Extended Range Truing, Why and How

For a hundred and fifty years, ballisticians have sought to improve their predictions of the path of the bullet after it leaves the gun. The bullet's behavior is primarily determined by the drag function of the bullet, or how does the deceleration of the bullet vary with the speed of the bullet. The influences of the atmosphere and the muzzle velocity are well known, and both atmospheric characteristics and muzzle velocity can be readily measured. Modern predictions are refined by the inclusion spin drift, muzzle jump, Coriolis, and other variables.

Until the advent of long-range measurements made with Doppler radar, the choice of drag functions was limited. Most widely recognized are the G1, G2 … G7, G8 family standardized by the government proving grounds. In actual practice, only the G1 and G7 functions saw significant use with small arms. By default, the G1 drag function has been accepted as the standard truth for sporting bullets. Recently G7 has been popularized and presented as a better alternative for modern low-drag bullets.

Roughly fifty years ago, the government abandoned the use of the Gx tables in favor of collecting representative radar drag data from guns firing type standardized ammunition. The guns ranged from different battle tanks down to different individual infantry rifles. Following the collection of firing data, the entire mass of data was delivered to a ballistics research group for reduction to a "firing table" representing typical performance from a typical gun. For each ammo type, the firing table provided the estimated muzzle velocity along with downrange characteristics such as sight elevation for a particular range, remaining velocity at a range, wind deflection, et cetera. While it does not show up directly in the firing table, there is a hidden drag function for each projectile. This hidden drag function was obtained from the radar data and was used in-house by the ballistics group to compute the firing table.

It has long been accepted that long-range ballistic predictions are just about as accurate as is the labeled nominal velocity for factory ammunition or predicted by a handloader's book. At best, velocity predictions represent average behavior from several different guns firing several samples of "identical" ammo. More likely, velocity predictions originate with one ammo lot fired in one gun. Shooters recognize that they must measure the actual muzzle velocity of their gun/ammo combo in order to make accurate long-range predictions for that combo. Determination of actual muzzle velocity is a significant part of the problem. Fortunately, measuring muzzle velocity is relatively easy, and there are several solutions available.

The bullet's downrange behavior does not always fit the prediction. Predictions are based on drag functions and ballistic coefficients. Recent tests have verified that the commonly accepted G1 and G7 do not accurately represent the bullet, and that the downrange behavior is significantly influenced by the individual gun used to launch the bullet. The bullet only knows to follow the laws of physics as it travels downrange. While we claim to understand the laws of physics and apply them to our prediction of the bullet's flight, we make small errors of approximation and application. The bullet's behavior is absolutely governed by the laws of physics, and it is influenced by subtle changes we didn't recognize or measure accurately. As Todd Hodnett explains, "The bullet doesn't lie." The bullet does just what nature tells it to do. We must modify our prediction procedures so that our prediction matches the measured behavior of our bullet fired from our gun.

This all sounds easy in theory. We can glibly talk about "downrange behavior" without defining it and without describing how to measure it. Most often we are talking about a drag function describing how fast a bullet slows down after it has already slowed to a particular velocity. We usually assume that either G1 or G7 exactly describes our "family" of bullets and then we measure bullet drag near the muzzle to determine a ballistic coefficient to indicate which curve of the family fits our bullet. Using this ballistic coefficient that fits near the gun, our muzzle velocity and atmospheric conditions, we predict the bullet's behavior over the entire range. After all these years of trying, nobody has found the perfect prediction. When the prediction is tested by actual long range firing, the results usually don't exactly match the prediction.

In order to make good predictions, we must measure downrange behavior. Traditionally, ballisticians think in terms of drag or velocity loss. We know that the bullet's drag plotted as a function of velocity is an excellent measure of downrange behavior. Drag is extremely difficult to measure. To measure drag or deceleration you must find velocity lost. To measure velocity lost, you must measure two velocities and subtract. Because both velocities are very large compared to the loss, a tiny percentage error in either velocity measurement will result in a large percentage error in the loss or drag.

A Doppler radar inherently provides an output signal with a frequency proportional to the velocity of the bullet. This is one step closer to the drag or velocity loss sought by the ballistician. The Doppler signal can be processed to indicate the change in frequency as the bullet slows and thus give a reliable indication of the drag. It is an excellent system favored by the government proving grounds. The primary drawback of the Doppler system is its cost. Doppler radars capable of measuring velocities near the muzzle are relatively inexpensive, but those systems capable of reliably tracking rifle bullets over thousands of yards are very expensive. While Doppler systems can provide very detailed data, such data comes at the expense of much post-processing and is often restricted to a few shots.

The down-range performance can be checked by observing bullet drop for targets at long ranges. Measurement of drop at long ranges is not easy; it is subject to the errors of visual scoring, wind conditions, range estimation and the ever-present aiming and holding uncertainties. The observed drop is compared to predicted drop and either the ballistic coefficient or muzzle velocity is adjusted so that predicted drop equals the observed drop. This procedure has been demonstrated to significantly improve the predictions, and is referred to as truing.

The choice of truing the ballistic coefficient or truing muzzle velocity is left to the user. Most agree on two points:

1. Truing MV or Truing BC provide similar results at the range tested.
2. You should true the variable whose data is most suspect.

The Oehler System 88 takes a different tack; it accurately measures the muzzle velocity and then trues the BC. This provides a better prediction at all ranges, including the tested range.

One downrange parameter can be measured accurately. We can now accurately and reliably measure the time-of-flight (TOF) to a distant target. Muzzle velocity can be measured accurately. Given a muzzle velocity, distance to target and TOF you have effectively defined down-range behavior. Given a drag function and the actual measurements, you can determine a ballistic coefficient that forces a match between measured and predicted TOF to a distant target. Prediction and results are *trued* at the long range of the target. Using this measured (or *trued*) ballistic coefficient, we can accurately interpolate ballistic behavior at intermediate ranges.

If you choose a test distance near the commonly accepted maximum range corresponding to a remaining velocity of approximately Mach 1.2, you have effectively trued for the most useful ranges. It matters little which of the Gx drag functions is chosen; an appropriate ballistic coefficient can be found that forces a fit between measured and predicted TOF at the test distance. More important, you can use any of the drag functions to compute drop and wind drift at intermediate ranges and the predictions typically agree with each other within 0.1 mil. Having started with the true muzzle velocity and measured TOF over the long distance, we see that the measured muzzle velocity and TOF (along with atmospheric data) define the downrange behavior of the bullet. The value of these measured points of truth completely over-rides any quibbling over which drag function to use. For the commonly accepted supersonic range, you can use G1, G7, Gx, a custom drag function, or a radar derived table of drag coefficients. You get the same results.

We like to look at the distance versus time curve for the bullet. The initial slope of this curve corresponds to the muzzle velocity; slope of the curve at any point corresponds to velocity, and the change in slope at any time corresponds to drag or deceleration. The shape of the curve changes only slightly with the drag function chosen. For a given muzzle velocity, all curves start from zero with the same slope. For any drag function, you will see a family of similar curves, all start with the same slope, but only one curve passes through the true downrange point observed during the test. The ballistic coefficient of the one curve passing through the downrange distance/TOF point provides proper predictions. You have found a ballistic coefficient based on the cumulative effect of the drag applied over the long distance instead of the drag at one velocity. Repeat the process with a different drag function but with the same initial velocity and TOF. Compare the curves passing through the downrange point; they are almost identical and yield similar predictions for drop and windage.

Truing over the common supersonic range is straightforward. This range includes practically all ranges commonly used by most riflemen. What happens if we measure TOF at a range where the bullet had dropped well subsonic? We now must account for significant differences in the commonly accepted drag functions at velocities near the speed of sound. A prediction curve that passes through the first distance/time point will pass through the subsonic point only if we are extremely lucky. We are seldom so lucky that our chosen drag function exactly describes our bullet. How do we force our prediction curve to match both points?

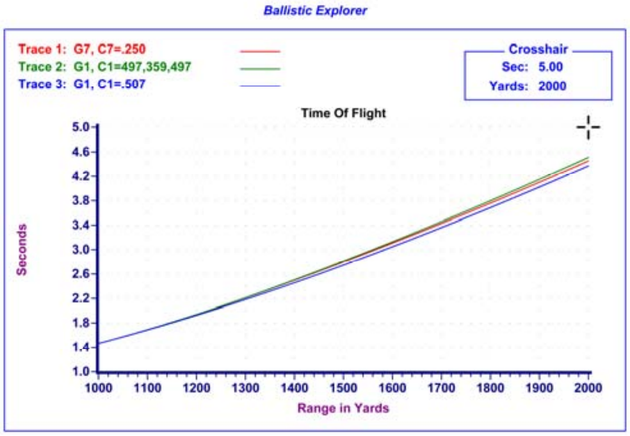
For many years, Sierra (and others) has provided some G1 ballistic coefficient values as “stepped” as a function of velocity. This means that the G1 drag function does not fit the tested bullet. The actual drag of the bullet differs from the drag predicted by the G1 function and the ballistic coefficient is adjusted in steps to reflect this misfit. There is nothing wrong with this procedure; it has provided reasonable accuracy for many years. Many ballistic programs allow use of stepped ballistic coefficients. Sierra’s stepped ballistic coefficients are typically provided only for supersonic velocities where variations in ballistic coefficient are relatively small. Our tests indicate that the stepped format is also applicable over longer distances if the steps are based on truing over a long distance.

We now have a ballistic coefficient providing accurate predictions down to Mach 1.2. The indicated target velocity is the lower limit for our first ballistic coefficient. To extend our procedure to include longer distances, you must fire a second test at a range corresponding to a velocity that is well subsonic. Using a ballistics program that properly allows for stepped ballistic coefficients, enter the ballistic coefficient and velocity boundary from your first test. Adjust the ballistic coefficient of the next step until the predicted TOF matches the observed TOF at the test range. This gives a set of two ballistic coefficients meeting the requirement of passing through both the experimental points. These stepped ballistic coefficients will yield accurate (typically within 0.1 mil) predictions of drop and windage at ranges from muzzle to the subsonic target point.

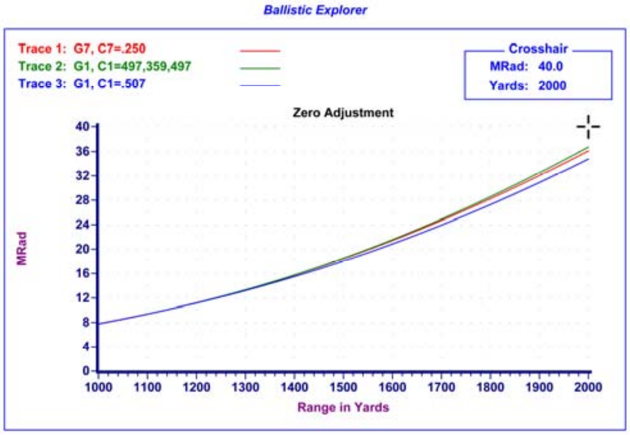
The Oehler Ballistic Explorer Version 6.6 or later properly accepts boundaries between ballistic coefficients with 10 fps accuracy. The Extended Range Truing program suggests boundaries between ballistic coefficients based on the actual distances to the test targets, and these distances are reflected in velocities given to a resolution of 10 fps. To get the accuracy provided by the truing procedure, the exterior ballistics program must accept and properly use boundaries expressed to 10 fps. Some programs will not work properly!

How do you obtain the muzzle velocities and TOFs required for entry? Oehler and others have been measuring muzzle velocities for years. Oehler's System 88 was specifically developed to measure the TOFs in addition to initial velocity. Don't worry about the math and computations required. The System 88 includes a program dedicated to this task.

Here are some graphic outputs from the Ballistic Explorer. The Extended Range Truing program expects the atmospheric data from the test along with the recorded muzzle velocity, distance to target and TOF. Rather than using actual firing data, we chose to use a perfect G7 bullet and the downrange values predicted by Ballistic Explorer. We assumed a muzzle velocity of 3000 fps and a C7 ballistic coefficient of 0.250. The G7 bullet predictions indicated a velocity of near Mach 1.2 at 1000 yards, so we used a TOF 1.46433 at this range. The G7 predictions indicated a TOF of 2.49754 at 1400 yards with a remaining velocity near Mach 0.9. With these values, the Extended Range Truing program advised that we use C1 = 0.497 down to 1420 fps and then step to 0.359 down to 1000 fps. We did not test below 1000 fps and reverted back to our initial estimate of ballistic coefficient below 1000 fps.

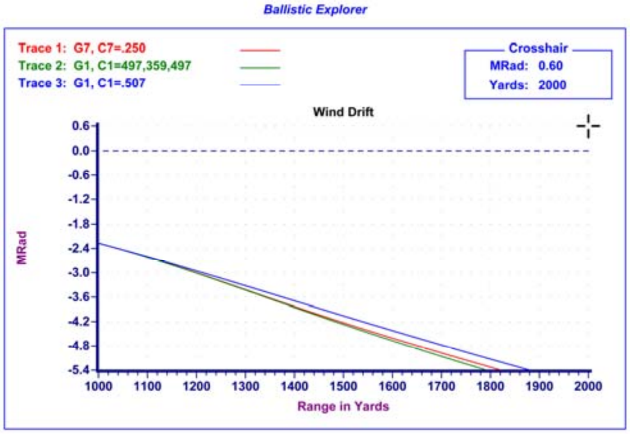


We show the graphic output only for the ranges between 1000 and 2000 yards. Less than 1000 yards the curves completely overlap each other and you can see no distinction. The red and green curves (actual G7 and stepped G1) overlap out to approximately 1500 yards. The blue G1 curve illustrates the G1 prediction with drag matched near the muzzle but without truing.



The predicted zero adjustment curve using the stepped G1 drag function continues to agree with the prediction given by G7 out to 1500 yards.

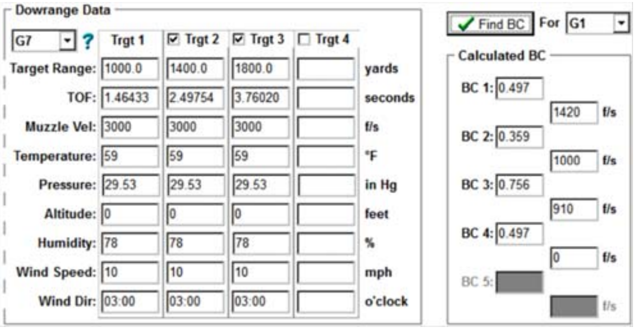
What have we accomplished? We have extended the effective range from 1000 yards to over 1400 yards provided that the gun/bullet combination can demonstrate stability as it passes through the speed of sound. The required stability will be indicated by consistent ballistic coefficients measured at the long range.



Looking at the wind drift there is again close agreement between the G7 prediction and the stepped G1 prediction. This agreement holds past 1400 yards.

The curves diverge at the longer ranges. The reason is simple. We tested only to 1400 yards; predictions beyond this range rely on unproven drag functions. If we want trued predictions at longer distances, then we must add another target test at longer distance. We could arbitrarily change the ballistic coefficient for velocities less than 1000 fps to make the curves match exactly, but we have no experimental data to back it up.

Add a third downrange target at 1800 yards corresponding to approximately 900 fps. This target is difficult to hit during either test firing at a sheet of plywood or at an actual target. With a TOF approaching 4 seconds, much can go wrong. At this distance, G7 gives a TOF of 3.76020 seconds. Include this target in the Extended Truing program to find the suggested ballistic coefficient for the lower velocity step.



For: G1

G7	Trgt 1	☑ Trgt 2	☑ Trgt 3	☐ Trgt 4	
Target Range:	1000.0	1400.0	1800.0		yards
TOF:	1.46433	2.49754	3.76020		seconds
Muzzle Vel:	3000	3000	3000		f/s
Temperature:	59	59	59		°F
Pressure:	29.53	29.53	29.53		in Hg
Altitude:	0	0	0		feet
Humidity:	78	78	78		%
Wind Speed:	10	10	10		mph
Wind Dir:	03:00	03:00	03:00		o'clock

Calculated BC

BC 1: 0.497
1420 f/s
BC 2: 0.359
1000 f/s
BC 3: 0.756
910 f/s
BC 4: 0.497
0 f/s
BC 5:
f/s

This is the working screen of the Extended Range Truing program. It is simple, and is typically applied to average muzzle velocity and TOF data collected by the System 88. It can just as easily be applied to TOF data from single shots or to TOF data provided by radar based programs. The program allows for downrange data to be collected on different days with different initial velocities and atmospheric data for each distance.

The individual round outputs of the System 88 are not to be ignored. Examination of the individual round results shows first the uniformity (standard deviation) of initial velocity of the actual gun/ammo combination. Proof velocity measurements provide a reliable measure of the actual accuracy of the velocity measurement. The observed ballistic coefficient provides a direct measure of bullet performance over the tested range. The individual standard deviation of the observed ballistic coefficients provides an indicator of both bullet performance and instrumentation accuracy.

Applying the ballistic coefficient of 0.756 to the velocities between 1000 and 910 fps show a zero adjustments agreeing to within 0.1 mil to 1600 yards and within 0.27 mil to 2000 yards. This maximum error is similar to an initial velocity difference of 10 fps.

The process can be extended to longer ranges, or you can use more intermediate test targets. We used theoretical G7 data as input only because it was convenient. You need tell the program only the muzzle velocity and TOF. What matters is that the inputs to the program are actual measured initial velocity and measured TOF over the long range. That's the System 88 exists! The process is subject to the usual compromises. You want more detailed data, but want to minimize testing. Analyzing the same firing data, but using different drag functions provides insight into which drag function best fits the bullet. Use the stepped ballistic coefficients to get drop and wind predictions with the different drag functions. Don't be surprised when predictions made with different drag functions are practically identical.

We conclude that the measurement of down-range true points of TOF versus distance and then forcing predictions to fit at these points is much more important than the choice of drag function. If the chosen drag function exactly fits the bullet, then the ballistic coefficient will remain constant. If the chosen drag function closely fits the bullet, then steps in ballistic coefficient will remain moderate. It the chosen drag function is a poor fit to the bullet, there will be larger changes in ballistic coefficient but the predictions made using these stepped ballistic coefficients will still be quite accurate. With any reasonable choice of drag functions, your predictions fit because you started with true data from your gun and bullet.

When we started developing the System 88, we naively anticipated that we could collect sufficient data to either generate a custom drag function or to at least select the most appropriate standard drag function. To our surprise, after we collected the true firing data, and forced our predictions to fit the true data of the distant points, we couldn't distinguish between predictions generated with the different drag functions. If we can't tell the predictions apart, how can we select the perfect drag function? Why should we even look for the perfect drag function if we can get the equivalent predictions using G1 or G7? Why should we seek the perfect drag function if it still requires "truing" before we can trust the predictions?

It is recognized that the users' highest priority is for predictions of elevation and windage. Truing based on time of flight directly trues or verifies the prediction for time of flight. The truing procedure also provides verification of the effects of bullet drag or deceleration. It does not directly verify the predictions for elevation and windage. However, predictions for elevation and windage are highly dependent on time; given the proper time, these predictions are very accurate. We do first things first; we true on measured time of flight.

The bullet doesn't lie,
You must listen.