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Effect of Crosswind on Direct-Fire Projectile Dispersion and Hit Probability and Considerations for Crosswind Estimation

by Paul Weinacht and Greg Oberlin

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14. ABSTRACT

The effect of crosswind on target impact dispersion and probability of hit for direct-fire projectiles and its implications on crosswind estimation strategies and technologies is addressed. Results are presented for a generic 5.56-mm small-caliber projectile. The results show that significant reductions in the target impact dispersion and improvements in probability of hit are possible, but only if the other Soldier system errors are reduced. The results show that existing methods of wind estimation employed by proficient shooters for reduction in crosswind drift can be effective. In spatially variable wind fields, estimation of the average wind across the trajectory provides a reasonable means of estimating the crosswind drift. The results also show that estimation of the wind field over a portion of the trajectory can lead to a meaningful reduction in crosswind drift.

15. SUBJECT TERMS

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1. Introduction

Wind can have a significant effect on the trajectory of a bullet, particularly at long range, and this can affect the ability of the shooter to hit the intended aim point or target. Typically, crosswinds lead to a larger relative deflection than head or tail winds, especially for direct-fire applications. System error budgets have shown that crosswind and ranging error are the dominant error sources for precision shooters such as snipers.[1] Crosswind and ranging error are, to first order, independent and affect the horizontal and vertical target impact dispersion, respectively.

If the wind field is known, the horizontal deflection of the trajectory can be determined and corrections may be made to adjust fire. Proficient shooters utilize a number of techniques to reduce the effect of the crosswind. These include estimating the wind field through observation of environmental clues or waiting for lulls in the wind before taking a shot. If an opportunity for a second shot is available, feedback from the first shot can be used to correct the second shot. Clearly, the ability to sense the wind field is critical to improving first shot probability of hit.

There are a variety of technologies available for wind sensing and each of these has its own merits. Von Wahlde[2] provides a brief survey of existing systems such as laser crosswind sensors, aerosol backscatter crosswind sensors, laser Doppler velocimeter crosswind sensors, and laser scintillation crosswind sensors. This reference also includes some test data on these systems, which provides a general idea of level of expected performance in the 1995–2001 timeframe. Arguably, none of the systems examined were within the size, weight, power, and cost constraints needed for incorporation into a modern carbine system, but the art of the possible was demonstrated.

Clearly, the "holy grail" for wind sensing would be a system capable of sensing the entire wind field from gun muzzle to the target at the instant of shot fire. Arguably, such a system does not currently exist in the required size, weight, power, and cost constraints. If a "holy grail" system is not available, the technical challenge is then to determine the important parameters of the wind field that drive the wind drift and determine the fidelity to which these parameters need to be sensed/measured to reduce the effect of the wind on the deflection of the bullet.

Once the wind field is determined, it is relatively straightforward to determine the trajectory of the bullet and determine the correction in aim point needed to hit the target. For direct-fire (flat-fire) applications, the crosswind drift can be determined from following differential equations[3]

$$\frac{dV_z}{dt} = \frac{\rho S C_D}{2m} V(V_z - W_z), \tag{1}$$

$$\frac{dZ}{dt} = V_Z, \tag{2}$$

or alternatively with downrange distance as the independent variable instead of time:

$$\frac{dV_z}{ds} = \frac{\rho S C_D}{2m} (V_z - W_z), \tag{3}$$

$$\frac{dZ}{ds} = \frac{V_Z}{V}. \tag{4}$$

Here, V_Z is the projectile lateral velocity due to crosswind, Z is the crosswind drift, W_Z is the velocity of the crosswind, s is the downrange distance, t is time of flight, V is the projectile total velocity, ρ is the air density, C_D is the projectile drag coefficient, S is the cross-sectional area that the drag coefficient is normalized by, and m is the projectile mass.

For constant crosswind, Eq. 1 can be integrated to find the simple expression for the crosswind drift[3]

$$Z = W_z \left(t - \frac{s}{V_{x_o}} \right), \tag{5}$$

where t is the time of flight and $\frac{s}{V_{x_o}}$ is the theoretical time of flight in the absence of drag.

For a variable crosswind, Eqs. 3 and 4 can be integrated to determine the crosswind drift. Alternatively, McCoy[3] developed an approach for predicting the crosswind by representing the variable wind field as a series of constant amplitude step functions. In many applications, McCoy's approach may represent an appropriate balance between numerical accuracy and fidelity of the measured wind field.

2. Effects of a Constant Crosswind

Wind drift can contribute significantly to the target impact dispersion and hit probability of a projectile. The crosswind drift of a generic 5.56-mm bullet fired from a current generation carbine subject to a constant 1-m/s (2.24-mph) crosswind is shown in Fig. 1. The crosswind drift is easily computed using Eq. 5. The time-of-flight is computed using the closed form solution presented in Weinacht et al.[4] using the parameters shown in Table 1. The crosswind drift produces a deflection of 0.33 m or 0.56 mils at 600 m.

This deflection alone is sufficient to drive the mean impact point outside the boundary of the E-type silhouette target. The crosswind drift more than quadruples from 300 to 600 m.

Table 1   Characteristics of generic 5.56-mm projectile

Muzzle velocity (m/s)	900
Muzzle retardation (m/s)/m	–1
Exponential drag variation "n"	0.5
Projectile mass – grains	62

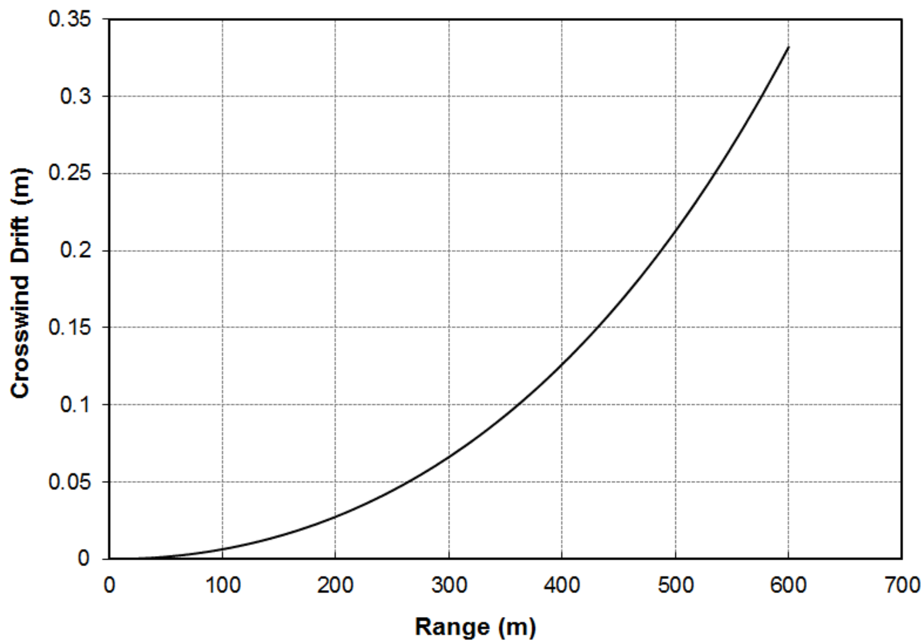

Fig. 1   Crosswind drift of a generic 5.56-mm bullet in a constant 1-m/s crosswind

Figure 2 shows the hit probability of a generic 5.56-mm projectile fired at an E-type silhouette target. The analysis is representative of first round probability of hit. A representative error budget is used to estimate the probability of hit. A Soldier aim error of 0.4 mils is used. This is representative of the Soldier aim error required to obtain an expert marksmanship qualification. A weapon/ammunition dispersion of 0.3 mils is representative of current weapon/ammunition rifle/carbine systems. A 5% ranging error assumes the use of a range-finding capability. An occasion-to-occasion crosswind variability of 3.353 m/s (7.5 mph) assumes an uncorrected crosswind in random wind conditions.[5,6] The probability of hit analyses throughout this report use these values for the aim error, weapon/ammunition dispersion, crosswind variability, and ranging error as the "nominal error budget" unless otherwise stated and assume that the target is an E-type silhouette.

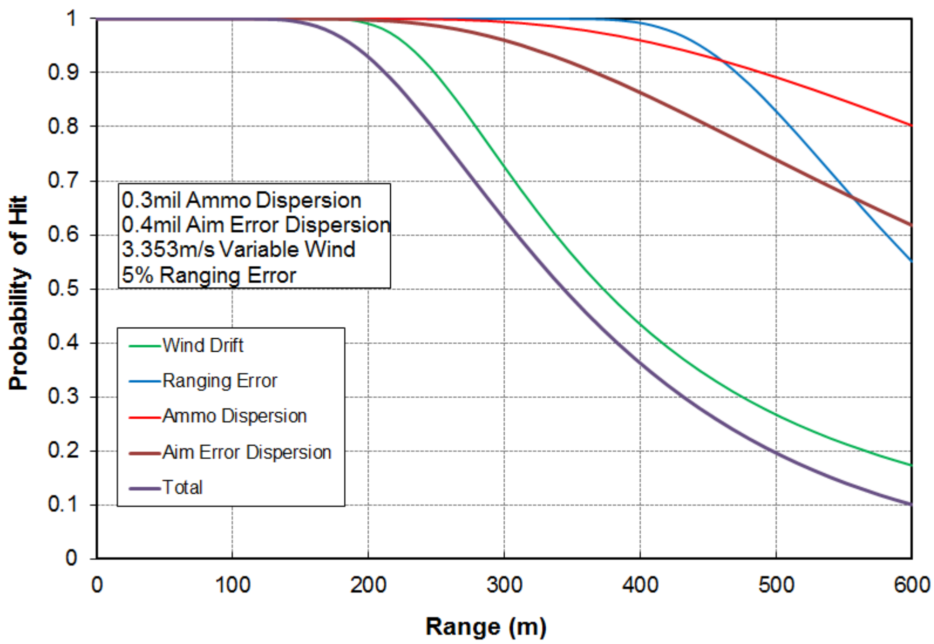

Fig. 2 Probability of hit vs. range for generic 5.56-mm projectile against an E-type silhouette target

Figure 2 shows that the hit probability drops significantly with range and is dominated by the uncorrected wind drift. While the other error sources (weapon/ammo dispersion, aim error, and ranging error) contribute to the overall system dispersion, when combined as a statistical root sum squared, the wind drift provides the most significant contribution as shown in Table 2. All errors listed are assumed to be the standard deviation of a normal distribution. The ability to correct for wind is critical to improving hit probability at ranges beyond 200 m. While improvements in muzzle velocity or retardation (velocity fall-off) through drag reduction or projectile mass characteristics can provide slight improvements in the wind drift performance, the error is primarily driven by the uncorrected crosswind.

Table 2 Dispersion due to various error sources for generic 5.56-mm projectile at 300 and 600 m

Range	300 m	600 m
Soldier aim error (expert marksman)	0.4 mils	0.4 mils
Weapon/ammo dispersion	0.3 mils	0.3 mils
Ranging error	5% of range	5% of range
Dispersion due to ranging error	0.14 mils	0.55 mils
Crosswind variability	3.353 m/s	3.353 m/s
Dispersion due to crosswind variability	0.76 mils	1.90 mils
Total vertical target impact dispersion	0.52 mils	0.74 mils
Total horizontal target impact dispersion	0.91 mils	1.96 mils

It should be noted that the probability of hit shown here is representative of first round probability of hit under conditions that are random. Essentially, this is the probability of hit for a shooter taking a series of single shots in different (unknown) wind fields such that the wind variability can be considered a random error.

It is important to understand that first shot probability of hit is distinct from a Soldier taking a series of successive shots on the same firing range over a period of time. Under this scenario, while the wind field may exhibit some randomness, there is likely a consistent bias in the wind field (the crosswind is generally from the same direction and at the same strength). If the bias in the wind field is significant enough, the drift produced by the bias may affect the overall probability of hit, in some cases, resulting in the consistent inability to hit the target if the wind drift bias is uncorrected.

Unfortunately, this is a likely test scenario for demonstrating wind sensing systems. If the capabilities of a wind sensing system are compared against a baseline system with no wind correction capability, then it may not be clear whether the wind sensing system is truly correcting the instantaneous random wind field or merely providing correction of the bias due to the general prevailing wind conditions. In this case, a more fair comparison might incorporate other less sophisticated methods for wind correction in the baseline system to determine the true capabilities of the candidate wind sensing system. Such methods are currently employed by more experienced shooters.

The error budget in Table 2 and Fig. 2 assumes that there is no correction made for the prevailing crosswind. Wind sensing and subsequent correction presents an opportunity for significant improvement in probability of hit, particularly at longer ranges. Figure 3 shows the relative improvements possible with reduction in dispersion due to wind drift relative to the error budget discussed in Fig. 2. The improvement shown in Fig. 3 only addresses the reduction in dispersion due to crosswind with the other error sources held fixed. There are additional increases in probability of hit possible with improvements in aim error, weapon/ammunition dispersion and ranging error, particularly when combined with reductions in crosswind dispersion.

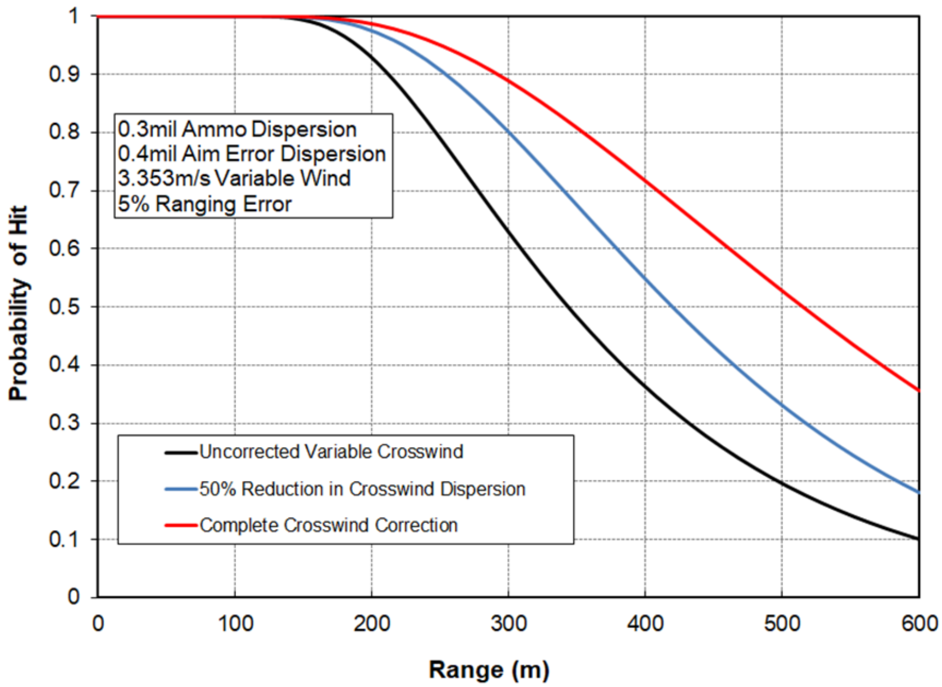

Fig. 3 Improvement in probability of hit vs. range with reduction in crosswind dispersion

Figure 4 shows the relative improvements in probability of hit as a function of the reduction of wind dispersion through wind sensing for ranges of 300, 450, and 600 m. The results show that modest reductions in wind dispersion through wind sensing produce continuous increases in probability of hit until the crosswind dispersion is driven to the level of the other dispersion components. The point where the crosswind dispersion reduction produces errors comparable to the other error sources occurs at larger percent reductions in wind dispersion as the range increases because the crosswind dispersion is increasing a larger portion of the error budget as range increases.

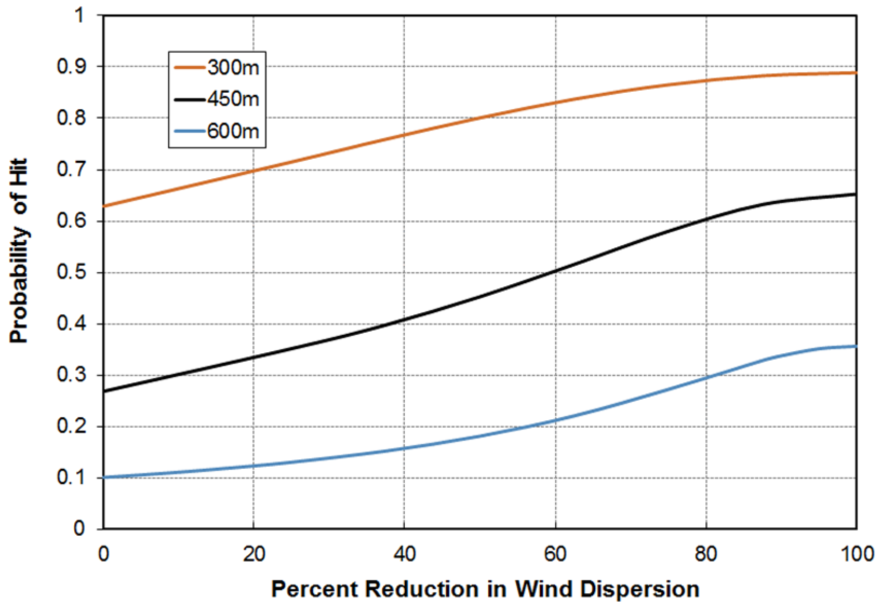

Fig. 4 Improvement in probability of hit with reduction in crosswind dispersion for various ranges

While improvements in hit probability are possible with reduction in the crosswind dispersion, the relative significance of the improvement is dependent on the other sources of error. Figure 5 shows the relative improvements possible with reduction in crosswind dispersion for a shooter with a 1.2-mil aim error. This aim error is representative of a Soldier shooting a marksmanship qualification with proficiency between threshold Marksman and Sharpshooter qualifications. In contrast to the results in Fig. 3, here the aim error plays a stronger role in the probability of hit, and the possibilities for improvements in probability of hit with reduced crosswind dispersion are significantly reduced. Wind sensing may not be of much value to the nonexpert shooter unless aim error augmentation is available to reduce the unaided aim error. The results also imply that some care must be taken when designing experimental programs to demonstrate the performance of wind sensing systems. Here, if error sources in the test are not controlled, then the wind sensing may not demonstrate any significant effect. Also, the results of the demonstration should not be directly extrapolated to total system performance without considering how any errors not included in the demonstration play into a realistic total system error budget.

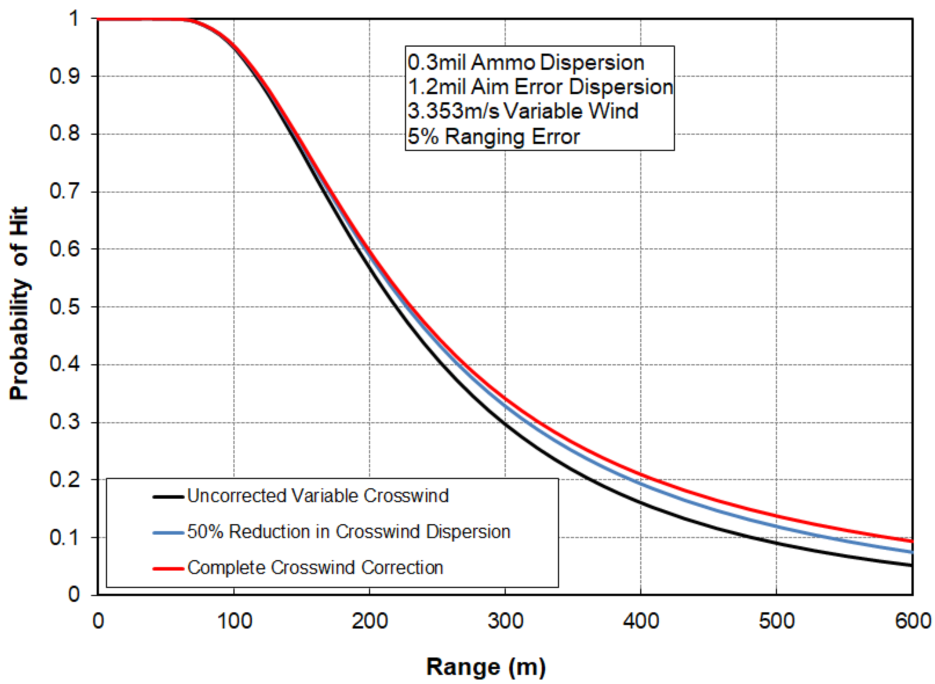

Fig. 5 Improvement in probability of hit vs. range with reduction in crosswind dispersion, non-expert shooter

3. Crosswind Estimation and Correction

There are methods currently used by shooters to reduce the effect of wind on the ability to hit targets at range. The Department of Army Field Manuals (FMs)[7,8] describe several methods to estimate crosswind and, from there, obtain a corrected point of aim to remove the crosswind drift. The estimate of the crosswind is likely the part of the process that creates the most uncertainty or error.

One of the methods described in the FMs to estimate wind is to observe the angle of the range flag and divide by four to estimate the wind in miles per hour (Fig. 6). This is primarily useful on a training range rather than in tactical situations. However, it does give an indication of the overall fidelity of the wind magnitude estimate required to perform wind correction. Alternatively, the Soldier can drop a light object (grass, paper, cotton) and observe the angle of trajectory relative to vertical and divide by four to again determine the wind speed in miles per hour (Fig. 7). It seems reasonable that the fidelity to which the angle can be determined might be on the order of 10°, indicating that the accuracy to which the wind might be estimated would be 2.5 mph.

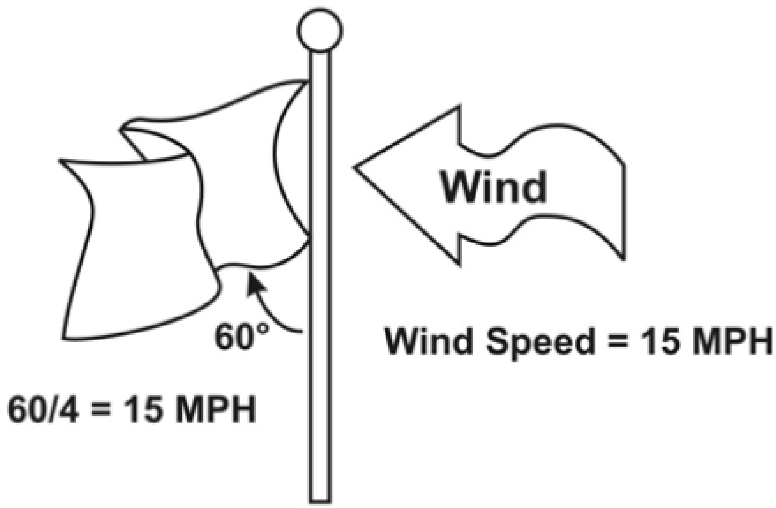

Fig. 6 Use of a range flag for estimating wind velocity[7]

Fig. 7 Estimate of wind velocity using a light object[7]

FM 3-05.222 also provides an alternative method of estimating wind velocity as shown in Table 3. Categorizing the wind magnitude in this manner would seem to be consistent with the 2.5-mph variability in wind velocity estimation discussed earlier.

Table 3 Alternative method of estimating wind velocity (from Special Forces Sniper Training and Employment[7])

Wind velocity (mph)	Effect
0–3	The wind can barely be felt but may be seen by mirage or smoke drifts.
3–5	The wind can be felt on the face. Grass begins to move.
5–8	The leaves in the trees and long grass are in constant motion.
8–12	The wind raises dust and loose paper and moves small branches in trees.
12–15	The wind causes trees to sway.

In addition to estimating the magnitude of the wind, the Soldier also estimates wind direction. Wind direction is estimated with the "clock system" with the clock face oriented with 12 o'clock facing down range. The wind direction is then classified by its orientation relative to the clock. Essentially, the wind is being classified in increments of 30° around the clock face. The crosswind is then estimated as the Full Value of the wind magnitude when the wind is from the 3 and 9 o'clock directions, Half Value of the wind magnitude when the wind is from the 1, 2, 4, 5, 7, 8, 10, and 11 o'clock positions, and Zero when the wind is from the 6 and 12 o'clock directions. The FM does mention that the Zero, Half Value, Full Value method is not exact and alternative values based on trigonometry can be used to improve the calculations.

As a means of estimating the effectiveness of approaches for wind correction, simulations of wind estimation techniques were made to determine the effect on probability of hit. The nominal error budget shown in Table 2 was utilized as the baseline error budget for the simulations with the effects of the wind dispersion modified by the wind estimation approach.

To perform the simulations, a model of the wind magnitude variability is required. Unfortunately, it is not possible to directly relate a normally distributed crosswind (used previously) to a normally distributed wind magnitude, which has a variation in wind direction that is uniform. However, through numerical experimentation, it was determined that the crosswind component from wind that has a uniform distribution in direction and a normally distributed wind magnitude with a standard deviation of 4.74 m/s can be reasonably approximated by a crosswind with standard deviation of 3.35 m/s. This resulting cumulative distribution function of crosswind field differs slightly from the theoretical cumulative distribution function for a normal distribution as shown in Fig. 8, but is a reasonable approximation to a normally distributed crosswind. This crosswind field produces a target impact dispersion due to wind for the generic 5.56-mm bullet discussed previously that was similar to the dispersion observed in the nominal 3.35-m/s crosswind variability.

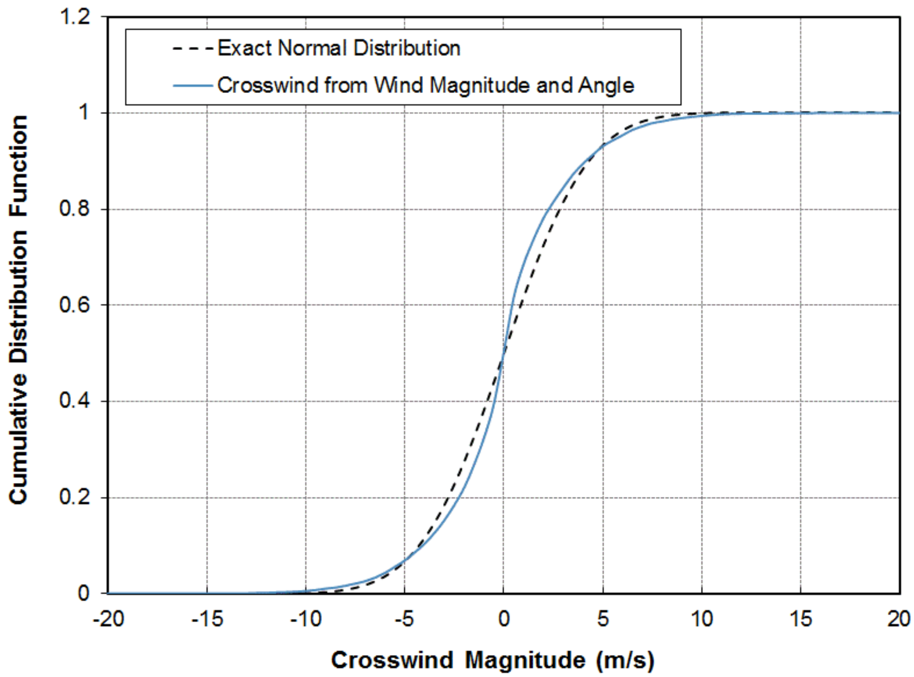

Fig. 8 Cumulative distribution function (CDF) for crosswind model based on normal distribution of wind magnitude and uniform wind angle compared with theoretical CDF for normal distribution

Monte Carlo simulations were then run to determine the effectiveness of the wind estimation methods discussed previously in reducing target impact dispersion. The Monte Carlo simulation consisted of 10,000 replications, each with a randomly drawn constant wind speed and direction. For each replication, the "called" value of the wind is determined from the actual wind drawn as a normal distribution with a variability of 4.74 m/s plus an error value drawn using normal distribution with a 1.12-m/s (2.5-mph) variability. The wind direction is drawn from a uniform distribution from 0 to 180° (note the sign of the wind is obtained from the wind magnitude) and an error value drawn as a normal distribution with a variability of 15°. Using the wind magnitude and the wind direction, the crosswind is determined and the crosswind drift is computed for both the corrected and uncorrected cases. The difference between the uncorrected and corrected impact locations due to wind yields the remaining error in the target impact location due to the crosswind.

The Zero, Half Value, Full Value method uses the called wind direction determined as described earlier and rounds the direction in 30° increments to determine the appropriate hour on the clock face. Zero, Half Value, and Full Value of the wind magnitude are then prescribed according to the “clock method” to determine the crosswind.

The Trig Method is similar, but uses the sine of the angle of each of the hour locations on the clock face to determine the crosswind from the wind magnitude. Essentially, this just provides a more exact calculation than the Zero, Half Value, Full Value method. The Trig Method is described as a note in FM 3-05.222 as a method “to determine the exact effect of the wind on the bullet”. While this method does provide a more correct calculation of the crosswind than the Zero, Half Value, Full Value method, the call of the wind direction likely still has an error associated with it.

The clock method allows the wind direction to be specified in 30° increments, which limits its precision. The level of precision may be well matched to the typical shooter’s fidelity in estimating the wind direction. More sophisticated wind sensing devices are likely not limited to this level of precision although they are likely to have some level of error that affects their accuracy. As a means of determining whether the precision of the clock method has any significant effect on the crosswind estimation, a modified approach which we define here as the “precise wind direction calculation” method uses the same approach discussed previously to compute the velocity magnitude and wind direction, except that the called wind direction is not “rounded” to a clock direction, but is used directly in the calculation of the crosswind. This simulates an implementation where the wind direction might be read from a sensor that provides the wind direction as direct output.

The results of the simulation are shown in Table 4. Included are results for no wind correction and full wind correction that completely eliminates the crosswind drift. The predicted values are similar to those shown previously, but differ slightly because the crosswind is determined from the distribution of the wind magnitude and direction rather than from the crosswind normal distribution. The results show that the wind call methods described in FM 3-05.222 do provide a significant reduction in the crosswind dispersion by 56% to 67% and a subsequent increase in the probability of hit. The improvements such as exact trigonometry calculations of the clock angles or even use of direct wind direction values provide a slight improvement over the Zero, Half Value, Full Value method for the level of wind direction error utilized here. However, as the wind magnitude and wind direction errors decrease further, additional computations show that the effect becomes more significant and the need for automatic/digital computation of the crosswind becomes more important.

Table 4 Crosswind dispersion and probability of hit on E-type silhouette from various wind estimate methods.

Method	Crosswind dispersion at 600 m	Probability of hit at 600 m
No wind correction	1.89 mils	0.101
Full wind correction	0	0.356
Clock method with crosswind determined as the Zero, Half Value, or Full Value of the wind magnitude	0.82 mils	0.2
Trig method with crosswind determined using the trigonometric value of the clock angle	0.70 mils	0.22
Precise wind direction method with crosswind determined using the trigonometric value of the wind direction angle	0.63 mils	0.24

These methods of wind estimation require both the wind velocity magnitude and the wind direction to be determined. Using the model, the relative contributions of each effect was examined. To eliminate any precision issues with the clock method, the wind direction was taken directly as the called wind direction (Precise Wind Direction Method) rather than the clock value. Table 5 shows that using errors in the wind magnitude and wind direction of 2.5 m/s and 15°, the crosswind dispersion error is more or less split between the wind magnitude estimation and the wind direction estimate. This indicates that both the wind magnitude and the wind direction are important contributors in the crosswind estimation and aim point adjustment.

Table 5 Relative contribution of wind magnitude and wind direction errors to crosswind dispersion and probability of hit on E-type silhouette

Method	Crosswind dispersion at 600 m	Probability of hit at 600 m
No wind correction	1.89 mils	0.101
Full wind correction	0	0.356
Clock method with crosswind determined as the Zero, Half Value, or Full Value of the wind magnitude	0.63 mils	0.24
Trig method with crosswind determined using the trigonometric value of the clock angle	0.45 mils	0.28
Precise wind direction method with crosswind determined using the trigonometric value of the wind direction angle	0.45 mils	0.28

The solutions presented represent up to a two-thirds reduction in wind dispersion over no wind compensation. As shown previously, in Fig. 4, further reductions in dispersion due to crosswind can provide increases in probability of hit. At 600 m, for the generic weapon/ammo system discussed here, reductions in dispersion due to crosswind of 85% are possible before the wind magnitude and wind direction errors start to be overtaken by the other system errors. As shown in the results in Table 6, reductions in both the wind magnitude and wind direction errors are required to attain this level of dispersion due to crosswind. A wind magnitude error of 1.1 mph (0.49 m/s) and a wind direction error of 6.25° are representative of the type of error reduction required to reach the overall 85% reduction in dispersion due to constant uniform crosswind. The 1.1-mph wind magnitude error translates into 0.78-mph (0.35-m/s) crosswind error using the same approach to transform the crosswind variability to wind magnitude variability used earlier. These would seem to be technically challenging error thresholds to reach this level of crosswind dispersion reduction. It is interesting to note that 1 m/s was the threshold crosswind error (wind magnitude error would be comparatively larger) specified in some of the efforts discussed in McCoy[3].

Table 6 Crosswind dispersion and probability of hit for an 85% reduction in dispersion due to constant uniform crosswind

Method	Crosswind dispersion at 600 m	Probability of hit at 600 m
No wind correction	1.89 mils	0.101
Full wind correction	0	0.356
Clock method with crosswind determined as the Zero, Half Value, or Full Value of the wind magnitude	0.278 mils	0.32
Trig method with crosswind determined using the trigonometric value of the clock angle	0.2 mils	0.34
Precise wind direction method with crosswind determined using the trigonometric value of the wind direction angle	0.2 mils	0.34

It should be clear from the results presented here that significant reductions in dispersion due to crosswind and, subsequently, increases in probability of hit are possible with methods that would seem to be practically obtainable. At the same time, the necessity of a "holy grail" system that completely eliminates the crosswind error needs to be balanced against the other error sources in the system, which at some point overwhelm any remaining crosswind error.

4. Crosswind Spatial Variability

Analyses such as those presented previously can provide significant insight into the effect of crosswind on the trajectory, impact dispersion, and probability of hit of a weapon system. Typically, these analyses are performed assuming a constant uniform crosswind. There are a limited number of studies that consider variable crosswinds. As indicated, approaches exist for computing the effect of variable crosswind if the crosswind field is defined.[3] The problem is defining a spatially variable crosswind in a systematic and meaningful way. The variability in a typical crosswind field is likely to be composed of variability due to atmospheric turbulence and local terrain, as shown in Fig. 9.

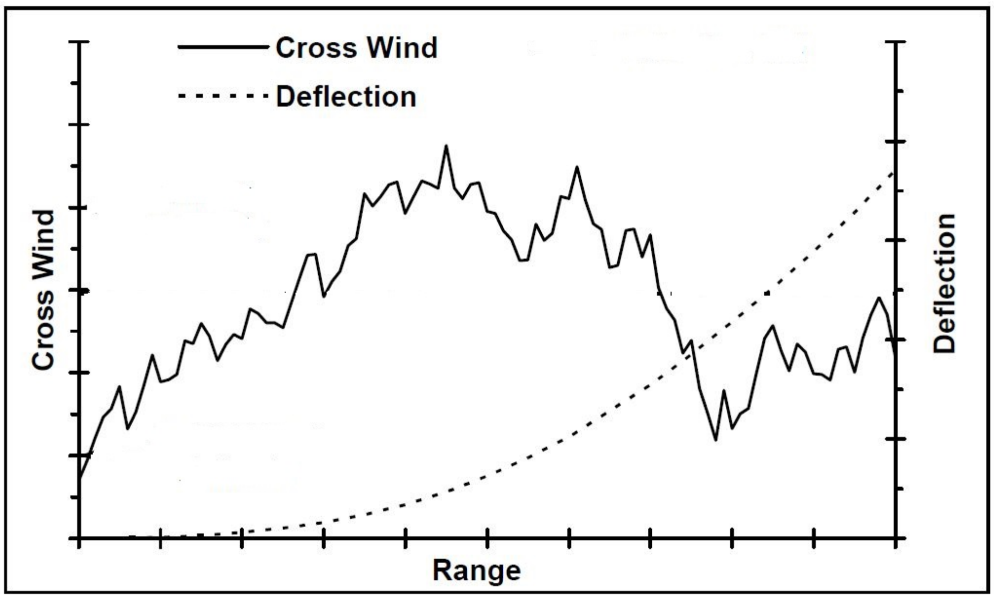

Fig. 9 Notional spatially variable crosswind field and resulting crosswind deflection (from Von Wahlde[2])

Some sense of relative effect of a spatially variable crosswind can be seen by examining the crosswind drift produced by a constant step function crosswind in each of the quarter of the trajectory (with the crosswind being zero in all other quarters.) Figure 10 shows the crosswind drift versus range for a constant step crosswind of 1 m/s occurring between 0–150, 150–300, 300–450, or 450–600 m, respectively. Also shown is the crosswind drift due to a constant crosswind of 0.25 m/s acting over the entire trajectory. The 0.25-m/s crosswind represents the 1-m/s step crosswind from any of the step crosswind discussed previously averaged over the entire trajectory. The crosswind drift begins to grow when the projectile enters the portion of the trajectory with a crosswind and continues at a constant rate once the projectile exits the portion of the trajectory with the step crosswind field. The rate of growth in the wind field is different from quarter to quarter because of difference in the projectile velocity along the trajectory. Also note the average crosswind provides a reasonable estimate of the crosswind drift when the step function crosswind field is in the first three quarters of the crosswind field.

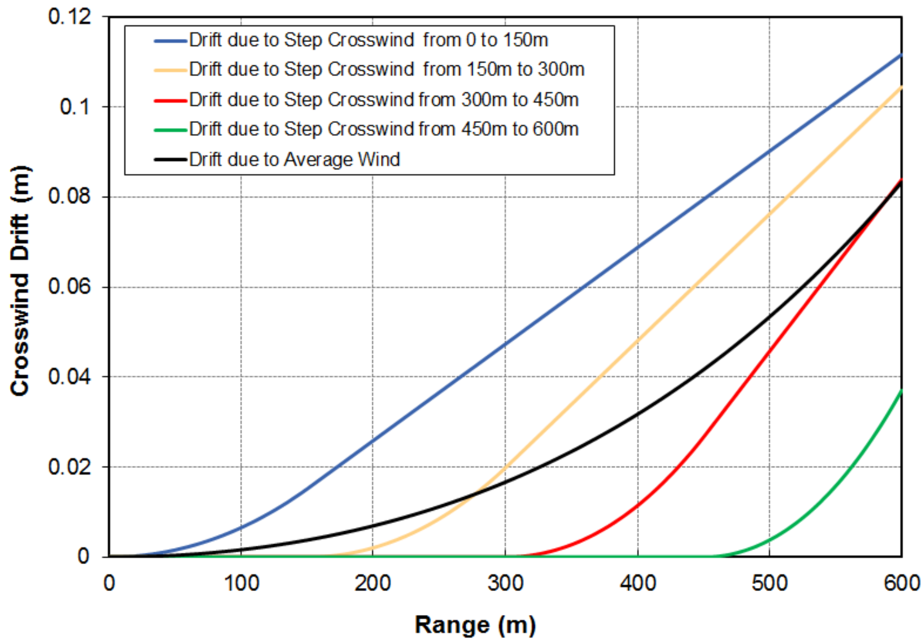

Fig. 10 Crosswind drift due to a step crosswind of 1 m/s acting at 0–150, 150–300, 300–450, and 450–600 m

Figure 11 shows the total crosswind drift at 600 m from a constant crosswind in each of the first through fourth quarters of a 600-m trajectory for the generic 5.56-mm projectile for a 1 m/s crosswind. The sum of the contribution from each quarter is equivalent to the crosswind drift due to a constant uniform crosswind of 1 m/s over the 600-m trajectory. The results in Fig. 11 show that the crosswind closest to the gun muzzle has a greater contribution to the total crosswind than the crosswind at the end of the trajectory. In fact, the crosswind in the last quarter of a constant crosswind trajectory only produces 11% of the crosswind drift due to a constant uniform crosswind of 1 m/s over a 600-m trajectory. Similar results have been shown previously in the literature.[3,10]

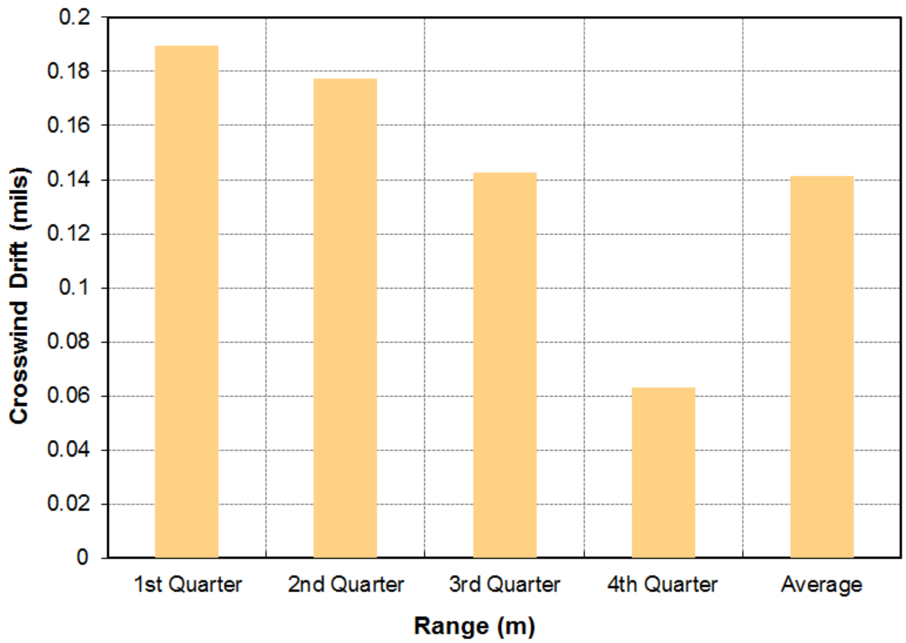

Fig. 11 Crosswind drift of 600 m produced by a constant 1-m/s crosswind in each quarter of a 600-m trajectory

While the relative contribution of the crosswind along the trajectory gives some indication of the effect of large-scale spatial crosswind variability, it does not define the expected variability in a manner that allows the spatial variability to be modeled in a statistical manner. Fargus[9] describes a novel approach for modeling the variability in a wind field based on statistical analysis of the crosswind field and determining its effect on the crosswind deflection of a bullet. While the methodology is fairly general, the particular implementation discussed in Fargus[9] applies to a specific set of measurements made on one particular range. An inspection of the data indicates that the characteristics of this particular wind field are driven by both atmospheric turbulence and the local terrain.

A spatially variable wind field provides an additional challenge over the uniform wind field because the shooter must determine how the spatial variability deviates from a constant uniform crosswind. Two different spatially variable wind fields are constructed to provide some measure of the effect of the spatially variable wind fields.

The first wind field (Wind Field 1) is a constant step crosswind field in each segment of the first and second half of the wind field. The crosswind in each segment of the first and second half has an uncertainty (standard deviation) of 3.35 m/s (with zero mean velocity) and is statically independent of the other. This is likely an extreme case since the wind field closer to the gun is likely to be related to the downrange wind field nearer the target. However, this wind field could be representative of a wind field produced by the interaction of a crosswind with significant terrain features, which produces large-scale changes to the wind field along the trajectory. The variability of the average crosswind over the entire trajectory is 2.4 m/s and less than the variability of each segment (3.35 m/s), because downrange wind is statically more likely to oppose the uprange crosswind resulting in the less net crosswind drift than the constant crosswind. As a result, this wind field is expected to produce less variability in the uncorrected crosswind drift than a constant uniform crosswind field.

Table 7 shows the resulting dispersion due to this crosswind field and probability of hit for a variety of cases where the crosswind is either uncorrected by the shooter or has various forms of correction of the crosswind drift. Also shown for reference are results for an uncorrected uniform crosswind and results where the crosswind dispersion is removed to within the wind call error of 1.1 m/s (2.5 mph) or completely removed with a perfect wind call. These results are similar to those shown previously in Table 4.

Compared with the uniform constant crosswind (Case a), Wind Field 1 produces less uncorrected dispersion (Case 1a) since the uprange and downrange winds typically offset one another. If the shooter is unable to the gauge the downrange wind and corrects the crosswind based on the uprange wind field (Cases 1b and 1c), only modest reductions in dispersion due to crosswind are possible compared with a more accurate wind call (Case b and c) within each segment of the crosswind field.

Table 7 Crosswind dispersion and probability of hit for Wind Field 1

		Average wind variability (m/s)	Dispersion due to crosswind (mils)	Probability of hit
Uniform wind field (Case a)	Crosswind variability 3.35 m/s, no wind call	3.35	1.90	0.10
Any wind field (Case b)	Wind dispersion removed to within wind call error (1.1-m/s wind call error)	NA	0.63	0.24
Any wind field (Case c)	Perfect wind call, wind dispersion removed	NA	0	0.36

Table 7 Crosswind dispersion and probability of hit for Wind Field 1 (continued)

		Average wind variability (m/s)	Dispersion due to crosswind (mils)	Probability of hit
Variable Wind Field 1 (Case 1a)	Random variability of 3.35 m/s in first and second half, no wind call	2.4	1.41	0.13
Variable Wind Field 1 (Case 1b)	Wind call based on first half wind (1.1-m/s wind call error)	2.4	1.16	0.155
Variable Wind Field 1 (Case 1c)	Wind call based on first half only (0-m/s wind call error)	2.4	0.97	0.18

In the absence of large disturbances to the crosswind field, the uprange and downrange components of the crosswind field are likely to be related in some fashion. For example, if the uprange crosswind is 8 mph to the right, the downrange crosswind is likely in the same direction with a statistical variability around that crosswind magnitude. To model this situation, a second wind field (Wind Field 2) was constructed. This wind field consists of a constant crosswind field in the first half (300 m) of the trajectory with a variability of 3.35 m/s (zero mean velocity). The second half of the trajectory is a constant crosswind with the crosswind velocity equal to the crosswind in the first half plus an additional variability of either 1 m/s or 3.35 m/s. The variability of the average crosswind over the entire trajectory for these two cases is 3.4 and 3.7 m/s, respectively. This crosswind variability is slightly larger than the constant crosswind variability used previously because of the additional component of variability added to the second half of the trajectory. In this scenario, the called crosswind is made based on the crosswind in the first half of the trajectory with a called crosswind uncertainty of 1.1 m/s (2.5 mph). Effectively, the actual crosswind in the first half of the trajectory as well as the portion of the crosswind of the second half that is equal to the uprange crosswind are corrected by the average wind call. The errors that remain are the called crosswind uncertainty/error, which exists over the entire trajectory, and the crosswind variability, which acts over the second half of the trajectory.

Table 8 Crosswind dispersion and probability of hit for Wind Field 2

		Average wind variability (m/s)	Dispersion due to crosswind (mils)	Probability of hit
Uniform wind field (Case a)	Crosswind variability 3.35 m/s, no wind call	3.35	1.90	0.10
Any wind field (Case b)	Wind dispersion removed to within wind call error (1.1-m/s wind call error)	N/A	0.63	0.24
Any wind field (Case c)	Perfect wind call, wind dispersion removed	N/A	0	0.36
Variable Wind Field 2 (Case 2a)	With additional 3.35-m/s variability in second half, no wind call	3.7	2.04	0.094
Variable Wind Field 2 (Case 2b)	With additional 3.35-m/s variability in second half, with wind call	3.7	0.93	0.18
Variable Wind Field 2 (Case 2c)	With additional 3.35-m/s variability in second half, with perfect wind call of first half wind	3.7	0.69	0.225
Variable Wind Field 2 (Case 2d)	With additional 1-m/s variability in second half, no wind call	3.4	1.93	0.099
Variable Wind Field 2 (Case 2e)	With additional 1-m/s variability in second half, with wind call	3.4	0.66	0.23
Variable Wind Field 2 (Case 2f)	With additional 1-m/s variability in second half, with perfect wind call of 1st half wind	3.4	0.21	0.335

Table 8 shows the resulting dispersion due to this crosswind field and probability of hit for a variety of cases where the crosswind is either uncorrected by the shooter or has various forms of correction of the crosswind drift. Similar to Table 7, it shows baseline results for uncorrected constant uniform crosswind and results where the crosswind dispersion is removed to within the wind call error of 1.1 m/s (2.5 mph) or completely removed with a perfect wind call.

As shown in Table 8, Wind Field 2 produces a slightly higher variability in the average wind field over the entire trajectory due to the additional variability (1 m/s or 3.35 m/s) in the second half of the trajectory compared with the baseline constant uniform wind field. This additional wind variability produces a small additional component of crosswind dispersion and reduces the probability of hit compared with the baseline uniform constant wind field as demonstrated by results of Case a, Case 2a, and Case 2d.

Case 2b shows that the wind call (with a wind call error of 1.1 m/s [2.5 mph]) produces more than 50% reduction in the crosswind dispersion. The remaining dispersion due to the crosswind is produced by both the variability/uncertainty in the crosswind in the second half of the trajectory and the called crosswind error. In this case, the relative contributions of the wind call error alone (Case b) and the crosswind variability in the second half of the trajectory alone (Case 2c) are relatively similar.

When the downrange wind variability is reduced from 3.35 m/s to 1 m/s, the relative importance of the wind call error compared to the downrange wind variability is increased. When no wind call is made, the dispersion due to crosswind variability for wind field with a downrange variability of 1 m/s (Case 2d) is only slightly larger than the constant uniform wind field results (Case a). When a wind call is made, the wind field with the downrange variability (Case 2e) only produces a slightly higher dispersion due to crosswind than the constant uniform crosswind (Case b). This is because the dispersion due to the crosswind variability from the second half of the trajectory is comparatively small (Case 2f). When the wind call error is eliminated and the only remaining error is the variability of the wind in the second half of the trajectory (Case 2f), the probability of hit approaches the probability of hit for zero dispersion due to crosswind (Case c).

As shown previously in Fig. 9, a spatially variable wind field can be composed of both large- and small-scale spatial variations. As a means of quantifying the relative contributions of these variabilities in the wind field, the crosswind drift produced by unit amplitude sine waves of unit amplitude and various frequencies was evaluated and compared with the crosswind drift of a unit amplitude constant uniform crosswind. Figure 12 shows the crosswind profiles for sinusoidal unit amplitude wind fields of wavelengths L, L/2, and L/5 (where L is the total range of 600 m) as well as a unit amplitude constant uniform crosswind.

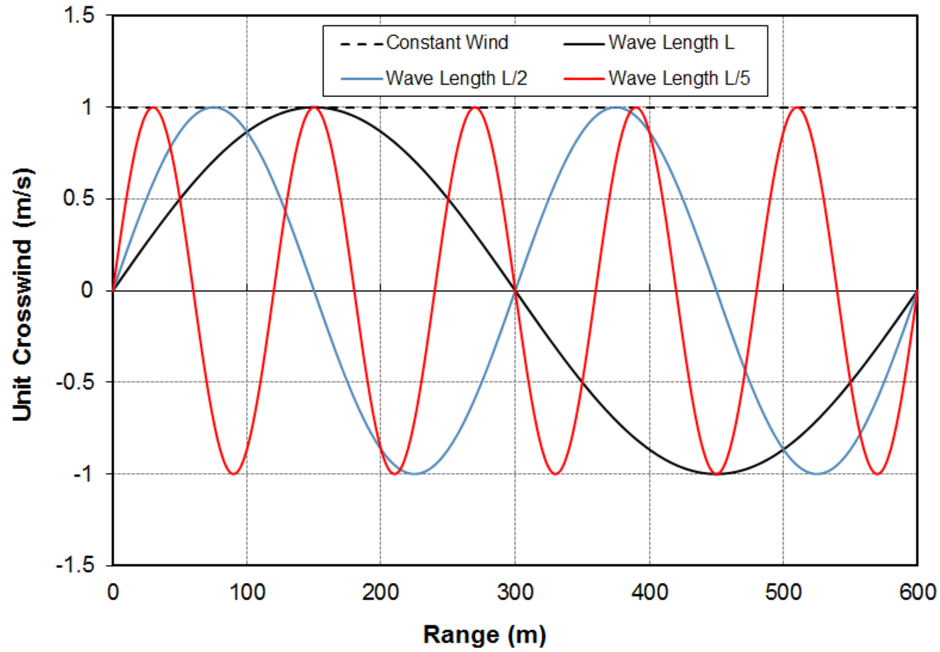

Fig. 12 Constant unit amplitude uniform crosswind profile and sinusoidal unit amplitude crosswind of various frequencies

The wind profiles shown in Fig. 12 assume a pure sine wave with no initial phase angle at the beginning of the trajectory. Since the wind profile is arbitrary, an initial phase angle was included to determine whether this had a significant effect on the resulting crosswind drift. As shown in Fig. 13, the pure sine wave (zero phase angle) produces a crosswind drift that is close to the maximum crosswind drift for that frequency. On the other hand, a pure cosine wave (90° phase angle) of the same amplitude produces a much smaller response. When comparing the relative magnitudes of the crosswind drift as a function of frequency of the sine wave, the pure sine wave (zero phase angle) produces a crosswind drift that is close to maximum of that frequency.

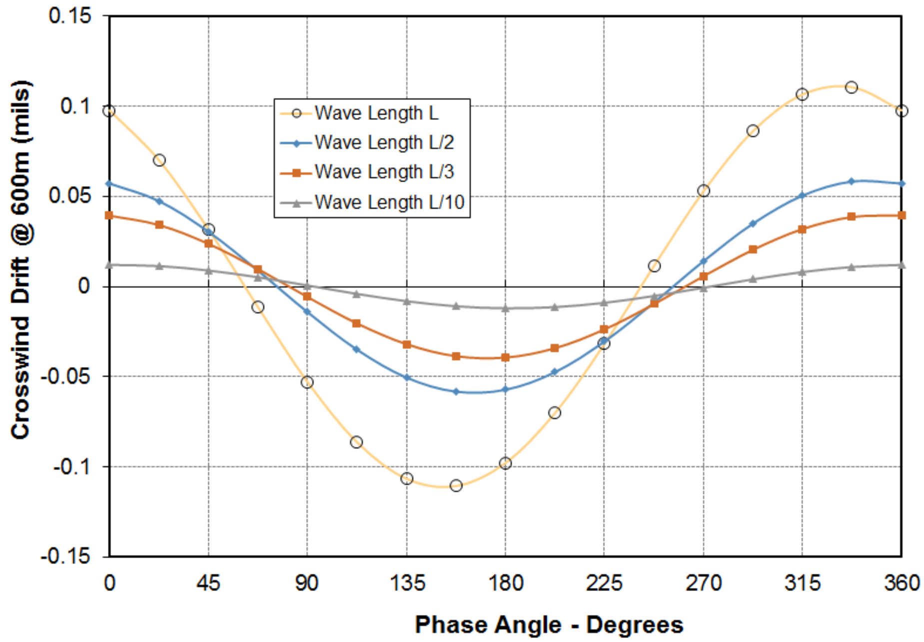

Fig. 13 Crosswind drift due to unit amplitude sinusoidal crosswind field as a function of initial phase angle

Figure 14 shows the crosswind drift resulting from a unit amplitude sinusoidal crosswind of varying frequency with zero frequency representing a constant amplitude uniform crosswind. The results show that the smaller-scale, high-frequency fluctuating components of the wind field produce a significantly smaller contribution to the crosswind drift than does the unit crosswind, since much of the crosswind drift from adjacent half cycles of the high-frequency fluctuations cancel each other out.

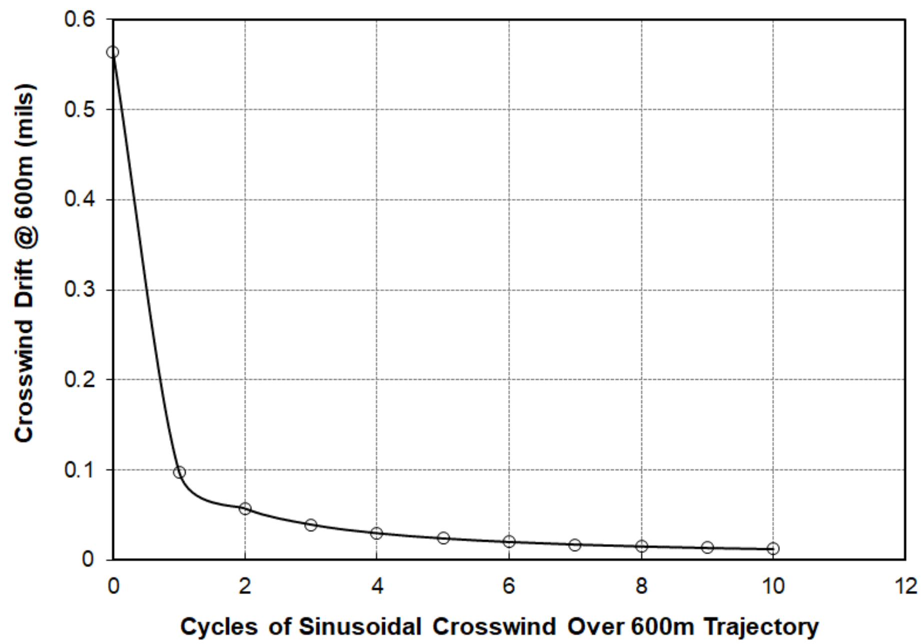

Fig. 14 Crosswind drift due to constant unit amplitude uniform crosswind and sinusoidal unit amplitude crosswind of various frequencies

To get a sense of the effect of large-scale spatial variations in the wind field on crosswind drift, several representative spatially variable wind fields were constructed, as shown in Fig. 15. These wind fields include linearly varying wind fields, which increase and decrease with range, a half sine wave wind field, and an inverted sine wave wind field. The linearly increasing/decreasing wind field includes those with an average crosswind velocity of 1 m/s over the trajectory with zero velocity at either the beginning or end of the trajectory as well as linearly varying wind fields with zero average crosswind velocity. The half sine wave wind field concentrates the bulk of the crosswind field in the middle of the trajectory while the inverted sine wave wind field concentrates the crosswind at the beginning and end of the trajectory. Both the sine wave and inverted sine wave wind fields have been normalized to produce an average crosswind of 1 m/s, although the peak wind for the inverted sine wave is significantly higher than the sine wave wind field.

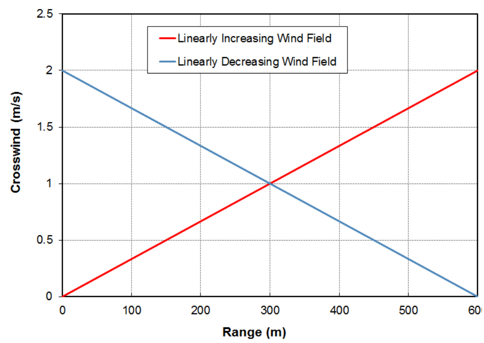

Fig. 15a. Linearly varying wind field

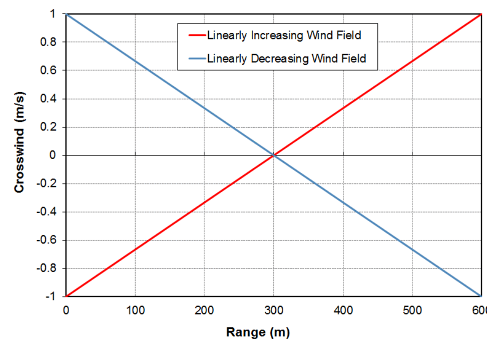

Fig.15b. Linearly varying wind field with zero average crosswind

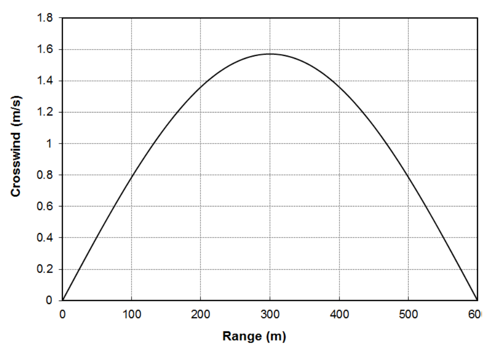

Fig.15c. Half sine wave wind field

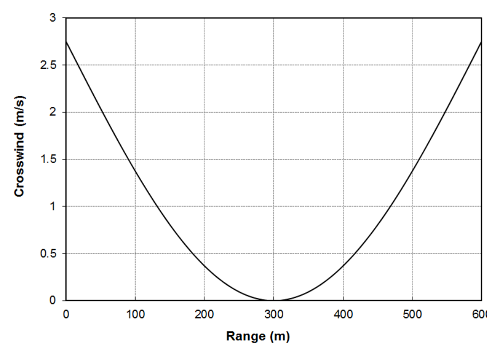

Fig.15d. Inverted half sine wave wind field

Fig. 15 Various types of spatially varying wind fields

Figure 16 shows the crosswind drift associated with each of the wind fields in Fig. 15. Also shown is the crosswind drift due to a constant crosswind with the same average velocity as the spatially variable wind fields. For the three wind fields with the 1-m/s average crosswind, the crosswind drift is relatively closely approximated by the crosswind drift due to constant uniform 1-m/s crosswind. Similar results were found in the step function crosswinds shown in Fig. 10, at least for the step crosswind in the first three quarters of the trajectory. While the detailed determination of the spatial variability of the wind field is the preferred approach in terms of accurate determination of the crosswind drift, the results indicate that an estimation of the average crosswind with some additional correction for the particular spatial features of the wind field may provide a very acceptable estimate for the crosswind. While digital devices provide more automatic means of computing the crosswind aim point correction, many current methods of crosswind aim point correction involve a correction that is based on the effective crosswind that is specific to each ammunition type. Deducing the average crosswind would seem to be a first-order approach to determining the effective crosswind.

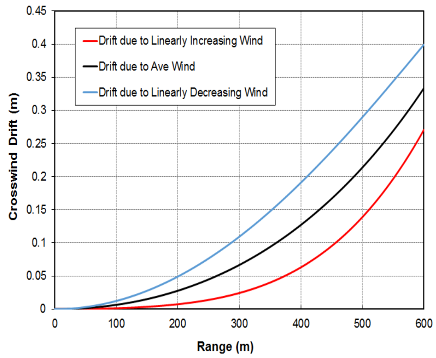

Fig. 16a. Crosswind drift due to linearly varying wind field

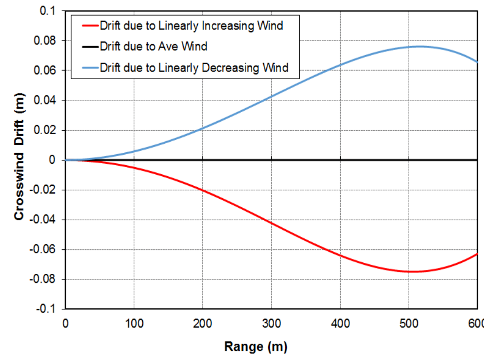

Fig.16b. Crosswind due to linearly varying wind field with zero average crosswind

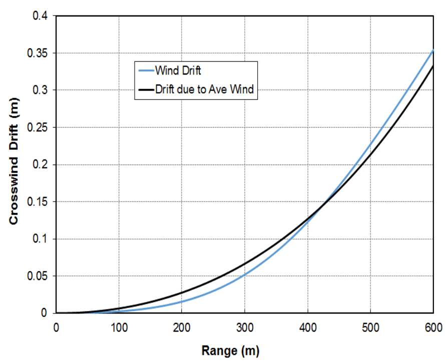

Fig.16c. Crosswind drift due to half sine wave wind field

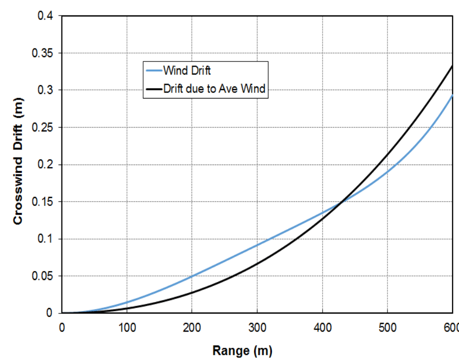

Fig.16d. Cross wind drift due to inverted half sine wave wind field

Fig. 16 Crosswind drift due to various types of spatially varying wind fields

5. Crosswind Temporal Variability

The current report does not address the time-dependent variability of the crosswind field, which may result from variability in the average and spatially dependent features of the crosswind field, although this is likely an issue that needs consideration and, perhaps, additional data collection. Von Wahlde makes brief comments about this issue in the context of an inertial reticle system, which determines a corrected aim point for the shooter based on range and crosswind.[2] As stated in the report, "The corrected aim point would likely be dynamically changing especially for real time measurements of varying crosswind." Thus the shooter must deal with a corrected aim point that may be changing as the crosswind field varies with time. The study in Von Wahlde revealed that "…field experiments where the corrected aim point was continually updated by real time measurements of downrange crosswind have shown that it is difficult to converge the two reticles when one is dynamically moving."[2] There may be technical solutions to this problem, but it is an additional consideration that likely needs to be made in the development of wind sensing systems and their implementation in a fire control system.

6. Conclusions

The drift of a projectile due to crosswind is a significant effect that may need compensation for accurate shot placement on targets, particularly at longer ranges and in realistic nonideal wind conditions. When other error sources are sufficiently reduced, in particular, for precision shooters or Soldiers using weapons with aim augmentation, the crosswind drift can significantly impact probability of hit if uncorrected. Crosswind correction for less precise shooters may provide reduced benefits.

Current manual (human-in-the-loop) methods of wind correction, such as those described by the Army FMs, appear to be fairly effective in reducing errors due to crosswind when properly employed. However, there are still possible gains in probability of hit that could be made with further reductions in crosswind dispersion for the precision shooter. The crosswind estimation error is a critical factor in both human and automated systems.

While crosswind fields likely show some spatial variability, the results shown here demonstrate that average wind across the trajectory provides a reasonable estimate for the effective crosswind correction. The ability to determine the crosswind field over the entire trajectory provides the best accuracy, though reasonable estimates of a portion of the wind field (particularly at the beginning of the trajectory) can provide measurable reduction of the crosswind drift. Increased accuracy of the wind sensing system likely involves accurate measurement of the crosswind as well as the ability to address the spatial variability of the wind field.

Finally, while crosswind drift can be a significant error source driving target impact dispersion and probability of hit, the effectiveness of reduction of dispersion due to crosswind must be considered in the context of the complete set of system error sources. Simply reducing the effect of crosswind with a wind sensing system may not provide much benefit to the average Soldier unless combined with an effective approach to reduce the other error sources, such as Soldier aim error or ranging error. When improved wind sensing is combined with other error source reductions, the potential for leap-ahead advances in weapon system performance is possible.

7. References

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List of Symbols, Abbreviations, and Acronyms

ARL	US Army Research Laboratory
CDF	Cumulative distribution function
FM	Field Manual

1 (PDF)	DEFENSE TECHNICAL INFORMATION CTR DTIC OCA
2 (PDF)	DIR ARL IMAL HRA RECORDS MGMT RDRL DCL TECH LIB
1 (PDF)	GOVT PRINTG OFC A MALHOTRA
22 (PDF)	ARL RDRL WML T SHEPPARD W OBERLE RDRL WML E P WEINACHT I CELMINS J DESPIRITO F FRESCONI V BHAGWANDIN J BRYSON L FAIRFAX G OBERLIN L STROHM J VASILE J PAUL J SAHU RDRL WML B N TRIVEDI RDRL WML C J SADLER RDRL WML D R BEYER RDRL WML F M ILG RDRL WML G C MERMAGEN M MINNICINO RDRL WML H J NEWILL RDRL WMM E S SILTON