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Fighter Weapons

Fighter aircraft exist to destroy other aircraft. The airplane itself may be considered only a weapons platform designed to bring the weapons system into position for firing. Fighter weapons have varied greatly over the years, and each weapon has had unique requirements for successful employment. The requirements might include effective ranges, aiming, relative position of fighter and target, or any number of other factors. All of the requirements of a particular weapon must be satisfied simultaneously in order for the weapon to be used successfully. Meeting these weapons-firing requirements, while frustrating those of the enemy, must therefore be the goal of all fighter tactics and maneuvering.

Before fighter tactics can be discussed effectively, an understanding of weapons systems must be developed, since these weapons are the driving forces behind tactics. This chapter discusses the major classes of weapons which have been used by and against fighter aircraft. Included in the discussion are operating characteristics, operating limitations, and countermeasures associated with these weapons.

Air-to-Air Guns

> The most important thing in fighting was shooting, next the various tactics in coming into a fight and last of all flying ability itself.
>
> Lt. Colonel W. A. "Billy" Bishop, RAF
> Probably the leading RAF Ace of WW-I
> 72 Victories

The gun is by far the most widely used and important air-to-air weapon ever devised. The story of the adaptation of this weapon for aircraft use is very interesting and has been the subject of several other works, so it will only be treated in summary fashion here.

Aircraft guns may be classified as "fixed" or "flexible." Fixed guns are installed in a stationary position relative to the aircraft, usually are forward firing, and are aimed by pointing the entire fighter. Flexible guns, although fixed to the aircraft, may be aimed up, down, and from side to side by the operator to cover a certain field of fire, which may be in any direction relative to the aircraft. Such guns may be manually operated or installed in power turrets.

Fixed, forward-firing guns have many advantages for small, maneuverable fighters. Their installation is generally lighter and produces less drag, so they have less negative impact on performance. Flexible guns usually require a dedicated operator in addition to the pilot, which further adds to aircraft size and weight. Maneuvering relative to another aircraft is also much simpler when the opponent can be kept in front of the attacker, which essentially requires a forward field of fire. For these and other reasons, fixed forward-firing guns have been found to be superior for small, offensive aircraft (fighters), while flexible guns are generally preferred for the defense of larger, less maneuverable aircraft.

By trial and error, fighter armament in World War I progressed from personal side arms to flexible machine guns and, eventually, to fixed machine guns. The standard fighter at the end of this conflict had two .30-cal-class fixed forward-firing machine guns, which often were equipped with synchronizers to allow fire through the propeller disc.

The tremendous progress in aircraft performance during the 1920s and 1930s was in large measure the result of the intense interest generated by the many international speed competitions of those years. Aircraft structural methods were also revolutionized, as essentially all-metal construction became standard. These developments, as well as the lessons of World War I on the value of firepower, led to significantly increased fighter armament by the outbreak of World War II.

The reasoning behind these developments is fairly clear. First, increased aircraft performance allowed the weight of greater armament to be carried. Second, designers recognized that the higher closure rates resulting from faster aircraft speeds would, in general, lead to shorter firing times, so more destructive power was necessary in a shorter period of time. Third, metal aircraft, particularly the bombers, were much tougher targets, and increased performance enabled the planes to carry additional armor that could be used to protect vital areas of the aircraft (armor for World War I fighters sometimes was an iron stove lid in the pilot's seat).

These developments created a need for greater firepower, which could be achieved by more guns, larger projectiles, higher rates of fire, greater muzzle velocities, or explosive bullets. Some pairs of these factors, however, are related in such a way that neither member of the pair can be increased independently. Probably the most important of these relationships is that between projectile weight and rate of fire. In general, the greater the weight of the shell (including bullet, charge, and casing), the slower the rate of fire, owing primarily to the inertia of the heavier moving parts required to handle this ammunition. Obviously, depending on the gun technology at a given time, there should be an optimum balance between these two factors. As guns and ammunition are made lighter for a given projectile weight, the optimum balance shifts toward heavier bullets. Another factor in this equation involves target vulnerability. The greater rate of fire possible with smaller bullets results in an increased probability of registering a hit, but greater projectile weight generally leads to more target damage given that a hit occurs.

Some of the armament variations of the combatants during World War II can be explained by this factor. For instance, bombers generally are relatively large, poorly maneuvering aircraft that are fairly easy to hit but hard to destroy because of the armoring of vital areas and greater redundancy of important systems. Such a target best may be destroyed by fewer numbers of more destructive projectiles. The opposite may be true of smaller, highly maneuverable fighters, which are usually harder to hit.

The search for more destructive projectiles led to the development of the aircraft cannon. A cannon is essentially a gun that fires explosive bullets. In general, these explosive charges are armed by the firing acceleration of the shell, and they explode on contact with a target. Although some use was made of single-shot cannon in World War I, truly effective automatic cannon were developed between the wars. These were generally 20- to 40-mm weapons and had projectiles significantly larger than those of the .30- and .50-cal-class machine guns in common use, with correspondingly lower rates of fire. The cannon themselves were also larger and heavier, leading to further tradeoffs in usable aircraft space and in performance.

The many variations and exceptions of aircraft armament used in World War II cannot be discussed in detail here, but some general trends deserve mention. The firepower of the earlier fighters was invariably increased in later versions of the same aircraft, as well as in new fighters introduced during the war; increased projectile/target specialization also was apparent as the conflict progressed through its various stages. For instance, U.S. fighter designers, primarily concerned with German and Japanese fighter opposition, tended to stay with high rate-of-fire machine guns. The standard armament of the more important U.S. fighters (P-51, P-47, F4U, F6F) at war's end was six or eight .50-cal Browning machine guns. These were usually mounted in the wings, where there was more room and no requirement for synchronization, so that the full rate of fire could be developed. German designers generally employed a combination of cowl-mounted (often synchronized) and wing guns, and they tended to use cannon for more potency against the heavy bombers that were their prime concern. Late in the war the Me 262 (jet) and Me 163 (rocket) fighters, primarily used as bomber interceptors, employed four 30-mm cannon and/or 50-mm unguided rockets. Even larger guns were used successfully by both sides in an air-to-ground role, as were unguided rockets.

The advent of wing-mounted guns led to increased problems with bullet dispersion. When all guns were cowl mounted, they were simply boresighted to fire essentially straight ahead (the sight might be aligned to allow for the normal gravity drop of the bullets at a selected range). But when guns were spread out over much of the span of the wings, bullet dispersion became excessive, leaving large holes in the bullet pattern at some firing ranges. The "lethal bullet density" was increased by a method known as "harmonization," which generally involved using one of two techniques.

"Point harmonization" aligned the outboard guns slightly toward the aircraft centerline so that the bullets met at a point that was assumed to be the optimum combat firing range (normally 700 to 800 ft). This method resulted in maximum lethal density near this particular range, but led to wide dispersion at much longer ranges. Point harmonization was often preferred by the pilots who had the best marksmanship and were confident they could place this maximum density point on target.

For most pilots, another method, known as "pattern harmonization," yielded better results. This involved adjusting each gun individually slightly up, down, left, or right to produce a fairly uniform bullet pattern of a certain diameter at the harmonization range. Although maximum lethal density was not achieved in this manner, the average fighter pilot had a better chance of getting hits. The advantages of this method were much like those of a shotgun over those of a rifle. More lethal projectiles also favored this technique, as maximum density usually was not necessary.

Mounting guns such that their line of fire does not extend through the aircraft center of gravity (CG) introduces other problems. Particularly when wing-mounted guns are located large distances from the CG, failure of a gun to fire on one side can cause the aircraft to yaw significantly, greatly complicating aim. Aircraft designed with asymmetrical gun mounts often require some automatic aerodynamic control coordination, such as rudder deflection, to compensate for these effects.

The recoil action of heavy, rapid-fire guns can be considerable and can often cause significant speed loss for the firing aircraft. At slow speeds, especially under asymmetrical firing conditions, this recoil can cause a stall and subsequent loss of control.

With the advent of jet aircraft, one further complication has arisen to the mounting of guns. The gun gases produced must be exhausted in such a manner that they are not ingested by the engine, as this can cause compressor stalls and flameouts.

The next significant technical breakthrough in air-to-air guns appeared following World War II. This was a new cannon, modeled from an experimental German gun and built around a rotating cylinder similar to a "revolver" handgun. This design, known as the M39 in the United States, resulted in a great increase in rate of fire.

Even greater performance was obtained in the late 1950s with the introduction of the "Gatling-gun" cannon. Rather than a revolving cylinder, this weapon employed multiple rotating barrels. Designated the M61 in the United States, this gun could develop a tremendous rate of fire with less barrel overheating and erosion. Additionally, this gun was usually electrically, hydraulically, or pneumatically propelled; because it was not dependent on the residual energy of the expended round, problems associated with duds were eliminated.

During the 1950s and 1960s there was a definite trend away from the gun as the fighter's primary armament. The feeling was that the high speeds of jet fighters and the heavy armament of new bombers made the gun obsolete, particularly for night and all-weather missions. During this period many fighters were not equipped with guns at all; their air-to-air weapons package consisted entirely of unguided rockets, and then of guided missiles (which are discussed later in this chapter). This trend was reversed in the 1970s, after further combat experience had once again demonstrated the value of the gun and the limitations of some of the more exotic weapons.

Table 1-1 is a collection of statistics on many of the guns which have been important in American combat aircraft, and it is fairly representative of the armaments of other nations, as well. A good indication of the technological development of a gun is the weight of the projectiles that it can fire in one minute (assuming barrel limitations and ammunition supply allows). In this table weight of fire is measured by the factor W_F. Tremendous progress can easily be seen here by comparing the post-World War I Browning .30-cal M2 machine gun with the 20-mm M61 Gatling gun of the 1950s. Improvement in this area has been one of the leading factors in the lethality increase of airborne gun systems.

The lethality of a gun can be measured by multiplying the destructive power of its projectile and the number of hits. For nonexplosive bullets, destructive qualities are generally proportional to kinetic energy: half the mass of the projectile times the square of its velocity. To be more technically correct, the velocity used should be the relative impact velocity, but for comparison purposes, muzzle velocity will do. The factor F_L in Table 1-1, a measure of the lethality of the gun, is proportional to the kinetic energy of each projectile and the rate of fire.

F_L should be roughly indicative of the lethality of a nonexplosive bullet fired at the specified rate from a given gun. Cannon are a somewhat different case, since much of the lethality of these weapons is derived from their explosive shells. Therefore F_L is a fairly accurate relative assessment of the destructiveness of machine guns, but it underrates the cannon in comparison. Likewise, it can be used to compare cannon of the same projectile size, but it would slight larger guns in comparison with smaller ones.

Even with its limitations, F_L can give a qualitative feel for the incredible increase in fighter gun-system lethality over the years. For example, the combined F_L of the two .30-cal-class synchronized machine guns typical of fighters at the end of World War I would be on the order of $F_L = 2$, while the six wing-mounted .50-cal guns of the World War II P-51D fighter would rate about $F_L = 38$. In addition, a much better gunsight on the P-51 and many other fighters of its day greatly increased the probability that hits would be scored. A further lethality increase can be seen in the gun systems of some present-day fighters, such as the F-14, F-15, F-16, and F-18, which mount a single M61 Gatling gun. Ignoring the increased lethality of the explosive shell and even better gunsights, these aircraft would rate about $F_L = 145$. Such technological advances, combined with inherent

Table 1-1. American Aircraft Guns

Type	Operational Date	Bullet Weight (lbs)	Rate of Fire (rounds/min)	Weight of Fire W_F (lbs/min)	Muzzle Velocity V_M (ft/sec)	Lethality F_L (W_F X V_M X 10^{-8})
Machine Guns						
.30-cal M2	*1929*	*.02*	*1,200*	*25*	*2,600*	*1.7*
.50-cal M2	*1933*	*.10*	*800*	*81*	*2,810*	*6.4*
.50-cal M3	*1947*	*.10*	*1,200*	*121*	*2,840*	*9.8*
Cannon						
20-mm M2	*1941*	*.30*	*650*	*196*	*2,850*	*15.9*
20-mm M3	*1944*	*.30*	*800*	*241*	*2,750*	*18.2*
20-mm M39	*1953*	*.22*	*1,500*	*332*	*3,330*	*36.8*
20-mm M61	*1957*	*.22*	*6,000*	*1,330*	*3,300*	*144.8*
37-mm M4	*1941*	*1.34*	*135*	*181*	*2,000*	*7.2*

reliability, cost-effectiveness, simplicity, and flexibility in comparison with many other weapons systems, make the gun a formidable asset of the modern fighter.

Regardless of the lethality of a given gun system, it is of little value unless it can be brought to bear on the target. The fact that even the relatively benign systems of World War I were effective in their time demonstrates that lethality is certainly not the only factor, and probably not even the most important factor, in gun effectiveness. The ability to achieve a hit initially is probably more relevant. By this reasoning, a simple comparison of rates of fire among the various guns and gun installations is likely to be a better measure of their effectiveness, since this factor is more closely related to the probability of a hit. Lethality and target vulnerability are still important, however, since they determine the number of hits required for a kill. Additionally, for the guns to be placed in a reasonable firing position, aircraft performance and pilot ability must be adequate. The location of this position is very much dependent on the effectiveness of the gunsight, as is discussed later.

Air-to-Air Gunnery Principles

The air-to-air gunnery problem is a difficult one; it involves hitting a moving target from a moving platform with projectiles that follow curved paths at varying speeds. This complicated problem can be better understood if each part of it is isolated in turn.

Most people who have fired a gun or an arrow or have thrown a rock at a stationary target realize that the projectile takes a finite length of time to reach that target. During this period the projectile is acted on by gravity, which causes it to curve downward. The longer the projectile time of flight (TOF), the farther the projectile drops. In the first second this gravity drop is about 16 ft. During its flight the projectile is also subjected to aerodynamic drag, which causes it to decelerate at a rate dependent on its shape, size, weight, and speed, as well as the density of the air. In general, the greater the muzzle velocity of a bullet, the shorter the TOF and the smaller the gravity drop at a given range. As range, and therefore TOF, increases, however, the rate of gravity drop also increases. Gravity drop may be negligible at very short ranges, but it becomes increasingly important as TOF increases.

This finite TOF also poses a problem if the target happens to be moving, since the target's position will change somewhat from firing of the projectile to its impact; thus lead is required for the projectile and target to arrive at the same point in space at the same instant. This will come as no surprise to anyone who has ever shot at flying birds or skeet. The lead required is roughly proportional to the crossing speed of the target, so if its track is directly toward or away from the shooter, no lead is necessary, but maximum lead is called for when the target's track is 90° to the line of sight (LOS) from shooter to target.

As shown in Figure 1-1, lead usually is described as a "lead angle." Lead angle is sensitive to target crossing speed and average bullet speed. Range is also a factor, since average bullet speed decreases with greater TOF. Lead angle is also dependent on the geometry of the firing situation because of the influence of this factor on target crossing speed and TOF. This geometry can be described as "target-aspect angle" (TAA), which is defined as the angle between the target's velocity vector (flight path) and the LOS betwen the target and shooter. When the target is moving directly toward the shooter, TAA is zero. The shooter would have a 180° TAA when he is situated directly behind the target, and a 90° TAA on the target's beam (i.e., "abeam" the target). As TAA varies, so does target crossing speed, changing the lead angle required.

> I had no system of shooting as such. It is definitely more in the feeling side of things that these skills develop. I was at the front five and a half years, and you just get a feeling for the right amount of lead.
>
> Lt. General Guenther Rail, GAP
> Third Leading Luftwaffe Ace, WW-II
> 275 Victories

To this point only nonmaneuvering targets (i.e., those traveling in a straight line at constant speed) have been discussed. To gain an appreciation of the effects of target maneuvering on lead angle, assume that the shooter is directly behind the target at the moment of firing, but before the bullet TOF the target begins a turn to left or right. If the shooter applied no lead angle (because target crossing speed was zero at the time of firing), the bullet might pass behind the target. The target's lateral acceleration (radial G) has generated an average crossing velocity that requires a lead correction. The amount of this lead correction is very sensitive to target G near nose or tail TAAs, but it is less dependent on target maneuver (and more dependent on target speed) near beam aspects when the target turns directly toward or away from the shooter.

Target movement and maneuver also affect range. If TOF, gravity drop, lead angle, etc., are calculated based on target range at the time of firing (position "1" in Figure 1-1), any movement or maneuver during projectile TOF could change the range, invalidating all calculations and causing a miss.

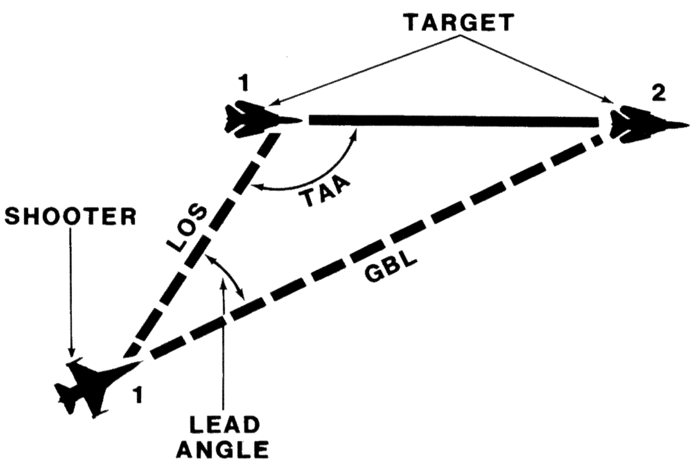

Figure 1-1. Gun-Firing Geometry

The final complication in air-to-air gunnery is the motion of the shooter aircraft itself. Accurate ballistics calculations depend on knowing the true velocity of the projectile as it leaves the barrel. The true airspeed of the shooter must be added to the muzzle velocity to determine launch speed. Shooter aircraft maneuvering will also have several important effects. For example, as the shooter maneuvers, the gun-bore line (GBL) may be displaced somewhat from the firing aircraft's direction of motion because of "angle of attack," sideslip, etc. (Angle of attack is discussed in the Appendix.) The actual trajectory at the instant the bullet leaves the muzzle will not, therefore, generally be aligned with the GBL. Motion imparted to the projectile by rotating barrels (Gatling gun), as well as aircraft flexing under maneuvering loads, may be factors. These and some other factors are usually grouped together under the term "trajectory jump," which includes any angular difference between the GBL and the initial trajectory.

Given all the foregoing factors that come into play, it's amazing that an air-to-air gun kill is ever recorded, especially when many of these factors are unknown quantities for the pilot. Little wonder that the most effective technique often is to "fill the windscreen with target and let 'er rip." Effective air-to-air gunsights have done much to aid the fighter pilot in this difficult task.

> As to gunnery passes, the best was when you dived with speed, made one pass, shot an opponent down quickly, and pulled back up. ... The secret was to do the job in one pass; it could be from the side or from behind and I usually tried to open fire at about 150 feet.
>
> Major Erich Rudorffer, Luftwaffe
> Seventh Leading Ace, WW-II
> 222 Victories (13 on One Mission)

Tracer bullets, introduced during World War I, were also a great aid to the pilot, since he could see the trajectory of his bullet stream and make corrections. Small pyrotechnic charges located in the rear of tracer bullets burn during the TOF, making the projectile visible. Although this feature can be an aid in placing bullets on the target, the benefits can work both ways. The pilots of many target aircraft do not realize they are under attack until the first shots are fired. Any tracer that misses the target will definitely get the target pilot's attention and cause him to maneuver defensively. Without tracers, attacking pilot normally gets a few extra seconds' chance at a steady target, greatly increasing the probability of a kill. For this reason it is recommended that tracer ammunition be used only for gunnery practice, to allow the student to develop a feel for bullet trajectories and dispersion.

> Sometimes you miss with the first bullets and the tracers give you away.
> Colonel Francis S. "Cabby" Gabreski, USAAF
> Leading American Ace in Europe, WW-II
> 5 Victories, WW-II and Korean Conflict

The usual practice with tracers is to intersperse these rounds among the normal ammunition (every fifth bullet, for example), since rate of fire is usually such that several will be in the air simultaneously anyway. Since the ballistics of tracer ammunition generally varies slightly from the ballistics of the nontracer rounds, the trajectories also are likely to differ slightly, which can be misleading, especially when the pilot is firing at long range. Difficulties in depth perception can also make assessment of tracer trajectories ambiguous. With the advent of effective air-to-air gun-sights, the disadvantages of tracers in combat probably began to outweigh the benefits.

> [The commanding officer] ordered the tracer ammo removed . . . I'll never forget the spectacular results we got. Our kill rate went up from 50 to 100 per cent.
>
> Colonel Charles W. King, USAF
> 5 Victories, WW-II

In the absence of an ammo-remaining indicator, tracers have been used to warn the pilot that his ammo is nearly spent. For this purpose, the last few rounds in the can might include some tracers. It doesn't take long for an observant enemy to pick up on this practice, however, and it may give him the advantage of knowing which fighters are low on ammo. Some other indicator of rounds remaining is, therefore, preferable.

Air-to-Air Gunsights

The earliest sights for air-to-air guns were of the fixed variety, most often consisting of a ring and bead, as illustrated in Figure 1-2. This arrangement usually included a ring or concentric rings with cross-braces located near the muzzle of the gun, and a vertical post located near the rear of the gun, closer to the pilot. (Sometimes these positions are reversed.) By moving his head so as to align the tip of the post (the bead) with the center of the ring, the pilot was sighting down the GEL. Since the size of the ring was known, as was generally the size of the target (wingspan is the most common measure used for target size), the relationship between the ring and the apparent target size varied with target range. This relationship provided a handy range-estimation method. For instance, the pilot might know that he was within the maximum effective range of his guns when the wing-

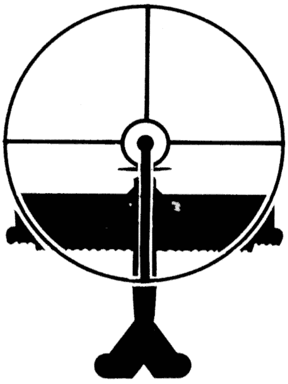

Figure 1-2. Ring-and-Bead Sight

span of the enemy aircraft just extended over half the diameter of his sight ring. The ring was also a useful tool in estimating the required lead angle. For a nonmaneuvering target of a given speed at a known range, the lead angle required is roughly related to the TAA. If the target was flying directly toward or away from the shooter, only a small correction would be required for gravity drop. However, if the attack was made from a position off the target's flight path, some lead would be required. The pilot would generally have a set of thumb rules, learned from the experiences of other pilots in his squadron as well as his own, which related target position within the sight ring to TAA at a given range. For instance, if the target fills the sight ring at a 90° TAA, the shooter might place the target's nose tangent to the bottom of the inner sight ring, about as shown in Figure 1-2. Of course, further corrections might be required for gravity drop and maneuvering target or shooter aircraft, making "Kentucky windage" an important factor.

Shots that require great amounts of lead, generally as a result of large angles off the nose or tail of the target, are called "high-deflection" shots, and the art of hitting targets under these conditions is known as deflection shooting. Only the best marksmen mastered this art with fixed gunsights, and their scores generally reflected their proficiency.

One of the factors which must be understood when shooting with a sight such as the ring and bead is the effect of the pilot's head position. If the pilot moves his head forward, closer to the sight, the ring will appear larger and will cover a wider angular cone at a given range. This cone angle can be measured in degrees or, more commonly, in mils (1° = 17.5 mils). A mil represents the span of an object 1 ft in length when viewed from a distance of 1,000 ft. A target with a 35-ft wingspan would appear to span 2° (35 mils) at a range of 1,000 ft, and 1° at 2,000 ft. Therefore, changes in the apparent span of the sight ring caused by pilot head position can result in large errors in both range and lead-angle estimation. Some installations included headrests to assist the pilot in head positioning.

This problem was normally addressed by the fixed optical sights, some resembling telescopic rifle sights, which largely replaced the ring-and-bead variety between late World War I and early World War II. The optics of such a sight required a certain pilot head position for a view of the entire sight picture or a clear target image or some other inducement, and largely eliminated this variable. The earlier designs were in tubular form, but these were generally replaced before World War II by reflector sights. This optical sight was usually in the form of a circle, or sometimes several concentric circles, of light projected onto a "combining glass" through which the pilot sighted the target. The combining glass was transparent, but it still reflected the sight image so that the sight and target could be seen simultaneously. These sight images were normally focused near infinity so that both the target and the sight would be in sharp focus to the pilot. This also eliminated any apparent changes in the size of the sight ring with head position.

Once again, the angular span of the sight rings could be used for range and lead estimation. Some of these sights also had an adjustable feature, often bars of light on each side of the sight image, which could be moved toward or away from the center of the sight to represent the wingspan of various targets at maximum or optimum ranges. The center of these sights was usually shown as a spot or a cross of light called the "pipper."

Optical sights of this type represented only a very small advance over the original ring-and-bead variety. The fighter pilot needed more help, particularly with lead estimation for high-deflection shots. For some, this help arrived during World War II in the form of the gyroscopic lead-computing optical sight (LCOS). There are many variations of the LCOS, both in sight picture and sophistication, so a general discussion is called for.

The three basic components of the LCOS are a sight display unit, a gyroscopic sensing unit, and a computer. The attacking pilot tracks the target by attempting to hold the pipper steady on the center or some vulnerable portion of the target. Simultaneously, he constantly adjusts the sight picture to the wingspan of the target, often by turning an adjustable throttle grip, which, when the type of target or its wingspan has been selected prior to the attack, allows the computer to calculate target range. Any turning required by the attacking aircraft in order to track the target is sensed by the gyroscopes and is also sent to the computer. Once the angular rate of the target LOS and target range are known, the computer can calculate the required lead angle. The gyros can also sense the shooter's attitude and enable the computer to calculate the direction and magnitude of the gravity drop for the target's range.

All these corrections are displayed to the pilot by the sight unit, which causes the sight picture to move opposite to the direction of the LOS movement. In order to continue tracking the target, the pilot must adjust his aim in the proper direction for the lead correction. For example, if the computer determines that more lead is required, the pipper slides toward the target's tail, requiring the pilot to adjust his aim farther forward, thereby providing the necessary lead correction.

Such a sight system attempts to predict the future LOS to the target based on the present LOS and its angular rate of change. The time for which this future LOS position is predicted is the TOF of a bullet fired at the present time. The TOF, in turn, is dependent on the firing conditions (essentially shooter speed and altitude) and the distance the bullet must travel to reach the target. This distance must also be predicted, based on range at firing and the range rate of change (closure).

Obviously, there is a lot of predicting going on here. The fire-control computer must make these calculations based only on the quality of the information available to it. Since not only current values of various parameters (LOS, range, etc.), but also the rates of change in these parameters, may be used in the calculations, smoothness of the input information (i.e., smooth, steady tracking and smoothly changing range input) is essential to avoid large errors caused by false rate information. Each computer also requires a finite amount of time, known as "settling time," to make calculations based on new data inputs. Rapid changes in these inputs can cause large, erratic pipper movements during this settling time, making the sight unusable.

> You can have computer sights or anything you like, but I think you have to go to the enemy on the shortest distance and knock him down from point-blank range. You'll get him from in close. At long distance, it's questionable.
>
> Colonel Erich "Bubi" Hartmann, GAF
> World's Leading Ace, Luftwaffe
> 352 Victories, WW-II

A significant advancement in gunsight technology was the addition of automatic ranging information, usually provided by radar. Early systems used a fixed radar beam, with fairly wide-angle coverage, centered directly ahead of the fighter. Whenever a target (or anything else) was placed within its field of view and range coverage (usually on the order of one mile), this range-only radar would measure the distance to the target, indicate the range through the sight system, and send values of range and range rate to the gunsight computer. Radar-measured range and range-rate information is ordinarily much more accurate and smoother than manual input. In case of a radar malfunction, manual backup might be possible, or the computer might simply assume some nominal range and range rate.

Radar is discussed in much greater detail later in this chapter, but two of its limitations can be mentioned now in connection with gunsights. One of the problems with most designs is encountered when the radar is looking down at low altitudes, where "ground return" might obscure return from a relatively small target and render the radar ranging unusable. In addition, radars are susceptible to a wide variety of electronic countermeasures (ECM). Figure 1-3 is an illustration of a typical radar LCOS display.

A gunsight that causes the pipper to move around within the sight field of view (as opposed to a fixed sight) in response to the maneuvers of the shooter aircraft is sometimes referred to as a "disturbed-reticle" system. Within this broad category there are many variations. The type of LCOS which has been described attempts to predict the position of the target (LOS and range) at one TOF in the future and then displays a pipper that directs the pilot in providing the proper amount of lead. This type is known as a "director" or "predictor" sight. Besides all these difficult predictions, the accuracy of this system is also dependent on the target maintaining a fairly constant maneuver (the closer to a straight line at constant speed, the better) for at least one TOF after the prediction is completed.

Another mechanization of the disturbed-reticle LCOS might be called a "historical" or "real-time" sight. This system only predicts the bullet trajectory and "remembers" this trajectory until its TOF would be complete. It then displays a pipper that represents the point of impact of that bullet on a geometric plane at the target's present range. Such a gunsight tells the shooter what is happening at the present time to bullets fired one TOF in the past, thus the term *historical.* If the pipper is superimposed on the target, bullets should be passing through the target if the shooter was firing one TOF earlier.

This system has several advantages over the predictor method. One of these is that the only calculations involved are based on the most accurate information: bullet ballistics and the shooter aircraft's attitude and maneuvers. Another is that the information displayed by the pipper is real-time, and so is not dependent on future target maneuvers.

With a historical sight, the pilot must remember to open fire at least one TOF before the pipper appears to touch the target on the sight unit in order to get the maximum number of hits. Tracking can also be somewhat more difficult, since there is a lag of one TOF between movement of the shooter aircraft and a change in the pipper indication. The pilot has little immediate control of the pipper (just as he can't control the flight path of bullets after they are fired) for fine tracking corrections. Even with these shortcomings, however, sights based on this real-time technique generally show better results against maneuvering targets than do director sights.

Many variations of these two basic methods have been tried with some success. Often the differences are only in display formats, and sometimes combinations of the two computational techniques are used. Several clever prediction and estimation tricks that are often employed result in a need for much less computer sophistication than the full historical sight requires.

Undoubtedly the quest will continue for the "perfect" air-to-air gunsight, but there are practical limits to the attainable accuracy, in large measure because of manufacturing variations in ammunition which cause slight ballistics changes. Barrel vibrations during fire and other factors also have an effect. The practical accuracy of air-to-air guns at present, discounting sight errors, seems to be about 5 mils.

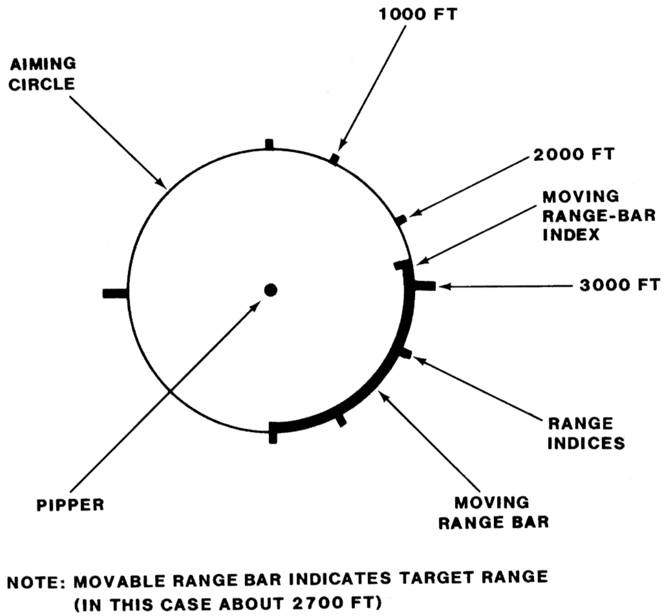

Figure 1-3. Typical Radar Lead-Computing Cunsight Display

Gun Employment

> When one has shot down one's first, second or third opponent, then one begins to find out how the trick is done.
>
> Baron Manfred von Richthofen
> Leading Ace of WW-I, German Air Service
> 80 Victories

In order to destroy a target with a gun system, the shooter must meet range, aiming, and firing-time requirements. Weapons-system range constraints usually involve both maximum- and minimum-range limits. Effective maximum range for air-to-air guns depends on many factors, including bullet ballistics, sight accuracy, fuzing requirements (cannon), dispersion, target vulnerability (including size), altitude, shooter and target speeds, and firing geometry. A reasonable effective maximum range for modern gun systems against fighter targets is about 3,000 ft.

Minimum range for a gun system is somewhat harder to define, being based primarily on the shooter's ability to avoid a collision with the target or the target debris. Closure, shooter maneuverability, deflection, and pilot reaction time are the primary factors here. Minimum range has generally increased with fighter speeds. At typical jet-fighter speeds in a maneuvering situation, 500 ft might be a reasonable minimum range.

Here is a firsthand account of just what a min-range gun shot is like. This passage is a description of Major John Godfrey's first victory; he was fly`ing a P-47 over Europe, and the victim was a German Me 109.

> Breathlessly I watched the 109 in between the breaks in the clouds as I dove. At 12,000 feet I leveled off and watched him up ahead. In diving I had picked up speed, and now had hit 550 miles an hour. I was about 500 feet below him and closing fast. *Quick now, I've got time.* I checked all around, in back and above me, to insure that no other Jerries were doing the same to me. My speed was slackening off now, but I still had enough to pick up that extra 500 feet and position myself 200 yards dead astern. The 109 flew as straight as an arrow, with no weaving. As his plane filled my gun sight I pressed the tit. The results were incredible. No sooner did I feel the plane shudder as the machine guns went off, than a huge flame engulfed the 109, followed immediately by a black cloud of debris extending fifty feet in all directions in front of me. Instinctively I threw up my arm over my face and pulled back on the stick, expecting any minute that the wreckage would break my windshield.[1]

The aiming requirement is to point the guns so that the bullets hit the target. The techniques and difficulty of this task depend largely on the sight design and the firing geometry. In general, the GBL must be pointed in front of the target by the amount of the required lead angle, as previously discussed.

The required firing time is related to both the number of bullets hitting the target over a given period of time and the number of hits required for a kill. Required firing time is therefore dependent on the lethality of the gun system, dispersion, range, firing geometry, and target vulnerability.

For a kill to be registered, the available firing time must exceed the required firing time. Available firing time commences when the guns are properly aimed between maximum and minimum ranges, and it ends whenever range or aiming constraints cease to be satisfied. It is sensitive to the range at which proper aim is first achieved, closure, firing geometry, and relative aircraft performance capabilities.

There are two broad categories of air-to-air gun-firing situations: "tracking" shots and "snapshots." The tracking shot occurs when the pipper remains steady on the computed aim point for longer than the settling time of the sight. A snapshot, sometimes called "raking guns," refers to a situation when the pipper merely passes through the proper aim point, never stopping.

Tracking Shots. Steady tracking is usually necessary for a predictor gunsight to calculate an accurate lead angle, and therefore tracking greatly improves the chances of achieving a hit with this type of sight. Tracking also enhances the effectiveness of a fixed sight, since a relatively long firing time generally is required to find the proper aim point. Since the historical sight usually requires only that bullets be in the air at least one TOF in order to display their impact point accurately, tracking is not generally a requirement with this sight, but it may provide greater chances of a kill by increasing the firing time.

> Aerial gunnery is 90 percent instinct and 10 percent aim.
>
> Captain Frederick C. Libby, RFC
> First American to Shoot Down 5 Enemy Aircraft, WW-I
> 24 Victories (10 as Observer, 14 as Pilot)

The best firing technique depends on many factors and tradeoffs. The improved lethality of tracking must be assessed relative to the shooter's sight design and gun-system lethality. This assessment then must be weighed against the tactical situation. Tracking requires the shooter to concentrate on the target and fly a predictable flight path for a longer time. If the situation is such that other hostile aircraft may achieve a threatening position during this time, tracking may not be advisable. Closure is one of the major factors in available tracking time, and since the shooter's speed contributes to closure, decreased speed usually increases tracking time. Performance and maneuverability are also affected by speed, however, so such a speed reduction may not be desirable because of its effect on the shooter's offensive or defensive maneuvering potential following the shot. One other factor is the time required to achieve a position from which a tracking shot is practical. Because of the resulting presented target size, reduced closure, and required lead, the optimum firing position for tracking a maneuvering target is generally in the rear quarter (about 30° to 60° off the tail with a LCOS, 0° to 30° for fixed sights), near the target's vertical plane of symmetry. Achieving such a position on an evasive target can take a considerable amount of time, possibly more than is prudent in a hostile environment. Target defensive fire is also a consideration. Multi-crew aircraft, such as many bombers, may be well defended in the area where tracking is best.

> I am not a good shot. Few of us are. To make up for this I hold my fire until I have a shot of less than 20° deflection and until I'm within 300 yards. Good discipline on this score can make up for a great deal.
>
> Lt. Colonel John C. Meyer, USAAF

In order to track effectively with fixed guns, the pilot of the attacking fighter needs to stop the relative angular motion between the pipper and the target. This relative motion can be broken down into two components when viewed through the shooter's gunsight: lateral motion and vertical motion relative to the shooter's windscreen. When the shooter is located in the target's plane of maneuver, target relative motion will appear to be in a straight line, which greatly simplifies tracking. To maintain this situation for any length of time, the shooter must establish a maneuver in the same plane as the target. To accomplish this, the shooter first maneuvers to a position in the opponent's rear hemisphere, inside his turn. The nose is placed to point well ahead of the target, and the aircraft attitude is adjusted to approximate that of the target aircraft, that is, the shooter aligns fuselages and matches bank angle. The shooter matches his turn rate to the LOS rate of the opponent so that the target stays a constant distance below the pipper. The target then might appear to move left or right in relation to the shooter's nose. Small bank corrections are made in the direction of this apparent motion, and the nose position and bank angle are readjusted to center the target again below the pipper. This procedure is repeated as necessary until the left/right drift of the target is removed, while the turn rate is continually adjusted as required to keep the target at the original distance below the pipper. Once all relative motion between the target and the shooter's nose has been stopped, the shooter is established in the target's plane of maneuver, a position sometimes referred to as "in the saddle." Although this sounds like a very involved process, it is fairly natural, and with some practice a shooter can "saddle up" rather quickly on a cooperative target.

Up to this point the gun-tracking technique is fairly independent of the sight system, but now the sight begins to dictate the procedures. As the desired firing range is approached with a fixed sight, the shooter relaxes his turn slightly, allowing the target to fly up toward the pipper. When the estimated lead angle is reached, firing commences. Because of the limited accuracy of such a sight in a high-deflection situation, the usual procedure is to fire a short burst (about one second) and check the flight path of the tracers. The lead can be readjusted in small increments until hits are achieved, and then a sustained burst can be fired until the target is destroyed, minimum range is reached, or tracking the target farther is impossible. Small adjustments will be required in lead angle and bank angle throughout the firing pass to maintain correct pipper position. Generally less lead is required as range decreases.

> Go in close, and then when you think you are too close, go on in closer,
>
> Major Thomas B. "Tommy" McGuire, USAAF
> Second Leading U.S. Ace, WW-II
> 38 Victories

With a disturbed-reticle sight the pipper moves around in response to shooter-aircraft maneuvers, and its direction and the rate of movement are not always predictable. Because of this the pipper is not a suitable reference for shooter nose position while maneuvering into the saddle, and some fixed point on the sight or windscreen is normally used. The shooter must concentrate on the target rather than on the pipper during this procedure to avoid "chasing the pipper," which always seems to be moving the wrong way. Once in the saddle, where maneuvering is at a minimum, the pilot should find the pipper to be fairly steady, and he can fly the target smoothly toward the pipper while still concentrating on the target. With a real-time sight, the shooter needs to estimate the point when the pipper is one bullet TOF from the target. This is the earliest effective open-fire point, but firing may be delayed until the target is centered and held steady in the pipper. A director sight usually requires that the target be tracked steadily in the pipper until the computer's settling time for an accurate firing solution has passed.

> Good flying never killed [an enemy] yet.
>
> Major Edward "Mick" Mannock, RAF
> Probably Second Leading British Ace, WW-I
> 50-73 Victories

In addition to chasing the pipper, another common mistake made in this process is getting into the target's plane of turn too early. The opponent must be beaten first, and then shot. If the attacker saddles up well out of range, angle off the tail (AOT) of a hard-turning target will increase rapidly, with concurrent increases in LOS rate (increasing the shooter turn rate required to track) and closure (decreasing available firing time). The attack should be planned so that the firing position (preferably in the target's rear quarter) is achieved just as desired firing range is reached.

Closure must also be closely controlled. High closure is desirable at long range to shorten the attack time, which reduces the target's reaction time and limits the attacker's exposure to other hostile aircraft. But as firing range is approached, the rate of closure should be reduced to provide increased tracking time. Even if the attacker reduces his speed to somewhat less than that of the target, his position inside the target's turn and his nose position in front of the target will generally result in some closure. In order to maintain a continuous tracking position in the rear quarter of the turning target, the shooter would need to be slower than the target. The shooter also would be turning on a smaller radius than the target, with about the same turn rate. Such a situation is not always advisable in combat, since this lower speed may not allow the attacker the necessary maneuverability to reposition for another attack or to escape in the event he fails to destroy the target on the first attempt. Some speed advantage is usually preferable, which inevitably results in closure. Excessive speed, however, limits tracking time and usually increases the shooter's required G, making tracking more difficult and increasing the probability of gun jams.

> Guns are like alcohol: valuable, useful, popular, and fun—but, without discretion, self-destructive to the user.
>
> Unknown

In making his guns approach, the shooter must also plan for the possibility of a missed shot. Approaching with high closure is conducive to overshooting the target, which may give the opponent an opportunity to reverse his turn and assume an offensive position. The shooter should also break off a gun attack whenever he is unable to maintain proper lead for the shot. Further turning in the target's plane of maneuver usually results in excessive loss of speed and often leads to an overshoot. Instead, the shooter can reposition for a second attack or disengage.

> Suddenly you go into a steep turn. Your Mach drops off. The MiC turns with you, and you let him gradually creep up and outturn you. At the critical qmoment you reverse your turn. The hydraulic controls [F-86] work beautifully. The MiG [-15] cannot turn as readily as you and is slung out to the side. When you pop your speed brakes, the MiG flashes by you. Quickly closing the brakes, you slide onto his tail and hammer him with your "50's."
>
> Colonel Harrison R. "Harry" Thyng, USAF
> 10 Victories, WW-II and Korean Conflict

Another typical error is not allowing sufficient excess lead in the saddle position. At long range, target LOS rate is relatively slow, making it easy to maintain excess lead. As the range closes, however, AOT, LOS rate, and required shooter G build steadily. In a rear-quarter attack on a turning target, AOT will usually increase to a maximum, stabilize, and then decrease again as minimum range is approached. Maximum G required by the shooter generally occurs soon after AOT begins to decrease. This maximum G is often greater than that of the target, particularly when the shooter has the usual speed advantage, and easily can exceed the shooter's turn-performance capabilities before he reaches minimum firing range. It is much more effective to allow, by stabilizing or slowing the rate of G increase, the target to fly up to the pipper as firing range is approached; this allows the target motion to take out the excess lead and is preferable to trying to "pull" the pipper up to the target from behind. Also, the excess G required to pull the pipper to the proper aim point can exceed the shooter's capabilities. Shooter G, particularly with a real-time gunsight, should be stable or constantly increasing during the attack for best pipper control.

> Pulling up into his blind spot I watched his plane grow larger and larger in my ring sight. But this German pilot was not content to fly straight and level. Before I could open fire, his plane slewed to the right, and seeing me on his tail he jerked back on the stick into the only defensive maneuver his plane could make. I banked my 47 over to the right and pulled back on the stick, striving to get him once more into my ring sight. This violent maneuver applied terrific G's to my body, and I started to black out as the blood rushed from my head. Fighting every second to overcome this blackness about me, I pulled back the stick, further and further, so that the enemy plane would just show at the bottom of my ring sight to allow for the correct deflection.

> We were both flying in a tight circle, *just a little more and I'll have him.* Pressing the tit I waited expectantly for the 109 to explode. *I've hit his wing.* A section two-feet long broke loose from the right wing as the machine guns cut like a machete through it. Too *low, a little more rudder and the bullets will find his cockpit.* I could see occasional strikes further up the wing, but it was too late. The 109, sensing that I was inside him on the turn, slunk into a nearby cloud. Straightening my plane I climbed over the top of the bank and poised on the other side, waiting for him to appear. But the 109 did not appear, and not wishing to tempt the gods of fate further, I pushed the stick forward, entered the protective cover of the clouds myself, and headed home.[2]

Snapshots. Although tracking shots may provide the highest probability of kill, they may not be tactically advisable, or even possible, in a given situation. Depending on the initial geometry, relative aircraft performance, and pilot ability, tracking may be impossible within the effective range of the gun system. A snapshot, however, may still be available and lethal.

Snapshots may be categorized by the shooter's G level during firing, ranging from zero to maximum load factor. For a low-G snapshot, the attacker first projects the target's flight path, and then he positions his pipper well in front along this path. The amount of lead taken depends on the target's maneuver, LOS rate, and time remaining before reaching firing range. Ideally the shooter positions the pipper and then flies a straight line while waiting for the target to fly through the aim point at firing range. As a practical matter some small corrections nearly always will be necessary as the firing point is approached. This technique usually results in very short firing times and is not highly effective except with very lethal gun systems or at relatively close range.

> I opened fire only when the whole windshield was black with the enemy... at minimum range ... it doesn't matter what your angle is to him or whether you are in a turn or any other maneuver.
>
> Colonel Erich "Bubi" Hartmann, GAF

The high-G snapshot is "almost a tracking shot," and the same procedures generally apply, with the exception that somewhat more initial lead is usually taken than for the tracking shot. The shooter normally attempts to get into the target's plane of maneuver, as in tracking, but this is not a requirement, although it does make the task of bringing pipper and target together in firing range much simpler. The dynamics of this shot may be such that the shooter is never quite able to saddle up by stopping the apparent motion of the target relative to the pipper; but G is applied, possibly up to the shooter's maximum capability, to slow the relative motion to a minimum during the actual firing period. The slower this relative motion, the greater the exposure time to the bullet stream. A further advantage of being in the target's maneuver plane at firing time is the greater lethality that usually results. The most vulnerable area of an aircraft is usually the fuselage, and since a fuselage is generally longer than it is wide, maximum exposure time results if the pipper slides the length of the fuselage from nose to tail, rather than diagonally, as it does when the shooter is out of plane.

Most snapshots lie somewhere between the low-G and max-G varieties. The low-G snapshot generally requires more initial excess lead than the high-G snapshot or the tracking shot. If the required excess lead is very great and the shooter is located near the target's plane of turn, the shooter may have to place the target below his nose, out of sight, to establish this lead. Although this technique can be quite effective when it is mastered, it has several drawbacks. First, it is difficult to judge the proper amount of lead and exact plane of turn when the target is not visible for several seconds, so the technique requires much practice. Practicing blind lead turns is exceedingly dangerous. The pilot of the target aircraft may not see the attacker, and a slight miscalculation on the shooter's part or a small change in target G can result in a midair collision, which could ruin the entire day. Additionally, in combat, if the target pilot sees the attacker performing a blind lead turn, he can easily change his G or maneuver plane, ruining the shot and possibly causing the attacker to lose sight. This could provide the target with an opportunity to escape or even to reverse the roles.

> I'd hate to see an epitaph on a fighter pilot's tombstone that says, "I told you I needed training." . . . How do you train for the most dangerous game in the world by being as safe as possible? When you don't let a guy train because it's dangerous, you're saying, "Go fight those lions with your bare hands in that arena, because we can't teach you to learn how to use a spear. If we do, you might cut your finger while you're learning." And that's just about the same as murder.
>
> Colonel "Boots" Boothby, USAF
> Fighter Pilot

A better technique for providing large amounts of lead (when time is available) is to turn slightly out of plane. This should allow the attacker to maintain sight of the target just to one side of the nose. After the range has decreased substantially, the attacker can roll toward the target and pull the pipper back to its flight path. The shooter then can allow the target to fly through the pipper (low-G snapshot), or he can quickly roll back in the opposite direction to get into the target's plane of turn and attempt to slow the LOS rate (high-G snapshot). Although this method takes a little longer, it does not have the disadvantages of the in-plane technique.

The chances for success with a snapshot depend on many factors, but one of the most important is the gunsight. With a fixed sight, the shooter is almost committed to being near the target's plane of maneuver when firing. This greatly simplifies the left/right aiming problem that results from target maneuver. The shooter's marksmanship is still tested, however, by estimations of gravity drop, trajectory jump, etc., but these are greatly diminished at close range. Firing commences as the target approaches the computed aim point, and it should continue as long as the tracers show bullets passing forward of the target's tail and near its flight path.

> I liked the whole front of my windscreen to be full of the enemy aircraft when I fired.
>
> Colonel Erich "Bubi" Hartmann, GAF

The predictor LCOS is little better than a fixed sight in this environment, though it may provide gravity, jump, and other minor corrections. Its major advantage, as long as the shooter's maneuver is fairly constant for the settling time of the sight, is an accurate indication of the plane of the bullet stream (left/right reference relative to the shooter's windscreen), which must be estimated with the fixed sight. Because relative motion remains between the target and the pipper, however, lead correction (up/down relative to the shooter's windscreen) is usually inaccurate and must still be estimated. Computed lead is generally less than that required, by an amount that is proportional to the apparent LOS rate. For a reasonable chance of success with this type of sight, the shooter must get into the target's plane of turn early and establish considerable excess lead; stabilize his maneuver until the sight settles down; make small, smooth corrections to place the pipper on the target's flight path; and open fire well before the target reaches the pipper.

The historical type of LCOS is optimized for the snapshot, but it is not without problems. It is designed to show the location of bullets fired one TOF in the past, so theoretically its lead projection is accurate as long as bullets were indeed in the air one TOF previously. Settling time is generally not a problem with this sight since it is normally quite short and, except at very close range, usually expires before bullet TOF, eliminating its effect on the pipper display. These characteristics require only that the shooter somehow get the target and pipper to converge, and that he open fire at least one bullet TOF prior to convergence. Although theoretically this can be accomplished in any maneuver plane and with high LOS rates, hit and kill probability are still enhanced by low LOS rates and in-plane maneuvering.

> A good fighter pilot, like a good boxer, should have a knockout punch.... You will find one attack you prefer to all others. Work on it till you can do it to perfection . . . then use it whenever possible.
>
> Group Captain Reade Tilley, RAF
> 7 Victories, WW-II

Air-to-air gunnery is one of the most difficult skills a fighter pilot can master. Regardless of the type of sight, consistent accuracy depends on total, intense concentration on the target. Whether attempting a tracking or a snapshot pass, the shooter must make minute, smooth aiming corrections while approaching the firing position. Usually such fine control can be achieved best with conventional controls by holding the stick firmly (but not squeezing out black juice) with both hands, resting the forearms or elbows on the knees or upper legs, and applying corrections with slight variations in finger and wrist pressure. Some positive back-pressure on the controls usually helps, but in very high-G situations the shooter may prefer to trim out excessive pressure to reduce fatigue. The aircraft should be flown as close to balanced flight as possible, since most sights do not correct for bullet curvature caused by the "Magnus effect" that results from a yaw angle. (This is the phenomenon that allows baseball pitchers to throw curves.) For ammunition conservation, short bursts (about one second) should be used until the shooter is fairly certain of his firing solution, then let 'er rip. "Hosepiping" tracers at a target with long bursts is generally ineffective and severely reduces ammunition endurance. Effective training in air-to-air gunnery techniques necessitates a gunsight camera for debrief purposes. Video cameras are ideal for this purpose since film-processing time is eliminated.

> I gained in experience with every plane shot down, and now was able to fire in a calm, deliberate manner. Each attack was made in a precise manner. Distance and deflection were carefully judged before firing. This is not something that comes by accident; only by experience can a pilot overcome feelings of panic. A thousand missions could be flown and be of no use if the pilot had not exchanged fire with the enemy.
>
> Major John T. Godfrey, USAAF
> 16.33 Victories, WW-II

Guns Defense

In discussing defenses against any weapon it is useful to look at the weapon as a system. Each component of this system must work effectively if it is to succeed in its mission. Defeating any one component will defeat the system, and the more subsystems degraded, the less the chances of system success. The components of a gun system are the gun and ammunition, the gun platform (aircraft), the sight, and the aircrewman firing the guns.

The gun/ammunition combination largely determines the maximum effective range of the system at various aspects about the target. Some of the factors involved are muzzle velocity, rate of fire, dispersion, bullet aerodynamics, and fuzing characteristics. Probably the best defense against a gun is to remain outside its effective range. This may be accomplished if the defending aircraft has speed capability greater than that of the attacker and the attacker is detected far enough away (depending on aspect and overtake) to allow the defender to turn away and outrun him. When this situation exists and the defender does not wish to engage, he can make a maximum-performance turn away from the attacker to place him as close to dead astern as possible, accelerate to maximum speed, and fly as straight a line as possible until he is no longer threatened. If the defender does not put the opponent close to the six o'clock position, the attacker may continue to close to guns range because of the geometry. Turning during the run-out (arcing) allows even a slower fighter to close the range by flying across the circle. Under some circumstances it may be desirable to keep the attacker in sight during this maneuver or to change the direction of the run-out after it has begun. To maintain sight and to reduce geometric closure to a minimum, the attacker should be kept near the defender's aft visibility limit. A series of small, hard turns can be made in the desired direction (allowing the attacker to be kept in sight), and each turn can be followed by a period of straight-line flight until the attacker drifts back to the aft visibility limit; this process can be repeated until the desired heading is reached. Sight can be maintained after this point by making a series of these small turns alternately left and right of the desired course. This technique is often called an "extension maneuver."

The next best thing to denying the attacker any shot at all is to deny him a good shot. This can be accomplished by complicating the task of any of the gun subsystems. Looking a little deeper into the requirements for a good gun shot will clarify the discussion that follows. Figure 1-4 is a representative guns "envelope," looking down on the target located in the center, which is heading toward the top of the page. It can be seen that the effective guns envelope is defined by the min-range boundary (primarily a function of closure) and the max-range boundary (primarily a function of gun/ammunition characteristics, dispersion, lethality, gunsight, closure, apparent target size, and vulnerability). Note that min-range is much greater in the target's forward hemisphere because of higher closure. Max-range is also generally greater in the forward hemisphere for the same reason. This relates to shorter bullet TOF, smaller dispersion radius, and greater bullet density on the target. Lethality is also improved in the forward hemisphere since greater bullet kinetic energy is provided by the closure. Maximum effective range increases in the target's beam because of larger apparent target size and better fuzing of the shells (cannon) resulting from a higher "grazing angle" with the target. Low grazing angles in the forward and rear quarters may allow shells to bounce off the target without penetrating or exploding.

As might be expected, within the overall effective envelope of the gun some areas are better than others. The tracking area is limited on the min-range side by the attacker's ability to turn fast enough to stop the target's LOS rate. In the case depicted, the target can be tracked slightly forward of the beam at long ranges. The forward limit is predicated on sufficient tracking time between max- and min-range to ensure destruc-

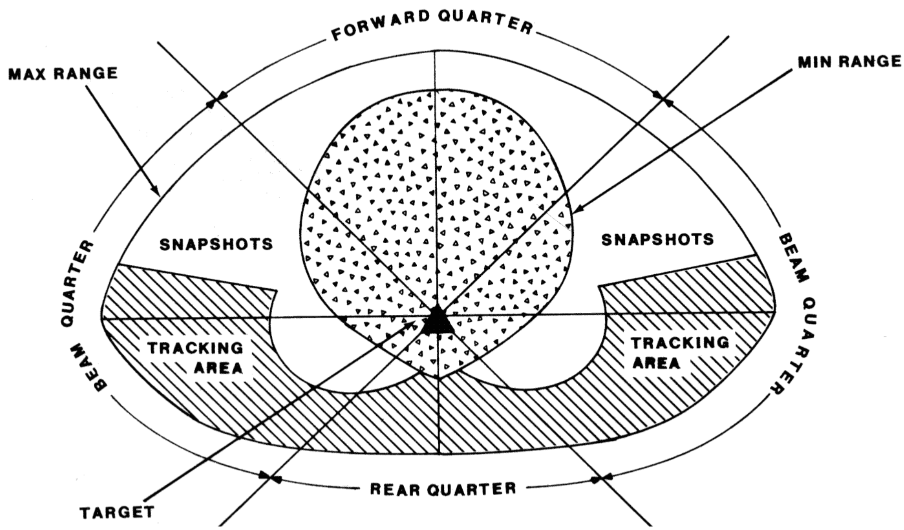

Figure 1-4. Effective Guns Envelope

tion of the target. As closure increases forward of the target's beam region, tracking time is reduced. Even within the tracking envelope there are many tradeoffs. When factors such as ease of tracking, closure, tracking time, and apparent target area are weighed, the optimum tracking region with a LCOS is generally found to be about 30° to 60° off the target's tail. Closer to the stern position may be better with fixed sights because of reduced deflection.

Although drawn in two dimensions, this envelope is actually three dimensional and would probably vary only slightly depending on the attacker's position relative to the target's plane of symmetry. The optimum LCOS tracking zone can be envisioned, therefore, as the volume between two cones extending rearward from the target's tail at about 30° and 60° angles, with appropriate max- and min-range limits. Outside the full tracking area as depicted, but still within effective range limits, is an area in which only snapshots are possible.

> As long as I look right into the muzzles, nothing can happen to me. Only if he pulls lead am I in danger.
>
> Captain Hans-Joachim Marseille, Luftwaffe
> 158 Victories (17 in One Day), WW-II

If the attacker cannot be prevented from reaching effective guns range, the next priority is to keep him out of the tracking area, where kill probability is highest. This is accomplished most effectively by performing a maximum-performance "break" turn toward the attacker to rotate him into the forward hemisphere, generally the farther forward the better, since this also degrades his snapshot capabilities. The AOT is increased most rapidly by placing the attacker in the plane of the break turn, which is accomplished by first rolling to put the attacker near the vertical plane of the aircraft, i.e., along the centerline of the canopy. However, an in-plane turn by the defender solves many of the shooter's sighting problems and must be used judiciously. The in-plane turn should not be used once the shooter's range and nose position indicate that he may be about to open fire. This point must be assessed visually by the defender, and determining it requires practice. In most cases, with any deflection at all, the shooter's nose must be pointed ahead of the defender to be threatening. This should give the defender a view of the belly of the attacking aircraft. One notable exception to this rule is a fighter designed with guns that are canted slightly upward relative to the axis of the aircraft. Such a fighter may have proper lead when its nose appears to point directly at, or slightly behind, the defender.

> Watching carefully over your shoulder and judging the moment he will open fire, you turn your machine quickly so as to fly at right angles to him. His bullets will generally pass behind you during the maneuver.
>
> Lt. Colonel W. A. "Billy" Bishop, RAF

The break turn does several things for the defender in conjunction with increasing AOT. High G and greater AOT increase the shooter's lead requirement. If he failed to allow adequate excess lead during his approach, he may not be able to generate it after the break. The resulting higher tracking G, shorter firing time, and increased min-range also make the attacker's job more difficult.

The following episode describes a successful guns defense begun just a little too late. Here John Godfrey is flying a P-47 and is attacked by an unseen Me 109.

> "Break, Purple Two, break!" It was too late, a 109 was right on my tail, and I heard the thunder of explosions as his cannon shells burst in my plane. Fiery red balls were passing on all sides of me. *Crunch,* I was hit in the wing. *Crunch,* one exploded in back of my armor plating, and chunks of shrapnel smashed against my instrument panel. It would be only a matter of seconds now. I had lost air speed, and even if I turned left or right, or dived, I would still, probably, not be able to escape him. But then I remembered sitting back in Eshott, listening to two RAF Battle of Britain pilots talking. Their words stuck in my memory: "The important thing is to do something. Make no movement gently, but be as violent as possible. Pull back on the stick and apply left rudder at the same time. It might rip the wings out of the plane, but if you're a goner anyway, what's the difference?"
>
> All this raced through my mind at the same time, no longer than it takes to blink an eyelash. I nearly pulled the control stick from its socket with my violent yank; at the same time I pushed with all the strength of a desperate man against the left rudder bar. The maneuver blacked me out.[3]

If the shooter is able to maintain his firing position, both range and lead, a continued break turn is no longer appropriate. Continuation of an in-plane turn past this point can result in sustained tracking or a very deadly in-plane snapshot. As the shooter regains his firing position the defender should roll quickly about 90° in either direction, using maximum-performance roll techniques, to throw the attacker rapidly out-of-plane. The defender then reapplies G to turn sharply in a plane perpendicular to that of the shooter. This second turn is continued until the shooter breaks off his attack for minimum range or no longer positions his nose for a shot. A slow roll toward the attacker is required to keep the shooter in the defender's horizontal plane, i.e., in the plane of the defender's wings, so that the perpendicular plane of maneuver is maintained throughout. The defender is actually performing a near "barrel roll," inscribing a circle around the shooter's aircraft. The attacker's closure will generally cause him to break off the attack or overshoot the defender's flight path well before the defender completes 360° of this maneuver. This tactic is illustrated in Figure 1-5.

At time "1" in this example the defender sees the attacker approaching from the right at about co-altitude and approximately 90° off the tail, apparently attempting to close to guns range. The defender quickly rolls right and breaks into the bogey in an attempt to increase AOT as much as possible. The attacker also rolls right and pulls to maintain his lead and begin the saddle-up process by maneuvering in the same plane as his target (in a level turn at the same altitude in this case) while continuing to close. At time "2" the defender judges by the attacker's range and nose position that he is about to open fire. A continued in-plane turn past this point could be fatal, since it offers the shooter a nice steady target to track.

Instead, the defender rolls farther right, almost to the inverted position, and pulls down hard. After this roll the defender will be looking at his opponent out the left side of the cockpit, near the left wingtip. The shooter is no longer in the target's plane of motion and must maneuver radically to reposition for the shot. In this case he also rolls inverted and tries to follow the target through its defensive maneuver. The defender continues to pull, and rolls slowly toward the bogey (i.e., left) in order to hold the attacker on the left wingtip. This technique continuously changes the target's plane of maneuver (spiral) and prevents the attacker from saddling-up. By time "3" the shooter can no longer follow the target through the maneuver; he loses the lead necessary for a shot and overshoots the defender's flight path.

Assuming the shooter's original plane of attack is nearly horizontal, this rolling out-of-plane maneuver will be initiated either nose-high or nose-low, as in Figure 1-5. The best choice depends on the tactical situation, but a turn toward the attacker's belly-side is probably tougher to counter. A nose-low maneuver, or a high-G barrel roll underneath, can result in considerable loss of altitude and is probably not wise at a low level. It does, however, have a gravity assist in its early stages and results in less speed loss during the maneuver, possibly providing better maneuverability for the defender. The high-G barrel roll over the top causes greater speed loss, which will increase the closure of an attacker in the rear hemisphere. If begun at too low a speed, however, it may leave the defender too slow and unmaneuverable on top, unable to avoid a close-range snapshot. Besides speed and altitude, the choice of nose-high or -low also depends on the

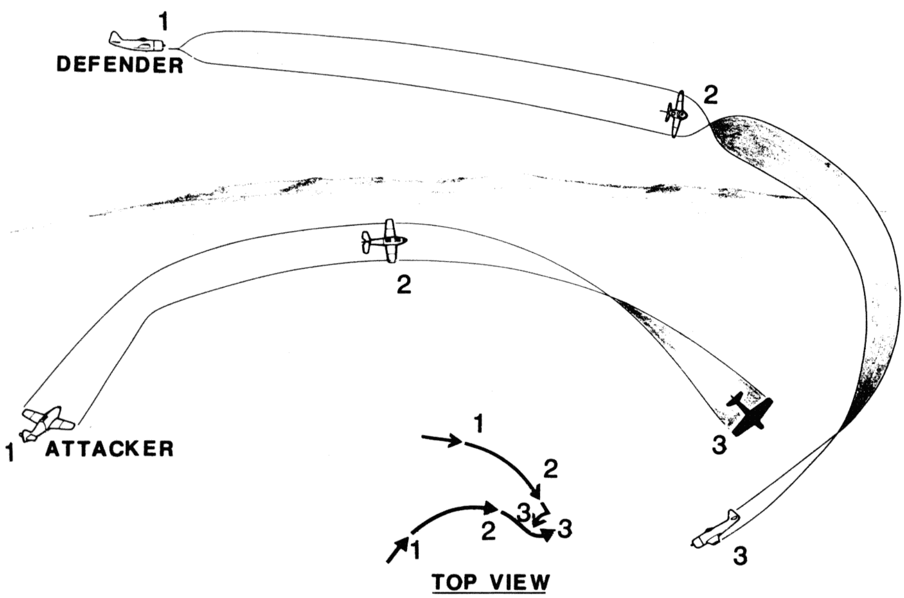

Figure 1-5. Guns-Defense Maneuvering

defender's intentions after he successfully defeats the attack. A nose-high turn usually results in a greater overshoot and may allow the defender to gain an offensive position by reversing back toward the attacker as the overshoot occurs. If the defender plans to disengage after defeating the attack, a nose-low barrel roll usually places him in a better position to begin a nose-low extension, as described earlier.

In some cases when an attacker is detected closing rapidly to guns range from the rear, defenders prefer to delay a break turn until the last possible instant, hoping that this break at close range will prevent the shooter from gaining enough lead for a snapshot and possibly cause an overshoot. Although this method can be effective, it cannot be recommended. Snapshots at high angle-off are relatively easy to defeat with out-of-plane "jinks." An attempt to avoid such a snapshot by delaying the break may give the attacker an even better shot if the break is misjudged, and it generally results in a more defensive situation for the defender after he beats the shooter's first pass.

One problem with out-of-plane maneuvers is that they require a good amount of angle off nose or tail to be effective. If the attacker is detected too late to generate AOT, or if he attacks from head-on, a turn in any direction is essentially an in-plane maneuver. When the shooter is located well to one side of the target (i.e., has a "beam aspect"), relative target motion and lead requirements are created by the target's speed, while relative motion head-on or tail-on must be generated by target G. The defender therefore must turn hard in any direction (using either positive G or negative G) long enough to change his flight path significantly, but not long enough to allow the shooter to correct his aim and track. If the defender can maintain sight of the attacker, he can estimate when the shooter has repositioned and again quickly change the plane of turn. If not, the defender must estimate the time for each new break based on what he knows of the attacker's sight system and maneuver capabilities. The clue he would like to avoid is the sight of tracers ripping by the cockpit. In either case, each jink should be made in a plane at least 90° from the direction of the previous jink. The pattern of jink planes must not be too predictable or the attacker, particularly if he is unseen, may position early for the next jink and wait for the defender to fly into his sight. The defender's roll rate and technique are of great importance in this maneuver. If the attacker has better roll performance, he may be able to track the defender from a stern position regardless of his evasive attempts.

> When he saw me behind he began to whip back and forth, left and right, as violently as he could. I followed, but it was hard to line him up for a shot. Finally, as we kept whipping back and forth, right and left, I began to shoot before he whipped and he had to fly through my fire.
>
> Major Robert S. Johnson, USAAF

This jinking procedure should be continued until the attack is terminated, usually either when the shooter closes to min-range or the defender opens to outside max-range. If the attacker already has closure and cannot be outrun, closure may be increased to hasten his passage through the firing zone by retarding power (or applying reverse thrust) and increasing drag (speedbrakes, etc.) while jinking. Once the attack has been defeated, a clean-up and max-power are normally in order for either reengagement or disengagement.

If little or no closure exists and the defender has the capability of outrunning the attacker, a slightly modified jinking procedure may be useful. Each jink can be continued until the defender has adequate rearward vision of the shooter, and might be followed by an unloaded acceleration until the shooter repositions for another shot. Another quick jink and straight-line acceleration should follow, with the periods of acceleration providing the defender with a quicker opening rate until he reaches max-range. Once again, the defender must have a roll-performance advantage if he is to have the luxury of any straight-line time. A detailed discussion of roll and acceleration techniques can be found in the Appendix.

The jink is also useful against a head-on shooter, but one or two jinks are usually sufficient to spoil this attack. Figure 1-4 shows that the effective head-on envelope is very narrow (if it exists at all), and high closure decreases firing time to only a flash. Of course, the best defense against head-on guns may be to fire first and let the other guy worry about defense. It is very difficult to aim while dodging tracers. Such a game of "chicken," however, is probably not advisable if the opponent has a more lethal gun system or a less vulnerable aircraft.

> About 3,000 yds. directly ahead of me, and at the same level, a [Me 109] was just completing a turn preparatory to reentering the fray. He saw me almost immediately and rolled out of his turn towards me so that a head-on attack became inevitable. Using both hands on the control column to steady the aircraft and thus keep my aim steady, I peered through the reflector sight at the rapidly closing enemy aircraft. We opened fire together, and immediately a hail of lead thudded into my Spitfire. One moment the Messerschmitt was a clearly defined shape, its wingspan nicely enclosed within the circle of my reflector sight, and the next it was on top of me, a terrifying blur which blotted out the sky ahead. Then we hit.[4]
>
> Group Captain Alan C. Deere, RAF
> 22.5 Victories, WW-II

Another effective tactic against a radar gunsight is chaff, the results of which are discussed later in this chapter. Briefly, chaff denies the shooter's gunsight accurate radar-range information, seriously degrading its performance. Chaff is particularly effective against range-only radars in the rear quarter, as well as against many tracking radars in beam aspects. Automatic electronic-countermeasures "black boxes" may also degrade sight performance. Another trick is to release something from the aircraft, such as drop tanks, bombs, or flares, which will tend to break the shooter's concentration and may require him to make an evasive maneuver to avoid collision.

> [The Japanese] are excellent stick-and-rudder men, but their weakness is that all their maneuvers are evenly co-ordinated. They make use of sharp turns

> and acrobatic maneuvers, seldom using skids, slips, or violent uncoordinated maneuvers in their evasive tactics.
>
> Lt. Colonel Gerald R. Johnson, USAAF
> 22 Victories, WW-II

A technique that has proven to affect adversely the performance of attacking aircrewmen is the defender's use of unbalanced flight during evasive maneuvers. This is usually done by applying large amounts of rudder in one direction or the other to make the aircraft slip or skid while making turns, causing the defender's aircraft to point at an angle to its flight path. The shooter's saddling-up technique is based almost exclusively on his ability to judge the target's flight path, and he uses the target's attitude as a cue (aligning fuselages, matching bank angle, etc.). Such out-of-balance flight gives the shooter false visual cues that can be very disturbing as well as difficult to overcome. Unconventional control systems, such as direct-lift and direct-side-force controls, and pivoting jet exhaust nozzles that "decouple" aircraft attitude from its flight path (i.e., provide turn without bank or increased load factor without increased pitch) may have even more dramatic effects. Negative-G maneuvers are also very difficult to counter.

> If a pilot sees an enemy aircraft behind him in firing range he must take evasive action immediately. He slips and skids the ship as much as possible giving the [attacker] maximum deflection. It is a good idea to turn in the direction of friendly planes, so they can shoot or scare Jerry off your tail.
>
> Major George Freddy, Jr., USAAF
> 26.83 Victories, WW-II

One further useful defensive maneuver against a near dead-stern attack is a continuous rolling turn rather than a jinking series. This tactic is similar to the out-of-plane barrel roll described earlier, but because of the attacker's lack of AOT, the out-of-plane LOS rates generated are not usually as large. The defender pulls maximum G available while rolling rather rapidly in one direction, again inscribing a circle around the attacker's flight path. This maneuver may be started either nose-high or -low and is usually accompanied by uncoordinated flight techniques, power reduction, and drag increase as available in order to increase the attacker's closure. This tactic also may be referred to as a high-G barrel roll (underneath or over the top), and it is most effective when the attacker is at close range with high overtake. It is not recommended if the attacker enjoys a substantial turn advantage over the defender (either by design or by relative airspeeds) since, if the shooter can control his overtake, he may still be camped at the defender's six o'clock after completion of the maneuver.

A modification of this maneuver has also proven useful under some circumstances. When the attacker is near six o'clock with little closure and inferior roll and acceleration performance, the defender can use a continuous low-G barrel roll. The aircraft is rolled in one direction just fast enough to prevent the attacker from matching wing positions, and a small load factor is maintained to produce a spiraling, "corkscrew" flight path.

This maneuver spoils the attacker's aim until the defender can dive and accelerate out of range using full power.

The guns defense tactics described here are designed first to defeat the gun itself (extension maneuver to deny max-range), then to defeat the gun platform (break turn to deny a tracking position), and, finally, to defeat or complicate the tasks of the gunsight and the attacking pilot (out-of-plane barrel rolls and jinks). The objectives are first, to deny any shot, second, to deny a good shot opportunity, and third, to make even a poor shot as difficult as possible. As long as the defender has awareness, speed, and altitude for maneuvering, he can make the task of an attacking gunfighter almost impossible. These are by no means the only guns defense tactics, but they have proven extremely effective.

Guided Missiles

When discussing missiles in relation to air combat this section refers to the guided variety that change their flight paths in response to target maneuvers. Unguided rockets may be thought of as big bullets, and essentially the same tactics and techniques may be applied to these weapons as to guns. Guided missiles are broadly categorized according to their mission, which is generally stated in terms of their launching platform and intended target: air-to-air, air-to-surface, surface-to-surface, and surface-to-air. This section deals primarily with air-to-air missiles (AAMs), but much of the discussion is also relevant to other types, particularly surface-to-air missiles (SAMs).

Figure 1-6 is a depiction of a generic guided missile indicating the subsystems commonly associated with these weapons. Depending on the design, some of the functions of these subsystems may be assisted or even replaced by equipment located with the launching platform. The functions of all these subsystems, however, must be performed in some manner for success of the entire system.

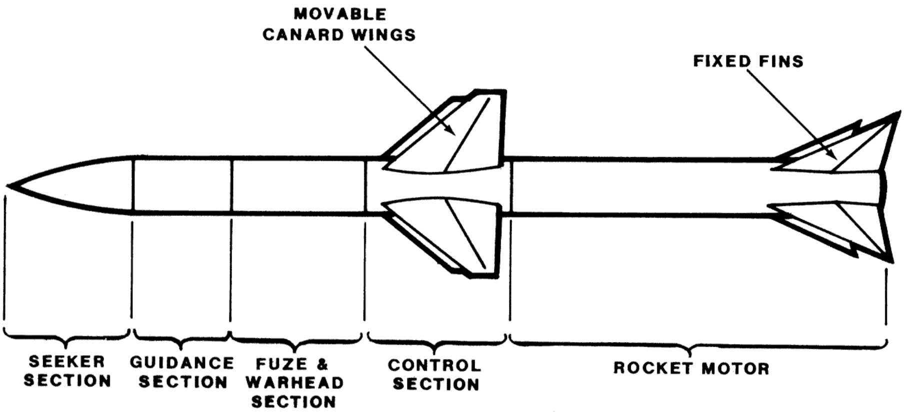

Figure 1-6. Typical Guided Missile

Missile Propulsion

The propulsion system of a missile may be of any type suitable for airborne vehicles, but because of the typically high speeds of their targets, AAMs and SAMs are generally rocket or jet powered. Rockets are usually preferred for shorter-range missiles, since rocket engines provide very high thrust-to-weight, generating great acceleration and high speeds during the short duration of the flight. Solid-fuel rockets are generally preferred because small engines of this type usually have higher thrust-to-weight, are simpler, and seldom require throttling.

As range requirements for the missile increase, so does the complexity of the motor design. Simply increasing the size of the rocket to provide greater endurance would cause the missile size and weight to grow rapidly, so more propulsive efficiency is required. For medium-range missiles this is sometimes accomplished by a solid-fuel rocket designed to produce two levels of thrust: an initial high-thrust booster and a longer-lasting, low-thrust sustainer. As the rocket grows in size to provide greater range, liquid-fuel designs become more competitive in thrust-to-weight while also providing convenient thrust control. Ramjet propulsion, however, is usually preferable to liquid-fuel rockets in this application as long as the missiles can remain within jet atmospheric limits. Often, particularly with SAMs, a solid rocket booster will be provided to assist the missile in initial acceleration to efficient ramjet operating speed.

Missile Control

The control system causes the missile to maneuver in response to inputs from the guidance system. Missiles are often controlled aerodynamically, like conventional aircraft, but they may also use thrust-vector control or an arrangement of fixed control jets. The aerodynamic controls of missiles vary little from aircraft controls. Since anti-air missiles are usually supersonic vehicles, they often use all-moving irreversible control surfaces. They also make frequent use of canard controls for improved maneuverability, as well as sophisticated autopilots to maintain stability. As with aircraft controls, missile aerodynamic controls are subject to the lift limitations of airfoils and the results of induced drag. Unlike fighters, however, missiles are seldom restricted to a limiting structural load factor, i.e., they generally operate at speeds below their corner velocities. (See the Appendix for a discussion of aerodynamics and performance.) Aerodynamically controlled missiles, therefore, often have their best turn performance at their highest speeds. With many rocket-powered missiles there is a short period of rocket thrust followed by "gliding, "or unpowered flight, for the remainder of their operation. Maximum speed, minimum weight (due to fuel exhaustion), and therefore greatest maneuverability for this type of missile would generally occur near the time of motor burnout. One of the advantages of aerodynamic controls is that they can provide control during the gliding portion of the missile's flight.

Thrust-vector control is provided by altering the direction of the exhaust gases to change the thrust line. This may be accomplished by swiveling the nozzles, by installing deflector vanes in the exhaust, or by other means to cause the missile to pivot about its CG in a severe sideslip. The thrust is then vectored to stop the body rotation at the proper heading, and, finally, it is centered to send the missile off in the desired new direction. Such a system is highly unstable and requires an extremely fast and sophisticated autopilot, but it has the potential for great maneuverability, such as the ability to turn nearly square corners at low speed. One obvious disadvantage of thrust-vector control is that the motor must be burning, making it inoperable during a gliding flight segment. This would tend to make the missile bigger for a given range and may limit its application to fairly short-range weapons.

Most thrust-vector-controlled vehicles are inherently more maneuverable at very low speeds, since there is less inertia in the missile to be overcome by the thrust in producing a change in flight direction. There are many other factors involved, however, including vehicle weight, moment of inertia about the vehicle's CG, and CG location. These factors generally tend to increase maneuverability near the point of motor burnout, so such a missile should remain very agile throughout its powered flight. This type of control is quite useful for very high-altitude missiles, since, unlike aerodynamic controls, it is not dependent on the atmosphere.

Fixed control jets, arranged around the missile body to pivot the vehicle about its CG, are just another method of thrust-vector control; in this case the thrust line is changed by rotating the entire missile rather than just the nozzle or exhaust gases. A system of fixed control jets may be lighter than a straight thrust-vector control system, since no large actuators are required. Some maneuverability may be lost, however, since greater control power is usually available from the main engine, but maneuverability characteristics are essentially the same.

Almost any control system requires actuators of some sort for movement of control surfaces, nozzles, valves, etc. The power source and the design of these actuators also have an effect on the maneuverability of the missile. These power sources are usually pneumatic, electric, or hydraulic, or some combination thereof. Pneumatic power may be provided by bottles of compressed gas or by a gas generator. Such systems are lightweight and simple, but they are generally fairly slow in reacting, particularly when heavy control loads are involved, and they have a rather limited endurance. Pneumatic control systems, therefore, are usually found only in small, short-range missiles.

Electric actuators are generally faster than pneumatic ones. Also, since virtually all guided missiles already have electrical systems, electric actuators may simplify the missile by eliminating additional systems. Electric actuators, however, are expensive and tend to be heavy when great amounts of control power are required.

Hydraulic actuators usually provide the fastest reaction time of these three methods, and they can produce great control forces efficiently. Missile hydraulic systems may be either "open" or "closed." In an open system used hydraulic fluid is vented overboard. In a closed system the used fluid is returned to the reservoir for reuse.

Missile Guidance

The guidance system provides inputs to the missile control system, which in turn maneuvers the missile to intercept the target. Guidance for AAMs and SAMs can be classified as one of the following: preset, command, beam-rider, and homing.

Preset guidance means that a prelaunch determination is made of the missile-target intercept point in space. Prior to missile launch the guidance system is provided with this information and the trajectory to be followed (by dead reckoning, inertial, or some other form of navigation) to the missile's destination. Since this information cannot be changed after the missile is fired, any inherent system inaccuracy or postlaunch target maneuver may result in a wide miss. Preset guidance is therefore closely related to the unguided rocket, and it is applicable to the anti-air mission only in conjunction with very large warheads (nuclear) or as an initial guidance mode in combination with more accurate terminal guidance techniques.

Command guidance may be likened to classic remote control. During missile flight the positions of both the target and the missile are monitored at the launching platform, and commands are sent to the missile to fly a course that will result in target interception. Tracking of target and missile is usually accomplished by radar, through electro-optics (television), or by sight. Of these three methods, only radar generally provides target/missile range information sufficiently accurate to allow computing of a lead-intercept trajectory for the missile, but since two tracking radars are usually required, this technique largely has been limited to SAM systems. Without range data the missile is ordinarily guided along the LOS between the target and the launcher. This technique, known as "command-to-LOS," can be accomplished with no range information at all and is applicable to visual and electro-optical systems as well as to radar and combination systems.

The guidance instructions to the missile are generally transmitted by radio data link, which is susceptible to jamming, as are most radar trackers. Trailing wires (wires connecting the missile and the launch platform) have been used for transmitting guidance commands with much success in several short-range air-to-surface and surface-to-surface applications. Such a system is highly resistant to jamming, and was employed by the first AAM. This was a German X-4, designed and tested late in World War II for use by the Me 262 and Fw 190. The X-4 was a command-to-LOS trailing-wire system that was controlled manually by the launching pilot along the visual LOS to the target aircraft. Apparently it was never used operationally.

Beam-rider guidance is somewhat similar to command-to-LOS guidance, except that the missile guidance system is designed to seek and follow the center of the guidance beam automatically, without specific correction instructions from the launching platform. The guidance beam may be provided by a target-tracking radar, by electro-optics, or by a visual system. Like radar-enhanced command guidance systems, radar beam-rider systems are not limited to daylight, good-weather conditions, but they are more susceptible to electronic countermeasures than are electro-optical and visual trackers.

One problem with beam-rider systems, as with command-to-LOS, is that the missile must have high maneuverability in order to intercept an evasive target. As they approach the target, beam-rider missiles often must tighten their turns continually to keep up. At high speeds tight turns may exceed the missile's capabilities. Using two radars, one for target tracking and a second for missile tracking and guidance, can reduce this problem somewhat by providing a more efficient lead trajectory, but such systems are more complex and their use is generally limited to SAMs. Beam-rider guidance, however, is usually more accurate and faster-reacting than command guidance systems, and it can be quite effective against even evasive aircraft targets.

The most effective type of guidance against evasive targets is homing. Within this broad category are three subtypes: passive, semi-active, and active. The simplest of these, passive homing, relies on emissions given off by the target itself (e.g., sound, radio, radar, heat, light) for its guidance information. Semi-active homing systems guide on energy reflecting off the target. This energy, usually radar or laser, is provided by a source external to the missile, often the launching platform. For active homing guidance the missile itself illuminates and tracks the target.

Before examining these guidance systems in more detail it would be helpful to investigate variations in missile trajectories. Figure 1-7 illustrates some rather simplified missile trajectories where the speed of the missiles is constant (about 1.5 times the target speed) and the target flies a

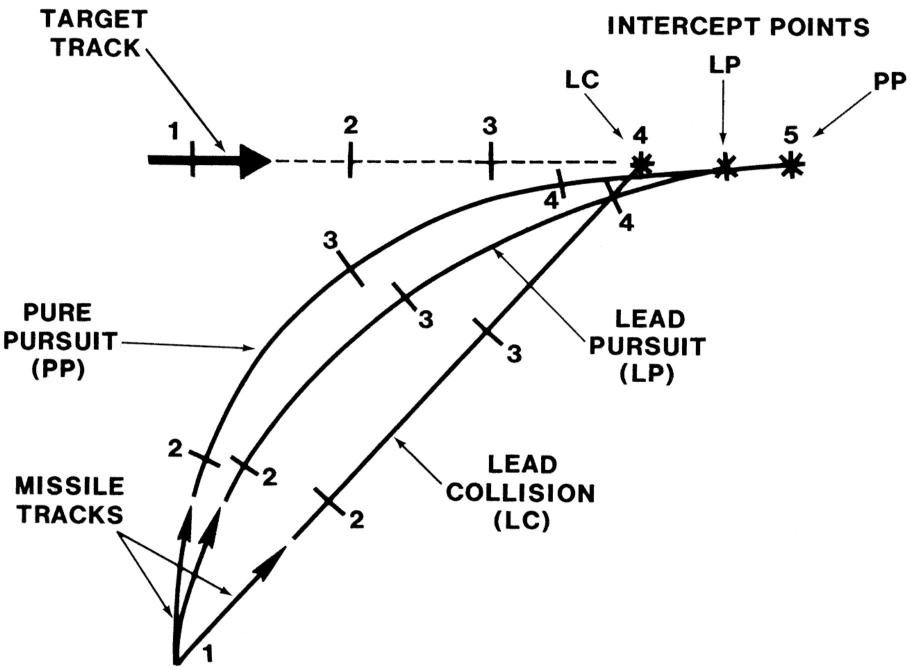

Figure 1-7. Pursuit Trajectories

straight path. The numbers along each trajectory denote time intervals after launch for ease in visualizing the geometry involved. The missiles are fired at time "1"

The missile following the "pure-pursuit" path keeps its nose (and its velocity vector) pointed directly at the target at all times, generating a curved flight path that ends in a tail-chase with the target and intercept at about point "5."

The "lead-pursuit" trajectory results from the missile leading the target somewhat, keeping its nose in front by a small amount. This is the trajectory that would be expected of a single-beam beam-rider or a command-to-LOS system where the launcher, missile, and target positions always lie in a straight line. This trajectory also terminates in a tail-chase, but the inherent lead of this system results in a slightly earlier intercept, between points "4" and "5."

The most efficient trajectory depicted here is the "lead collision," which is a straight line with an intercept near point "4." Such a path is possible for preset, command, or beam-rider guidance systems with separate tracking and guidance beams.

Homing guidance systems may be programmed to follow any of these trajectories to the target. Pure pursuit is probably the simplest course to follow since it requires a less sophisticated guidance computer. For heat seekers, pure pursuit has the added benefit of tending to keep the missile farther into the target's rear hemisphere, which aids in maintaining a good view of a jet aircraft's tailpipe. Pure pursuit has some serious problems, however. One is reduced maximum range under many circumstances, a result of the inefficient trajectory. Another is the great amount of maneuvering required when significant AOT exists as the missile nears a fast target. This requirement is accentuated if the target turns toward the missile, and the required maneuvering may easily exceed the weapon's turn capability.

Lead collision is probably the optimum missile trajectory, since it is generally the most efficient and ideally requires the least maneuvering. It does, however, require a more sophisticated guidance system.

A lead-pursuit course, in which the missile pulls some lead but not enough for a collision course, requires essentially the same guidance complexity in a homing system as lead collision and has nearly all the problems of pure pursuit. Thus, it is seldom used by homing systems, but it is quite common with beam-riders and command guidance. Another trajectory type, known as "lag pursuit," causes the missile to point its nose behind a moving target. Because of trajectory inefficiency it is not commonly used by missiles, but it may result of necessity if the missile is unable to make its intercept turn and overshoots the target's flight path.

Passive homing has become quite popular among AAM systems because of its simplicity and resultant reliability. The first AAM to score a kill in combat [1958] was the passive heat-seeking Sidewinder missile developed by the U.S. Navy. Since that time many versions of heat-seeking missiles have emerged worldwide. The high heat output of jet engines makes heat seekers especially effective, but to some extent they may also home on reciprocating engine exhaust. Because modern aircraft can travel at speeds comparable to or even faster than the speed of sound, acoustic homing tends to result in inefficient lag-pursuit trajectories and is seldom used. This method may, however, be very effective against slow, noisy aircraft such as helicopters.

Passive homing systems are often designed to follow pure-pursuit trajectories, since target LOS is usually the only input to the guidance system. It is possible, however, with only this information, to compute a lead-collision course by a process known as "proportional navigation." This involves turning the missile until a heading is found which stops the target's apparent LOS drift rate. By maintaining this constant lead angle, the missile will theoretically fly a straight path to intercept a non-maneuvering target. In actuality the lead required to stop the LOS drift rate depends on target speed and aspect, as well as missile speed (note: no range dependence). For a nonmaneuvering target (constant speed and TAA), the lead required for a proportional-navigation course varies with missile speed. Figure 1-8 illustrates the resultant flight path of a boost-glide missile initially launched directly at the target. Immediately at launch the missile senses the target drifting to the right of its nose and turns right to stop the LOS rate (apparent target drift across the horizon) by time "2," establishing an intercept course. At this point the missile is still accelerating and its speed advantage over the target is small, requiring a rather large lead angle. As the missile's speed continues to increase, however, it requires less lead to maintain the constant LOS, and it turns back toward the

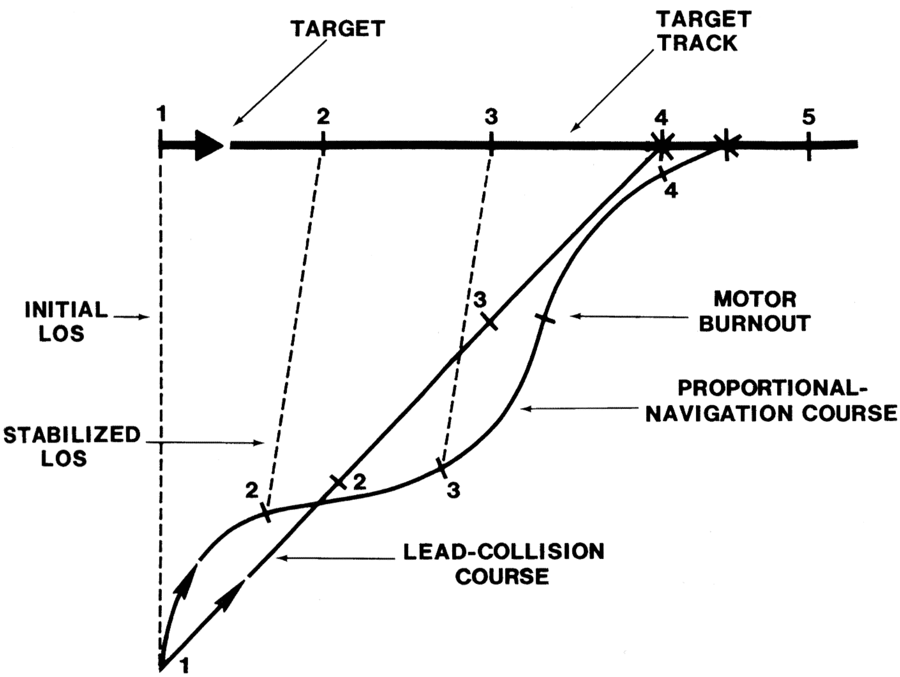

Figure 1-8. Missile Velocity Effects on Lead-Collision Trajectory

target to correct. After motor burnout the missile begins to decelerate and once again must increase its lead to complete the intercept. The ideal proportional-navigation course (or lead-collision course) for a constant-speed missile with about the same average speed is shown for reference. For a constant-speed missile, a proportional-navigation course is identical to a lead-collision trajectory against a nonmaneuvering target.

Proportional navigation assumes that the target is traveling in a straight line at any moment; should the target be maneuvering, constant lead-angle changes are required. The "perfect" lead-collision course is a straight path to the intercept point, but since the target is generally free to change its maneuver during the missile's flight, this intercept point is difficult to predict. It is usually not greatly advantageous for the missile to attempt to predict the impact point for maneuvering targets, so many "lead-collision" guidance systems actually use proportional-navigation principles.

One of the major drawbacks of passive homing is its dependence on a cooperative target that continues to emit the energy required for homing. Semi-active homing avoids this problem by having the missile home on reflected energy that is provided by another source, often the launch platform. The missile can derive LOS information from the reflected beam; or, by comparing the characteristics of the reflected beam with those of the same beam received directly from the guidance platform, it may also be able to compute target range, closure, and maneuver, for guidance and warhead-fuzing purposes. Although this guidance system provides capability against uncooperative targets, one of its major problems is greatly increased complexity, and added complexity usually results in reduced reliability. Essentially this technique requires two separate, properly operating tracking systems (one in the missile, the other in the launch platform) to be successful. Another serious drawback is the requirement for target illumination by the guidance platform throughout the missile TOF. This requirement makes the illuminator vulnerable to passive-homing weapons, and with airborne illuminators it often restricts the maneuvering options of the aircraft providing target illumination. As is explained later, predictable flight paths greatly increase vulnerability in air combat situations, and destruction of the illuminator effectively terminates its missile threat.

An active-homing system provides the source of illuminating energy in the missile itself. Although this method requires a more complex, a larger, and a more expensive missile, the total guidance system is no more involved than the semi-active system, and in some ways it is simpler and more reliable. It also gives the launching platform "launch-and-leave" capability, as do passive systems. One disadvantage, however, is the possibility of reduced target detection and tracking ranges. The maximum range of radar systems using a given power and level of technology is proportional to the area of the antenna. Since the missile is usually limited by size to carrying a smaller antenna than a launching aircraft or ground-based system can support, semi-active homing may provide greater maximum launch ranges than active homing.

The various forms of homing guidance generally offer improved capability against airborne targets, especially highly maneuverable targets. More efficient trajectories and better guidance accuracy in the critical terminal phase of the intercept are often available. Each guidance method, however, has some advantage over the others in certain situations, so combination systems are sometimes employed. An example is the use of preset or command guidance during the early portion of a long-range shot to get the missile close enough to the target to allow passive or active homing. Advances in solid-state electronics technology have made it practical to place more sophisticated guidance and sensor capability in small, lightweight missile packages.

Missile Seekers

The seeker system of a missile is responsible for sensing and tracking the target and providing the information necessary for performance of the guidance system. Preset and command guidance do not require a seeker in the missile, since the tracking function is accomplished by the launching/guidance platform. Beam-rider missiles usually have a receiver in the tail to collect information from the host guidance/tracking beam. Passive missiles generally require a sensor receiver in the nose, as do semi-active homers; but semi-active homers may also include a rear receiver for interception of information directly from the illuminating platform which can be compared to the reflected energy received by the forward sensor to derive additional guidance data. Active homers require both a transmitter and a receiver, generally located forward.

The maximum range of its seeker operation often limits the effective range of a missile system. Passive seekers have an inherent advantage here, because their received power is inversely proportional to the square of the target range, while the max-range of active and semi-active systems varies inversely with the fourth power. Several other factors also are involved. For passive systems these include the intensity of the target radiation in the direction of the sensor, the type of radiation (which determines the rate of signal attenuation by the atmosphere), and the seeker sensitivity. For active and semi-active systems maximum range depends on, in addition to transmitted power and receiver sensitivity, the reflective characteristics of the target relative to the type of illumination used. These reflective characteristics are usually sensitive to target size, and also to the target's construction material, shape, surface contours, and aspect, all of which may combine to increase or decrease reflectivity.

The most common passive seeker now in use is the heat seeker. This device contains a material (the detector) which is sensitive to heat (infrared—IR—radiation) that is produced primarily by the target's propulsion system. The detector is often cryogenically cooled to eliminate internally generated thermal "noise" and allow detection of even very small amounts of IR energy coming from an external source. The seeker must still have the capability to discriminate between target radiation and background radiation, however. Such differentiation is essential for all sensor systems, which normally require that the strength of the target signal exceed that of the background (i.e., the signal-to-noise ratio must be greater than one).

Background IR radiation is generated by the sun, by reflections off water, snow, etc., and also by clouds and hot terrain such as deserts. If the temperature of the background is within the band of sensitivity of the sensor material and is of sufficient intensity, it will be detected along with the target heat. When sensors are made sensitive to cooler targets for improved detection, the seeker becomes more susceptible to background noise also. This problem is partially resolved by designing the seeker to track only small, "point-source" radiations, usually associated with aircraft targets, rather than the broader areas of IR energy common to many background sources. In general, the seeker tends to track the most intense point-source target within its band of temperature sensitivity. The greater the background radiation within the band of temperature sensitivity of the seeker, the stronger the IR signal received from the target must be if it is to be detected and tracked. This fact may limit the detection range for a target of given IR intensity.

A hot object emits IR energy in a rather wide band of frequencies. As the object becomes hotter the radiated power increases very sharply (proportional to the fourth power of absolute temperature), and the frequency of the most intense IR radiation is shifted higher. The hot metal of jet tailpipes can be expected to emit IR energy of greater intensity and higher frequency than that of the hot exhaust gases, which begin to cool rapidly. Depending on the sensor material used, a heat-seeking missile may detect only the tailpipe, or it may also be sensitive to the cooler exhaust gas and even to the heat generated by air friction on a very fast aircraft. One disadvantage of tailpipe guidance is the likelihood that the hot metal may in some views be shielded by part of the aircraft structure. Hot exhaust gas is usually more difficult to shield, and this fact has led to heat seekers with "all-aspect" capability. However, the pilot of the target aircraft can reduce substantially the IR signature of his exhaust gases easier and faster (by power reduction) than he can his metal tailpipe, which tends to retain heat longer. The physical size of an exhaust plume may also cause problems for hot-gas seekers, as they may become "saturated" at close range. Rather sophisticated guidance techniques are required to cause such missiles to aim forward of the heat source in order to hit the target. Discrimination between this cooler target and the background radiation may also be a problem, as explained previously.

IR energy is absorbed and dissipated by water vapor, making heat seekers all but useless in clouds or rain. Even in relatively dry air this energy is attenuated more quickly than many other types of radiation, with the rate largely dependent on altitude and humidity. This characteristic makes heat seekers most compatible with short-range weapons.

Radar-guided missiles, using many of the guidance techniques discussed, are currently the most widely used all-weather AAMs. Besides weapons guidance, radars are also valuable for providing fighters with the information necessary to detect enemy aircraft at long range, at night, and in bad weather, so that they might be intercepted and attacked on advantageous terms. There are three types of radars which have application to fighter weapons: pulse, continuous wave, and pulse Doppler.

Pulse radars work by transmitting a burst of radio energy (pulse) and then receiving echoes of that pulse reflected off distant objects. If the antenna is highly directional, aiming the energy pulse almost entirely within a very narrow beam, the LOS to the target (azimuth and elevation) can be accurately determined. This narrow beam can be formed mechanically (parabolic-shaped antenna) or electronically (phased-array antenna). Also, since radio waves travel at a known speed, the time elapsed between transmittal of the pulse and receipt of the echo can be measured to derive target range.

Radar electronics requires many compromises. Desirable features include small size, light weight, long range, good range and angular accuracy (resolution), and short minimum range. Unfortunately, improvement in one area often leads to degradation in another. Light weight and small size are important characteristics for aircraft radars, and obtaining them usually requires relatively low-power, high-frequency units, which place limitations on range. The small size of practical antennas also results in wider beams, reducing angular resolution.

Range resolution is enhanced by shortening the duration of each pulse (pulse width) so that the complete echo of a near target is received before the first echo of a farther target arrives. Shortening the pulse width, however, reduces the average transmitted power of the radar, thereby lessening its maximum range. There are some electronic processing techniques which can largely overcome this problem, allowing longer pulse widths for greater range while maintaining range resolution, but minimum-range performance, which is also proportional to pulse width, usually must be sacrificed.

As the name implies, continuous-wave (CW) radars are not pulsed, they transmit continuously. This means that the antenna used for transmission cannot be used for reception, as with pulse radars, so multiple antennas are required. CW is used quite often for semi-active and beam-rider missile guidance, with the host platform transmitting and the missile seeker receiving the transmission and/or the reflected energy. For long-range shots the CW energy may be formed into a narrow beam and directed at the target by the host tracking system. For short-range firings a fixed, wide-angle antenna may be used to illuminate targets within its field of view.

CW radars generally measure target closing velocity by the Doppler principle, which most often is illustrated by the change in pitch (frequency) of the whistle on a passing train. While the train is approaching, one pitch is heard (higher than that actually produced by the whistle), and as the train passes the pitch seems to decrease to a lower frequency. Relative motion changes the frequency of sound waves or other waves such that closing velocity between the source of the transmission and the receiver causes an apparent frequency increase, while opening velocity causes a decrease. This frequency shift is proportional to the closure and offers a direct means of velocity measurement.

Since CW radars have no pulses that can be timed for range determination, another method is necessary. This is generally accomplished through a frequency-modulation (FM) technique. If the transmitter frequency is varied continuously up and down, the reflected wave will vary in the same manner. The peaks of the reflected wave, however, will be delayed (phase shifted) by a length of time proportional to the range between the receiver and the target. The accuracy of FM ranging is usually inversely proportional to target range (i.e., accuracy improves as range decreases), unlike pulse-ranging accuracy, which is fairly independent of range. So, although FM ranging can be very accurate over short distances, its accuracy is usually inferior to that of pulse technique at greater ranges.

The great advantage of CW over pulse radar is its much higher average transmitted power, since the transmitter does not have to turn off and wait for an echo. The pulse-ranging technique requires long listening periods between each pulse because of the time necessary for the pulse to reach a distant target and return. Such a radar is classified as having a low pulse-repetition frequency (low PRF). Low PRF results in less average power and fewer pulses of energy reaching the target per second, reducing range performance. Another method, known as high PRF, allows many pulses to be in the air at a given time and substitutes FM-ranging techniques for conventional pulse ranging. This results in greater average power and the long-range benefits of CW, while allowing the double use of a single antenna, as with pulse.

Pulse-Doppler radars are commonly of this high-PRF variety. They send out pulses of a very finely tuned (coherent) frequency and listen for returns of a different frequency, which would indicate Doppler effect from bouncing off a moving object. This technique offers the great advantage of being able to distinguish moving targets from stationary ones, such as the ground. Again, FM ranging normally is employed.

One of the most severe limitations of pulse radars is ground clutter, or reflections off the earth's surface. These reflections may be returns of the radar's main beam, or of any of the many weaker side lobes of energy radiated in all directions because of antenna imperfections and other factors. Clutter is seen by a receiver as noise, and the strength of the target return must exceed that of the noise by a given amount for target detection. When a target is close to the ground its return may lie within the main-beam clutter (MBC) of an illuminating radar. In this case the target will most likely be obscured by the noise created by the ground. Likewise, when the radar platform is near the ground, reflections from the side lobes generate noise in the receiver, even when the radar is looking up, requiring increased power in the target return before detection is possible, and reducing maximum range.

Doppler radars in moving aircraft also have problems with clutter, since returns off the ground reflect the host aircraft's own airspeed. Because this speed is known, however, MBC can be eliminated by "blanking out" returns of the approximate frequency associated with this closing velocity, so that the intensity of the clutter return will not overpower the receiver.

Of course, this technique also eliminates any returns from real targets having about the same closure, which includes those with beam aspects (approximately 90° TAA). MBC is less of a problem with high-altitude targets or when the radar is looking up at the target. By not blanking out the MBC, radar missiles may retain a capability under such conditions against targets with beam aspects.

Because Doppler radars only detect relative motion, targets flying in nearly the same direction at about the same speed as the host aircraft may not be detected either. Since side-lobe clutter (SLC) is associated with closing speeds equal to or less than the host aircraft's own airspeed, it too may be eliminated. But because this procedure would limit detectable targets to those with forward aspects, and SLC is usually fairly weak, this is generally not done. Doppler SLC does, however, limit detection ranges when the host aircraft is in the target's rear hemisphere. The amount of this degradation is largely dependent on the host aircraft's altitude.

Doppler's great advantage is in detecting targets with high closure (forward aspects), in which case clutter is not a problem even when the radar is looking down. This leads to radars with so-called "look-down" capability. A missile directed by such a system is said to have "shoot-down" capability. A given Doppler radar is limited, however, in the band of return frequencies it can detect. It is theoretically possible, therefore, for a target to be closing or opening too fast to be detected.

Besides detection problems, various types of missile seekers have other limitations. Most missiles that employ proportional-navigation techniques require a movable seeker to keep track of the target. Such seekers have physical stops in all directions, called gimbal limits, which restrict their field of view and therefore limit the amount of lead the missile may develop while the seeker points at the target. If the seeker bumps the gimbal limit, the missile usually loses its guidance capability. Such situations most often develop when the missile's speed advantage over the target is low and the target LOS rate is high. This may occur early in the missile's flight, before it has accelerated fully, with a high target LOS rate. It also becomes a problem near maximum range, when the missile has decelerated greatly and must pull more and more lead to maintain a stationary target LOS.

Although the gimbal limit may be bumped in a hard-turning intercept with a maneuvering target when the missile's turn capability cannot quite stop the target LOS drift, this situation more often leads to exceeding the seeker's tracking-rate limit. Missile seekers are usually gyro-stabilized to point along a fixed line in space, much like the needle of a magnetic compass. The body of the missile is then free to turn about the "fixed" seeker. Such motion causes little problem and generally is limited only by the missile's turn capability and the seeker's gimbal limits. If the seeker's LOS must be changed, however, because of changing target LOS, its gyro must be precessed. The rate at which this can be accomplished (known as the target's maximum gyro tracking rate) is limited, and it is often dependent on the target's signal-to-noise ratio.

Missile Fuzes

The purpose of a missile fuze system, is to cause the detonation of the warhead at the time that produces the maximum target damage, while also ensuring the safety of the firing platform and personnel. Typically, a fuze is "armed" (made capable of causing warhead detonation) when it senses that firing has occurred and that safe separation from the firing platform has been achieved. The acceleration of the missile during motor burn may be used to start a timing mechanism for arming, or any number of other methods may be employed. Once a fuze is armed, another fuze function is required in order to detonate the warhead.

Fuzes can be classified as contact, time delay, command, and proximity. Contact fuzes were discussed previously in conjunction with explosive cannon projectiles. Nearly all anti-aircraft missiles have such a fuze, either alone or in combination with another type. Time-delay fuzes are preset before launch to explode at a given time that is calculated to place the missile in the vicinity of the target. This is a fuze commonly used by large-caliber anti-aircraft artillery, but seldom by missiles because of its lack of accuracy. Command fuzes are activated by radio command from the guidance platform when the tracking system indicates that the missile has reached its closest point of approach to the target. This method is most applicable to command-type guidance systems and generally requires relatively large warheads to be effective against airborne targets.

Proximity fuzes are probably the most effective fuzes against maneuvering aircraft; they come in many designs, including passive, semi-active, and active. Passive fuzes rely for their activation on a phenomenon associated with the target. This might be noise, heat, radio emissions, etc. Semi-active fuzes generally function on an interaction between the guidance system and the target, such as rapidly dropping Doppler frequency or high target LOS rates. An active fuze sends out some sort of signal and activates when it receives a reflection from the target. Popular designs include radio-proximity fuzes and laser fuzes. For maximum effectiveness the proximity fuze should be capable of detecting the target out to the maximum lethal radius of the warhead.

Because of the wide range of intercept conditions possible in engagements with aircraft targets, fuze design is one of the weakest links in missile systems. Proximity fuzes are usually tailored to the guidance trajectory of the missile, the most probable target, and the most likely intercept geometry. "Functional delays" are generally used for this purpose. For instance, if a missile is expected to approach the target from the rear with a relatively low closure, a fairly long functional delay might be incorporated to allow the missile to travel from the target's tailpipe area (where detection would presumably occur) to some point near the middle of the target, where an explosion would probably do the most damage. However, if this missile intercepted the target from the side or head-on, such a time delay might cause detonation past the target, resulting in little or no damage.

All-aspect missiles, because of their larger variety of possible intercept conditions, offer the greatest challenge to the fuze designer. One approach is sometimes called an "adaptive" fuze, which might alter fuze delays during the missile's flight based on projected intercept conditions calculated from guidance data. Such a fuze might also "aim" the warhead to cause maximum destructive effects on the target side of the missile at intercept.

Missile Warheads

The warheads used in AAMs are typically blast-fragmentation types, incendiary or explosive pellets, or expanding-rod types. Blast-fragmentation warheads are intended to cause damage through the combined effects of the explosive shock wave and high-velocity fragments (usually pieces of the warhead casing). Pellet designs are similar, except some of the fragments are actually small bomblets that explode or burn on contact with, or penetration of, the target. Because of the decreased air density at high altitude, the damage to airborne targets from blast effect alone is not usually great unless the missile actually hits the target, penetrates, and explodes inside. Fragments tend to spread out from the point of the explosion, rapidly losing killing power as miss distance increases. Explosive or incendiary pellets reduce this problem somewhat since a single hit can do more damage. The expanding-rod warhead also addresses this problem. It is comprised of many short lengths of steel rod placed side by side in an annular arrangement around the explosive material. The rods are welded together at alternate ends so that when detonation occurs they expand outward in a solid, continuous ring, much like an expanding watch band, until reaching their maximum radius. In theory this continuous rod is more likely to cut through control cables, hydraulic and fuel lines, and structural members than are individual fragments. In addition, the lethality of such a warhead should be maintained to greater distances, since the damaging fragments do not spread apart. In practice, however, such expanding rods often separate early in the explosion, leaving large gaps in the warhead coverage.

The lethality of a warhead depends largely on the amount of explosive material and the number and size of the fragments. Warheads should be designed with specific target types in mind, and they must complement the missile guidance and fuze design. Larger expected miss distances and imprecise fuzes require bigger warheads.

Fuzes must make allowance for the fact that the missile's forward velocity is imparted to the warhead fragments on detonation, so that as they expand they are also moving forward, forming a cone-shaped lethal volume ahead of the warhead detonation point. Warheads have been developed which can aim most of their fragments in the direction of the target based on fuze command. "Shaped charges" have been used to enhance target penetration, particularly with contact fuzes. Nuclear warheads also may be employed for special situations.

Missile Employment

Employment of AAMs involves satisfying the requirements of the particular missile in the given situation. Missiles are complicated systems comprised of many interdependent subsystems, each having limitations. All these limitations must be observed for a successful shot.

One method of visualizing the capabilities and limitations of a missile is to study its firing envelope. Figure 1-9 illustrates two such envelopes for a hypothetical Doppler-radar-homing AAM. One envelope is for a non-maneuvering target, and the other is for a target in a continuous level turn.

The nonmaneuvering envelope is a scale diagram looking down from above a target (the arrow) which is flying toward the top of the page. The various boundaries depicted illustrate the missile capabilities and limitations. Assume first of all that the shooter has obtained the required radar track on the target and has aimed the missile in the proper direction for launch.

The outermost boundary is the maximum aerodynamic, or "kinematic," range at which the missile is capable of guiding to within the lethal miss-distance of the target. This boundary reflects the capabilities of the missile propulsion, guidance, and control systems, as well as the speeds of the launching aircraft and target and the aspect (position relative to the target) from which the missile is launched. One of the most striking features of this boundary is the great difference in maximum range between forward-quarter and rear-quarter shots: here, about five to one. This obviously reflects the fact that the target is flying toward a missile fired in its forward quarter and is running away from a rear-quarter shot.

The seeker-limit line shows the tracking limit of the missile's radar seeker based on the reflectivity of this particular target. Remember that this reflectivity is a function of target size and other factors. Since missile radar antennas are necessarily small, their range is limited. In this case the seeker capability restricts the maximum forward-quarter firing range; but with a larger target, or at a lower altitude (where maximum aerodynamic range is reduced), it may not.

The narrow zones marked "look-up required" on both sides of the target are associated with ground clutter, the Doppler MBC previously discussed. Missiles required to look down on the target, especially at low altitude, from a beam aspect are likely to lose track of the target in the clutter. Looking up at the target reduces MBC and allows continuous track of the target.

The wider areas on either side of the target reflect the fuzing and warhead problems associated with beam-quarter target intercepts. The missile may guide to well within lethal distance, but the geometry of the intercept and the design of the fuze and the warhead may cause detonation to occur on the far side of the target, possible resulting in no damage. A missile launched from this area is not considered to have a high probability of success. The small area in the stern quarter near maximum-kinematic range is also the result of a fuze limitation. In this case there is insufficient missile closing velocity at target intercept for proper fuze functioning.

The inner boundary surrounding the target is the minimum-range limit. Depending on the aspect this may be the result of fuze-arming time, the missile's turning capability, guidance reaction time, or the seeker's gimbal limits or gyro-tracking rate.

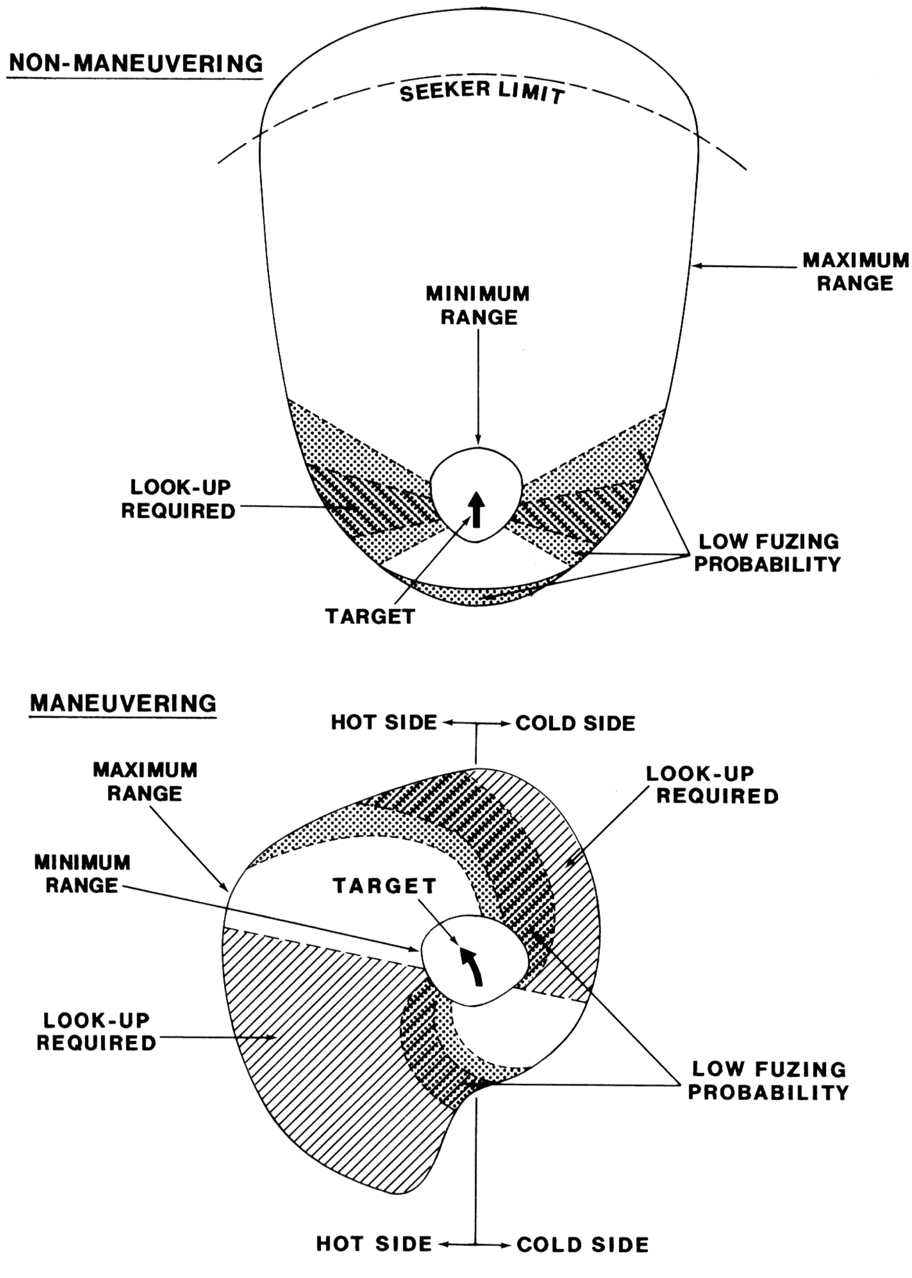

Figure 1-9. Typical Missile Envelopes

The maneuvering envelope illustrates the same conditions, with the target still flying toward the top of the page, except this time the target begins a level left-hand turn just as the missile is launched and continues this turn throughout the missile TOF. The diagram is labelled "hot side" and "cold side" to define the target's direction of turn. The labels "inside the turn" or "outside the turn" also could have been used. These terms reflect initial conditions only (i.e., the instant of missile launch), as the cold and hot sides rotate with the target aircraft as it turns. An observer on the hot side of the turn at any point normally would be looking at the top of the target aircraft, while on the cold side he would have a belly view.

The maneuvering aerodynamic max-range envelope is highly asymmetrical, with the hot-side range being much greater than the range on the cold side, as the timing of the turn is such that the target essentially is flying out to meet missiles fired from its left side, and flying away from those initially coming from the right. By choosing the direction and rate of turn, the target can exert tremendous influence on this max-range envelope. The min-range boundary is also affected, expanding somewhat on the hot side, but not to as great an extent.

The regions of the envelope requiring look-up are greatly expanded in the maneuvering case. A missile fired from these regions would have to pass through the target's beam area before intercept could occur, greatly increasing the chances of losing target track in clutter, especially if it was looking down. These regions comprise a considerable portion of the entire kinematic envelope, particularly at longer ranges, and serve to emphasize the importance of look-up when employing this type of missile against maneuvering targets.

The fuze-limited regions are also increased somewhat in the maneuvering case. A missile launched in one of these regions would intercept the target at close to a beam aspect, either hot side or cold side, with low probability of warhead damage. Also note that all max-range limits have been reduced to below the seeker-sensitivity limit, so that restriction does not affect this case.

These envelopes are already confusing, but a full picture of the capabilities of this missile would require many such charts to cover a wide range of possible target maneuvers, shooter/target speeds, and altitudes. In addition, a single fighter may carry two or three different kinds of missiles, all with widely differing operating characteristics and envelopes. Envelope recognition, therefore, becomes one of the major difficulties in AAM employment. Even if the fighter pilot could draw each envelope from memory, how would he determine the vital parameters necessary to decide which envelope was valid (including target speed and turn rate) and his position within that envelope (including range and target aspect)?

Probably the most workable solution to this problem is to equip the fighter with a tracking radar system and a fire-control computer. Such systems can accurately assess and display to the pilot the missile's aerodynamic capabilities, and as many of the other limits as might be deemed desirable, almost instantaneously. Most modern fighters have such systems.

In order to make inputs to the fire-control computer it is necessary that the radar track, rather than just detect, the target. Automatic radar tracking is possible using electronic methods that vary with the design of the particular radar system. The transition from radar detection to automatic track is called the "acquisition" or "lock-up" process. Depending on the sophistication of the radar, this too may be an automatic procedure requiring very little time or aircrew effort, or it may be a manual process of designating the target LOS and range or closing velocity so that the radar can determine which return is the desired target. Manual methods are generally adequate at longer ranges, when LOS rates are low, but once a fighter is engaged in a close-range swirling "dogfight" some automatic means of target acquisition is almost a necessity. The ability of Doppler radars to distinguish between moving airborne targets and ground clutter makes automatic acquisition systems more practical.

In some cases, however, a radar lock may not be available. If the missile (a heat seeker, for instance) does not require a host-aircraft radar lock for guidance information, then some other means of envelope recognition is necessary. Generally it is achieved by reducing the many envelopes to a very few, relatively simple "rules of thumb" which describe optimum firing zones for the missile under expected combat conditions of altitude, speed, target turn rate, etc. Pilots then must memorize these thumb rules, along with any special operating restrictions for the missile, such as requirements for look-up, acceptable load factor at launch, etc. In essence these rules of thumb provide the pilot with very simplified envelopes that give him a "ballpark idea" of his missile's capabilities. Of necessity, such simplifications will underestimate the weapon's true performance under some circumstances and be overly optimistic in others.

Once the envelope is known, recognition of the critical parameters becomes the problem. Often range and target aspect must be estimated visually, based on the apparent size and presented view of the target. Stadiametric ranging, the method by which gunsight mil dimensions are compared to the apparent size of a target of known size, was discussed in relation to air-to-air gun employment. This method may also be used with missiles, but because of the typically longer ranges of AAMs, where slight variations in apparent target size may equate to very great differences in distance, it is generally useful only at short range. A more widely used method involves the ability to discern various features of the target aircraft and equate this ability to approximate target range. For instance, at some range the target will appear to change from a mere black dot to something recognizable as an aircraft. A little closer, depending on aspect, its type may be apparent, then the canopy may become visible, followed by its markings and color scheme. Mastering such methods requires a great amount of practice, and at best this method results in rough approximations. In tests of experienced fighter pilots estimating the range of familiar aircraft, it has been found that errors of 50 to 200 percent can be expected. The results will be even worse against unfamiliar target aircraft.

> We always underestimated our range.
>
> Air Vice-Marshal J. E. "Johnnie" Johnson, RAF

Target aspect estimation presents a similar problem, with ± 30° accuracy being about the norm. The difficulty is compounded with hard-maneuvering targets, since missile envelopes are generally based on the direction of the target's velocity vector, not on its attitude, which is the only visual reference available to the attacking fighter pilot. These two references may vary widely with high target angle of attack (AOA), making visual estimation of target aspect more prone to error.

In addition to the restrictions imposed by their operating envelopes, AAMs also usually have aiming requirements. Since guided missiles can correct for some aiming error, the aiming restrictions for them are much looser than those for unguided weapons, but there are restrictions nevertheless. Some missiles, including many heat seekers, must be launched along the LOS in order to detect and guide on the target. Others may be launched with lead or lag, i.e., pointing ahead of or behind the target. A lag heading at launch is seldom beneficial for missile guidance since it requires a larger turn to establish a collision course and usually results in greater LOS rates. Lead heading can be quite helpful, however, particularly for min-range launches, by reducing the required missile maneuver. Fire-control computers often provide the pilot with an indication of the optimum lead heading, ideally allowing the missile to fly a straight path to target intercept. These inputs often make the assumption that the target is nonmaneuvering, and they may or may not account for the effect of the shooter's angle of attack on apparent lead heading, an effect that can be considerable during heavy maneuvering. AOA is a factor since missiles usually weathercock toward the relative wind immediately after launch.

Although each missile design has its own set of unique problems, most missiles are affected to a greater or lesser degree by difficulties in distinguishing the target from its background. Even though Doppler-radar guidance has largely eliminated the clutter obstacle for forward-hemisphere targets, the hypothetical maneuvering missile envelope demonstrates that limitations remain. The guidance performance of radar missiles is, in general, enhanced when the missile is looking up at a target with only sky in the background. Because of the effects of SLC, the performance of such missiles may also be degraded at low altitudes, even with look-up.

The effects of clutter are sometimes bewildering and difficult to predict. However, it usually can be said that the impact varies with the roughness of the earth's surface along the target LOS and the "grazing angle," or degree of look-down. Over land, particularly rough terrain, clutter is usually a greater factor than it is over water.

Background is also a serious problem for heat-seeking missiles, with the sun being the culprit, either directly or indirectly. The sun is much more intense than any target exhaust and will "capture" the missile seeker if the target LOS approaches too near at any point from launch to intercept. (Don't worry; nobody has hit it yet.) Reflections of the sun off water, snow, clouds, etc., can also cause problems. These produce a wide area of background IR noise, as opposed to a point source, reducing target acquisition ranges and degrading guidance through a decrease in signal-to-noise ratio. Look-down may have much the same effect, especially against hot desert backgrounds. As with radar missiles, a clear, blue sky is the optimum background for heat-seeking missile employment.

Besides the guidance problems already discussed, very low altitude employment of AAMs offers other difficulties. Most guidance and control systems cause the missile to oscillate some distance around the intended trajectory. At very low altitudes one of these corrections may result in ground impact. Fuzing can also be a concern, especially with active fuzes, since the surface may be mistaken for the target by the fuze, causing premature detonation. Ground clutter may have the same effect with Doppler-rate fuzes.

Extremely high altitudes also can cause problems for missiles, as the thin air reduces the maneuvering capability of aerodynamic controls and results in sloppy guidance.

The advent of AAMs having capability against targets with forward aspect, particularly semi-active AAMs, has increased the importance of a performance parameter known as "relative range." A missile Bred at its maximum relative range results in target impact at the greatest distance from the launching aircraft. The shooter-to-target range at impact is often called "F-pole" or stand-off distance. When two missile-equipped fighters approach nearly head-on, the one with the greater F-pole generally has the advantage, since its missile would arrive on target first. In the case of semi-active missiles, which require target illumination by the launching aircraft, this also terminates any threat from the enemy's missile still in flight. Maximum stand-off distance occurs when the missile decelerates to the speed of the launching aircraft. After this point the shooter would begin to close on his own missile, decreasing the range at target impact.

Maximum relative range is generally somewhat less than the ultimate aerodynamic range, but a missile launched at this point will arrive on target first. So, depending on average missile speed, the aircraft firing first is not necessarily the winner of such a game of "chicken." However, a missile in the air has an uncanny ability to attract the attention of the pilot in the target aircraft, often causing him to forget all about launching his own weapon. Because of this psychological factor missiles are sometimes "fired for effect" even when the shooter knows there is little chance for success. The target's defensive reaction may place the shooter in a much more favorable position. In some cases it may be advantageous to fire one missile at maximum aerodynamic range, or even beyond, for effect, and follow it with another at maximum relative range. This is often possible with radar missiles, but a second heat seeker may conceivably guide on the tailpipe of the first one, limiting the usefulness of this tactic with heat-seeking missiles. Missiles of two different types are often fired together, since target defensive countermeasures employed against one may be ineffective against the other.

Increased stand-off distance is also valuable in that it may allow assessment of the results of the first missile and, if necessary, permit the firing of another before minimum range is reached. Under almost any imaginable circumstances, missiles with launch-and-leave capability are preferable to semi-active types with about equal range, since the former do not restrict the shooter's maneuver capability after launch.

Maximum F-pole normally can be increased by firing the missile at higher aircraft speed (which in turn increases the missile's velocity), and then slowing the launching fighter as much as practical, allowing the weapon to gain greater separation. The firing fighter may also be able to turn away from the target by some amount after launch, further increasing target range at missile intercept. Slowing down and turning away from a target in the forward hemisphere also tends to reduce the opponent's effective firing range.

Missile Defense

> Here come the SAMs! The trick is seeing the launch. You can see the steam. It goes straight up, turns more level, then the booster drops off. If it maintains a relatively stable position, it's coming for you and you're in trouble. You're eager to make a move but can't. If you dodge too fast it will turn and catch you; if you wait too late it will explode near enough to get you. What you do at the right moment is poke your nose down, go down as hard as you can, pull maybe three negative Gs up to 550 knots and once it follows you down, you go up as hard as you can. It can't follow that and goes under. In a two-minute period [the North Vietnamese] once shot thirty-eight SAMs at us.[5]
>
> Brigadier General Robin Olds, USAF

The philosophy of successful missile defense is parallel to guns defense, discussed earlier. First, prevent the missile from being launched at all. Failing this, attempt to present the shooter with the least favorable shot opportunity, and then endeavor to make the missile's task as difficult as possible by attacking the capabilities and limitations of its various subsystems. The more of these subsystems with degraded performance, the less the chance of a successful missile shot. Guided missiles are normally much more complicated than gun systems, and they have more subsystems to attack. Usually the firing ranges and projectile speeds involved also will result in greater TOF, allowing the defender more time to defeat the weapon.

In order to prevent a missile firing, it is necessary to deny the shooter his required launch parameters, usually including range, aspect, and aim. The ability to achieve this objective depends on knowledge of the threat weapon system, largely based on intelligence information and prior experience. The more the defender knows about his adversary's capabilities and limitations, the more effective can be his defensive tactics. Ideally, this knowledge should include launch envelopes such as those presented in Figure 1-9, as well as any other restrictions, such as aiming requirements, threat-aircraft radar capabilities, and expected tactics.

Once these factors are known, the defender is faced with the same problem he encounters in employing his own missiles; namely, envelope recognition. The task here is often made more difficult for two reasons: the defender does not always know the type of missile he is facing, and in defensive situations his own fire-control system may not be effective in assessing his position relative to the threat envelope.

Even allowing for these limitations, there are some basic tactics which are generally effective in reducing the size of the launch envelope for missiles within broad categories. Altitude probably has the greatest effect on missile range and effectiveness. In general, the range of both jet- and rocket-powered vehicles increases when they are operating at higher altitudes. Although higher altitude reduces jet thrust, drag usually decreases even faster, particularly for supersonic vehicles, up to about the level of the tropopause. For rockets, thrust usually increases with higher altitude. This in conjunction with lower drag results in significant improvement in range with increasing altitude. Figure 1-10 gives an approximation of the effect of altitude on a rocket-powered missile's maximum aerodynamic range against a co-altitude target, using sea-level performance as a standard. Similar variations can be expected in both rear- and forward-quarter launches. Note that missile aerodynamic range increases dramatically with altitude, particularly at the higher levels. Range at 20,000 ft above mean sea level (MSL) can be expected to be about double the sea-level value, with performance doubling again by 40,000 ft. For look-up or look-down shots, range is closely related to the median altitude between the shooter and the target. Look-down shots, however, are more likely to be limited by factors other than aerodynamics.

When operating against fixed SAM sites, low altitudes can offer some benefit. Earth curvature and terrain masking provided by hills, trees, etc., may limit target acquisition range even below aerodynamic range. Ground clutter is also a proble for radar-controlled SAMs, but it can be reduced by Doppler techniques and alternative optical guidance systems. When considering very low altitude operations, the pilot must balance the benefits against mission objectives and the greater effectiveness of small arms, anti-aircraft artillery (AAA), and very short range SAMs. Within their operating envelopes most missiles can be expected to be more maneuverable at low altitude because of better aerodynamic control. Low-level operations may also limit the usefulness of the fighter's own offensive weapons system.

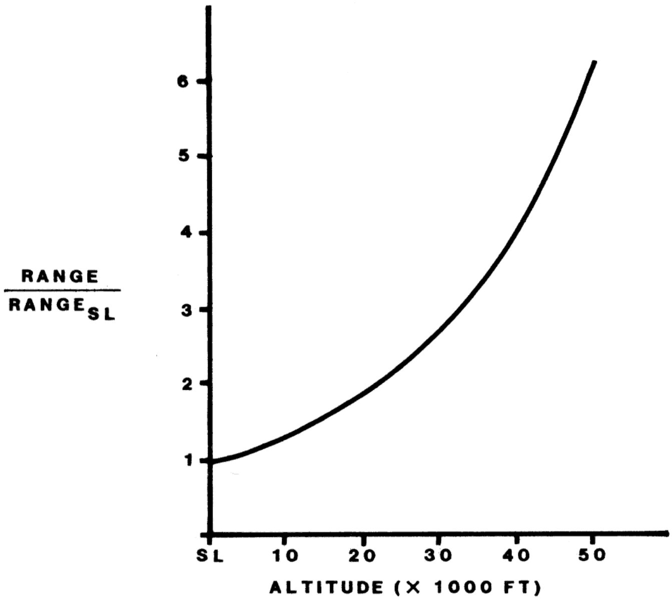

Figure 1-10. Effects of Altitude on Missile Range

Shooter and target speeds are critical elements in the aerodynamic range of missiles. Increasing the speed of both aircraft tends to reduce the range of rear-quarter missiles and increase forward-quarter range. Figure 1-11 shows typical range variations for co-speed shooter and target at various Mach numbers, using .4 M as a reference. For example, with both shooter and target aircraft at 1.0 M, forward-quarter missile range might increase by over 50 percent, and rear-quarter range might decrease more than 30 percent, as compared with the same shots when the aircraft speeds are .4 M. A target speed advantage over the shooter affects maximum aerodynamic range even further, with the percentage impact being very sensitive to the particular missile's average flight speed. The effect therefore varies widely from missile to missile, but typically a 100-knot target speed advantage (range increasing) decreases rear-quarter max-range 5 to 25 percent, with slower missiles suffering the greatest effect. Large target speed advantages can also cause acquisition difficulties for many Doppler-radar missiles fired from the rear.

In summary, the combined effects of low attitude, high speeds, and a target speed advantage can yield a dramatic reduction in the rear-quarter missile envelope. Greatest reductions in the forward quarter can be achieved by low-altitude, slow-speed operation.

Missile minimum kinematic range can also be influenced by target speed and altitude. Forward-quarter min-range is of greatest interest, since during close-in visual combat with all-aspect missiles this limit is often the most difficult to satisfy. In this instance high altitude and high speed serve to increase minimum forward-quarter range. This is because of the greater distance traveled by the target during the minimum fuze-arming time of the missile and the quicker guidance reactions required for high-

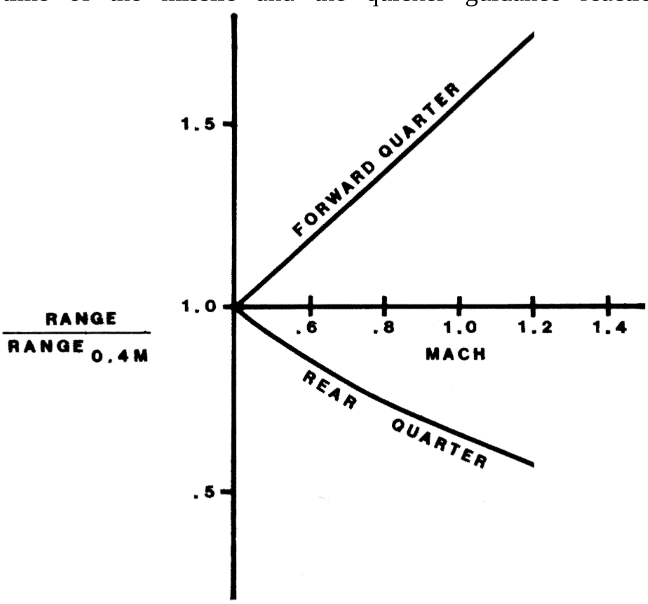

Figure 1-11. Effects of Target/Shooter Speed on Missile Range

speed targets. Higher altitudes tend to reduce missile maneuverability and increase reaction time.

Particularly with rear-quarter AAMs, but also to some extent with all-aspect missiles, a further benefit of a target speed advantage is the increased difficulty encountered by an unseen attacker in placing his aircraft within the envelope and satisfying his aiming requirements in the reduced time made available by a faster target. Especially with short-range rear-quarter weapons, for an attacker to have a reasonable chance of achieving a firing position on a nonmaneuvering target, he must be in an ideal position even before the target is detected visually.

Aircraft designers can decrease fighter vulnerability to missile attack by using many camouflage and suppression techniques. These include reducing the aircraft's radar reflectivity by using nonreflecting materials and radar-absorbing paint, when practical. Reflectivity is also sensitive to engine inlet design and placement, and to the physical size and shape of various aircraft parts. IR signatures can be suppressed by using special jet-nozzle designs, by monitoring, exhaust placement, by using engines with cooler exhausts, and by adding chemicals to the exhaust. Even optical tracking can be made more difficult by using camouflage techniques that reduce the aircraft's contrast with the background.

Besides reducing the size of his vulnerable envelope, the target has other means of preventing a missile shot. Countering an attacker's attempts to satisfy his aiming requirements is a matter of generating LOS rates that exceed the shooter's turn capability. The techniques involved with this are discussed in much greater detail in the chapters on maneuvering.

> The weapon where the man is sitting in is always superior against the other.
>
> Colonel Erich "Bubi" Hartmann, GAP

Denying the attacker a favorable target aspect is also a function of maneuvering. This is one of the primary defenses against weapons with a limited-aspect capability, such as rear-quarter heat seekers. Obviously, such a defense is more difficult to accomplish against all-aspect missiles. Some aspects, however, are less favorable than others for almost any weapon. We have already discussed the problems encountered with Doppler-guided missiles and beam aspects, especially in look-down situations. Special limitations of particular weapons, such as this one, often may be exploited to prevent or degrade a shot. For example, power reductions and IR-masking techniques can be used at critical times to prevent or delay heat-seeking missile acquisition, and to degrade guidance after launch.

A special problem encountered by most radar tracking systems is known as glint. This is a phenomenon that may cause the radar to shift auto-track among several targets that have approximately the same range (pulse radars) or closing velocity (Doppler radars) and that are closely spaced along the LOS of the tracking beam. The radar may tend to lock on one target, then another, in a random, unpredictable manner. In the case of very large targets, the radar may shift lock from one part of the aircraft to another continuously. A missile relying on such a radar for guidance often will exhibit large, jerky course changes as it attempts to guide on different targets. These maneuvers tend to increase aerodynamic drag and reduce maximum range. As the missile approaches the terminal phase it may simply guide on a point near the centroid of the target mass, resulting in a wide miss on any individual target.

Passive seekers have a similar problem. When confronted with several hot tailpipes in close proximity, a heat seeker, for instance, may guide on the centroid of the target group based on the relative intensities of the various sources.

These limitations may be exploited for defensive purposes by large numbers of aircraft flying in carefully spaced formations, usually called "cells." This tactic is more effective against missiles with remote tracking platforms, such as command and beam-rider weapons, where the tracking radar is at greater range than the missile itself. A homing missile is less susceptible since, as it nears the target cell, its tracking beam encompasses fewer and fewer targets, possibly allowing the weapon to "cut one out of the pack."

Although such tactics may be very effective against selected threats under some conditions, many radar missile systems, particularly SAMs, have alternative optical tracking, which is not susceptible to glint. Highly maneuverable fighters usually have other defensive options which are more dependable and somewhat less nerve-racking for the pilots than flying straight-and-level and watching missiles whiz through their formations.

> No matter how many SAMs a pilot might defeat, he respected them. Each SAM call brought doubts of survival and numbing fear. They were never faced complacently.
>
> Commander Randy "Duke" Cunningham, USN

A broad classification of defensive techniques is known as electronic countermeasures. These methods can be subdivided into two categories: noise and deception. Noise jamming is an attempt to produce a strong signal that will overpower the target return when it is received by the enemy radar. The attacker ideally obtains a very strong return along the LOS to the target, but he cannot get range information, since the reflected pulse is overpowered and indistinguishable in the noise. Doppler radars are generally less susceptible to this technique, since they do not require pulse timing.

The effectiveness of noise jamming is related to the ratio of the jamming power received by the enemy radar to the strength of the target return. Since reflected target energy is much more sensitive to target range than is the received noise, this method is very effective at long distances, but as range decreases the radar return power increases at a faster rate, possibly allowing "burnthrough" and target detection. Noise is also more effective if it can be concentrated in a narrow beam at the enemy radar, rather than being radiated in all directions. The jamming may be done by the target itself, or by a "stand-off jammer," which attempts to conceal other aircraft with its noise. Noise jamming actually may allow the radar receiver to detect the target LOS at much greater than the normal range, but by denying range information, noise can prevent or delay missile launch, force some missiles into less efficient pursuit trajectories, and possibly degrade fuzing.

Deception jamming involves many techniques, including generation of false targets and causing radars to lose automatic track. False targets may be produced by delaying or altering the characteristics of the reflected radar energy, by chaff, or by decoys, which either enhance the radar's return energy or continuously transmit signals that may be mistaken for echoes, thereby causing missile guidance on the wrong target. Inability to auto-track may force less efficient manual tracking and may also degrade fuzing.

One of the earliest forms of ECM was chaff, generally large quantities of radar-reflective material (often small lengths of foil or wire, but also possibly gases) released into the air to produce false targets or large "clouds" of clutterlike noise. More than forty years after its first use in World War II, it is still among the simplest and most effective ECM techniques. Since the effects of chaff are much like those of ground clutter, Doppler radars, if affected at all, are usually deceived only in beam aspects, but missile fuzing may be vulnerable at any aspect. Doppler radars may also be deceived if the chaff is blown by a strong wind.

The most common form of infrared countermeasure (IRCM) is the decoy flare. When expelled by the target this flare presents a point source of IR energy, generally more intense than that of the target, which tends to attract a heat-seeking missile. IR deception is also possible by use of a pulsing heat source, which tends to confuse IR-missile seekers. In the future there may even be defensive laser systems that can be directed at the missile to saturate its seeker.

As micro-electronics technology makes it possible to place larger amounts of "intelligence" into small missile packages, these weapons are becoming "smarter." Given sufficient information-processing capability, electronic and infrared counter-countermeasures (ECCM and IRCCM) can be devised for almost any defensive deception techniques. Such CCMs are, however, more effective in some situations than in others. If enough is known about any particular CCM technique, methods can be found to defeat it,

The quantum advances in electronics over the past few years have made the air-combat environment, and most other battlefields, virtual electronic jungles. Few air combat engagements of the future can be expected to be totally free of electronic-warfare (EW) considerations. Unfortunately for fighter aircraft, which are inherently small in size, have limited aircrew numbers, and have high aircrew task loads, most defensive ECM must be highly automated. Except for the possibility of manual deployment of chaff, flares, or small decoys, fighter aircrew involvement in ECM must be limited essentially to turning the equipment on and off once during the mission.

So far this discussion has centered on how to avoid or delay missile shots; but what if, in spite of the defender's best efforts, he suddenly receives warning, either visually or through a radar warning receiver

(RWR), that an enemy missile is airborne, possibly intended for his aircraft? The pilot's first defensive reaction is dependent on the situation; namely, what type of warning he receives, the direction and range of the threat, and the particular type of weapon approaching him. RWRs usually give the pilot a good idea of the direction of the guidance platform and, often, a fairly good idea of the type of missile that has been launched, but they do not usually provide, adequate information on the range of the threat. In addition, some weapons, particularly passive homers, may not be indicated at all by a RWR. IR or Doppler warning systems, however, may detect a missile's approach.

Visual detection of the missile, and possibly the launch platform, provides probably the best early defense against this weapon. Such a sighting furnishes a reliable threat direction, often a good indication of range, and possibly knowledge of the type of weapon involved. Because of the small size of many AAMs (particularly when viewed from the head-on aspect), their great speed, and the often limited relative motion they generate, visual range estimation can be very difficult. Visual acquisition of the launching platform at the moment of firing usually provides a better reference. Intelligence, RWR indications, and identification of the launch platform may provide reliable threat classification. The more information the target pilot receives in a timely fashion, the more effectively he can defend.

> There is nothing, absolutely nothing, to describe what goes on inside a pilot's gut when he sees a SAM get airborne.
>
> Commander Randy "Duke" Cunningham, USN

If the defender receives any warning at all, it is usually a rough indication of the threat direction by RWR or voice call. With only this information he is forced to assume a worst-case situation, i.e., imminent missile impact by an unknown weapon. Even so, he is usually far from helpless. Immediate employment of ECM, chaff, flares, and decoys is appropriate. Simultaneously a break (hard as possible) turn should be made, accompanied by a quick power reduction if any possibility of a heat seeker exists. There are several purposes for this break turn. One is to increase the LOS rate, making it more difficult for a missile to track and maneuver to an intercept. A second is to degrade seeker and guidance performance by rotating the heat source away from a rear-hemisphere IR missile or by gaining a beam aspect against a radar weapon. Attaining a beam aspect also may degrade fuze and/or warhead effectiveness. In addition, particularly when the threat has appeared in the rear hemisphere, the break turn allows the earliest visual acquisition of the missile and launch platform.

> Just as [my] missile left the rail the MiG [-21] executed a maximum G, tight turning, starboard break turn. He couldn't have seen me. Either his wingman called a break or his tail warning radar was working. I had an instantaneous plan view of him and he was really hauling.... The missile couldn't handle it, exploding out of lethal range.
>
> Commander Randy "Duke" Cunningham, USN

For forward- or rear-quarter threats, the effectiveness of a missile break depends on the target's G. Because of the usual large speed advantage of the missile over the target, a good rule of thumb is that the missile will require about five times the G capability of the target to complete a successful intercept. Although the LOS rate increase is primarily a function of target G, the time required to produce a beam aspect is dependent on target turn rate. Since the optimum instantaneous-turn-rate performance and maximum G of an aircraft are obtained near its corner velocity, it behooves the fighter aircrew to maintain at least this speed when in hostile airspace. (A discussion of turn performance can be found in the Appendix.) Faster speeds are usually not as injurious to turn performance as slower speeds, since deceleration is generally much quicker than acceleration in break-turn situations. Turn rate and radial G may also be enhanced by breaking downward, altitude permitting, to exploit the added G of gravity. Nose-down breaks have the additional advantages associated with lower altitudes and increased missile look-down. If a heat seeker is suspected, however, a break toward the sun or into a cloud might be the best move. Other defensive measures (i.e., chaff, flares, etc.) should be continued during the break turn as long as the threat may still exist, or until additional threat information is received.

The direction of the defensive break turn depends on the aspect of the threat, and usually should be in the closest direction to achieve a beam aspect. For rear-hemisphere missiles this generally means breaking toward the threat, and turning away from forward-hemisphere threats. For nearly head-on or tail-on threats, the break direction is the pilot's choice, with vertically nose-down usually preferable if that option is available. Particularly for forward-hemisphere threats, the optimum maneuver plane may have to be altered somewhat if the defender is to maintain sight of the missile.

If a threat is detected near a beam aspect, or if a break turn succeeds in producing a beam aspect before intercept, continuation of the break turn in the same plane is usually not advantageous, as this would tend to rotate the missile out of the beam region. In addition to the other possible problems already mentioned, the beam aspect presents the greatest LOS rate to the missile. One exception to this rule pertains if the threat is suspected of being a rear-hemisphere-limited heat-seeking weapon, in which case a continued turn toward the missile rotates it into the forward hemisphere, further degrading its chances of guidance.

Otherwise an out-of-plane break turn, similar to the maneuver described for guns defense (Figure 1-5), usually should be initiated against a missile in the beam region. This could mean an immediate upward or downward break on missile launch warning, or an approximate 90° change in the plane of a turn already commenced. For example, if the reaction to a rear-quarter threat had been a nose-low vertical turn (split-S) of about 90°, and indications were that the missile was then near the beam, an approximate 90° roll should be made, followed by a pull-up. This out-of-plane maneuver should be continued, while turning toward the missile (i.e., barrel-rolling around it) only fast enough to keep it in a beam aspect, until the threat has ended.

Missile range information, acquired either visually or by other means, as well as some indication of the type of weapon involved, can allow the defender a much more reasoned response. For instance, if the missile is detected near its forward-hemisphere maximum aerodynamic range, the target pilot may choose a hard turn away to place the threat in his rear quarter, accompanied by a dive and acceleration simply to outrun the reduced range capabilities of the weapon. Likewise, a max-range rear-hemisphere missile may be outrun by turning away to place it as close to dead astern as possible, diving and accelerating away. If any doubt exists as to the range capabilities of the weapon, the defender should maintain visual contact so that a last-second break turn can be accomplished as the missile approaches intercept.

Visual acquisition of the missile and its launch platform provides the defender with a wealth of valuable information. Since many missiles are of the boost-glide variety, with engines that produce large quantities of highly visible smoke or dust at launch, acquisition near the moment of firing may be critical. Weapons with smokeless engines are particularly difficult to spot visually, but even these usually produce a vapor contrail at high altitudes which can be seen for many miles.

Knowledge of the various threat weapons systems and visual sighting of the missile in flight usually can provide missile identification and an indication of the most effective defense. Missile smoke characteristics and the weapons available to a particular launch platform are two indications. The launch conditions themselves provide another. It can be assumed, for instance, that a weapon launched in the forward hemisphere has forward-hemisphere capability. If it does not, it normally will be of little danger even if the wrong identification is made. The missile's guidance trajectory offers another clue. A proportional-navigation weapon will attempt to gain lead and stabilize its position relative to the distant horizon. A beam-rider will appear to superimpose itself on the LOS to the guidance platform. A pure-pursuit missile will keep its nose pointed directly at the target and will appear to drift back along the horizon toward the rear of the defender's aircraft.

Watching the missile's flight path also can provide the defender with feedback on how well the weapon is performing. If a radical defensive maneuver is made and no missile correction is observed, the weapon is either ballistic or guiding on another aircraft in the flight. Missile trajectory response may be misleading, however. Once the weapon is at close range, defensive measures should be continued through the point of closest approach regardless of missile maneuver, since termination of such defenses could result in reduced miss distance and possible damage.

Visual acquisition of the missile provides other benefits, including knowledge of the weapon's plane of attack. The initial break turn against the missile usually should be made in this plane, since the generation of aspect and LOS rate is maximized in this manner. Timing is also important, as the effectiveness of maneuvers designed to produce large LOS rates varies with range. An out-of-plane maneuver performed too early will have little effect, while one begun late just may be too late. When in doubt, however, a slightly early response is usually preferable.

> Waiting for a proper moment to begin my evasion tactic was agonizing. Panic rose up in my throat, urging loss of reason. At the last moment I pulled up with eight Cs after breaking down and starboard. The missile couldn't take the turn, going off a thousand feet below.
>
> Commander Randy "Duke" Cunningham, USN

One example of the value of visual sighting and timing is a forward-quarter missile shot at relatively close range. Generally the rule is to turn away from such threats, but if the defender determines that intercept will occur before he can generate a beam aspect and commence an out-of-plane maneuver, another tactic may be preferable. A break turn toward the threat, actually pulling it across the target's nose, will require a large lead correction on the part of the missile. Depending on the missile's maneuver capabilities, such a correction may not be possible in the short time available because of high forward-quarter closure. If this tactic is used and the defender sees the missile correcting, presumably within sufficient time, a rapid reversal should be made back toward the missile, pulling it back across the nose from the other direction. If started soon after the missile begins its first correction, this reversal will often produce a wide overshoot in the direction of the initial break turn, since missile guidance corrections will lag target maneuvers and produce out-of-phase missile responses. A variation on this tactic is a rolling-turn maneuver that causes the target's nose to inscribe a circle around the missile (i.e., a barrel roll). Again, this move causes the missile to make continuous large lead corrections. This variation is usually most effective when the missile is 30° to 60° off the target's nose. Both tactics can be expected to produce best results against larger, less maneuverable missiles and at higher altitudes, where missile-control reaction time is usually increased.

Missile defense often requires instant analysis and rapid reactions. The tactics to be employed in any conceivable situation must be predetermined and practiced often so that they become automatic. Once the missile is launched, it is too late for leisurely development of a response.

Notes

1. John T. Godfrey, *The Look of Eagles,* pp. 79-80.
2. Ibid, p. 81.
3. Ibid., p. 85.
4. Alan C. Deere, *Nine Lives,* p. 90.
5. Edward H. Sims, Fighter Tactics and Strategy, 1914-1970, p. 245.