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Ballistic Missile Defense Guidance and Control Issues

Paul Zarchan[a]

Ballistic targets can be more difficult to hit than aircraft targets. If the intercept takes place out of the atmosphere and if no maneuvering is taking place, the ballistic target motion can be fairly predictable since the only force acting on the target is that of gravity. In all cases an exoatmospheric interceptor will need fuel to maneuver in order to hit the target. The long engagement times will require guidance and control strategies which conserve fuel and minimize the acceleration levels for a successful intercept. If the intercept takes place within the atmosphere, the ballistic target is not as predictable because asymmetries within the target structure may cause it to spiral. In addition, the targets' high speed means that very large decelerations will take place and appear as a maneuver to the pursuing endoatmospheric interceptor. In this case advanced guidance and control strategies are required to insure that the target can be hit even when the missile is out maneuvered. This tutorial will attempt to highlight the major guidance and control challenges facing ballistic missile defense.

PREDICTING WHERE THE TARGET WILL BE

Before an interceptor can be launched at a ballistic target, a sensor is first required to track the threat. For example, if the sensor is a ground radar, the range and angle from the radar to the target are measured. From these raw measurements the position and velocity (and in some applications acceleration) of the target can be estimated.

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[a] The Charles Stark Draper Laboratory, Inc.
Mailstop 84
555 Technology Square
Cambridge, MA 02139

The quality of the estimates depend on the measurement accuracy of the radar and how often data are received. From an estimation point of view, higher data rates are better, but with higher data rates the radar will be able to track fewer potential targets at the same time.

Based on the filter estimates, a prediction of where the target will be in the future must be made (i.e., the estimated intercept point is approximately the estimated target position plus the estimated target velocity, times the time to go until intercept). The accuracy of the prediction depends not only on the quality of the filter estimates but also on our knowledge of what the target will do in the future. This future target location is known as the predicted intercept point. If the predicted intercept point were known perfectly, a fire control solution could be achieved so that a missile could simply be launched at the correct angle and right time to also arrive at the predicted intercept point. For this simplified case a missile guidance system would not be required since there would be no errors to take out.

For non-maneuvering exoatmospheric targets prediction is easier since gravitational effects are well known. In this case the predicted intercept point can be extrapolated forward from position and velocity estimates plus knowledge of Newton's law of universal gravitation. Longer engagement times will have larger intercept point prediction errors. However, there will also be more time available to take out the errors.

It is impossible to know precisely where the target will be in the future. For example, an aircraft target may not be maneuvering when it is being tracked by the radar, but may maneuver or change course a few seconds later. In this case the predicted intercept point would be in considerable error and the missile would have been launched in the wrong direction. For missiles which perform intercepts in the atmosphere, it may be desirable to launch the missile in the "wrong" direction (i.e., not at the expected intercept point) to reduce drag or to prevent hitting structures (i.e., in the case of a ship launched missile). Certain types of missiles are initially launched in this way but then soon enter a phase of flight in which they are commanded to pitch over in order to fly towards the expected intercept point. In practice, guidance updates can also be sent to the interceptor during the flight as our knowledge of the predicted intercept point continues to improve.

Although in our example the ground radar is used to track the target and help generate the information necessary to determine when and at what angle to launch the missile, homing missiles must eventually see the targets for themselves. The eyes of the missile are known as the seeker. For homing missiles, guidance commands are based on seeker information. Some short range missiles have seekers which can acquire and see the target throughout the entire flight, whereas longer range missiles may have to guide on information from the ground based radar until the seeker is close enough to the target to make acquisition possible. Some missiles have a wide enough seeker beam in which it makes sense to have a search phase for the seeker to acquire the target. Other missiles have a very narrow seeker beam and are expected to acquire the target as soon as the seeker is turned on. Therefore another complicating factor is the requirement that missiles be flown in such a way that it makes seeker acquisition easier.

Long-range endoatmospheric missiles use thrust to build up speed only for a fraction of the flight. After the fuel is expended the missile must glide to the target. Control surfaces are moved to generate the lift or acceleration so that the missile can respond to acceleration commands in order to intercept the target. For endoatmospheric missiles the amount of available acceleration depends on the missile speed and altitude of engagement. Higher speeds and lower engagement altitudes work in the direction of increasing the missile acceleration capability. Therefore, for endoatmospheric interceptors, trajectories may have to be flown to maximize the missile velocity so that there is sufficient acceleration left to intercept the target. Heating considerations will place an upper limit on the maximum achievable speeds at the lower engagement altitudes.

Once the seeker can see or has acquired the target, the major issues determining a successful intercept will be the time remaining until intercept, the amount of acceleration available, and the errors which must be taken out (i.e., intercept point prediction error accumulated before seeker acquisition). In general, maximizing the homing time is considered to be beneficial for a variety of reasons. Technologies which increase the seeker acquisition range will also increase the the homing time.

A major error source in influencing interceptor performance is target maneuver. An aircraft target may maneuver to avoid interception while a ballistic target may unintentionally maneuver due to asymmetries in the fins or the natural slowdown of a high speed object reentering the atmosphere. The natural slowdown of the ballistic target may appear as a maneuver to the interceptor. Another error source is known as the heading error or the intercept point prediction error. As the name implies, this error source is due to the fact that the missile had been flying in the wrong direction until the missile seeker acquired the target. Another error source is noise contaminating the seeker measurements. Some of the potential noise is related to the seeker design while other noise is a property of the target. For example, targets with low radar cross sections will result in more seeker noise and thus make interception more difficult. Low radar cross sections are encountered with stealthy aircraft targets and physically small pieces of a ballistic target. At times, even a large tumbling target can appear to have a small radar cross section.

Guidance and Control

Most homing missiles use a form of proportional navigation once the seeker has acquired the target. This simple but effective guidance law has been in use for more than four decades on most of the worlds operational homing missiles. With proportional navigation, acceleration commands are issued which are proportional to the line-of-sight rate between the missile and target (i.e. the line-of sight angle λ is the angle between an imaginary line connecting the

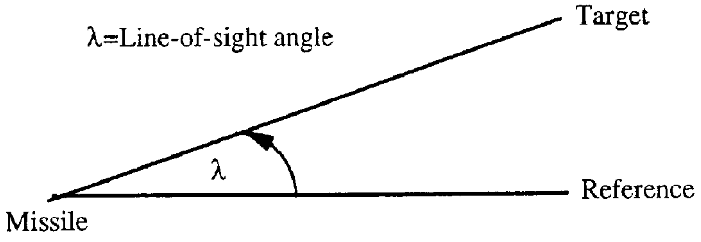

Figure 1:A missile can intercept a target based on line-of-sight rate information.

missile and target and a fixed reference as shown in Figure 1. A more complete discussion of proportional navigation and its effectiveness can be found in Chapter 2 of Reference 1. Guidance is different than navigation in the sense that absolute information concerning the present or future location of the target is not required for interception. One can almost say that if you know where you are and where you want to go, navigation would be the method for getting there. However, if you didn't know where you were or where you wanted to go, guidance would the method of getting you there.

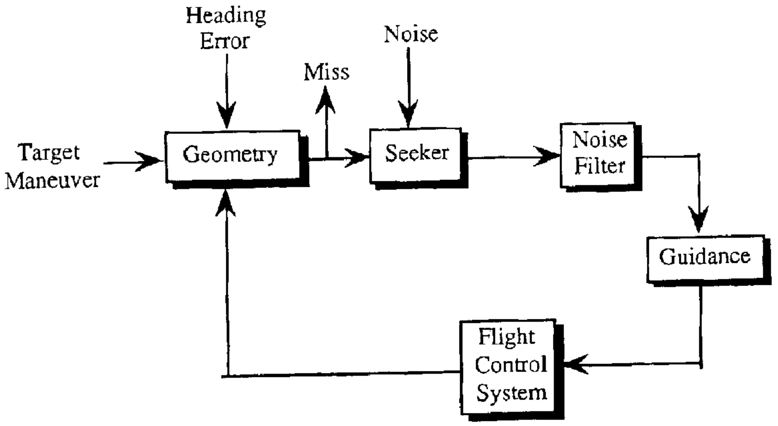

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Figure 2:A missile guidance system can be shown in the form of a control loop.

A block diagram of a typical missile guidance system is shown in Figure 2. This type of block diagram is sometimes known as a homing loop to control engineers because it is drawn in the form of a feedback control system. In the Geometry section of the diagram, missile acceleration is subtracted from target acceleration to form a relative acceleration. Two integrations will provide distance, and the relative separation between the missile and target at the end of the flight is known as the miss distance. Although the missile designer would like there to be zero miss distance, other factors may cause a miss distance. In conventional missile systems a warhead is used to kill the target because it is believed that there will always be a miss distance. In newer systems being proposed such as THAAD (i.e., hit-to-kill missiles) the warhead has been eliminated to reduce weight and cost and body to body contact is required for a kill.

The missile seeker attempts to track the target. Effectively the seeker measures the geometric line-of-sight angle, and an error signal within the seeker electronics provides a noisy estimate of the line-of-sight rate. A noise filter must smooth the noisy seeker signal in order to provide an estimate of the line-of-sight rate. A guidance command is generated, based on the proportional navigation guidance law, from the noise filter output. The flight control system must enable the missile to maneuver in such a way that the achieved acceleration matches the acceleration commands from the guidance law. Endoatmospheric missiles move control surfaces to get acceleration while exoatmospheric interceptors use divert engines to get the appropriate acceleration.

If we neglect the dynamics of the seeker, noise filter and flight control system, we have a perfect or zero-lag guidance system. In this type of system proportional navigation is so effective that there will be no miss distance due to any of the error sources provided the missile has sufficient acceleration capability. Figure 3 presents a normalized plot of how much acceleration is required to ensure zero miss distance against either target maneuver or heading error. The formulas upon which Figure 3 is based are also derived in Chapter 2 of Reference 1. In the notation of the figure n_c is the missile acceleration command in units of g, t_F is the flight time or the amount of time from seeker acquisition until intercept in units of seconds, V_M is the missile velocity in units of feet/second, HE is the heading error in units of degrees, t is time in units of seconds and n_T is the target maneuver acceleration level in units of g. We see from Figure 3 that the maximum acceleration required to take out heading error will occur at the beginning (i.e., at seeker acquisition) while the maximum acceleration to take out target maneuver will occur near intercept.

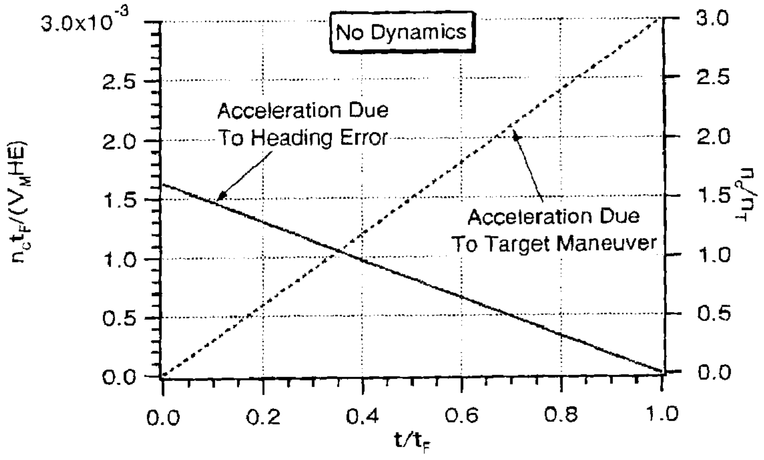

Figure 3: The maximum missile acceleration due to heading error occurs at the beginning of flight while the maximum acceleration due to target maneuver occurs at the end of the flight.

In order to illustrate the use of the normalized figure above, consider the case where the missile speed is 3000 ft/s, there is 10 deg of heading error and 10 s of time remains from seeker acquisition to intercept. In this example in order to find the acceleration required to take out the heading error in order to achieve zero miss distance we read $1.6*10^{-3}$ or 0.0016 from the left hand ordinate of Figure 3 at a normalized time of zero or

$$\frac{n_c t_F}{V_M HE} = 0.0016 \qquad (1)$$

Therefore the required acceleration at the beginning of the flight can be found by inverting the preceding expression:

$$n_c = \frac{0.0016 V_M HE}{t_F} = \frac{0.0016 \quad 3000 \quad 10}{10} = 4.8g \qquad (2)$$

If a higher frequency seeker was used with reduced acquisition range, then the effective homing time would be reduced and the required acceleration would increase. For example, if a higher frequency low noise seeker was used which yielded an effective homing time of 2 s (down from 10 s) then the required acceleration would increase by a factor of 5 to 24 g. For an endoatmospheric missile, a 24 g requirement might not present a problem at low altitudes but it might not be possible at the higher altitudes. Divert engine technology might not permit this amount of acceleration for an exoatmospheric interceptor. Therefore, the allowable heading error or intercept point prediction error will be much less for an exoatmospheric intercept. This means that predicting where the target will be in the future is much more important for exoatmospheric engagements than it is for endoatmospheric engagements.

We also see from Figure 3 that the missile needs three times the acceleration capability of the target in order to be effective no matter what type of seeker is used. A 6 g target maneuver requires a missile with at least an 18 g capability in order to ensure a hit. Usually a 3 to 1 acceleration advantage over the target does not present a problem for the endoatmospheric interceptor when the target is an aircraft since the missile is usually traveling at a much faster speed and does not have the physiological constraints of the pilot to consider. However, if the target is a ballistic missile the speed advantage of the pursuer vanishes and there may be huge decelerations (which appear as maneuvers) to contend with. Since it is usually not anticipated that exoatmospheric targets will employ large maneuvers, the interceptor acceleration requirements for exoatmospheric targets are usually much smaller than for endoatmospheric targets.

The preceding discussion assumed there were no dynamics within the guidance system. In reality, guidance commands can not be implemented instantaneously and there will be lags or dynamics within the guidance system. For simplicity, we will associate a time constant with the guidance dynamics.

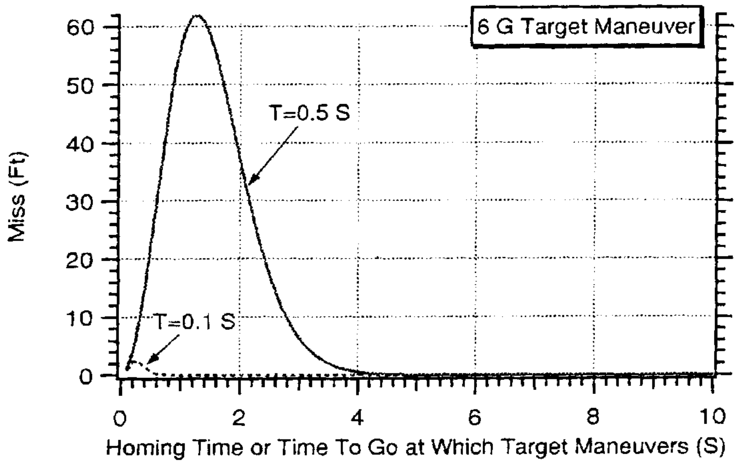

Figure 4: A target maneuvering right before intercept can induce a large miss distance if the guidance system time constant is large.

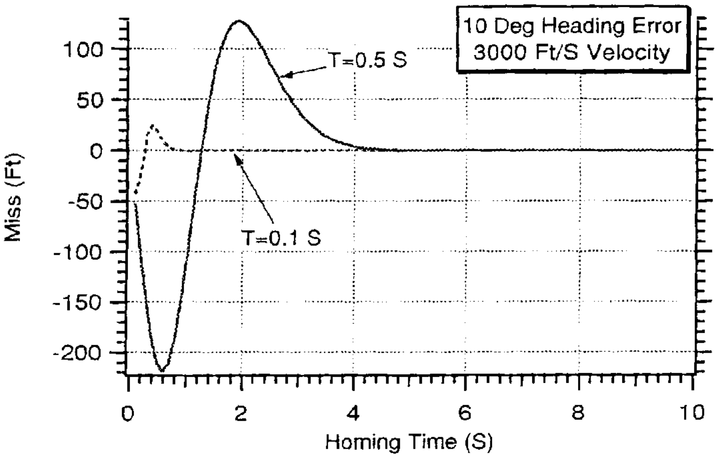

Figure 5: Long seeker acquisition ranges will help reduce the miss due to heading error.

In other words, if the flight control system had a time constant of 0.5 s (i.e., this is based on the exponential solution to a differential equation and is more fully discussed in Chapter 3 of Reference 1), it would mean that if a 10 g acceleration command were issued it would take 0.5 s for the output acceleration to reach 6.3 g, 1 s for the output acceleration to reach 8.6 g and 1.5 s for the output acceleration to reach 9.5 g. In practice the guidance system dynamics can be quite significant. In endoatmospheric missiles the dominant portion of the total system time constant is usually associated with the flight control system, while in exoatmospheric missiles the dominant time constant is usually associated with noise filtering.

Figures 4 and 5 show that guidance system dynamics can have a profound influence on the miss distance. From these figures we see that if there is sufficient homing and there is sufficient missile acceleration there will not be any miss distance. This is the main reason that seekers with longer acquisition ranges are beneficial. Usually the rule of thumb is to ensure that the ratio of the homing time to the effective guidance system time constant is greater than 10. If the ratio is less than 10 there can be considerable miss distance. The abscissa in Figure 4 can either be interpreted as the homing time or the time to go before intercept at which the target maneuvers. We can see that if the guidance system time constant is 0.5 s the miss distance due to a 6 g target maneuver can be quite large and if the time constant can be reduced to 0.1 s the miss distance can be made near zero. Similar results can be seen in Figure 5 where the error disturbance is a 10 degree heading error. Therefore, we can conclude that a system with a small guidance system time constant has the potential for having very small miss distances. However, we shall see later that there are technology issues associated with how small the guidance system time constant can be made.

It might appear from Figures 4 and 5 that if the flight time was very large (i.e., long seeker acquisition range) that there would never be any miss distance. Figure 6 presents the normalized miss distance due to semiactive homing noise as a function of the normalized homing time. We can see that even if the seeker had an infinite acquisition range there would always be a finite miss due to this error source. We see from the ordinate that if a better seeker were used the noise spectral density Φ_{RN} would be reduced with the result that the standard deviation of the miss distance would decrease. We also see that as with target maneuver and heading error, reducing the guidance system time constant has similar beneficial effects. The missile closing velocity V_c is approximately the sum of the missile and target velocities for head-on engagements. We can see that if the closing velocity is doubled, the miss distance will quadruple. In other words, all other things being equal, the semiactive noise miss distance will be greater against a high-speed ballistic target than it will be against a low-speed aircraft target. Therefore, it is very important to have a low noise seeker against a ballistic target.

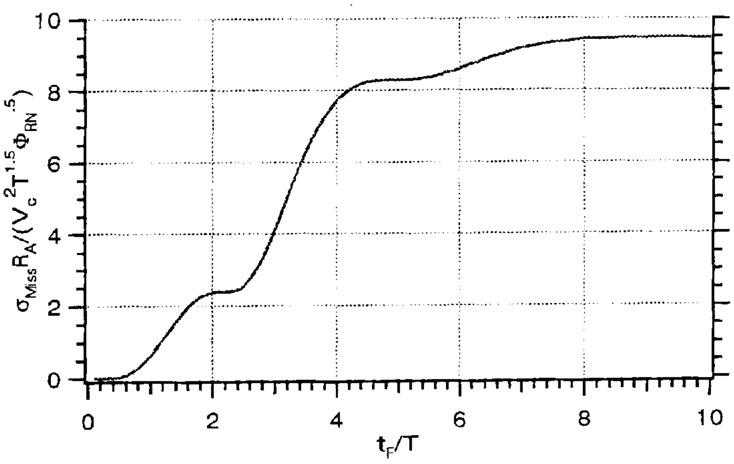

Figure 6: The miss due to semiactive receiver noise does not decrease with longer flight times.

Why Reducing the Time Constant Might Be Difficult

Thus far, from all of the results presented, it would appear that the guidance system designer has an easy job, since all the graphs indicate that smaller guidance time constants appear to improve system performance. In actual practice, parasitic or unwanted feedback paths within the homing loop will work in the direction of larger time constants to get acceptable performance. One of the most serious unwanted feedback paths is created in tactical radar homing missile applications by the missile radome. The radome causes a refraction or bending of the incoming radar wave, which in turn gives a false indication of the target location as is indicated in Figure 7. Figure 7a presents the case in which the missile is flying directly at the target. In this case the reflected energy (i.e., transmitter on ground in semiactive case or in missile for active case) passes straight through the radome directly to the seeker. Therefore, the seeker is looking directly at the target and there is no problem since the missile will continue to fly in the correct direction. Figure 7b shows a more interesting case in which the missile is pitched up. In this case the radar energy reflected from the real target is bent as it passes through the radome, giving the seeker the impression that the apparent target is below. Therefore acceleration commands are generated to point the missile in a downward direction to chase the apparent target as is shown in Figure 7c. Here we see that the bending of the reflected radar energy now causes the missile to pitch up in attempt to chase the apparent target. The resultant missile porpoising (going up and down) is actually an instability within the guidance system. The amplitude of the porpoising will depend on the guidance system time constant and the aerodynamic properties of the airframe. Missiles which are more responsive (i.e., smaller time constants) and pitch more for a given acceleration command (i.e., all aerodynamic missiles do this at high altitudes) will suffer more from the radome problem.

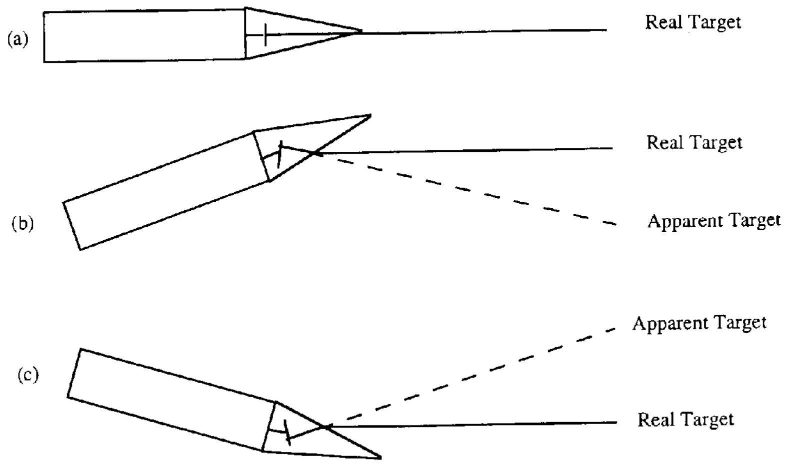

Figure 7: Radome problems can cause a stability problem within the guidance system.

A quantity known as the radome slope (see Chapter 6 of Reference 1 to see how radome slope is related to refraction angle) is used to quantify radomes and is used by the guidance system engineer in analyzing the radome stability problem. The radome slopes can either be positive or negative. If the magnitude of the radome slope is large more bending or refraction will take place and the stability problem will worsen. Therefore the guidance system designer would like to use small radome slopes. Seekers operating at higher frequencies or having larger apertures will tend to yield smaller radome slopes. Missile noses which have lower fineness ratios (smaller length to diameter) will also tend to reduce the radome slope. In theory, a hemispherical nose will yield zero radome slope but for endoatmospheric interceptors the drag penalty might be unacceptable. Many believe that only radar homing missiles suffer from the radome slope problem. However, infrared missiles suffer from a similar problem and this problem is usually solved by paying the drag penalty and using a hemispherical front end.

One method for dealing with the radome slope problem is to intentionally increase the guidance system time constant at higher altitudes. This will make the missile more sluggish and dampen the tendencies for the missile to porpoise. Of course, we have seen that increasing the guidance system time constant may increase the miss distance to other error sources to unacceptable levels. Another method is to artificially reduce the radome slope by the use of digital compensation tables in flight. The compensation tables are derived from extensive laboratory measurements on sample radomes. If the radome material used has electrical characteristics which are a function of temperature, this temperature dependency must be taken into account in the derivation of the compensation tables since intercepts will not take place at room temperature. Another possibility for alleviating the radome problem is to use advanced filtering techniques to estimate the radome slopes in flight and then compensate. Although the preceding discussion on radome pertains to radar homing missiles there are similar but less understood effects in other types of missiles as well.

For negative radome slopes it can be shown that the guidance system will only be stable if the minimum guidance system time constant T_{Min} is given by

$$T_{Min} = \frac{3.8 V_c R T_\alpha}{V_M} \tag{3}$$

where R is the radome slope, V_M is the missile velocity, V_c is the closing velocity, T_α an aerodynamic parameter known as the turning rate time constant measured in seconds (i.e., amount of time it takes missile to develop an angle of attack for a given acceleration level). We see from the preceding relationship that endoatmospheric engagements with larger closing velocities (i.e., involving ballistic targets) or those taking place at higher altitudes (i.e., larger turning rate time constant) will require a larger guidance system time constant in order to keep the guidance system stable for a given radome slope. Figure 8 plots the preceding equation in order to demonstrate another reason why ballistic targets are more challenging than aircraft threats. Consider the case in which the missile speed is 3000 ft/s, the target speed is 1000 ft/s and the turning rate time constant is 5 s. Suppose the radome technology was

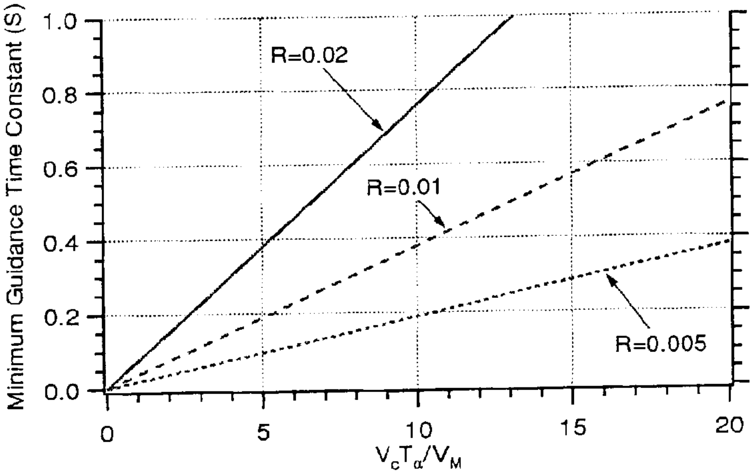

Figure 8: Minimum achieveable guidance time constant increases with increasing randome slope.

such that negative slopes of 0.005 could be achieved. Since the closing velocity is 4000 ft/s (3000+1000=4000) the normalized abscissa turns out to be 6.67 (4000*5/3000=6.67) and so we see that the smallest time constant which could be achieved would be 0.12 s. If everything remained the same but with the target traveling at 6000 ft/s (i.e. a ballistic target), the closing velocity would increase to 9000 ft/s (3000+6000=9000) and the normalized abscissa would be 15 (9000*5/3000=15) increasing the minimum guidance system time constant to approximately 0.3 s. Less advanced radome technologies would yield larger slopes and the minimum time constant to keep the guidance system stable would also increase. Therefore, pushing the limits of radome technology is

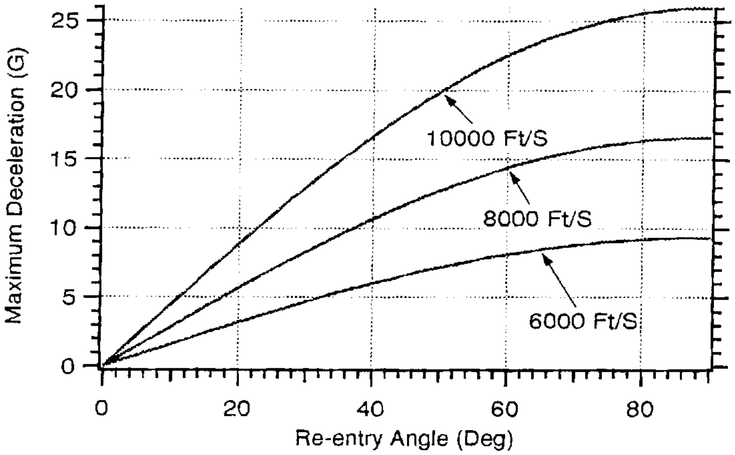

Figure 9: Ballistic targets experience high declarations.

critical for successfully achieving high altitude intercepts against ballistic targets within the atmosphere.

Why More Acceleration Capability is Better

A ballistic target will decelerate at it reenters the atmosphere. Depending on the engagement geometry, some or all of the deceleration could appear as a target maneuver to a pursuing interceptor. To first order, the deceleration experienced by the ballistic target is proportional to the square of its initial velocity and the sine of the reentry angle (see Chapter 17 of Reference 1).

Typical maximum deceleration levels are shown in Figure 9. We can see that a target whose initial speed is 6000 ft/s with an atmospheric reentering angle of 45 degrees will experience a maximum deceleration of 6 g. If the initial speed increases to 8000 ft/s the maximum deceleration would increase to 12 g. An initial speed of 10,000 ft/s would give rise to a maximum deceleration of 18 g.

If for practical reasons the minimum achievable time constant was 0.2 s, Figure 10 shows how the miss distance varies with flight time (or time to go at which the target maneuvers) for the case in which there is a 6 g target maneuver. We see that for the case of an interceptor with an infinite acceleration capability, the missile is vulnerable to miss distances in excess of 2 ft for flight times of less than 1 s (i.e., short seeker acquisition range) or for maneuvers which occur with less than 1 s to go before intercept. The miss can be as large as 10 ft if the maneuver occurs at approximately 0.5 s before intercept even if the seeker had an infinite acquisition range. If the missile has a 30 g acceleration capability (i.e. five times the maneuverability of the target) the results remain unchanged. However, if the missile has an 18 g acceleration capability (i.e., three times the maneuverability of the target) then the vulnerability of the missile can increase substantially.

Therefore, from Figure 10 we see that more acceleration capability is better (i.e., miss gets smaller as acceleration capability increases). For endoatmospheric missiles the maximum achievable angle of attack will determine how much of an acceleration capability the missile will have. For a given angle of attack the missile acceleration capability will decrease with increasing altitude. Against low-speed aircraft targets this phenomenon is not a problem since the aircraft maneuverability will also decrease with increasing altitude. However, against high-speed ballistic targets this presents a guidance system challenge since the target can easily out maneuver the missile for high altitude intercepts (i.e., see Figure 9). Decreasing the intercept altitude (i.e., where the ballistic target deceleration will be smaller) is often not possible for population safety reasons.

In more conventional endoatmospheric missiles, the maximum angle of attack is chosen to avoid cross-coupling problems within the flight control system. However since needed missile acceleration is proportional to the square of the angle of attack (i.e., see Chapter 22 of Reference 1) there is a big advantage in pushing the limits of flight control technology in order to get more maneuverable interceptors.

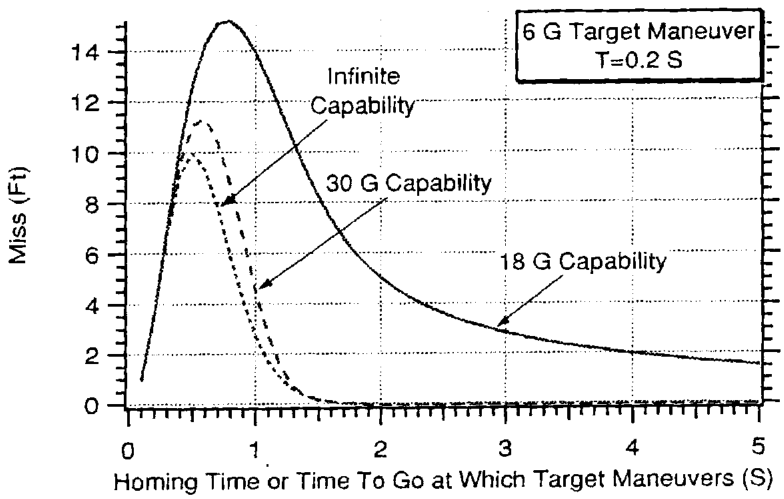

Figure 10: Limited missile maneuverability will increase the miss distance.

Why Less Acceleration Capability is Sometimes Better

It might appear from the discussion so far that exoatmospheric engagements are easy because there probably are no maneuvering targets, there is very little sensor noise because electro-optical seekers are used and the time constants within the guidance system are small because divert engines are used to get the required acceleration. However, in exoatmospheric engagements a warhead will not normally be effective and virtually zero miss distance is required against the target warhead. At long distances the whole target will be seen by the interceptor's electro-optical seeker and the missile will guide to a track point which is usually at the power centroid of the target. Later on, the warhead will be imaged and it will become the new target for the interceptor. When resolution occurs (i.e. target is imaged), the missile guidance point shifts instantaneously from the track point to the warhead. As far as the interceptor is concerned, there has been a step change in target position. In other words, there are two guidance problems which are sometimes called end games. The first end game starts when the seeker acquires the target and the second end game begins when the warhead is imaged. The success of the first end game is necessary but not sufficient for the success of the second end game. This is similar to many basketball games in which the outcome always appears to be determined by the last few minutes of play.

The apparent step in target displacement occurs late in the flight, which is the worst possible time from a missile guidance system point of view. Significant miss distances, as measured from the target's warhead, may result because of insufficient remaining homing time.

Figure 11 presents an example of how the miss distance varies as a function of the time left after warhead resolution for the case in which the warhead is 10 ft from the initial tracking point (i.e., target power centroid). In this example, the overall guidance system time constant is 0.1 s and curves are presented for various missile acceleration capabilities. If there is zero time left after warhead resolution, the missile will hit the track point and miss the warhead by 10 ft. If we have more than 0.8 s left after warhead resolution, the missile will hit the warhead (i.e., zero miss distance) - even if it only has 2 g of acceleration capability. If there is insufficient homing time after warhead resolution the missile will at least hit the target (i.e., miss distance between 0 ft and 10 ft) if the missile has either a 2 g or 5 g capability. However, if the missile had an infinite acceleration capability, and there were only 0.2 s left after warhead resolution, then it is possible not only to miss the warhead but also the missile itself. In this case the apparent instantaneous step in target displacement causes the agile missile to overshoot the warhead. This is one of those rare instances in which limited acceleration capability is a virtue.

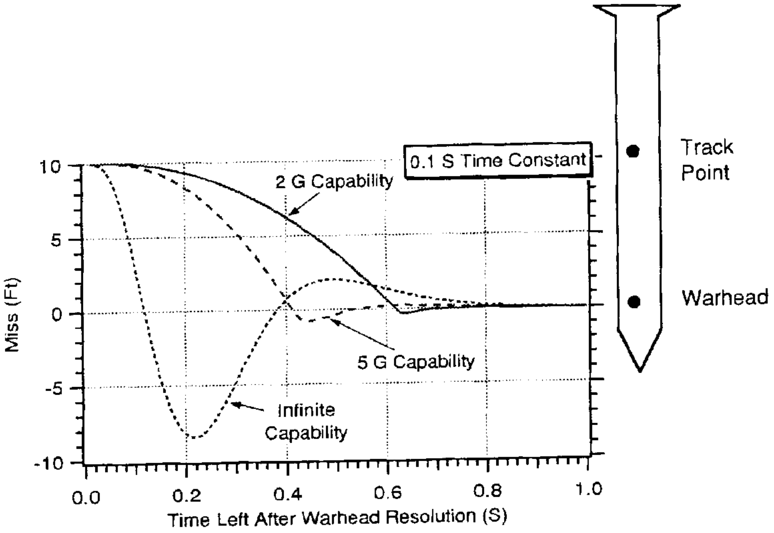

Figure 11: There must be sufficient time left after resolution in order to hit the warhead.

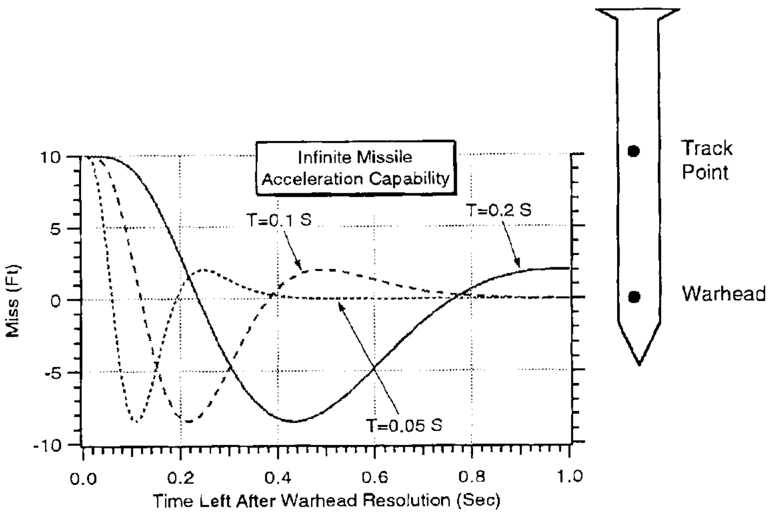

Figure 12: Small time constants are required to hit the warhead.

Figure 12 shows how the guidance system time constant influences system performance. In general, smaller guidance system time constants enable the missile to hit the warhead with less homing time (i.e., time left after warhead resolution). We can see from Figure 12 that if the guidance system time constant is 0.05 s, only 0.4 s of homing are required for the missile to hit the warhead. In this example, a 0.1 s guidance time constant requires at least 0.8 s of homing and a 0.2 s time constant requires much more than one second of homing to hit the warhead. It can be shown that the ratio of the time left after warhead resolution to the guidance system time constant must be at least ten to be sure that the missile will always hit the warhead. This means that the missile guidance system time constant must be as small as possible. For exoatmospheric intercepts, the lower limit on the guidance system time constant is governed by maximum allowable acceleration saturation due to sensor noise. Therefore the development of low noise seekers is an important component of the solution to the aimpoint shift problem.

Improving the Guidance

The examples chosen in this tutorial have assumed proportional navigation guidance. Although this guidance law is extremely popular because of its simplicity and ease of implementation, more advanced guidance laws can yield better performance under certain circumstances.

Proportional navigation only requires line-of-sight rate information to work. One can show mathematically that this guidance law predicts the intercept point assuming that the target is not maneuvering. This does not mean that missiles employing proportional navigation can not hit maneuvering targets. It does mean that if more information were taken into account less acceleration would be required to hit the target. An example of a more advanced guidance law is known as augmented proportional navigation. If the target acceleration is known exactly, the normalized plot of Figure 13 shows how the acceleration requirements to hit a maneuvering target can be reduced significantly. We can see that proportional navigation requires three times the acceleration capability of the target for a successful intercept whereas augmented proportional navigation only requires half the acceleration.

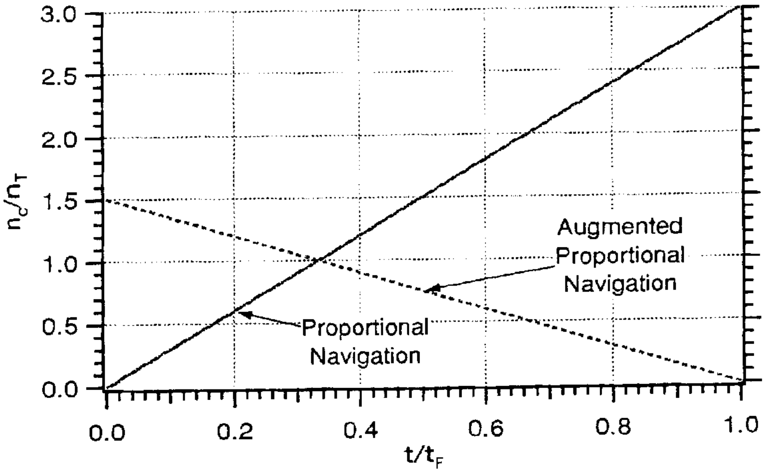

Figure 13: Augmented proportional navigation can significantly reduce acceleration requirements against maneuvering targets.

Of course, the level of target maneuver can not be known but must be estimated using advanced filtering techniques. These techniques require range from the missile to target measurements in addition to line-of-sight rate information. For many radar homing seekers, range information is available but for other seekers (i.e., infrared) this information is lacking and it is not possible to apply advanced guidance techniques directly. The idea of obtaining range information from angle-only measurements is known as passive ranging. Although passive ranging has been successfully applied in other applications, its implementation in homing applications is more challenging because of observability problems.

Other advanced guidance laws attempt to make use of a more precise estimate of the predicted intercept point. These guidance laws require accurate knowledge of the time to go before intercept and a good model of what the target is doing. The "mother of all guidance laws" is known as predictive guidance in which the predicted intercept is calculated in flight by rapidly integrating the nonlinear missile and target equations forward in flight at each guidance update. Guidance commands are proportional to the expected miss distance (sometimes called the zero effort miss) and inversely proportional to the square of the time to go until intercept. When the information required for predictive guidance is available, extraordinary levels of performance can be achieved. When the information is lacking or in error, the performance of predictive guidance may be substantially worse than that of proportional navigation. The technology for developing robust guidance approaches must be pushed if we hope to hit targets when working at an acceleration disadvantage.

SUMMARY

This tutorial has attempted to highlight some of the major guidance and control challenges in intercepting ballistic targets. We have seen that longer seeker acquisition ranges and less measurement noise are often beneficial. Advances in seeker technology are required to yield accurate measurements and increase the homing time. Generally, smaller guidance system time constants will work in the direction of making near zero miss distance possible. However, advances in radome technology are required so that guidance system stability issues can be solved and small time constants can be obtained. Usually more missile acceleration is required to engage high-speed ballistic threats in the atmosphere. Advances in flight control system technology are required to allow an endoatmospheric missile to work at higher angles of attack so that more acceleration can be obtained. Finally, advances in practical guidance law technology are required if we are to engage threats which can out maneuver the missile.

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