Understanding Wind Drift

By James A. Boatright

Air Drag

Air drag is the largest and most powerful force affecting the flight of the bullet. The only non-aerodynamic force acting upon the free-flying bullet is its weight due to gravity—and that is only about one forty second of a pound for the **168-grain** *Sierra MatchKing* bullet used as a convenient example in this discussion. If the bullet is flying exactly point-first through the air, its air drag is well defined by the bullet's *ballistic coefficient* (**BC = 0.462**, based on the **G1** standard projectile, for our example bullet at speeds above **2600 FPS**), by its muzzle velocity (**2600 FPS** from our short-barreled example rifle in *308 Winchester*), and by the density of the atmosphere through which it is moving. For standard atmospheric temperature (59 degrees, Fahrenheit), pressure and humidity conditions, at sea level, the drag force on our example bullet at **2600 FPS** is **1.27 pounds** (or **53 times the weight** of our bullet). I calculated this drag force from the bullet's speed loss and time-of-flight over the first ten yards of its trajectory as printed out by *Sierra's Infinity* (Version 6.0) external ballistics program.

The ballistic coefficient of a given bullet in a given speed range is a measure of its relative aerodynamic efficiency. The BC describes how well that bullet, launched at a given muzzle velocity, can retrace the well-studied trajectory of a particular (**G1**) "standard projectile" in flat-firing, horizontal flight. The BC of a bullet can be thought of as the *sectional density* of the bullet divided by a *form factor* that describes the degree of streamlining of the bullet in supersonic flight (at least in our example here). The form factor of a bullet is the ratio of its air drag to that of the selected standard projectile under similar conditions. The form factor of the standard bullet is unity, of course, and the BC of the standard one-inch diameter bullet, weighing one pound, is also taken to be unity. The sectional density of the bullet, as used here, is the weight of the bullet (in pounds) divided by the square of its diameter (in inches). But, "sectional density" is properly defined in mechanics as the mass of an object divided by its cross-sectional area. [The convention of omitting some constants from this definition in ballistics came about so that a **1.0-inch** diameter "**G1** standard projectile," made of **1.0-pound** of pure lead, could have its "sectional density," "form factor," and "BC" each equal to ***unity***.]

Any bullet will generate more drag when it has to fly through a *denser* atmosphere. The highest density air is encountered on the coldest, driest, highest-barometric pressure day on the lowest-elevation, below-sea-level, horizontal firing range. On the other hand, the warmest, highest-water-vapor-content, lowest-pressure air at the world's highest-altitude horizontal firing range would be opposite in each of these respects—producing the least amount of bullet drag ever likely to be encountered in flat firing.

It is important to note that the ***direction*** of the aerodynamic *drag force* does ***not*** depend in any way upon the bullet's *attitude* (orientation with respect to its forward velocity vector) or upon its *angle of fire* (or even upon its *angle of attack* in flight). Air drag is always acting in a ***downwind*** direction by definition. By "downwind," I mean "in the direction of apparent motion of the undisturbed local air mass" as seen from the perspective of the moving bullet itself at any instant. Figure 1 shows the apparent wind encountered by the moving bullet.

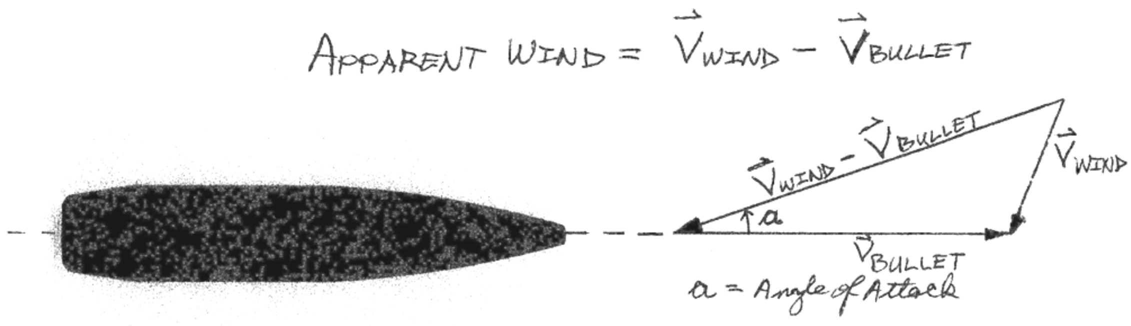

FIGURE 1. APPARENT WIND CONCEPT

At any point in space and time along the bullet's flight, a *single force vector* applied toward the center of pressure against the surface of the bullet can define the entire aerodynamic force exerted upon the bullet. If this aerodynamic force vector is not aligned perfectly with the bullet's "minus V" direction (so as to produce a purely "ballistic" drag), the rectangular force component *perpendicular to the drag force* is called ***"lift,"*** regardless of the radial direction in which this side force is acting to pull the bullet away from its ballistic trajectory. Figure 2 shows the aerodynamic forces on the bullet in flight. The term "ballistic" implies "zero lift" in this context. The magnitude of the force vector called "lift" is inherently positive, without regard to its orientation with respect to the force of gravity acting on the bullet.

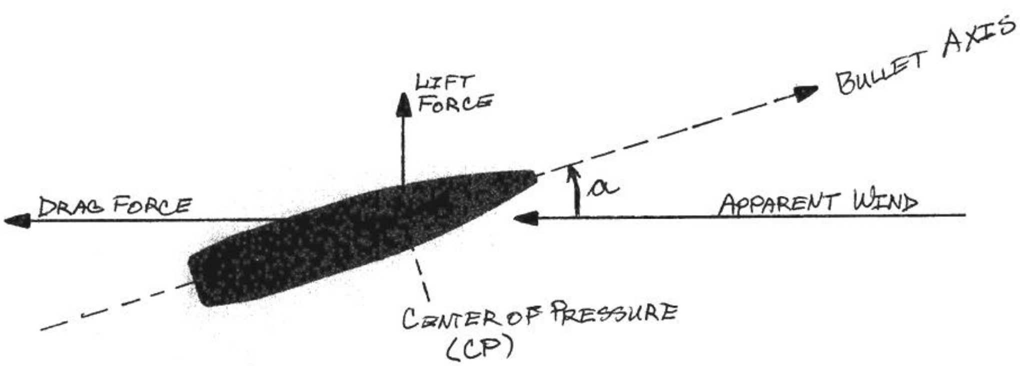

FIGURE 2. AERODYNAMIC FORCES ON BULLET IN FLIGHT

Crosswinds

Real winds during a match are constantly changing in direction and strength. Typically, they also contain headwind or tailwind components as well as vertical updraft or downdraft components. But perhaps most confounding to the shooter is the tremendous non-uniformity of the various wind conditions encountered by the fired bullet as it traverses the range from muzzle to target. Not unusually, the winds may simultaneously blow from opposite directions in different parts of the same firing range. This difficult situation results from vortices and turbulent flows attributable to obstacles interfering with the wind blowing near the surface of the earth. Our wind indicators are always overloading us with information as we prepare for each shot. Yet, somehow, the good shooters who practice a lot on that particular target range can “read the wind” and make consistently good shots.

Let us set up a diabolically simple ambient wind situation in order to be able to study the effects of crosswinds on our target bullets. Let us imagine that we have set up a sturdy portable bench in the middle of a huge, sea-level western salt flat at dawn when the wind is a steady **10 MPH** (blowing exactly horizontally) at the muzzle height of three feet (and up to a height of three feet four inches, the maximum ordinate of our firing trajectory) over the unobstructed terrain from a due west direction, and that this wind condition remains incredibly steady in both speed and direction. If we fire at a target set up three feet above the ground plane at a distance of **200 yards** due north of our bench (for exactly horizontal firing), our bullet will encounter a *uniform* **14.67 FPS** crosswind from 9:00 o’clock (from left to right) all the way from the muzzle to its target.

My *Sierra Infinity* exterior ballistics program says that their **168-grain** *MatchKing* bullet launched at **2600 FPS** will slow to **2220 FPS** over this **200-yard** range in exactly these ambient conditions of a uniform **10 MPH** crosswind from 9:00 o’clock in this sea-level, standard atmosphere at an air temperature of 59 degrees Fahrenheit. Furthermore, the time of flight should be **0.2498 seconds**, and wind drift should be **3.35 inches** (**1.60 MOA**) off to the right of our no-wind zero at this **200-yard** range. See the included printout from *Sierra’s Infinity* ballistics program. The program uses sophisticated numerical integration techniques to compute these well-accepted trajectories and time-of-flight values. Let us further assume that our bullets are all perfectly balanced and always exit the muzzle having suffered no in-bore yaw. Now, let us see if we can calculate a good estimate of the wind drift in these uniform conditions by using a simple physical model to illuminate how this drift *actually occurs*.

As soon as the bullet clears the blast cloud at the muzzle, it simultaneously encounters a **2600 FPS** headwind and a **14.67 FPS** crosswind from 9:00 o’clock. As any sailor knows intuitively, these two wind components will combine to create an “apparent wind” impinging on the bullet nose from just slightly left of dead ahead. The bullet fired through a crosswind encounters an *apparent wind* equal to the *vector difference: wind velocity minus bullet velocity*. [The crosswind and bullet velocity are three-dimensional vectors and each is defined in an “earth-fixed” coordinate system. The apparent wind vector is the relative motion of the local air mass as seen from the moving bullet.] The speed of the initial apparent wind in our example is still essentially **2600 FPS**, and the angle off the bow is only **20 MOA** (or a third of one degree—the same angle at which we often taper down our scope bases for use at long ranges). Thus, the just-fired bullet finds itself flying through the crosswind at a very slight *angle of attack* (of **20 MOA**) off to the right, rather than straight ahead into the local atmosphere (as it would have done, at least for a short time, had there been no crosswind). For reasons pertaining to its spin stabilization, the bullet is ***not*** driven off to the right by the lift force attributable to this angle of attack. If it were, we would have to contend with wind effects *ten times larger* than we actually experience.

Trajectory for Sierra Bullets .308 dia. 168 gr. HPBT MatchKing at 2600 Feet per Second
At an Elevation Angle of: 0 degrees
Ballistic Coefficients of: 0.462 0.447 0.424 0.405 0.405
Velocity Boundaries (Feet per Second) of: 2600 2100 1600 1600
Wind Direction is: 9.0 o'clock and a Wind Velocity of: 10.0 Miles per hour
Wind Components are (Miles per Hour): DownRange: 0.0 Cross Range: -10.0 Vertical: 0.0
The Firing Point speed of sound is: 1120.27 fps
The bullet does not drop below the speed within the max range specified.
Altitude: 0 Feet with a Standard Atmospheric Model.
Temperature: 59 F
Data Printed in English Units

Range (Yards)	Velocity (Ft/Sec)	Energy (Ft/Lbs)	Bullet Path (inches)	Bullet Path (1 MoA)	Wind Drift (inches)	Wind Drift (1 MoA)	Time of Flight (Seconds)
0	2600.0	2521.3	-1.5	0.0	0.0	0.0	0.0000
10	2580.3	2483.1	-0.88	-8.4	-0.01	-0.1	0.0116
20	2560.5	2445.3	-0.31	-1.5	-0.03	-0.1	0.0233
30	2540.9	2408.0	0.21	0.7	-0.07	-0.2	0.0350
40	2521.4	2371.1	0.67	1.6	-0.13	-0.3	0.0469
50	2501.9	2334.6	1.07	2.1	-0.2	-0.4	0.0588
60	2482.5	2298.5	1.43	2.3	-0.28	-0.5	0.0708
70	2463.2	2262.9	1.72	2.3	-0.39	-0.5	0.0830
80	2443.9	2227.7	1.96	2.3	-0.51	-0.6	0.0952
90	2424.8	2192.9	2.14	2.3	-0.65	-0.7	0.1075
100	2405.7	2158.6	2.26	2.2	-0.8	-0.8	0.1200
110	2386.7	2124.7	2.32	2.0	-0.98	-0.8	0.1325
120	2367.9	2091.2	2.32	1.8	-1.17	-0.9	0.1451
130	2349.1	2058.1	2.26	1.7	-1.38	-1.0	0.1578
140	2330.3	2025.4	2.13	1.5	-1.6	-1.1	0.1706
150	2311.7	1993.1	1.94	1.2	-1.85	-1.2	0.1836
160	2293.1	1961.3	1.69	1.0	-2.11	-1.3	0.1966
170	2274.7	1929.8	1.37	0.8	-2.39	-1.3	0.2097
180	2256.3	1898.7	0.98	0.5	-2.69	-1.4	0.2230
190	2238.0	1868.0	0.53	0.3	-3.01	-1.5	0.2363
200	**2219.7**	**1837.7**	**0.0**	**0.0**	**-3.35**	**-1.6**	**0.2498**

Wind Drift

Shooters have known for generations that the amount of wind drift that occurs when firing in a uniform crosswind seems to be proportional to the air-drag-induced *delay* in time-of-flight as well as to the speed of the crosswind. This calculation technique is attributed to Dedion in 1859. The delay in the time-of-flight (**0.0190 seconds** in this example) is entirely due to air drag. That is, if we were firing in the vacuum of space, there would be no delay in flight time due to air drag—and no possibility of wind drift either. However, in this discussion we are *not* going to start by quantifying the amount wind drift directly from this delay in the bullet's time-of-flight.

Instead, we shall use a few values calculated by the external ballistics program to find the average bullet ***drag force*** over our **200-yard** range (a vector force of about one pound, more or less, pointing rearward in the "downwind" direction of the apparent wind flow past the bullet). As shown in Figure 2 above, when we are firing through a crosswind, the air drag ***force vector*** acting on the bullet will ***no longer point directly back from the target toward the shooter***. But this drag force will now have a small ***cross-track component*** (in the crosswind direction) that will, in turn, ***accelerate (or move) the bullet downwind*** to produce approximately the wind drift routinely seen on the target.

If our **168-grain** bullet has slowed from **2600 FPS** to **2220 FPS** in **0.2498 seconds** over the first **200 yards** of its flight, the average deceleration of the bullet must have been **1521 feet per second per second (FPS/S)**. And the average drag force needed to slow our bullet (of mass equal to **0.746 thousandths of a slug**) at this average rate must have been **1.135 pounds**. [A mass of one slug weighs **32.16 pounds**. Here, I am making use of Newton's Second Law of Motion in the form: "Force equals mass times acceleration." I am using **32.16 FPS/S** as the acceleration of gravity (**g**), and I hope that our "metric" friends can bear with us through all these strange units. We also realize that the drag force on the bullet, and consequently its deceleration, are *not* constant, but are slowly decreasing over our **200-yard** range. This over-simplification can be expected to introduce a slight error in our calculated values, but our purpose here is *merely to demonstrate the correctness of this **"drag force component"** causation of wind drift*.]

The crosswind component of this average force at **20 MOA** off the launch axis is **0.5641 percent** of this force, or **6.404 thousandths of a pound**. Again, this angle of attack is not constant, but increases gradually as the bullet slows its forward speed while flying through the uniform crosswind. But this tiny force is enough to accelerate the similarly tiny mass of our match bullet at an average of **8.581 FPS/S** cross-track, off toward the right. [We could have jumped straight to this average cross-track bullet acceleration (just over one fourth of the acceleration of gravity) from the average deceleration and the (initial) angle of attack, but here I wanted to work through the whole physical model in an effort to persuade any skeptics.] The cross-track velocity at **200 yards** down range will be **2.144 FPS** if this average cross-track acceleration is constantly applied. Starting from an initial zero cross-track velocity, the cross-track displacement after **0.2498 seconds** of flight time would be **3.213 inches** due *solely* to this cross-track component of the air drag force. The program computed **3.35 inches** of wind drift for this **200-yard** range. This is "close enough for government work," as we used to say at NASA, and serves to demonstrate the correctness of designating this "drag force component" as the principal cause of the bullet's wind drift when shooting through a crosswind.

Wind Drift Equations

Now that we have established that *wind drift is caused by air drag*, let us develop some simple equations to systematize the calculation of the size of this wind drift. We will actually *re-derive **Dedion's Equation*** from the *air drag component* experienced by the bullet *in order to show that they are **equivalent***. We will also derive a similar expression to calculate the cross-track velocity of the bullet at the target due to flying through a crosswind.

Let us introduce some symbols to represent the values used in the example narrated above:

Let: **Muzzle Velocity = V_0 = 2600 feet/second**

Range = R = 200 yards = 600 feet

Impact Velocity = V_R = 2220 feet/seconds

Time-of-Flight = t_R = 0.2498 seconds

Crosswind Velocity Component = V_W = 14.67 feet/second.

So, the first item to calculate is the *average deceleration* **A**:

$$A = (V_0 - V_R)/t_R = (2600 - 2220 \text{ ft/sec})/(0.2498 \text{ seconds}) = 1521 \text{ feet/seconds}^2$$

We can also calculate the **DELAY** in time-of-flight due to air drag to be:

$$DELAY = t_R - R/V_0 = 0.2498 - 600/2600 = 0.0190 \text{ seconds}.$$

From physics, we can write an expression for the down-range distance **R** and the time-of-flight to that distance t_R, if we assume that the average *deceleration rate* **A** due to air drag is applied *constantly*:

$$R = V_0*t_R - (A/2)*t_R^2$$

Rearranging this, we can write:

$$(A/2)*t_R^2 = V_0*t_R - R$$

Now, let us formulate an expression for the bullet's *cross-track* set-over distance S_c at the target distance **R** due to a crosswind of velocity V_W:

$$S_c = (A_c/2)*t_R^2$$

where A_c represents the *average cross-track deceleration* of the bullet due to air drag:

$$A_c = (V_W/V_0)*A.$$

The velocity ratio in parentheses is just the ***small** angle-of-attack* (**20 MOA** expressed in *radians*) of the *apparent wind* as seen by our example bullet moving through this crosswind. This ratio (V_W/V_0) also represents the fraction of the air drag force that acts to push the bullet cross-range, off to the right. Technically, these expressions for **R** and S_c result from *doubly integrating* their respective down-range and cross-track "*equations of motion*" with respect to time. The expression for A_c is only approximately correct. But, ballisticians have been making this approximation for the past 150 years, and we merely continue the practice. We should actually divide V_W by the bullet's *average velocity* to the range **R** to estimate the *average angle of attack*, but this ***implicit range dependence*** would complicate this simple approach too much.

Substituting the expression for A_c into the expression above for S_c, and then utilizing the expression just above that, we have:

$$S_c = (V_W/V_0)*(A/2)*t_R^2 = (V_W/V_0)*[V_0*t_R - R],$$

or, $S_c = V_W*[t_R - R/V_0] = V_W*DELAY$, which is just ***Dedion's Equation***.

Using our example data values, we find that:

$$S_c = (14.67 \text{ feet/second})*(0.0190 \text{ seconds})*(12 \text{ inches/foot}) = \underline{3.345 \text{ inches}}.$$

Notice that this value rounds to the *exact value* printed-out by the *Sierra Infinity* program (**3.35 inches**).

We could also formulate the cross-track set-over distance $\mathbf{S_c}$ as:

$$\mathbf{S_c = (V_c/2)*t_R} ,$$

where $\mathbf{V_c}$ is the final cross-track velocity of the bullet due to wind drift when the bullet impacts the target. The bullet's cross-track velocity is **zero** at the muzzle, so the division by two is done in order to calculate the *average* cross-track velocity of the bullet.

But, $\mathbf{V_c}$ can also be given by:

$$\mathbf{V_c = A_c*t_R = (V_W/V_0)*(A*t_R) = (V_W/V_0)*(V_0 – V_R) = V_W*[(V_0 – V_R)/V_0]}.$$

This expression is now in a form similar to *Dedion's Equation*. We could say that:

"*The cross-track velocity of the bullet at the target is given by the proportion of the muzzle velocity lost due to air drag times the cross-track wind velocity component.*"

Using our example values, we find:

$$\mathbf{V_c = (14.67\ feet/second)*[(380\ feet/second)/(2600\ feet/second)] = 2.144\ feet/second.}$$

This value agrees with our earlier calculations.

Summary

I hope that this discussion adds incrementally to the general understanding of how our benchrest bullets fly through the air to their short-range targets. Notice that we have successfully calculated the "accepted" amount of cross-track wind drift at a **200-yard** range based on our "drag force component" model, and we have also re-derived *Dedion's Equation* of 1859 for calculating wind drift—all without resorting to bogus "crosswind over spinning bullet" hand-waving arguments. The only values that we chose to use from the air drag model contained in my store-bought external ballistics program were the bullet speed remaining at **200 yards** and the time of flight to **200 yards**. Our crudely calculated wind drift value matched the one printed by the program within **4 percent**, and our re-derivation of *Dedion's Equation* allowed us to recreate *exactly* the wind drift value printed out by ***Sierra's Infinity*** ballistics program. ***Moreover, I am confident that aerodynamic lift and drag forces acting on the spinning bullet in flight can account for each of the wind-caused bullet impact displacements that we observe on our targets when firing our most accurate competition benchrest rifles in real crosswinds.***