Deflections and Drift of a Bullet in a Crosswind

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On July 8, 2003 we received a question in the Forum section of Sierra's Exterior Ballistics Website from Mr. David Hollister. This equation is repeated verbatim here:

"Your explanation of the turning of a bullet in a crosswind to produce vertical deflection is the opposite to that experienced by shooters. A wind from the right sends a bullet to 10 o'clock and a wind from the left to 4 o'clock. (A right wind produces a little more vertical deflection than a left wind.) This has always been my experience shooting smallbore (22 rimfire) and 300 m ISSF with both your 155, 168 and 180gr MK and 6mmBR 107MK. Even a 5mph wind produces this phenomenon, but I must say that that as the crosswind increases the vertical component does not continue to increase relative to the horizontal.

What is the cause of this deflection?"

This was an excellent question and a difficult one to answer. This writer replied a few days later in the Forum that he needed more time to study this phenomenon and promised an answer. The writer has performed this study, mainly using Modern Exterior Ballistics by Robert L. McCoy, but with the aid of other references also. Mr. Hollister's observations are correct. Section 4.3 of the Exterior Ballistics chapter of the Sierra Rifle and Handgun Reloading Manual, Edition V, is not correct. This author will eat some humble pie and correct that section at the next printing of the Sierra Manual. This article has been prepared to answer Mr. Hollister's question and to serve as a reference on crosswind deflections until the error in the Sierra Manual has been corrected and published. Regrettably perhaps, some mathematics are necessary to answer the question, but the writer will do his best to explain in English what the mathematics are telling us about the motions of the bullet.

In this article we will assume a level fire shooting situation, that is, where the firing point and the target are at the same (or nearly the same) elevation above sea level. This is usually true for target shooting. We also will describe the effects of a crosswind only, because the analysis is simplified a great deal, vertical air currents (vertical winds) are usually very small on level ranges, and headwinds or tailwinds are known to cause much smaller deflections of a bullet on a target than crosswinds. We also will assume that the bullet has a right hand spin, but we will consider the effects of crosswinds in both directions. Right hand spin is produced by rifles with right hand rifling twist, which is the usual case.

When a bullet flies through the air, the velocity of the bullet relative to the ground is affected by the wind. The following vector equation is the beginning point for every analysis of wind deflections:

$$\mathbf{V}_{\text{bullet relative to the ground}} = \mathbf{V}_{\text{bullet relative to the air}} + \mathbf{V}_{\text{air relative to the ground}} \qquad (1)$$

where $\mathbf{V}_{\text{bullet relative to the ground}}$ is the bullet velocity relative to the ground
$\mathbf{V}_{\text{bullet relative to the air}}$ is the bullet velocity relative to the air mass through which it flies
$\mathbf{V}_{\text{air relative to the ground}}$ is the velocity of the air mass relative to the ground (i.e., the wind velocity)

The boldface letter (**V**) in each symbol in equation (1) denotes that each quantity is a vector. Velocity is a vector quantity, that is, a quantity which has both a magnitude and a direction. The magnitude of any velocity is speed, but the direction of each velocity must be taken into account when using equation (1). All aerodynamic forces and torques on the bullet as it flies through the air are caused by the velocity of the bullet relative to the air, that is, $\mathbf{V}_{\text{bullet relative to the air}}$.

When a bullet exits the muzzle of a gun, it immediately begins some angular pitching and yawing motions which have several possible causes including the crosswind. These angular motions are small, cyclical, and transient. They typically start out with amplitudes of a degree or so, and damp out, or at least damp to some very small residual values, after the bullet travels a relatively short distance. From our experience measuring ballistic coefficients, these motions damp within 100 yards or less of bullet travel downrange.

Throughout the trajectory, including the initial transient period, the bullet has an “average” angular orientation which aligns the longitudinal axis almost exactly with $\mathbf{V}_{\text{bullet relative to the air}}$. In this orientation the principal aerodynamic force on the bullet is drag, which acts in a direction opposite to $\mathbf{V}_{\text{bullet relative to the air}}$. The side forces on the bullet are essentially nulled in this “average” angular orientation. Only a tiny lift force and a tiny side force are maintained to generate moments of torque which cause the nose of the bullet to turn. We will describe these tiny effects a little later. First, let us consider the “average” angular orientation.

When the bullet exits the muzzle, its nose turns **upwind**. This is the necessary direction to align the longitudinal axis with $\mathbf{V}_{\text{bullet relative to the air}}$. If the bullet did not turn in this direction, the crosswind would cause a strong side force on the bullet which would ultimately destabilize it. The bullet turns because of its gyroscopic stabilization. When the bullet exits the muzzle, there is an initial misalignment between the bullet axis and $\mathbf{V}_{\text{bullet relative to the air}}$. This misalignment disappears quickly due to the gyroscopic stabilization, and the bullet takes the “average” angular orientation. Looking at Figure 2 below, at the muzzle the “average” angle the bullet must turn into the wind is almost exactly given by:

$$\theta_{\text{muzzle}} = \arctan\left[V_{\text{crosswind}} / V_{\text{muzzle}}\right] \qquad (2)$$

where $V_{\text{crosswind}}$ is the speed of the crosswind (the V symbol without boldface denotes the magnitude of the **V** vector velocity)
V_{muzzle} is the bullet speed at the muzzle (“muzzle velocity”)

arctan means “the angle whose tangent is”

This angle is small. For example, for a rifle firing the 308 Winchester cartridge with Sierra’s 168 grain MatchKing bullet at 2650 fps muzzle speed in a 25 mph crosswind, θ_{muzzle} = 0.793 degree = 47.6 minutes of angle. For lower wind speeds higher muzzle velocities values of θ_{muzzle} are even smaller.

Figures 1, 2, and 3 have been prepared to support the rest of this discussion. Figure 1 is a side view of the trajectory as would be seen from a position to the right of the trajectory. The X-axis is downrange from the shooter toward the target; the Y-axis is vertically upward at the firing point; and the Z-axis is horizontal and toward the shooter’s right at the firing point. The side view then looks in the direction backward along the Z-axis. The black circle marked “Z” is meant to indicate that the viewer “sees” the Z-axis arrowhead.

The trajectory is then viewed as if it were projected on the X-Y vertical plane. On this plane the elevation angle of the trajectory, called ϕ, is the angle between the horizontal direction (the X-axis) and the velocity vector projected onto the X-Y plane. The projected velocity vector, $\mathbf{V}_{projected}$, is the projection of both $\mathbf{V}_{bullet\ relative\ to\ the\ air}$ and $\mathbf{V}_{bullet\ relative\ to\ the\ ground}$, because the wind velocity $\mathbf{V}_{air\ relative\ to\ the\ ground}$ is parallel to the Z-axis and points at the viewer.

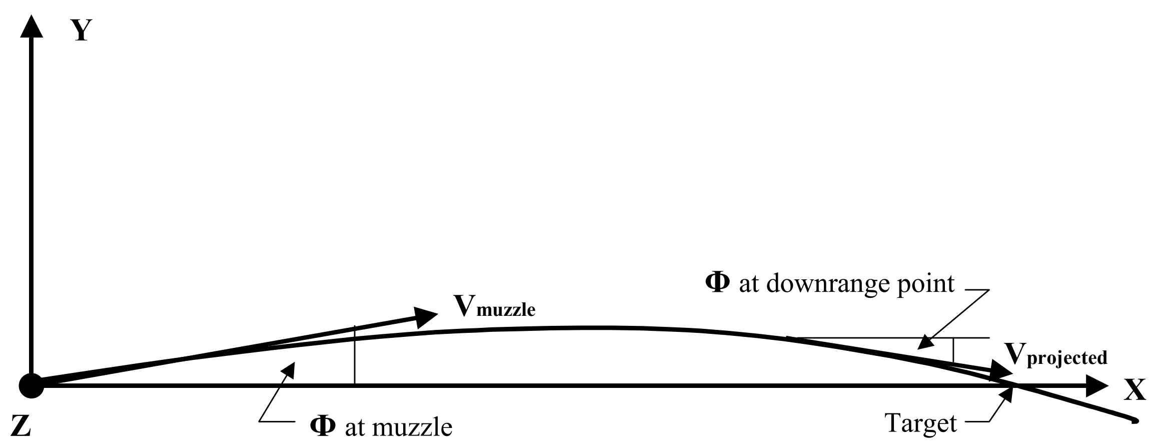

Figure 1 Side View of Trajectory

At every point on the trajectory the trajectory elevation angle ϕ is the angle between the horizontal direction (parallel to the X-axis) and the projected velocity vector. As shown in Figure 1, ϕ changes as the bullet flies. For the level fire situation, at the muzzle ϕ is the superelevation of the bore required to put the bullet on the target, and this is a small positive elevation angle (positive because the trajectory starts upward). For the 308 Winchester example used above, the superelevation angle for a target at 1000 yards is 0.739 degrees = 44.3 minutes of angle. As the bullet flies the trajectory curves downward, and ϕ decreases, going through zero at the summit of the trajectory, and then going negative and increasing in magnitude as the trajectory steepens. The bullet noses downward, and this is one of the small turning motions caused by a moment of torque on the bullet.

Figure 2 shows a top view of the trajectory as would be seen from a point above the shooter. The top view then looks in the direction downward (backward) along the Y-axis. The black circle marked “Y” is meant to indicate that the viewer “sees” the Y-axis arrowhead. The trajectory relative to the ground is then seen as if it were projected on the X-Z horizontal plane.

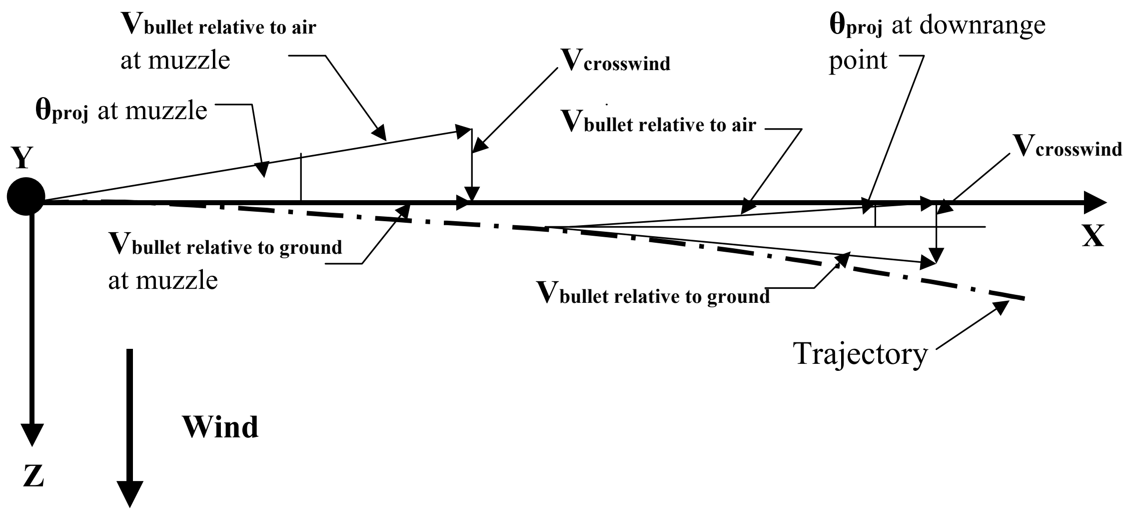

Figure 2 Top View of Trajectory, Left to Right Crosswind

Note that all the velocity vectors in Figure 2 are projections on the horizontal X-Z plane. Only $\mathbf{V}_{crosswind}$ is always parallel to the horizontal plane.

Figure 2 is drawn for a bullet with right hand spin, and for a crosswind blowing from the shooter’s left. The trajectory then curves to the shooter’s right to follow the crosswind. As the trajectory curves the bullet gains a component of velocity relative to the ground in the crossrange direction. It is moving crossrange, so it must have a component of velocity in that direction. The direction of this velocity component is parallel to the Z-axis, and its speed is:

$$V_{crossrange} = V_{crosswind} [1.0 - (V_{downrange} / V_{muzzle})] \qquad (3)$$

where $V_{downrange}$ is the downrange speed of the bullet, and the other speeds have been defined under equation (2). Now $V_{downrange} = V_{muzzle}$ at the muzzle, but $V_{downrange}$ decreases as the bullet flies. So equation (3) tells us that $V_{crossrange}$ is zero at the muzzle and then grows toward the value $V_{crosswind}$ as the bullet flies downrange. Figure 2 attempts to show what this means. As the bullet flies downrange the velocity vector $\mathbf{V}_{\text{bullet relative to the air}}$ turns gradually to the right, approaching an orientation where it would lie in a vertical plane parallel to the X-Y plane.

In the formal analysis of bullet motion the angle θ is defined mathematically. This angle is a measure of how far the velocity vector $\mathbf{V}_{\text{bullet relative to the air}}$ is turned away from a vertical plane parallel to the X-Y plane at each point on the trajectory. This angle is complicated to describe, and even more complicated to sketch, without lots of vector algebra. However, it is necessary to the analysis, and Figure 2 shows the projection of this angle on the horizontal X-Z plane, denoted by the symbol θ_{proj}. For a level fire shooting situation, the projected angle θ_{proj} is almost equal to the true angle θ at all points between the muzzle and the target. So, Figure 2 is a pretty good representation of how the true angle changes as the bullet flies from the gun to the target. The true angle is given by the equation:

$$\theta = \arctan \{[(V_{\text{crosswind}} – V_{\text{crossrange}}) / V_{\text{downrange}}] (\cos \phi)\} \qquad (4)$$

where all parameters in this equation have been defined previously. Equation (4) is accurate for all values of the trajectory elevation angle ϕ. For the level fire situation ϕ always has a very small value everywhere between the muzzle and the target so that $(\cos \phi)$ has a value very nearly equal to 1.0 in this segment of the trajectory. Under this condition equation (4) tells us that θ begins at the muzzle with the value given by equation (2), and then grows smaller as the bullet flies downrange.

If there were no crosswind, equation (1) tells us that $\mathbf{V}_{\text{bullet relative to the air}}$ would be equal to $\mathbf{V}_{\text{bullet relative to the ground}}$. Figure 2 for this special case would show that the full trajectory of the bullet would lie in the vertical X-Y plane. (This is not quite true as we will see later; because the yaw of repose would cause a drift to the right.) Under this condition equation (4) tells us that the angle θ is zero, which means the same thing. However, the trajectory shown in Figure 1 would not change. The trajectory would still curve downward from the muzzle, and $\mathbf{V}_{\text{bullet relative to the air}}$, which is the same as $\mathbf{V}_{\text{bullet relative to the ground}}$, would turn downward as the bullet flies.

If the crosswind blows from the shooter’s right to the left, the top view of the trajectory would be as shown in Figure 3. This figure is again drawn for a bullet with right hand spin, but the crosswind direction is reversed. The velocity of the bullet relative to the air is **upwind** as shown, and the bullet initially turns to align itself with $\mathbf{V}_{\text{relative to the air}}$. As the bullet flies downrange it gains a component of crossrange velocity relative to the ground. The angle θ decreases in magnitude, and the vector $\mathbf{V}_{\text{bullet relative to the air}}$ turns gradually toward a vertical plane which is parallel to the X-Y plane. The magnitudes of the angles given by equations (2) through (4) are the same. And Figure 1 still applies to this case; the bullet pitches downward as the trajectory curves downward, and from Figure 3 $\mathbf{V}_{\text{bullet relative to the air}}$ turns gradually to the left as the bullet flies.

It is important to understand that the trajectories shown in Figures 2 and 3 are <u>deflections</u> of the bullet as it tries to “catch up” with the crosswind. In order for the velocity vectors to turn, torques must be applied to the bullet, and the forces which create those torques cause additional small drifts of the bullet. We will now describe those drifts.

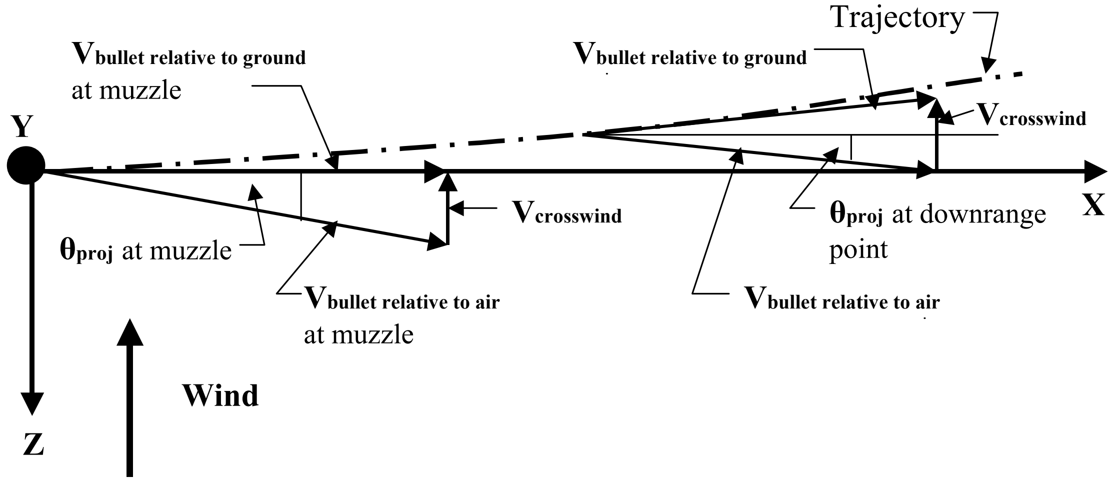

Figure 3 Top View of Trajectory, Right to Left Crosswind

At this point we have established graphically and verified analytically that the bullet velocity vectors turn in both the vertical direction (Figure 1) and the horizontal direction (Figure 2 or 3) as the bullet flies in a crosswind. The bullet itself stays aligned with this velocity vector on the "average," and so it also turns in both of these directions. We know from the laws of physics that when a gyroscopically stabilized bullet turns, torques must be applied to cause this to happen. These torques can come only from aerodynamic forces. To generate such aerodynamic forces, the bullet must have small aerodynamic yaw and pitch angles relative to the velocity vector $\mathbf{V}_{\text{bullet relative to the air}}$. These angles are small deviations from the "average" angular orientation of the bullet, and they are known collectively as the "yaw of repose."

Ballisticians have long referred to "yaw" as an angle of tilt of the bullet nose in any direction with respect to $\mathbf{V}_{\text{bullet relative to the air}}$. This is known as "aeroballistic yaw." "Aeroballistic yaw" is composed of an aerodynamic pitch angle (nose up or down) followed by an aerodynamic yaw angle (nose right or left). The yaw of repose is an aeroballistic yaw, and it can have both an aerodynamic pitch component and an aerodynamic yaw component. The yaw of repose is just the angle of tilt the bullet nose must have relative to $\mathbf{V}_{\text{bullet relative to the air}}$ to cause the bullet to remain stable as it flies, and turn as it moves along the trajectory.

We will follow McCoy's presentation in Chapter 9 of Modern Exterior Ballistics. The yaw of repose of a bullet in a crosswind has two components. The first is an angular tilt of the nose of the bullet to the right of $\mathbf{V}_{\text{bullet relative to the air}}$ (for a bullet with right hand spin). This tilt is the same for both directions of crosswind and has the value:

$$\beta = \alpha_{Ro} (\cos \theta) \qquad (5)$$

Because the nose of the bullet is tilted to the right with respect to **V**bullet relative to air, an aerodynamic side force to the right is generated. This force causes a moment of torque (another vector) directed vertically downward. This moment causes the bullet to pitch downward as it flies.

If there were no wind, then θ would be 0, $(\cos \theta) = 1.0$, and $\beta = \alpha_{Ro}$. So, regardless of whether there is wind or not, the bullet nose is tilted slightly to the right of **V**bullet relative to the air. This generates the side force on the bullet pointed to the right and the moment of torque directed vertically downward. The rotational equations of motion of a spin stabilized bullet tell us that the angular momentum vector (pointed out the nose of the bullet for right hand spin) turns toward the moment of torque vector. This causes the nose of the bullet to pitch downward as it flies, keeping the longitudinal axis of the bullet essentially tangent to the trajectory. At the same time, the side force causes an acceleration of the bullet to the right, which in turn causes the bullet to drift to the right.

This description is for a bullet with right hand spin. If the bullet had left hand spin, the nose would be tilted to the left, and the aerodynamic force would be directed to the left. The aerodynamic torque moment would be directed upward. But since the angular momentum vector would be pointed out the tail of the bullet, it would still pitch downward as it flies and remain tangent to the trajectory.

The angle term α_{Ro} in equation (5) depends on both aerodynamic and static characteristics of the bullet and on environmental parameters:

$$\alpha_{Ro} = (2I_x p g) / (\rho S d V^3 C_{M\alpha}) \qquad (6)$$

where I_x is the polar moment of inertia of the bullet
- p is the bullet spin rate
- g is the acceleration due to gravity
- ρ is the density of the air through which the bullet is flying
- $S = \pi d^2/4$ is the cross sectional area of the bullet, where d is the bullet diameter
- V is the magnitude of **V**bullet relative to the air
- $C_{M\alpha}$ is the overturning moment coefficient for the bullet

In equation (6) all the parameters are known or can be measured easily, except for $C_{M\alpha}$. This aerodynamic characteristic of a bullet is measured in firing tests in spark photography ballistic ranges, usually not available to manufacturers of sporting bullets. $C_{M\alpha}$ is measured on military bullets, but is unknown for almost all sporting bullets.

The angle α_{Ro} is small but unknown for sporting bullets, but it is useful for understanding the causes of bullet deflections observed in the field. It also varies with the speed of the bullet, because the bullet speed appears directly in equation (6) and $C_{M\alpha}$ changes with Mach number.

Now consider the other component of the yaw of repose, the angular tilt downward or upward. This is either a negative or positive angle of attack:

For a crosswind blowing from left to right:

$$\alpha_{attack} = - \alpha_{Ro} [(V_{crosswind} - V_{crossrange}) / V_{downrange}] (\cos\theta) (\sin\phi) (\cos\phi) \quad (7)$$

For a crosswind blowing from right to left:

$$\alpha_{attack} = + \alpha_{Ro} [(V_{crosswind} - V_{crossrange}) / V_{downrange}] (\cos\theta) (\sin\phi) (\cos\phi) \quad (8)$$

In equations (7) and (8) the crosswind speed is always greater than the crossrange bullet speed, ($\cos\theta$) is always positive, and ($\cos\phi$) is always positive. However, ($\sin\phi$) is initially positive on the ascending part of the trajectory (see Figure 1) before the bullet reaches the summit, but it is negative on the descending part of the trajectory beyond the summit.

Now, let us interpret these equations. First, consider that there is **no wind**. In this case $V_{crosswind}$ and $V_{crossrange}$ are both equal to zero. Equation (4) then tells us that the angle $\theta = 0$ for no wind. This means that the bullet trajectory lies almost completely in the X-Y plane. There will be a small drift out of this plane due to the yaw of repose.

In equation (5) for no wind the term ($\cos\theta$) = 1.0, and then:

$$\beta_{no\ wind} = \alpha_{Ro} \quad (9)$$

which means that the nose of the bullet is tilted slightly to the right of $\mathbf{V}_{bullet\ relative\ to\ the\ air}$ as the bullet flies.

Equations (7) and (8) then tell us that, for the case of no wind, the angle of attack is zero, that is, the nose of the bullet is not tilted either upward or downward with respect to $\mathbf{V}_{bullet\ relative\ to\ the\ air}$. So, the yaw of repose for the no wind case is simply a nose tilt to the right (away from the X-Y plane) as the bullet flies.

With a slight nose tilt to the right, the aerodynamic force to the right will accelerate the bullet to the right (out of the X-Y plane). This in results in the crossrange drift of the bullet observed by target shooters. This drift is to the right of the target if the bullet has right hand spin. If the bullet has left hand spin, the drift is to the left of the target. If the spin rates are the same (barrel twist rates are the same), the drift to the left will be the same as the drift to the right.

There is an equation for the force caused by the yaw of repose. However, this equation involves aerodynamic properties of the bullet which are simply unknown for sporting bullets and unmeasurable in a manufacturer's laboratory. So, a calculation of this drift is not possible. A target shooter therefore must determine the drift experimentally for each cartridge and each bullet, muzzle velocity, and range distance to the target, and apply appropriate windage corrections for different range distances. It is known that this crossrange drift is relatively small, being a few inches at 1000 yards range distance for most cartridges.

Now, consider the case when a **crosswind is present**. The bullet follows the crosswind, so that the bullet crossrange speed $V_{crossrange}$ approaches the crosswind speed $V_{crosswind}$. So, the bullet.deflects in the direction of the crosswind, and we know that this is quite a large deflection. This deflection is calculated by the Sierra *Infinity* software. In addition to this deflection there will be drift caused by the yaw of repose. This drift will be in both the horizontal and vertical directions. We cannot calculate this drift, but the equations will tell us the directions and relative magnitudes.

In equation (4) the term ($\cos \phi$) is almost exactly equal to 1.0 because for level fire ϕ is always small over the bullet trajectory between the muzzle and the target. So, equation (4) tells us that the angle θ begins at the muzzle with the value θ_{muzzle} [see equation (2)] and then decreases toward zero as the crossrange speed of the bullet grows toward the crosswind speed. So, the ($\cos \theta$) terms in equations (5), (7), and (8) can be set to 1.0, as can the term ($\cos \phi$). For this condition equation (5) becomes:

$$\beta_{crosswind} = \alpha_{Ro} \qquad (10)$$

Equation (10) is the same as equation (9), telling us that with a crosswind there will be a nose tilt of the same magnitude and in the same direction as there is with no wind. This means that for a crosswind in either direction there will be a drift to the right (for right hand spin) superimposed on the deflection caused by the bullet following the wind. However, **when the crosswind is left to right, the deflection is to the right and the drift adds to the deflection. When the crosswind is right to left, the deflection is to the left and the drift subtracts from the deflection. So the total horizontal movement of a bullet on the target should be a little larger for a crosswind blowing from left to right than it would be from a crosswind of the same speed but blowing from right to left.** This effect reverses if the bullet has left hand spin.

Now consider the angles of attack. Equations (7) and (8) become:

For a crosswind blowing from left to right:

$$\alpha_{attack} = - \alpha_{Ro} [(V_{crosswind} - V_{crossrange}) / V_{downrange}] (\sin \phi) \qquad (11)$$

For a crosswind blowing from right to left:

$$\alpha_{attack} = + \alpha_{Ro} [(V_{crosswind} - V_{crossrange}) / V_{downrange}] (\sin \phi) \qquad (12)$$

In these equations note that ϕ is positive between the muzzle and the summit of the trajectory, is zero at the summit, and then is negative between the summit and the target. Equation (11) tells us that for a crosswind blowing from left to right the angle of attack is negative (nose down) between the muzzle and the summit of the trajectory, goes through a zero value at the summit, and then is positive (nose up) between the summit and the target. This is for a bullet with right hand spin; for left hand spin the nose is up between muzzle and summit, and then down between summit and target. If the crosswind is in the opposite direction, equation (12) tells us that these conditions simply reverse. Both equations show us that the angles of attack decrease in magnitude as the crossrange speed of the bullet grows toward the crosswind speed.

Equation (11) tells us that for the portion of the trajectory between the muzzle and the summit of the trajectory the bullet nose turns downward with respect to the vector $\mathbf{V}_{\text{bullet relative to the air}}$ for a crosswind from left to right. This means that a small aerodynamic force directed downward is applied to the bullet before it reaches the summit. This downward force accelerates the bullet downward. This force goes to zero at the summit. After the bullet passes the summit the angle of attack becomes positive. The bullet nose then turns upward and the aerodynamic force becomes directed upward between the summit and the target.

Using *Infinity* to search a number of level fire trajectories for the summit, we have found that the summit occurs at about 58 % of the range distance between muzzle and target. The acceleration of the bullet downward before it reaches the summit is larger than the upward acceleration after it passes the summit. The downward acceleration propagates into a downward ddrift of the bullet. The upward acceleration after the bullet passes the summit is smaller in magnitude and has less time to act on the bullet before it reaches the target. But, it tends to reduce the downward drift of the bullet. **This is the reason for the observations in Mr. Hollister's question that (a) the total bullet drift in a crosswind blowing from left to right is toward 4 o'clock, and (b) as the crosswind speed increases, the vertical drift of the bullet does not increase as rapidly as the crossrange drift.**

If the crosswind blows from right to left, equation (12) tells us that the stronger acceleration of the bullet is upward as it deflects to the left to follow the crosswind, and the weaker acceleration is downward, reducing the upward drift of the bullet. **This sends the bullet imprint on the target to 10 o'clock. Mr. Hollister's observation (b) above also happens in this case because of the same effect.**

There remains one more part of Mr. Hollister's question to answer. This is his observation that a **crosswind blowing from right to left produces a little more vertical drift than a crosswind blowing from left to right**. The equations above do not directly reveal the cause of this effect. However, it was mentioned above that the horizontal drift produced by the yaw of repose adds to the horizontal deflection of a bullet following a left-to-right crosswind, and subtracts from the deflection of a bullet following a right-to-left crosswind. The vertical drifts, however, have the same magnitudes, provided the crosswind speeds are the same, but different directions.

This writer believes that the reason for Mr. Hollister's observation is the following. A left-to-right crosswind of a certain speed produces a horizontal bullet displacement at the target equal to the deflection caused by the crosswind **plus** the horizontal drift due to the yaw of repose. Suppose the horizontal deflection is 10 inches and the horizontal drift is 4 inches. Further, suppose that the vertical drift caused by the yaw of repose is minus 2 inches. So, the bullet hole on the target should appear 14 inches to the right and 2 inches down, relative to the bullseye. Now, a right-to-left crosswind of the same speed produces a horizontal bullet displacement at the target equal to the crosswind deflection **minus** the horizontal drift due to the yaw of repose. The vertical drift caused by the yaw of repose is plus 2 inches for the right-to-left crosswind. Then, the bullet hole on the target for this crosswind would appear 6 inches to the left and 2 inches up, compared to the bullseye. This would make it appear to the shooter as though the right-to-left crosswind produced vertical drifts greater than a left-to-right crosswind. However, this would be an illusion.

If this is not true, then the reason for this observation by Mr. Hollister could possibly be in the assumptions that McCoy lists leading to the derivation of the equation for the yaw of repose. These assumptions make the yaw of repose dependent only on the lift force and the overturning moment. Other aerodynamic effects (Magnus force and moment, pitch damping force and moment, and others) are smaller and assumed negligible.

If a bullet has left hand spin, the bullet still deflects to follow the wind. However, the yaw of repose reverses direction, and the aerodynamic forces associated with the yaw of repose reverse direction. The displacement of the bullet on the target then is toward 2 o'clock for a left-to-right crosswind, and toward 8 o'clock for a right-to-left crosswind.

The bullet deflections by a crosswind depend on the ballistic coefficients of the bullet, which can be measured in a manufacturer's shooting laboratory. The deflections therefore can be calculated, and this is done in *Infinity*. However, the horizontal and vertical drifts due to the yaw of repose cannot be calculated because the necessary aerodynamic characteristics of sporting bullets are unknown and unmeasurable without very expensive laboratory instrumentation. Luckily, the drifts are small compared to the deflections. But, the drifts can be observed by skilled target shooters. So, it may be important to measure them experimentally on the shooting range and use both elevation and windage corrections when adjusting the sights on the gun for targets at various range distances.