A Primer on Exterior Ballistics for Infantrymen

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"The modern infantry rifle is an instrument of precision and is a very powerful weapon. To attain the maximum of its effect it is necessary that he who assumes to direct or control its use should study its powers and limitations ...not only of many rifles fired on the testing grounds, but of many rifles fired by and considered in conjunction with the human, error-introducing Soldier who will use it in war."

— **CPT H.E. Eames**
The Rifle in War,
Staff College Press, 1908

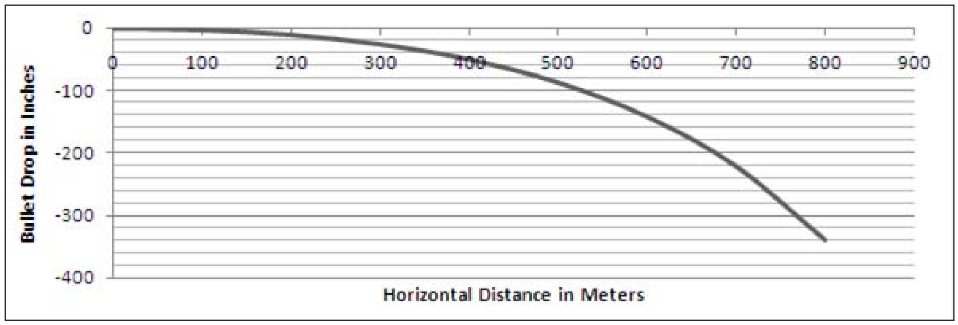
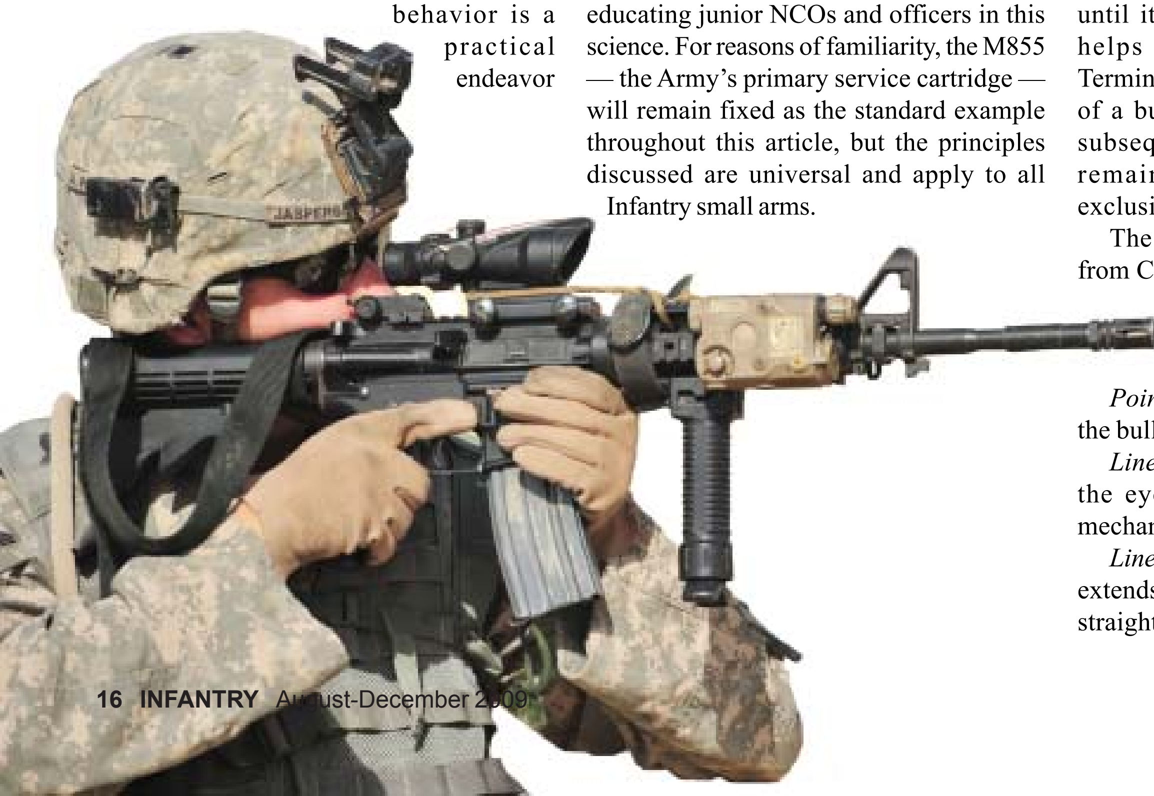


Figure 1 — M855 Trajectory at 0 Degrees Elevation

Too often, we as Infantry leaders are content to simply know that something works and are not especially curious with why or how — until there is a problem. The study of ballistics is similarly neglected. The intimidating mathematics married to this science can deter the otherwise interested marksman. Thus, the purpose of this article is to elevate the understanding of ballistics among line Infantry leaders and stimulate a thirst to master the science of marksmanship. Learning the how and why of projectile behavior is a practical endeavor for the modern Infantryman. The various climates, terrain, and enemies our Soldiers encounter on deployment demand a higher order of understanding to properly employ our direct fire weapon systems. In response, I have prepared an abridged primer on basic exterior ballistics. Being an introduction to ballistics, we will only scratch the surface of this topic, but hopefully create an itch to further its study. The point is to make the fundamentals of exterior ballistics accessible to Infantrymen to improve marksmanship and lethality in situations that are difficult or impossible to be replicated in training; and to suggest a methodology for educating junior NCOs and officers in this science. For reasons of familiarity, the M855 — the Army's primary service cartridge — will remain fixed as the standard example throughout this article, but the principles discussed are universal and apply to all Infantry small arms.



General Ballistics

The Ballista was one of the earliest missile weapons widely employed in warfare and subsequently gave its name to the science of projectile motion, according to Robert McCoy in his book *Modern Exterior Ballistics*. Over time ballistics coalesced around three major subdivisions of study — interior, exterior, and terminal ballistics. Interior ballistics is the science of projectile behavior from the beginning of movement to the moment it exits the muzzle of the firearm. Exterior ballistics is the study of projectile behavior from the time an object exits the muzzle until it reaches the point of impact and helps describe a bullet's trajectory. Terminal ballistics focuses on the behavior of a bullet as it strikes a target and the subsequent effects on that target. The remainder of this article will focus exclusively on exterior ballistics.

The following terms and definitions are from Charles S. Cummins' book *Everyday Ballistics* and are necessary language to know when discussing trajectory:

Point of Impact — the actual location the bullet strikes at the end of its trajectory.

Line of sight — the extended line from the eye, through the optic or sighting mechanism to the target.

Line of departure — the notional line that extends from the center of the rifle's bore straight out.

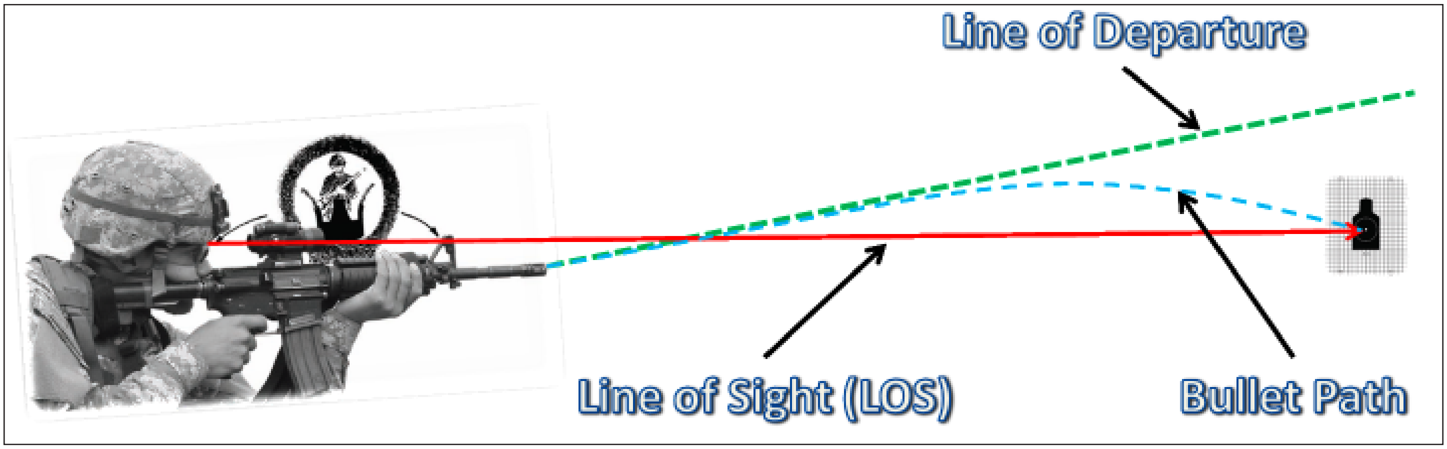


Figure 2 (Author-created graphic from FM 3-22.9)

Bullet path — the arcing trajectory of the bullet from muzzle to target.

Bullet drop — the distance measured between the bullet and the line of departure as the bullet falls.

We will first develop the elementary concepts of bullet trajectory and describe how they relate to the process of zeroing and qualifying with a service rifle at the range. If a rifle was fired such that the line of departure was completely horizontal to the ground, the bullet would rapidly plummet to the earth without reaching its 600-meter effective range. Its trajectory would look something like the one seen in Figure 1.

Therefore, to be able to engage targets at practical ranges, we must slightly elevate the weapon so that the bullet path arcs above the horizontal plane and comes back down at a known point, the target. This angle of elevation is so subtle, only a couple of degrees, that it is probably unnoticeable to the casual observer. To make this process easily repeatable, adjustable aiming devices were added to the weapon system in the form of iron sights and optics. When the rifleman looks through his correctly aligned sights, he will see the center of mass of his target. The line from his eye through the sighting apertures to the target is known as the line of sight, henceforth the LOS (see Figure 2). We may now describe the act of zeroing in ballistics terms.

Most riflemen zero based on the 25-meter standard prior to qualification (although there are strong arguments for using a 200-meter zero). The purpose of the 25-meter zero is to bring the line of sight into alignment with the bullet path at both the 25-meter and 300-meter marks. To overcome gravity, the rifle is angled slightly upward, but the LOS is not because, by definition, it is a straight line from the eye, through the sight aperture or optic to the target. The result is the intersection of the LOS and the bullet path at two locations. It occurs once when the bullet goes above the LOS near the muzzle and again when it reaches the target (In Figure 2, the differences are exaggerated to make them obvious).

Initially, beginner marksmen are taught to aim at the target's center of mass when qualifying. While it is possible to score hits on the qualification range by aiming center of mass on every target, one may increase the probability of a hit by knowing the location of his bullet along the path of its trajectory and altering the point of aim to compensate. Figure 3 displays the distance in inches from LOS at 50-meter intervals along the practical trajectory of the M855 bullet. Once a minimum level of proficiency is acquired, leaders can transition a Soldier into the more advanced practice of "holding off" based on the known trajectory of the M855.

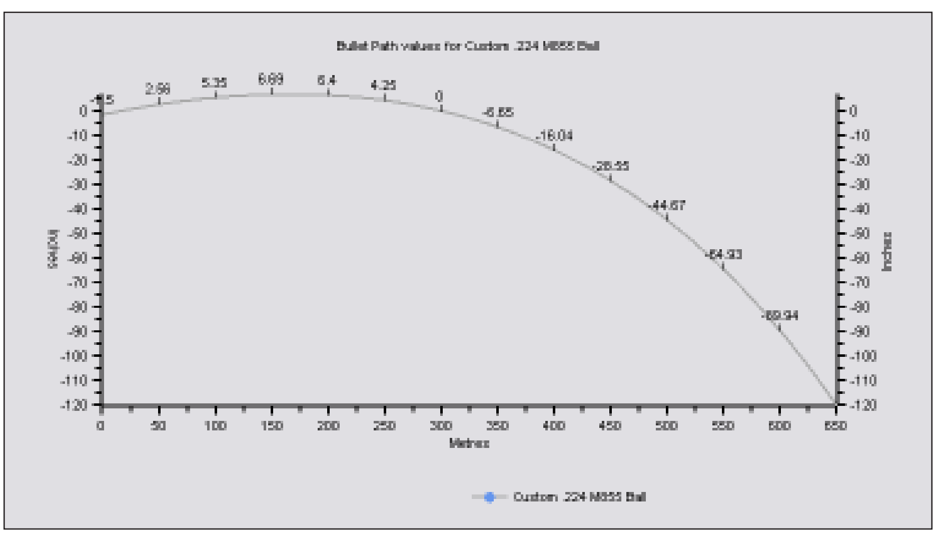


Figure 3 — Bullet Path Values for Custom .224 M855 Ball

Effects of Drag

When a bullet exits the muzzle of a standard service rifle, it reaches a velocity of about 3,025 feet per second (fps) before beginning to decelerate rapidly, according to Technical Manual (TM) 43-0001-27, *Army Ammunition Data Sheets for Small Caliber Ammunition*. In .86 seconds the velocity drops by more than half from 3,025 fps to 1,478 fps. The force of drag accounts for this rapid deceleration. While gravity's effects are reasonably predictable and change very little based on the location, drag may change the M855's trajectory in the *same* firing position from one day to the next.

Environmental Factors	AIR DENSITY	DRAG	BULLET STRIKE
Increase Altitude	*Decrease*	*Decrease*	*Higher*
Decrease Altitude	*Increase*	*Increase*	*Lower*
Increase Temperature	*Decrease*	*Decrease*	*Higher*
Decrease Temperature	*Increase*	*Increase*	*Lower*

Table 1 — Environmental Conditions' Relationship to Air Density and Drag

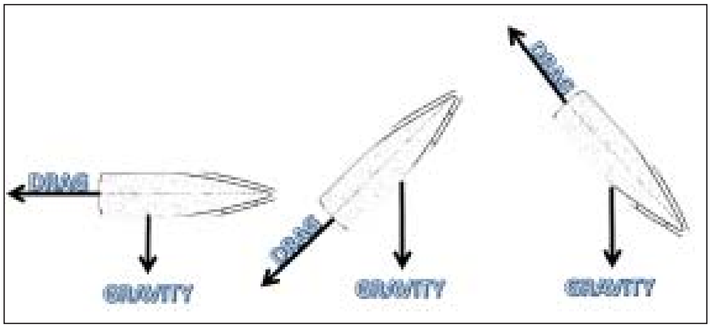


Figure 4

Drag is the force that works opposite the bullet's direction of travel. It is affected by many factors. Bullet diameter and shape are factors of drag, but they are unchanging quantities and do not require correction. The speed of sound, altitude, humidity, and temperature all affect drag because they are components of air density, and since atmospheric conditions change often this can ultimately cause bullet strike to be higher or lower than expected, according to Professor Gilbert Ames Bliss in *Mathematics for External Ballistics.* To conceptualize atmospheric conditions affecting bullet behavior, it may be useful to think of air as a fluid. In fact, physicists consider gases and liquids to be fluids (*World of Physics*, ed. Kimberley A. McGrath). Imagine the resistance on a marble if it were dropped in a kettle of hot maple syrup and then again in cold syrup. You would probably expect a different amount of resistance in each case. The concepts that govern drag's effects on a bullet traveling through air are similar and require some consideration as Soldiers deploy from one climate to a markedly different one.

Table 1 shows that as altitude increases, air density decreases. This occurs because air molecules are more widely distributed at higher altitudes and create less resistance for the bullet to pass through, thus drag too, decreases. The net effect is higher bullet strike than the firer expects. At lower temperatures air is denser since air molecules tend to become less active as the temperature drops. Again, the result is lower bullet strike. If any of these conditions is changed, the air density changes proportionally as seen in Table 1. Consider these effects when deploying or even during missions where changes in atmospheric conditions may be severe.

Uphill/Downhill Shooting Explained

From a ballistics perspective, one of the most striking features of the current operating environment is the possibility for uphill and downhill engagements. In Afghanistan, combat outposts are frequently perched on the summit of the dominant terrain feature in the area and in the urban terrain of Iraq's cities high rise buildings create metropolitan mountains and valleys. High or low angle engagement scenarios are largely unfamiliar to Infantrymen because they are not replicated in home station training leaving them ignorant of the ballistics changes that occur in such situations. The unfortunate result is that Soldiers are then baptized by fire in the valley floors of Afghanistan or narrow streets of Baghdad without appropriate training experience to draw from. Thus we must make an effort to address the physical difference in uphill and downhill marksmanship and how leaders can impart this knowledge to troops.

The reader should first take into account the forces that act on a bullet in flight. The most significant force in high or low angle scenarios is gravity. Over the entire course of a bullet's path, the force of gravity is constantly pulling the bullet directly toward earth. In contrast, drag is acting directly opposite the direction of travel. Figure 4 demonstrates this relationship.

The effects of gravity become more or less pronounced based on the distance a projectile travels *horizontally*, not based on the *actual distance* of the bullet's path, according to Cummins. When a bullet is fired in a relatively flat trajectory like a qualification range, which does not exceed four degrees of angle, these two distances are virtually the same (*Mathematics for External Ballistics*). However, if a target is elevated or depressed at a large angle, these distances can become considerably different.

The downward force of gravity acting on a bullet is less at trajectories that are angled high or low and therefore alters the trajectory at these angles. Consider a Soldier who is engaging an enemy in a hillside bunker that is at a 45-degree angle above his position. The Soldier is zeroed for 300 meters and has correctly estimated the range to target as 300 meters. He properly applies the basic rifle marksmanship principles he learned in basic training.

Table 2 — Distance Above Normal Aim Point Needed To Compensate for High/Low Angle Fire (Calculated for the M855 Cartridge)

Range (meters)	30 degrees	45 degrees	60 degrees
100	0.33 in	0.72 in	1.23 in
200	1.43 in	3.13 in	5.35 in
300	3.51 in	7.71 in	13.19 in
400	6.87 in	15.09 in	25.82 in
500	11.91 in	26.16 in	44.76 in
600	19.18 in	42.1 in	72 in

The Soldier fires and sees dust kick up several inches above his target's head. Why? When the Soldier zeroed his weapon, the terrain was flat, but now the target is at a significant angle and the effects of gravity on the bullet are reduced because the horizontal distance to the target is less at 45 degrees than at zero degrees when he zeroed. This would also be true if the target was at a downward angle of 45 degrees. (Some minor differences do develop between high and low trajectories of the same angle due to changing air densities and gravity conditions; however, they are so minute as to be negligible.) To visualize the difference these angles can make, compare the trajectories depicted in Figure 5.

The equations needed to correct these errors are not especially difficult, but it is not practical for an Infantry Soldier on patrol to attempt such calculations under fire. Rather than demonstrate the math and suggest the use of tactical mathematics, it is best to furnish these tables for the rifleman to study and visualize the compensation necessary to bring his rounds on target quickly. The chart can be recreated, laminated, and attached to the weapons' butt stock with the Soldier only needing to estimate the angle and range to use in such a situation (See Table 2).

Returning to our example, our Soldier who is engaging the enemy bunker at 300 meters away at a 45-degree elevation can see that his bullet will strike about eight inches higher than his optics indicate. He lowers his point of aim by eight inches, squeezes the trigger, and kills the enemy. It is worth reiterating that this holds true for a 45-degree decline as well. In fact, gravity's effect on trajectory is identical whether the large angle is up or down hill.

Just a Few Inches

After describing the kinds

Figure 5 — Variation Bullet Path Values for Custom .224 M855 Ball
(The solid line shows the flat range trajectory for th eM855 zeroed for 300 meters. The dashed line shows where the bullet would travel using the same zero to fire at a 300-meter target that is 45 degrees above the rifleman.)

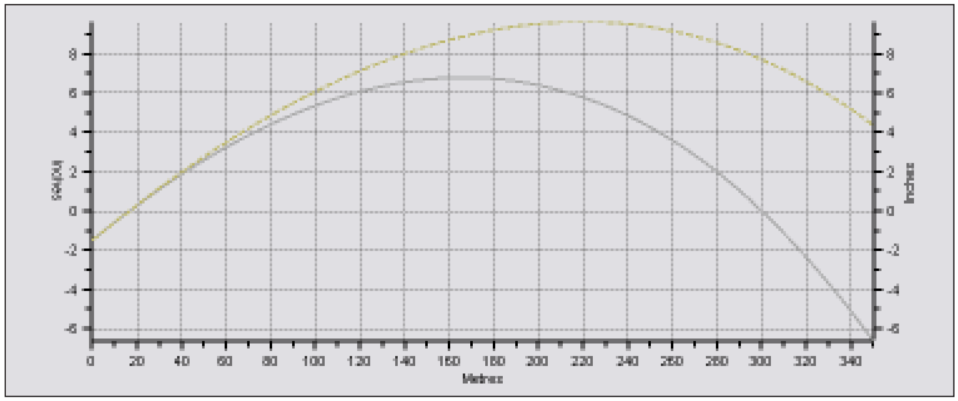
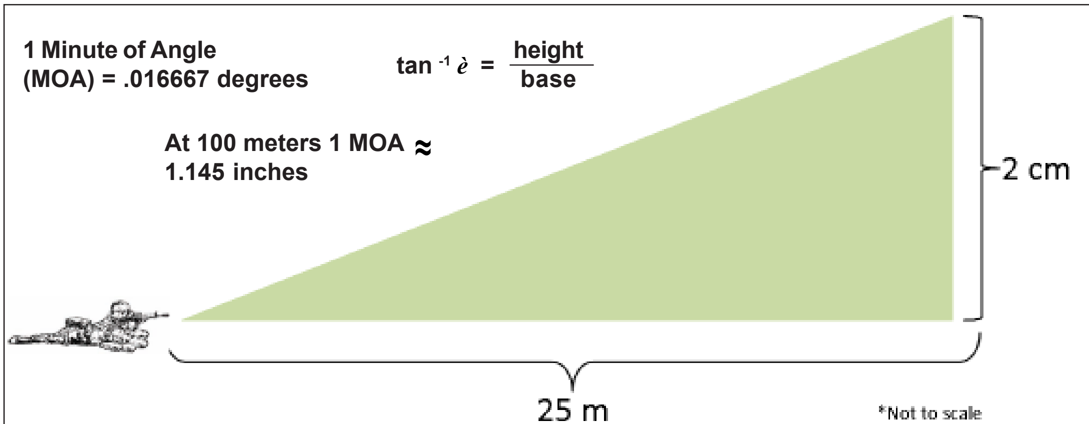


Figure 6 — Given Data and Formulas



First convert units: $\frac{2 \text{ centimeters}}{1} \times \frac{1 \text{ meter}}{100 \text{ centimeters}} = .02 \text{ meters}$

Calculate the angle of the 2 cm shot group in degrees: $\tan^{-1} \frac{.02 \text{ meters}}{25 \text{ meters}} = .0458^\circ$

Then convert from degrees to minutes of angle (MOA), a unit of measure for angles commonly used in ballistics: $\frac{.0458^\circ}{1} \times \frac{1 \text{ MOA}}{.016667} = 2.75 \text{ MOA}$

Simple multiplication reveals the error can grow to a diameter of 3.15 inches at 100 meters: $\frac{2.75 \text{ MOA}}{1} \times \frac{1.145 \text{ inches}}{1 \text{ MOA}} = 3.15 \text{ inches}$

At 200 meters, that error increases to 6.30 inches: $\frac{2.75 \text{ MOA}}{1} \times \frac{2}{1} \times \frac{1.145 \text{ inches}}{1 \text{ MOA}} = 6.30 \text{ inches}$

GROUPING ERROR CAUSED BY A 2 CENTIMETER GROUP AT 25 METERS

100 Meters	200 Meters	300 Meters	400 Meters	500 Meters	600 Meters
3.15 in	6.30 in	9.45 in	12.60 in	15.74 in	18.89 in

of errors that are prone to develop under unique terrain or weather conditions, the reader may consider them to be small and therefore inconsequential in the larger scheme of things. It is true that these errors are sometimes measured in only a few inches and it might be tempting to dismiss them as beyond the scope of necessary marksmanship training. Understandably, the concepts above probably are too advanced for a beginner rifleman, but to ignore them completely is an unhealthy approach to marksmanship for a few important reasons. The occurrence of rifle wear and tear, ammunition inconsistency, and the fleeting nature of rather small target dimensions in combat situations can erode probability of successful target engagement.

Non-human Causes for Inaccuracy

While the rifleman is often responsible for poor shooting accuracy, there are other factors that will adversely affect the weapon's potential to shoot accurately. Ammunition inconsistency and weapon wear can both detract from accuracy. Due to these factors, the Army considers a dispersion of two centimeters at 25 meters with no human error to be acceptable. It is useful to calculate and tabulate the effects of that standard out to the edges of the weapon's practical ranges. The calculations in Figure 6 demonstrate that an Infantryman can expect a high degree of error at the farther reaches of the M4's range.

First, we are looking for the angle between the shooter and his shot group assuming a 2-centimeter group at 25 meters. Afterward with some conversions and then some multiplying, we can mathematically demonstrate the expected size of a shot group at all ranges along the trajectory.

The reader can see that without any human error whatsoever, the Infantryman's shot group is the size of a dinner plate at 300 meters. The smallest of errors is magnified downrange, thus leaders must train marksmen to intuitively eliminate as much human error as possible.

The Target

The desired end-state of engaging another human being with lethal fire is incapacitation, which may be defined as a "sudden physical or mental inability to pose any further" threat to friendly forces, according to FBI Special Agent Urey W. Patrick in *Handgun Wounding Factors and Effectiveness*. To incapacitate, the Soldier inflicts a wound that either destroys the central nervous system, damages it too severely to function, or causes blood loss so rapid and severe that the central nervous system fails. A rifleman does so by engaging the lethal and immediate incapacitation zones.

The areas designated as lethal zones are called so because of the high probability of rapid incapacitation if the bullet strike is within these zones. Strikes outside of the target area can be equally deadly; however, the probability for rapid neutralization is significantly diminished. While the human head offers the only target for instantaneous incapacitation, it is too small to be rapidly and accurately engaged in most situations. The average target area in the human head is only about 8 inches high and 7 inches wide.

By doctrine, Infantrymen are trained in the concept of incapacitation by targeting a human enemy's "center of mass." The size of the target area is obviously dependent on the individual anatomy of the target, but the torso of an average-sized man would present a target area 23 inches high and 21.5 inches across assuming he was standing up straight and facing the rifleman. Aiming center of mass allows between 10-13 inches of error in any direction. However, the target area becomes smaller and less accessible to the firer if his target is fighting from a covered position or laying in the prone. Considering the relatively small size of the optimal target area, a few inches of previously unconsidered error can be of enormous importance.

For the Infantry to incapacitate the target there is little time for "trial and error marksmanship." Getting on target quickly is imperative, and knowing the science of our trade equips the willing student to do so.

Conclusions

Long range engagements are a challenging reality of the Infantry experience in the current operating environment. Error, both human and mechanical, accumulates and is particularly evident at these longer ranges. Moreover, the enemy is loath to expose himself and is likely to break contact after only a few shots. Cross winds, moving targets, inaccurate range estimation, heavy breathing, poor sight picture and dozens of other factors, some of them not even combat related, reduce hit probability in the field. For the Infantry to incapacitate the target, there is little time for "trial and error marksmanship." Getting on target quickly is imperative, and knowing the science of our trade equips the willing student to do so. While the inexperienced marksman may not initially be ready for the lessons proposed in this article, they should eventually be a part of his development and absolutely must be a consideration for tactical leaders whose responsibilities include directing fires in combat. It is appropriate to close with the remainder of the quote that began the essay. They are thoughtful words from an officer who understood the necessity to impart a curiosity in the science of our profession to thinking combat leaders.

"He…who seeks to perfect himself in marksmanship must study the rifle itself and from a certain class of experiments and data arrive at conclusions upon which to base his actions. He, on the other hand, who as a leader of troops in battle will reap the reward of success or shoulder the blame for failure of a tactical decision 'where fire is everything, the rest of small account', must study the rifle and the Soldier in an inseparable union, and from the study of this combined weapon and of data quite different from that above considered, he must arrive at conclusions which will govern his actions in the moment of supreme trial."

— CPT H.E. Eames,
The Rifle in War

CPT Wesley A. Moerbe is currently assigned to 199th Infantry Brigade at Fort Benning, Ga., and is a student in the Manuever Captains Career Course. His previous assignments include serving as a rifle platoon leader, anti-armor platoon leader, and assistant operations officer all while serving with 1st Battalion, 502nd Infantry Regiment, 2nd Brigade Combat Team, 101st Airborne Division (Air Assault). CPT Moerbe was commissioned in 2004 through the United States Military Academy.