

Measure First, Then Predict

We often hear that exterior ballistic programs won't fit actual shooting data. If you ask the author of any ballistic program, he will explain in detail how he processes the chosen drag function, ballistic coefficient, muzzle velocity, and atmosphere to give a prediction of the bullet path. His method of processing can range from the old Siacci method, to modern numerical integration or even Pejsa's clever approximations. Each author rigorously defends his program as being accurate. There are no holes in his mathematical analysis or his implementation on the computer. He has thoroughly checked his results against results from other reputable programs, and they always agree. (Matter of fact, virtually all modern programs will provide the same answers to the same questions.) When a program is checked by actual shooting, there are differences between the programs predictions and the actual target. How can this be?

In some ways a ballisticians can be like a politician, magician, or statistician. Ask a politician a question, and he will give you a response. His response may answer some question, but it won't be the one you asked. Watch a magician do a trick and you don't see what you thought you saw; you were distracted at just the right time. Ask a statistician for a decision and he can carefully craft a hypothesis to include a little bias into his answer before he crunches all the numbers.

A ballisticians will start the defense of his program with a statement something like, "We'll use the G1 drag function because it is standard." He might even say, "We'll use the G7 drag function because it fits most modern bullets better than the old G1 function."

He may say, "You may choose which drag function to use." As a user, you must obediently choose what you believe to be an appropriate drag function. The ballisticians doesn't tell you that none of the drag functions offered actually fit your bullet. Some may fit better than others. Your choice is similar to ordering hunting boots from a catalog offering boots in whole sizes and unspecified width. They might fit. At best, the drag function chosen is a compromise.

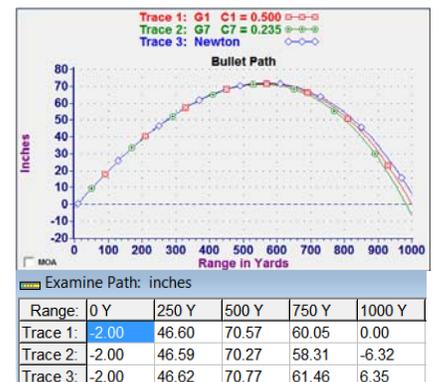
After you've guessed which drag function to use, you must provide a ballistic coefficient. The ballistic coefficient can be interpreted as a score of, "How good is my bullet compared to the reference bullets measured to define the drag function?" This number usually comes from the bullet manufacturer or may be measured by a third party. Either way, it probably was measured over a relatively short distance, typically 200 yards.

We want to trust our ballistic predictions out past 1000 yards, but the ballistic coefficient provided was probably measured over a range of 200 yards. This is akin predicting the outcome of a mile race by timing the runners over the first 100 yards. If we want to predict a runner's time for a mile, we'd better find out how fast he ran the mile last week. We don't base our prediction on his time for the first 100 yards and how much he slowed down for the second 100 yards.

Looking at the other portions of the ballisticians' programs, we see few problems. With modern chronographs, proper muzzle velocities are easy to get. Temperature and pressure can be measured and recorded to provide

the correct atmospheric density. Temperature is more important and varies faster than most shooters realize. Humidity is insignificant.

Look at predicted bullet path using *Ballistic Explorer*. Take the expected muzzle velocity, choose a drag function to fit the bullet and find the ballistic coefficient for that bullet. The ballistic coefficient probably came from drag measured near the muzzle. For illustration, we will compare three different drag functions. G1 represents the standard in use for over a century. G7 represents our best approximation for typical long-range bullets. Newton represents the original "velocity squared" drag postulated by Sir Isaac Newton three centuries ago. We'll adjust our sights for 1000 yard zero with G1 and look at the downrange bullet path predicted by the three different drag functions.



Ballistic coefficients for G7 and Newton were computed in the customary fashion with drag equal to G1 at muzzle velocity. With this muzzle velocity and distance, the three different drag functions give very similar predictions. This is not always the case. Differences are more apparent at higher muzzle velocities and longer ranges, especially if the bullet goes through the transonic velocity range. At

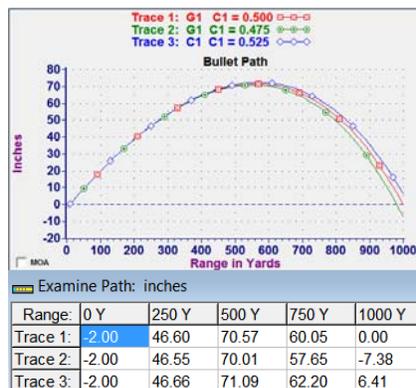
1000 yards, the path of G7 is 6 inches lower than the path of G1 while the path predicted by Newton is only 6 inches higher than predicted using G1. Note that we are not saying that our predictions will fit the shot; we are only comparing predictions to each other. All things considered, the predictions are remarkably close if all inputs are valid.

In this example, we have simply taken a published ballistic coefficient and assumed that it was exact. In our experience, we learned that measuring ballistic coefficients is at least ten times more difficult than simply measuring velocity. Twenty times the difficulty is a better estimate. If maximum range is limited to 200 yards, it is hard to get ballistic coefficients with accuracy significantly better than 5 percent. We have learned that it is not practical to measure ballistic coefficients by taking the difference between two velocities. (The spacing between the two chronographs must be very large to get a significant velocity loss. If the velocity loss is not large compared to the absolute accuracy of the chronographs, then accuracy of the resulting ballistic coefficient is worthless. With the long distance between units, it's usually too far to reliably shoot through the distant screens.) The most accurate ballistic coefficients are those determined by muzzle velocity and time-of-flight over a long distance.

Not only are ballistic coefficients difficult to measure, they are known to vary with velocity level and from bullet-to-bullet and gun-to-gun. Variation of ballistic coefficient with velocity level is actually an indication that the assumed drag function does not fit the bullet tested. Changing the ballistic coefficient with velocity is simply a

crutch to force the drag function to better fit the test results of the bullet. Variations of ballistic coefficient from bullet to bullet are a matter of manufacturing tolerances, but are often observed to be less than one percent. Significant variations are frequently seen from gun-to-gun. These differences are not only apparent with different twist rates and muzzle crowns, but also have been observed between "identical" guns. It is not uncommon to see differences of five percent with the same lot of loaded ammo in different guns. There appear to be many variables that we can't measure or even recognize.

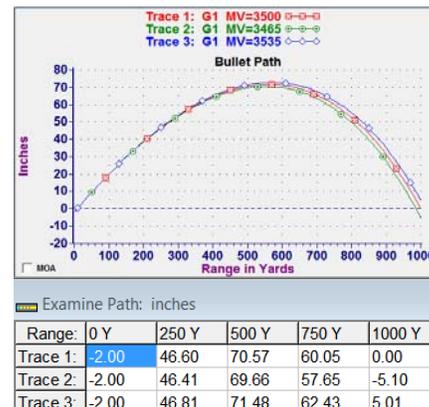
A plus or minus five percent uncertainty in ballistic coefficient is a reasonable assumption. Again we will assume a G1 drag function with a muzzle velocity of 3500 fps, same sight setting, and ballistic coefficients of 0.500, 0.475, and 0.525



Again we see differences of 6 or 7 inches at 1000 yards. That's barely enough to notice.

The third significant input to the prediction is muzzle velocity. The shooter can influence the accuracy by the ammunition selected. In our experience, it is routine to see 100 fps velocity spread in a box of factory hunting ammo. It is routine to see 50 fps spread in "match" ammo. Some dedicated long-range

bench-rest shooters claim to see only 5 fps spread in their carefully selected and loaded ammo. These typical spreads do not include variations between guns nor variations in temperature. For purposes of illustration let's just assume plus or minus one percent velocity difference.



Here again we can see roughly the same variations in bullet path at 1000 yards.

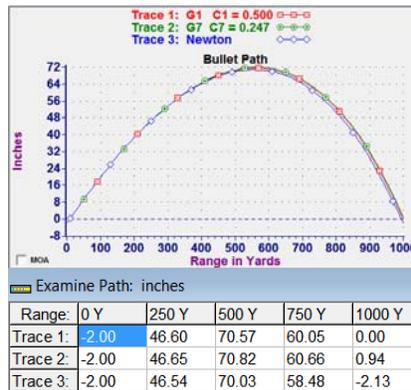
Now we've placed the ballistician in the position of using a model that may not fit your bullet, adjusted by bullet data measured only over a short range, using a questionable muzzle velocity to predict how your bullet will behave at long range. All the individual errors we have noted can add to give significantly larger errors. Approximately sixty years ago, the military decided to relegate the old idea of drag functions and ballistic coefficients to use in approximations and discussions. The military now uses Doppler radar data to define a "Firing Table" for each standardized round. This is the equivalent of making a special drag function to custom fit each bullet and saying that the bullet has a ballistic coefficient of 1.000 when used with that table. Doppler data works well, but it costs much time and money!

We've worked on making better ballistic predictions for many years. Measuring muzzle velocity is the easy part. If the shooter accurately measures muzzle velocity using his gun and tests over the expected temperature range, he should be able to provide muzzle velocity to an accuracy approaching 0.25% instead of the 1% used in the example. This is not an easy standard to meet. It requires use of a chronograph with a screen spacing of at least 4 feet and extreme care with ammo uniformity.

Thanks to some military work, we found that if we had four points along the time-distance curve, we could measure muzzle velocity very accurately. Then we found that we could measure ballistic coefficients very accurately from muzzle velocity and time-of-flight over a long distance, using any of the common drag functions.

We were especially interested in the velocity range commonly used for long range shooting. For this application, the muzzle velocity practically always ranges between Mach 2 and Mach 3.5. Shooters want bullets to remain above Mach 1 all the way to the target because strange things happen near the speed of sound. In this velocity range we found that if we evaluated the ballistic coefficients based on muzzle velocity and time-of-flight to 1000 yards, then it matters little which drag function we choose. Predicted bullet paths from muzzle to 1000 yards are almost identical.

Take a look at what happens to bullet path with the same sight settings but using the G1, G7 and Newton drag functions with ballistic coefficients measured with equal times-of-flight to 1000 yards.



What we have accomplished? The path difference between G1 and G7 predictions is reduced to 1 inch and even Newton's original formulation is close. We have demonstrated that the choice of drag functions is not critical if you use each drag function with its proper ballistic coefficient measured over a long distance. The accuracy of the ballistic coefficient measurement has been increased by a factor of 4 or 5 by increasing the range from 200 yards to 1000 yards.

Some would argue that we are measuring an "average" ballistic coefficient over the long range, instead of a "real" ballistic coefficient measured at different velocity levels over shorter ranges. This is absolutely correct. However, if the chosen drag function truly fits the bullet tested, then the measured ballistic coefficient remains constant over all velocity ranges. What we are measuring with the long time-of-flight is the cumulative effect of the drag over the long distance, and we can conveniently express this cumulative effect as an equivalent ballistic coefficient. If the measured ballistic coefficients are similar as the muzzle velocity is varied, then you are assured that your drag function is appropriate to your bullet. The measurement of the ballistic coefficient over a very long range is much more important than which drag function you choose for your

analysis. When you force your analysis to fit at the longer range, fit at the shorter ranges takes care of itself.

For the first half of the twentieth century, ballisticians spent most of their effort making better prediction models. That's why they went through the exercise of formalizing G1, G2, ..., G7, and G8. They used exotic spark photography to accurately measure retardation or drag over short distances near the muzzle. Most military effort in this area was abandoned in the middle of the century when the large Doppler radars and their attached computers became commonplace on the proving grounds. The output from a Doppler radar is inherently a record of velocity, or *Doppler frequency*, versus time. This record can extend for several seconds as the radar tracks the bullet for several miles downrange. Thus one radar track can cover velocities all the way from the muzzle velocity down to impact with the ground at extended range, usually at low subsonic velocities. (At the proving ground you can shoot with thirty degree muzzle elevation. Terminal ranges are far and terminal velocities are low.) The observer immediately has the record of velocity versus time. The magical computer can quickly convert velocity versus time to distance versus time or drag versus time. With just a little more computer manipulation, they can see the data as drag versus velocity. This drag function exactly fits the shot just observed. They use the drag function measured with that bullet from that gun. There is no guessing which of the canned drag functions to use or the exact ballistic coefficient. They predict what will happen with the next round, by measuring what happened with the previous round.

This use of Doppler radar measurements left civilian and amateur ballisticians out in the cold. An adequate Doppler system costs as much as a fleet of luxury limos; it's hard to find a trained crew of operators; and you still need a firing range of over a mile. Civilian and amateur ballisticians were forced to stay with the canned drag tables and ballistic coefficients measured near the muzzle.

Just what makes the Doppler radar so good? With the Doppler radar, you actually measure velocity through the entire flight and then you have effectively measured both distance and drag versus time. The best civilians have been able to do is to measure muzzle velocity and estimate ballistic coefficients. We've had to predict downrange velocities and flight times. Bullet path is the only thing we can attempt to measure downrange. Bullet drop or path is very important, but it is difficult to measure consistently. We have little to measure that will verify the accuracy of our predictions.

It is hard to compete with a high-quality Doppler radar system for the long-range measurements. We have found only one long-range parameter than can be accurately and reliably measured. The time-of-flight measurement, combined with the initial velocity and range, describes the cumulative effects of the drag over the entire flight path. With the time-of-flight measured over a known long distance, you have measured a key parameter. You know exactly what ballistic coefficient to combine with your drag function for long range fit.

Why haven't ballisticians used long flight times before? We suspect that many have wanted to, but no practical instruments (other than Doppler) have been available. Over several years the Oehler team has developed an instrumentation system that makes such measurements practical. System cost is similar to that of a sub-compact sedan instead of the fleet of luxury limos. It's a leap in our ability to make predictions fit the shot.

Much remains unknown about the drag behavior in the transonic velocity range. There are many unanswered questions regarding stability (twist, spin rate decay, and velocity) and the variations in air flow as the bullet slows through the transonic region. We don't have magic answers of why things happen, but we can now measure the total drag effect of whatever happened. Although the bullet has gone subsonic and won't trigger our acoustic target, we recognize that the time-of-flight is still critical. Oehler's system is designed with this in mind as we continue work on alternative target sensors to provide the stop signal for a subsonic bullet.

You can repeat this exercise using your favorite ballistics program. You will find that the differences we noted at 1000 yards will become much larger at extended ranges and slower bullets. Just remember to calculate your ballistic coefficients to give the same time-of-flight over your maximum expected range.

System 88

The Oehler System 88 provides accurate measurement of flight times over long ranges. These times are essential to the measurement of a proper ballistic coefficient. The System 88 is made up of two or more identical timing units, connected by a radio network to a Windows type computer. The first System 88 unit precisely measures initial velocity with proven Oehler Skyscreen III units set on a wide spacing. A second System 88 unit is typically used as an acoustic target at 1000 yards or beyond. Even more important than hit location, this acoustic target provides an accurate "stop" for the flight time.

Optional third and fourth units can be used for additional targets, either intermediate or beyond the primary acoustic target. They will provide accurate times measured at different ranges on the same shot for redundant measurements of ballistic coefficients.

The acoustic targets use Oehler's new target microphones. These mics are much more rugged than earlier units and are perfectly suited for the portable System 88. The square microphone array with its exceptional accuracy is used as the terminal target. Optionally, four microphones can be arranged in a straight line for either "fly-over" or "fly-by" sensing at intermediate ranges.