problem that provides the requisite 10 time constants of homing. For the tightly spaced raids, the handover range has little effect on the miss distance. The reduced handover missile-to-target range allows immediate resolution for raid separations as low as 1100 ft.

Reducing the missile time constant and subsequently allowing shorter homing times may be a good choice in that this will allow more tightly packed raids to be resolved at handover. The use of the shorter time constant does not increase the miss against the tightly spaced stacked raids with separations less than 200 ft.

The effects of the handover aspect angle as defined in Fig. 1 on the stacked attack are now considered. For the stacked attack, the missile velocity is nearly normal to the raid scintillation axis. Thus, one would not expect large changes in performance with small variations in the handover aspect angle. When using a semiactive rf seeker, only small changes in the aspect (or approach) angle off of the horizontal are possible due to the need to counter multipath effects. Both 100- and 1400-ft separations are considered.

The results shown in Fig. 10 bear out these observations for the 100-ft separation raid. The miss for this raid is a weak nonmonotonic function of aspect angle. Thus, for this raid control of the handover aspect angle through midcourse trajectory shaping is of little use. For the 1400-ft raid, which is just resolved for the nominal horizontal flight with a perfect handover, the nonzero aspect angle increases the miss distance by denying the resolution of the raid at handover. Thus, there is some benefit to controlling the aspect angle against stacked raids on the edge of resolution. When combined with the downward biased heading error, the miss for positive aspect angles is near zero. Providing a dive angle and thus a positive aspect angle for the biased heading error trajectory does not cause large miss distance as is indicated for the perfect handover results. For separations far greater than that required for resolution, the aspect angle has no significant effect.

Stream Attack

The stream attack is now considered. Here the two targets fly at the same altitude with the first target leading the second target. Unlike the stacked raid, for this case the main axis of scintillation is parallel to the line of sight between the raid and the missile. Thus, the angular extent of the raid from the perspective of the missile is much less than the first scenario. For modeling simplicity, the targets are not opaque and signals from the secondary target may pass through the first to reach the missile seeker. For antiparallel intercepts with the missile flying horizontally with a perfect handover, the stream raid does not affect the intercept, and the miss is near zero for all horizontal raid separations.

In the stream raid, the Doppler frequencies of the two targets are extremely close. This arises from the fact that a collision heading for the missile against the primary and lead target requires a lead angle. Because of the lead angle, the line of sight to the second target is shallower than it is to the first target. This reduces the projected missile speed onto the second target line of sight relative to the first target. The projection of the target speeds onto the respective lines of sight has the opposite trend. For missile and targets that have nearly equal speeds, the Doppler separations are very small. It should be noted that this lead angle is set up with the handover conditions or by proportional navigation guidance, which eventually turns the missile onto this course during a successful intercept.

The effects of handover errors are now considered for the antiparallel intercept against the stream attack. In Fig. 11, the miss distance for the 100-ft-spaced raid is shown as a function of the heading error and seeker pointing error at handover. The miss is a monotonic function of the heading error. In this case, heading error brings the interceptor trajectory out of parallel with the raid scintillation axis. This will increase the miss distance, and as the heading error grows beyond 2 deg, miss increases. The trend is not clear cut for the seeker pointing error. For raids with larger horizontal separations, the effects on the miss increase.

The effects of varying the handover aspect angle, as defined in Fig. 1, on the stream raid are now considered. For positive values of the handover aspect angle, the missile is diving on the stream raid. Because of this geometry, the axis of target scintillation is readily visible to the interceptor, and significant miss distances are to be expected even for perfect handovers.

The perfect handover results for two stream spacings as a function of the handover aspect angle are shown in Fig. 12. As the aspect angle increases and the missile follows steeper dives onto the stream raid, the miss increases. For the larger handover aspect angles, the sensitivity to aspect angle declines as the angular discrimination of the monopulse becomes more effective, due to the increased angular separation apparent to the missile. The decline is more significant with the larger raid separation.

Clearly from these results, the miss is a strong function of the handover aspect angle. This indicates that it is best to attack parallel

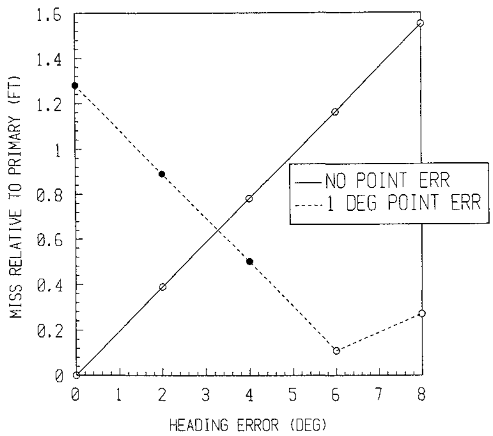

Fig. 11 Effect of handover errors on miss for 100-ft stream raid.

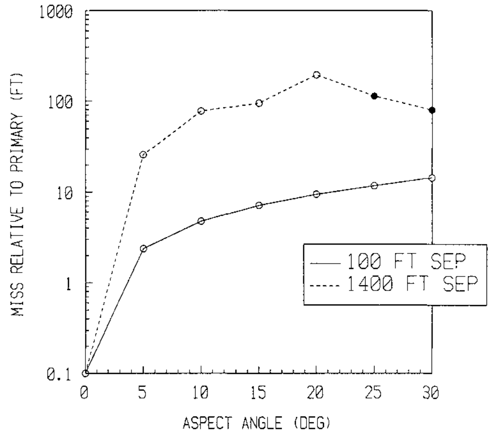

Fig. 12 Effect of handover aspect angle on two stream raids.

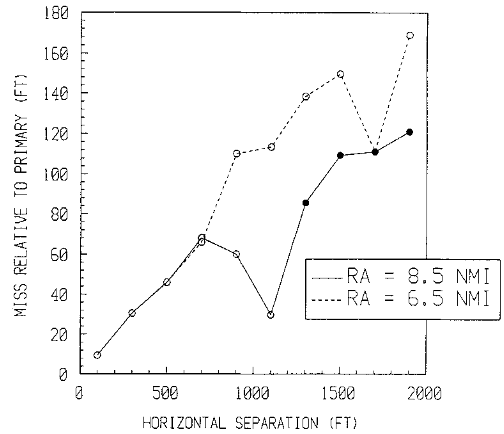

Fig. 13 Effect of handover missile-to-target range (RA) on stream raid miss.

to the scintillation axis of the raid. The orientation of the scintillation axis may be known since it is assumed that the ship sensor has resolved the raid. An implication of this concept for crossing targets is that azimuthal shaping to bring the interceptor handover velocity antiparallel to the raid axis may significantly improve terminal performance.

The effect of the selected missile-to-target range to go against the stream raid is now considered. The miss distance with perfect handover for two handover ranges is shown as a function of the stream separation in Fig. 13. For the stream raid, the use of shorter homing times seems to be of little benefit.

Conclusions

Terminal homing performance against multitarget raids was investigated. The miss was largely determined by 1) the raid geometry and type, 2) the target spacing in the formation, and 3) the interceptor aspect or approach angle relative to the raid scintillation axis. For the stacked attack, miss distances were large until the target separation exceeded 1000 ft. For the stream raid, the miss was large for all separations except for very shallow handover aspect angles. For the stacked raid, the handover aspect angle was important only for the band of target separations, which is somewhat dependent on the handover range to go.

For the band of stacked raid target separations between the values of about 400 and 2000 ft, some additional parameters are important. This range represents the region between the definitely resolvable and the practically unresolvable separations. For this range of separations the handover range to go and the heading error did effect the resolution capability leading to effects on the miss. The introduction of heading error against the stacked raid in this band increases the Doppler separation. If the heading error relative to the designated target is away from the raid, then resolution throughout the homing is enhanced. If the heading error relative to the designated target is toward the other target, then the missile has an increased likelihood of later resolving and homing on the incorrect target. Shortening the handover range to go to the minimal acceptable value has a relatively minor effect in that it decreases the stacked raid separation that is resolved at handover and that is then successfully maintained during the homing. For the larger raid separations in this band, there is a possible midcourse shaping counter that improves the miss. If the lower target is the designated target, then careful control of the heading error so that it is biased downward and the use of the shortest possible handover range can increase the set of target separations that can be successfully engaged. There seems to a benefit to increased accuracy of the handover though improved ship senors in this band so as to be able to control the heading error. But outside this band of raid separations, there is no counter and no benefit to a high-accuracy handover.

For the stream raid, a significant counter exists. Unlike the stacked raid, the large target separations do not allow separation at handover. Increased raid separations continued to degrade the missile track accuracy and the final miss distance. The effect of the stream raid can be nulled largely though the application of midcourse trajectory shaping to bring the missile in nearly antiparallel to the raid scintillation or velocity axis. The range of acceptable dive angles is compatible with the values normally associated with multipath mitigation trajectories for semiactive missiles. By extension for crossing stream raids, the missile should approach along the raid scintillation axis, which implies the need for horizontal plane trajectory shaping as well as vertical plane shaping. For a raid with three-dimensional spacing, it may not be possible to define a scintillation axis. For this situation, trajectory shaping may not be of use.

The missile has little potential to discriminate the multitarget raid. The broad beamwidth of its rf seeker antenna prevents effective angular discrimination until the very end. Thus, the multitarget raid drives the monopulse track loop erratically, and the resulting missile motion changes the Doppler shifts and the engagement geometry, which makes solution of the association problem unreliable. To successfully solve the association in a robust manner, an additional source of information must be provided throughout the homing phase. Examples include precise Doppler or relative Doppler of the targets from an advanced ship sensor suite, additional fine angular position data from a missile-borne IR sensor, and additional position or rate data from an advanced sensor suite on the ship. Since hit-to-kill missiles must reliably solve the association and discrimination problem to completely remove any decoy or secondary target effects, these systems are driven to application of multiple sensor suites on the missile or on the ship system to provide an additional source of information that the missile is capable of measuring and comparing to the uplinked value.

Acknowledgments

Several colleagues at the Naval Surface Warfare Center provided invaluable assistance. Ernest Ohlmeyer provided a great deal of insightful commentary and originally developed the terminal homing simulation that was combined with the signal processing model. Bernard Finn and Timothy Carsola provided an invaluable perspective. June Drake developed several of the rf signal simulations. Craig Martell conducted some of the initial numerical analysis.

References

[1]Adler, P., "Missile Guidance by Three-Dimensional Proportional Navigation," *Journal of Applied Physics*, Vol. 27, No. 5, 1956, pp. 500–507.

[2]Nesline, F. W., and Zarchan, P., "A New Look at Classical vs Modern Homing Missile Guidance," *Journal of Guidance, Control, and Dynamics*, Vol. 4, No. 1, 1981, pp. 78–85.

[3]Nesline, F. W., and Zarchan, P., "Miss Distance Dynamics in Homing Missiles," AIAA Paper 84-1844, Aug. 1984.

[4]Chadwick, W. R., "Miss Distance of Proportional Navigation Missile with Varying Velocity," *Journal of Guidance, Control, and Dynamics*, Vol. 8, No. 5, 1985, pp. 662–666.

[5]Murtaugh, S. A., and Criel, H. E., "Fundamentals of Proportional Guidance," *IEEE Spectrum*, Dec. 1966, pp. 75–85.

[6]Miwa, S., Imado, F., and Kuroda, T., "Clutter Effect on the Miss Distance of a Radar Homing Missile," *Journal of Guidance, Control, and Dynamics*, Vol. 11, No. 4, 1988, pp. 336–342.

[7]Nesline, F. W., "Missile Guidance for Low Altitude Air Defense," *Journal of Guidance, Control, and Dynamics*, Vol. 6, No. 3, 1983, pp. 207–212.

[8]Zarchan, P., "When Bad Things Happen to Good Missiles," AIAA Paper 93-3781, Aug. 1993.