Luckenbach Ballistics (Back to the Basics)

Most of you have probably heard the old country-western song, *Luckenbach, Texas (Back to the Basics of Love)*. There is really a place named Luckenbach near our family home in the Texas Hill Country. There's the old dance hall, there's the general store, and there are a couple of old homes. The few buildings are near a usually-flowing creek with grassy banks and nice shade trees. The gravel parking lot is often filled with Harleys while the riders sit in the shade and enjoy a beer from the store. Locals drive by and shake their heads as they remember the town before it was made famous by the song and Willie Nelson's Fourth-of-July Picnics.

Don't think of Luckenbach as a place. The song really describes an attitude or way of life. The phrase *Back to the basics …* is key.

We've been so busy
Keepin' up with the Jones
Four car garage and we're still building on
Maybe it's time we got
Back to the basics of love

In our quest for more accuracy we consider finer and finer details of ballistic predictions. Our mind gets overwhelmed with all the details and perfections demanded by modern ballistics. Even eminent ballistician Bob McCoy recognized this (page 29), "*There are, of course, many situations in which the older methods are entirely sufficient for all practical purposes. One broad class for which this is generally true are the small-yaw, flat-fire trajectories typical of ground-launched small arms.*" We can get back to the basics using the older methods.

We won't ignore the advances made during the last 300 years by ballisticians from Isaac Newton to Bryan Litz. I certainly appreciate the advances such as the Kestrel that puts both a weather station and a powerful ballistics computer in my palm. We give credit to Sir Isaac Newton for formulating the basics of ballistics and calculus we still use. Newton's greatest contribution is that he thought of ballistics in terms of time, not distance. One of Newton's best known equations tells us the distance an object falls depending on gravity and fall time. With distance in meters and time in seconds, Newton's equation is

$$\text{Distance} = 4.9 \times \text{Time} \times \text{Time}.$$

At a time of 2 seconds the distance is 19.6 meters. A rock dropped from 19.6 meters takes 2 seconds to reach the ground. A rock thrown straight up to a height of 19.6 meters takes 2 seconds to go up and another two seconds to come back down. This may not appear to have much to do with ballistics, but it does.

Examine the Army's firing tables for 105mm tank guns and the 25mm cannon. Instead of starting with the distance column, look at the time column for times near 4 seconds (2 seconds up plus 2 seconds back down). Estimate the distance corresponding to a 4-second time-of-flight and determine the maximum distance above the line-of-sight for that distance. The following table includes sample results from the big guns. We also include the results for a 22 rim-fire and a 175 grain 308 at 2600 fps. A football punt with 4-second hang-time is included for variety even though we had to estimate the maximum height.

Ammo	Approx Range Meters	Max Height Meters
105mm M735, APDS	5500	19.2
105mm M3456A1, HEAT	2950	20.7
105mm M450, TP	2950	20.6
25mm M791, APDS-T	3900	19.3
25mm M793 TP-T	2150	19.9
7.62, 175 gr Federal	1600	20.3
22 RF, Federal Match	800	21.4
Football, 4-sec Hangtime	50	19.6

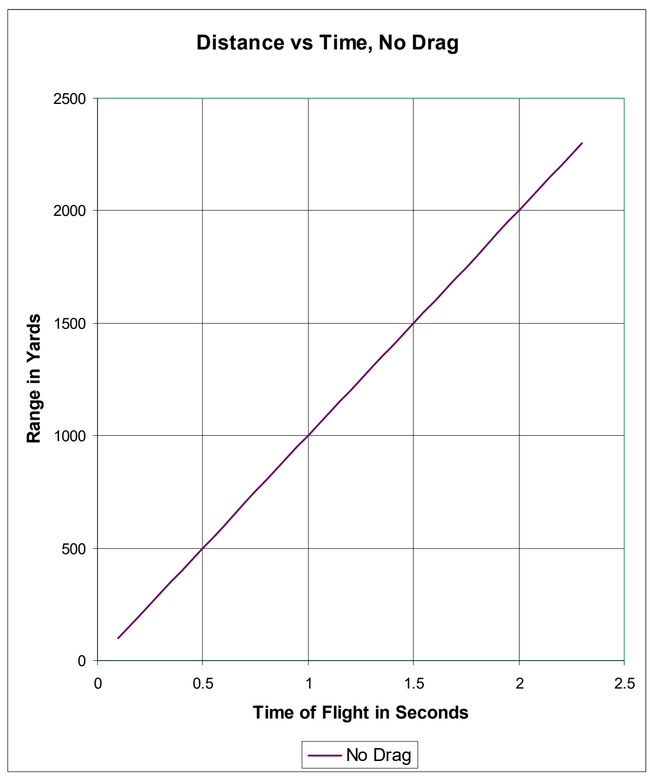
Maximum Height for 4-Second Time-of-Flight

What is important? The table shows that the maximum height remains essentially constant at the 19.6 meters predicted by Newton 300 years ago. The horizontal range traveled by the bullet makes little difference; maximum height and drop are governed by time-of-flight. The maximum height is governed by the 4-second flight time. The important thing is time!

To make things practical, the time-of-flight must be tied to distance. Shooters don't see time; shooters see range or distance. Ballisticians compute and think in terms of time; distance is secondary. Things get difficult when time and distance must be tied together. Historically, this has been done using drag functions or drag tables. These tables don't fit our bullets exactly, but they still are the basis for our predictions. Our predictions are often sufficient to get hits on the paper out to the range where a rangefinder becomes essential. Beyond this range, our predictions often fail.

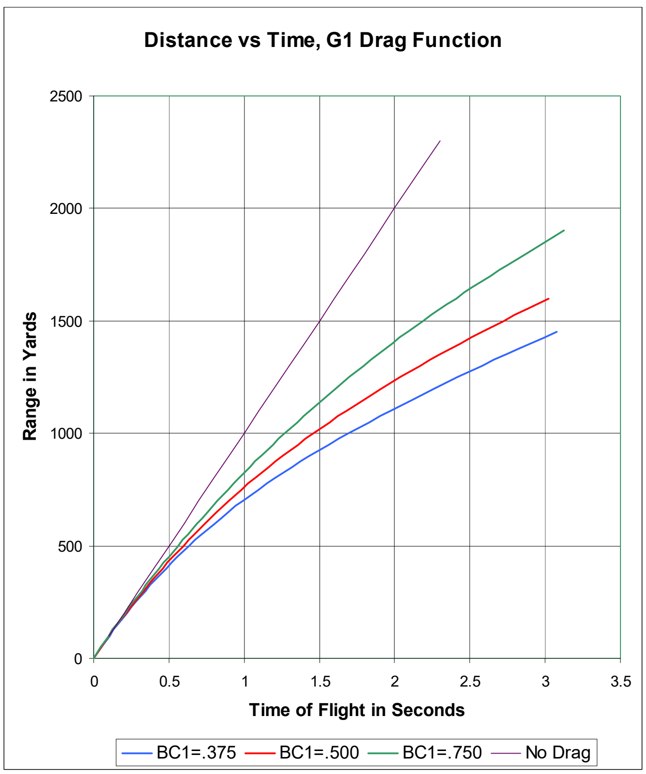
For the last few years the premier instructor Todd Hodnett has taught a procedure he calls "truing". He has seen that the finely crafted predictions and specified ammo did not fit every situation. Gremlins remained. To improve their predictions, Todd requires each student to fire at a long-range target. Each student must then adjust the inputs to their prediction model until their predictions give good hits on the long-range target. This usually involves changing either the assumed muzzle velocity or the assumed ballistic coefficient. The resulting values for velocity and ballistic coefficient are assigned to that gun with that lot of ammunition. The procedure is simple; the procedure works; but procedure can be improved.

If the problem is relating time to distance, let's go back to the basics. Somewhere in school we were introduced to something the teacher called "distance, rate, and time problems". If a car goes sixty miles per hour, how far can it go in two hours? If it takes five hours to walk ten miles, how fast must you walk? Remember those? If a bullet leaves the gun at 3000 feet per second, how long does it take to travel 100 yards or 300 feet? We are still working the same problems, but we talk about velocity, range and time.



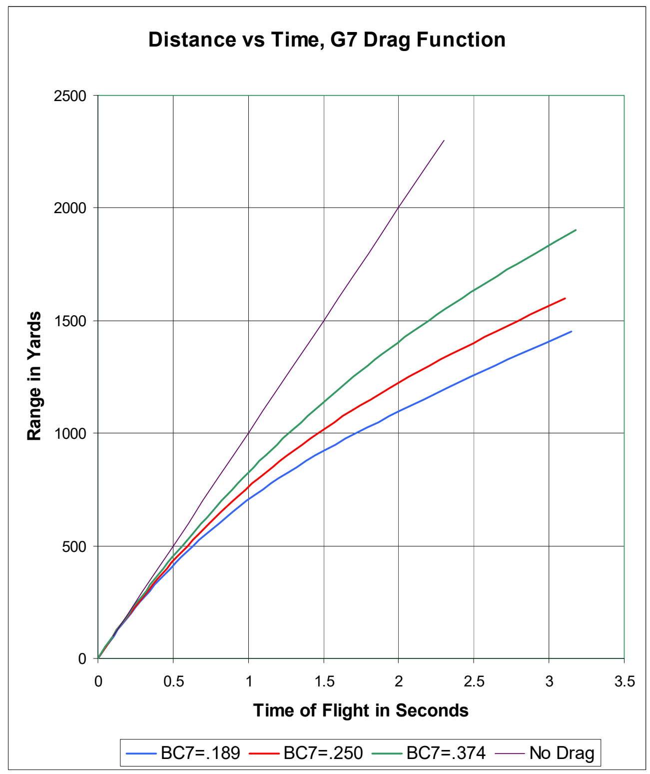
Look at the picture. The curve shows our elementary relationship between distance and time. If we start at 3000 feet per second and have no air drag, we reach 1000 yards in exactly 1 second. The relationship between time and distance is simple and constant. We have a straight line.

Now add air drag to the problem. We no longer have constant velocity, and the distance versus time curve is not a simple straight line. At each instant in time the bullet slows an amount dictated by its velocity at the time and the assumed drag function. Air drag slows the bullet and it doesn't travel as far in a given time. An extremely high ballistic coefficient coupled with thin air may get us close to the straight-line plot we solved many years ago, but in the real world we must contend with the air drag.



Here are the distance-versus-time curves for three bullets. All have a muzzle velocity of 3000 feet per second. The nice thin black line at the top of the cluster is our old friend with no air drag. The lower curves are those predicted using the common G1 drag function with ballistic coefficients of 0.750, 0.500 and 0.375. The green curve from the 0.750 BC is closest to the straight line, and the curves get progressively farther from the line as the BC diminishes.

There is much discussion of G1 versus G7. G1 is customary and G7 is advocated as being a notch closer to perfection. You would logically expect to see a big difference. Let's generate another set of curves using the G7 predictions instead of G1 predictions.

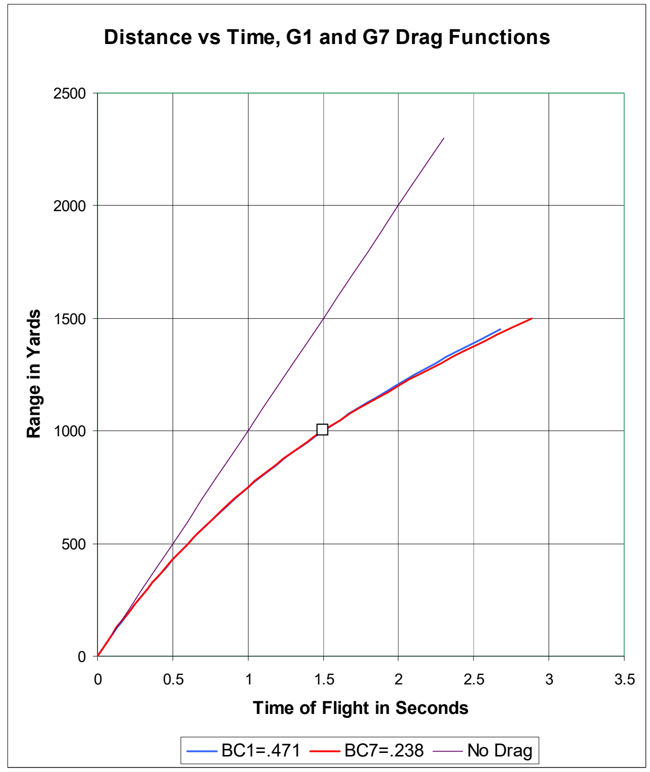


Can you tell the pictures apart? Even if you expand the pictures or look at the numerical data, the curves appear practically identical to 800 yards. What we have shown are two families of behavior governed by the two most common drag functions. We have shown only three curves of each family, each corresponding to a unique ballistic coefficient. Just imagine the clutter we would have if we tried to picture the curve for each ballistic coefficient and then multiply that by the number of different muzzle velocities. There are literally tens-of-thousands of possible curves.

How do we choose a curve that accurately predicts the behavior of our bullet fired from our gun? Time-of-flight is most important, but we want to think in terms of range. We start by measuring the muzzle velocity along with the time of flight out to a distant target. Because we are relatively confident shooting to maximum ranges where the bullet remains supersonic, we place our distant target to cover most of that maximum range. The range where we expect the remaining velocity to be near Mach 1.2 or 1350 fps is a practical range for truing.

With no air drag, our sample bullet starting at 3000 fps takes exactly 1 second to travel 1000 yards. Assume that the air drag slows the bullet so that it actually takes 1.500 seconds to travel 1000 yards. That gives a data point on our picture of distance-versus-time. If we look at our family of curves predicted using the G1 drag function and a muzzle velocity of 3000 fps, we find that one curve with ballistic coefficient C1 = 0.471 passes through the downrange data point where the time is 1.500 seconds at the range of 1000 yards. Eureka! We've found the predicted curve that fits the bullets behavior. It's as if we have "trued" in advance.

What if we had chosen to fit our downrange data point using a prediction from the G7 family? Using the same muzzle velocity and time-of-flight, we find the curve from the G7 family with ballistic coefficient C7 = 0.238 also passes through the downrange point. Now we might anticipate trouble. We have two solutions for the same problem. Which one should we use? Resort back to pictures and plot both curves.

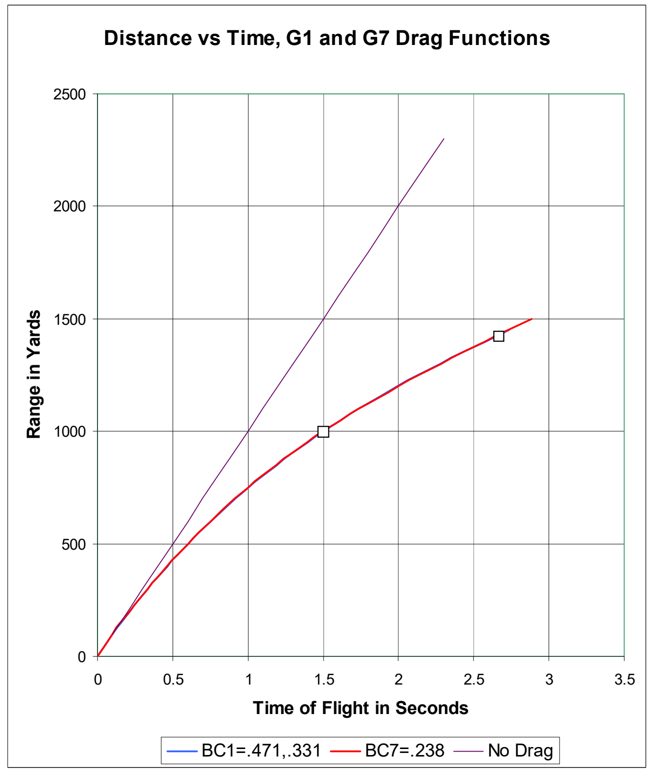


Do you wonder why you can't see the blue BC1 line on the chart? It remains perfectly hidden behind the red BC7 line out well past 1000 yards or 1.5 seconds. Conclusion? It makes no practical difference if you choose to use G1 or G7 out to 1000 yards **if** you have accurately trued at 1000 yards. If you first measure both muzzle velocity and the time-of-flight, then your prediction is trued when you determine the ballistic coefficient that causes the curve to pass through the long-range true point. Comparing the G1 and G7 based predictions for drop and wind, you will find that they agree within 0.05 mils out to 1000 yards. Bob McCoy would say, "*sufficient for all practical purposes.*"

There are slight differences beyond 1000 yards, but we can take care of that. For many years, Sierra and others have provided some G1 ballistic coefficient values "stepped" as a function of velocity. The measured 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. This procedure has provided good accuracy for many years. Many ballistic programs properly 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 procedure is applicable over longer distances if the steps and ballistic coefficients are based on times-of-flight measured over the longer distances.

We have shown how to determine a ballistic coefficient for accurate predictions down to Mach 1.2. To extend our procedure to include ranges where the bullet becomes subsonic, fire a second test at a range where the bullet has dropped well subsonic. Using a ballistics program that 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 time-of-flight matches the observed time-of-flight at the test range. This gives a set of two ballistic coefficients meeting the requirement of passing through both the experimental points of the distance versus time curve. These stepped ballistic coefficients may look rough, but they yield accurate (typically within 0.1 mil) predictions of drop and windage at ranges from muzzle to the subsonic target point.

Let's continue looking at our curves. If we assume that the bullet fired actually behaved like a G7 bullet, then it would have a time-of-flight of 2.57823 seconds at 1400 yards and its C7 ballistic coefficient would remain BC7=0.238. If we choose to work using G1, we must adjust the G1 ballistic coefficient to BC1=0.331 at velocities below 1350 fps.



After adding the stepped change in the G1 ballistic coefficient, the blue G1 curve is obscured by the red G7 curve out to approximately 1500 yards. If you want your predictions to reliably extend to even longer ranges, then you must test at longer ranges and add the additional trued steps to your ballistic coefficients.

This procedure is automated in the Extended Range Truing program included with the Oehler System 88. The Extended Range Truing program suggests boundaries between ballistic coefficient steps based on distances to the test targets. (Remaining velocities are estimated and targets placed to fit the estimates. Estimates need only be reasonable, but the actual test range must be recorded precisely.)

What has been demonstrated is a greatly improved version of "truing" where the prediction procedure is forced to match actual long-range results. You cannot predict drag functions or ballistic coefficients from published data any more than you can predict muzzle velocity from factory specs or reloading books. They will all vary from rifle to rifle, and you must true with your gun and your ammo. Application of this procedure forces your predictions to match your results at long range. Time and range are forced to fit at long range and that ensures proper predictions. This procedure eliminates uncertainties due to visual drop estimations, wind induced errors, hold errors, and the use of too-few shots.

This procedure can use any reasonable drag function. If you are comfortable with G1, and your computer handles stepped G1 ballistic coefficients, then you can use G1 with no significant loss in accuracy. If your computer handles custom drag functions or radar drag functions, use the procedure with your favored drag function. Adjust or "true" your ballistic coefficient so that your predictions match measured long-range times-of-flight.

Things get difficult in ballistics when you must relate time to distance. By shooting and actually measuring time-of-flight to a distant range, you have measured "truth" at this point. By adjusting your prediction method until your prediction matches reality, you have trued the relationship. What could be simpler? It's *"Back to the basics…"*.

Luckenbach Ballistics (Basic Proving Ground)

Just as the Luckenbach song begs for *Back to the basics of love*, we long for a basic proving ground. The government has wonderful proving grounds with expensive Doppler radars operated by experienced crews. The instruments are backed by rooms full of ballisticians to analyze the data. We want an affordable system we can haul to an unimproved range in a POV, operate ourselves, and give the needed results.

We've outlined how practically any ballistics program can be trued so that its predicted time-of-flight matches the true observed time-of-flight at a long range. Once the program is trued, the output predictions are true at the long range and at intermediated ranges. Because of uncertainties in drag function, muzzle velocity, and ballistic coefficient, truing will always be essential. We do not require a Doppler radar with its complications, but we need actual firing test data. This data includes

- Metro data.
- Accurate distance to target.
- Muzzle velocity.
- Time-of-flight to distant target.
- Friendly software for our computer to analyze raw data.

The metrological data, especially pressure and temperature, are easy to get from a Kestrel.

The distance to target can be obtained with a laser rangefinder. The laser rangefinder must have been verified to give distance readings accurate to 0.1 percent and should be used with a proper reflective target.

Muzzle velocity measurements are simple. Use Oehler's proven chronographs and skyscreens. Other systems are available; they are considered accurate if "Readings agree with the Oehler."

The time-of-flight measurement is difficult. Time between two signals can be measured accurately. It is easy to get a "start" signal from the muzzle skyscreens and apply it to the timer. It is difficult to get a "stop" signal at the long-range target. It is easy to hear supersonic bullets as they pass a downrange microphone, but the delay between bullet passage and arrival of the sound at the microphone introduces error. Even if you detect the passage or impact of the bullet at the distant target, you must still transmit this signal back to the timer located at the gun. You can use 1000 yards of cable to send the signal. The cable usually works well the first day; nasty things (moisture, vehicles and vermin to name a few) happen to cable left overnight.

Oehler solved this timing and communication problem for the proving grounds back in the 1990s. We provided an acoustic target system that linked the gunner to several downrange targets by radio and incidentally provided the bullet's arrival time (measured in microseconds-after-midnight) at each target. The customer was primarily interested in target impact location, but the significance of the arrival-time information was recognized. Knowing where the bullet passed with respect to the microphones, we could correct for delay times. We could convert arrival-times to times-of-flight and found that we could use these times to make ballistic predictions with uncanny accuracy.

Approximately seven years ago, Oehler began the process of converting the proven System 86 Acoustic Target into a simplified System 88. Instead of an elaborate target system incidentally giving arrival times in addition to target information, the new system gives muzzle velocity and times-of-flight. The new system incidentally provides target information. The

System 88 includes the radios required to replace downrange cables and the GPS receivers to provide time synchronization between units.

The System 88 includes the software required for the operator to conveniently control the several measurement units with their microphones and skyscreens. The software computes the appropriate ballistic coefficient for each shot using the actual measurements and the desired drag function. This arrangement provides direct output of the trued initial velocity and ballistic coefficient trued for the longest test range. No further analysis or data processing is needed. This is the usual mode of operation. The recorded raw test results may be replayed to compute the ballistic coefficients referenced to a different drag function. Ballistic coefficients are all defined by the same initial velocity, distance, time-of-flight and metro conditions.

Downrange microphones can be arranged in the proven square array (up to 10 feet on a side) or in a straight line array. The square array provides excellent target accuracy in addition to the time-of-flight measurement. The straight-line array is easy to deploy as a *flyover* terminal target or on a vertical pole for *flyby* measurements at intermediate ranges. Rugged microphones have been developed especially for use with the System 88. These microphones can be used to detect the Mach cone of supersonic bullets or the impact of a subsonic bullet on a physical plane of wood, metal, or drywall.

If the fit between the assumed drag function and the actual bullet performance is questionable in the sonic range, or if you just want to verify your choice of drag function over a longer range, then you must measure and compute the ballistics over a longer range. This often includes flight into the subsonic velocity region. Application of your measured data will require that you use stepped ballistic coefficients.

You have already trued your prediction procedure to the test range, or equivalently you have trued your prediction down to the velocity corresponding to the test range. Leave that portion of your prediction alone!

After firing a subsequent test at longer range, the results of that test must be appended to your earlier test. The Extended Range Truing program supplied with the System 88 automates this detailed procedure. In order to properly combine the test results, all results must be converted to behavior in the standard metro atmosphere. Behavior of the bullet when fired at the initial range is defined by the initial velocity and time-of-flight to target. If these values of average initial velocity, average time-of-flight, distance and metro conditions are introduced into the Extended Range Truing program, the program yields a ballistic coefficient providing a match down to the velocity at the target. We now have the ballistic coefficient and lower velocity limit for the first step of a “stepped ballistic coefficient.” This ballistic coefficient will be the same as was originally determined by the test firing with the System 88 at the first range.

Enter the average muzzle velocity, time-of-flight, distance, and metro conditions for your second test. As before, the program will compute the ballistic coefficient for the first step. The program keeps this ballistic coefficient for the first step and then computes the ballistic coefficient for the second step. Application of this stepped pair of ballistic coefficients forces agreement of predicted and measured time-of-flight at the longer range.

This process may be repeated at even longer ranges. Each repetition forces the match between predicted and measured time-of-flight at progressively longer ranges.

What's significant? This is the "proving ground in a box" we've been looking for. The System 88 lets you accurately characterize the actual ballistics of your ammo fired from your gun. It includes all hardware and software. Your predictions can now be based on true measurements.

It's basic and it works.