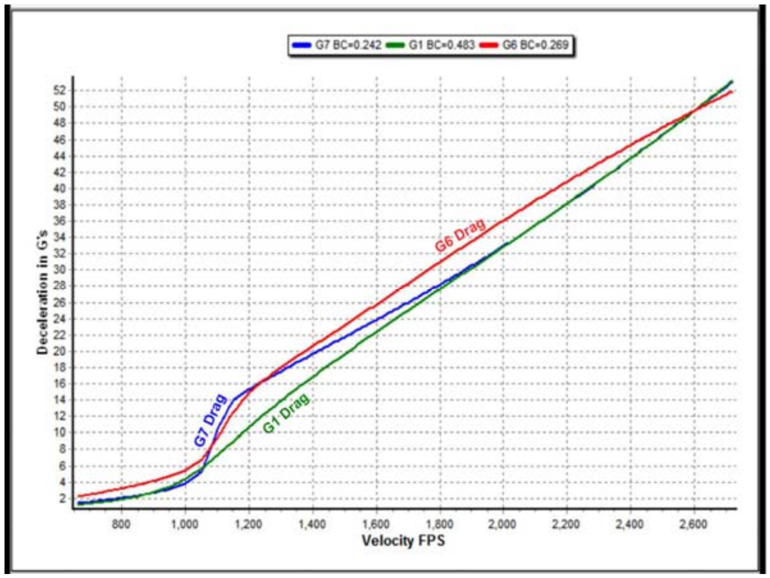
Extended Ballistic Predictions

The System 88 was conceived and designed to measure the "effective" ballistic coefficient that gives agreement between the predicted time-of-flight at a long distance (typically corresponding to a velocity of Mach 1.2) and the observed time-of-flight at this same distance. It had been previously observed that if this time-of-flight equality was met, then all reasonable drag functions with their appropriate ballistic coefficients would provide very similar values for intermediate ballistic parameters such as drop and wind drift. This similarity (almost equality) was apparent at all ranges extending from gun to instrumented target. Beyond the range of the instrumented target, the agreement between prediction and measurement depends on the fit of the assumed drag function to the actual performance of the bullet. If the bullet flies like the theoretical G7 projectile, then G7 will provide proper predictions at longer range, and G1 predictions will be in error. If the bullet flies like the theoretical G1 projectile, then G1 will provide accurate predictions and G7 predictions will be in error.

If neither G1 nor G7 functions fit the bullet, then we must make adjustments. Historically, these adjustments have been made by using different ballistic coefficients for different velocity ranges. Sierra has provided "stepped" ballistic coefficients for many years. The real difficulty has been hidden; how do you determine [measure] the proper ballistic coefficient to use with a particular bullet from a particular gun at each velocity level? The choice of appropriate drag function is an educated guess at best, and ballistic coefficients can change with barrel twist rates and other parameters (some of which we recognize). This problem is made more difficult when ballistic coefficients are measured at ranges of 300 yards or less

A bullet's position, velocity, and acceleration can be completely described by a curve of distance versus time. The initial slope of the curve represents muzzle velocity and slope at further points represent velocity at any time. The second derivative of the curve represents drag or deceleration as a function of time. The System 88 measures points along the distance versus time curve. Legacy drag functions (G1, G2, etc.) can be used to interpolate between observed data points.

It is beneficial to collect distance versus time data at points where the nature of the drag tends to change significantly.



For example, the graph above illustrates the drag (deceleration) of a bullet described by three common drag functions. Ballistic coefficients are selected so that all three functions have the same drag at the muzzle velocity of 2600 fps. Observe that at velocities above approximately Mach 1.2 (or 1350 fps) all curves are relatively straight. Most long-range shooting takes place within this velocity range. The System 88 is primarily adapted to determining a ballistic coefficient that accurately describes bullet performance from gun to the range corresponding to a velocity of

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approximately Mach 1.2 or 1350 fps. The System 88 determines a ballistic coefficient so that the predicted time-of-flight over the long range matches the experimental time. In this velocity region, all common drag functions are similar (typically corresponding to the approximation that the drag coefficient is proportional to one divided by the square root of the velocity), and all can provide accurate and useful results with appropriate ballistic coefficients.

We can use our confirmed time and distance at the Mach 1.2 range as the starting point of predictions applicable to extended range. The common drag functions differ significantly over the velocity range from approximately Mach 1.2 down to Mach 0.9 (or 1350 fps down to 1000 fps). These differences are apparent just from looking at the plots of the different drag functions as they pass through this region. What causes all the differences? Ballisticians have argued and tried to explain behavior in this region for many years; we simply admit that the Mach gods are hard to appease. We do not pretend to understand or measure the drag between 1350 and 1000 fps; for practical purposes it is not required. However, we must measure the cumulative effect of the drag after the bullet passes through the transition. This provides a second accurate data point on our distance versus time curve. For the prediction model to match reality, we determine a ballistic coefficient to be applied over the velocity range of 1350 down to 1000 fps. The proper ballistic coefficient for this velocity range is such that the predicted time-of-flight matches the observed time-of-flight after the bullet has passed through the sonic region.

Below 1000 fps, the drag coefficients are well behaved and are similar to the constant drag coefficients postulated by Newton centuries ago. We would like to collect a third data point on that time versus distance curve after the velocity has slowed well below 1000 fps. The proper third ballistic coefficient is determined to give a match between prediction and experiment when it is applied at velocities less than 1000 fps.

The particularly unique feature of the following procedure is the use of the experimental data points of cumulative time-of-flight collected at measured distances near the ballistic coefficient break points. The behavior between break points can be predicted using legacy drag functions, but it is essential that one set of predictions end at a specific point on the distance versus time curve and that the following predictions start at this same point. A similar procedure can be used with custom drag functions. Similar procedures may be implemented using observed projectile drop data at distant points.

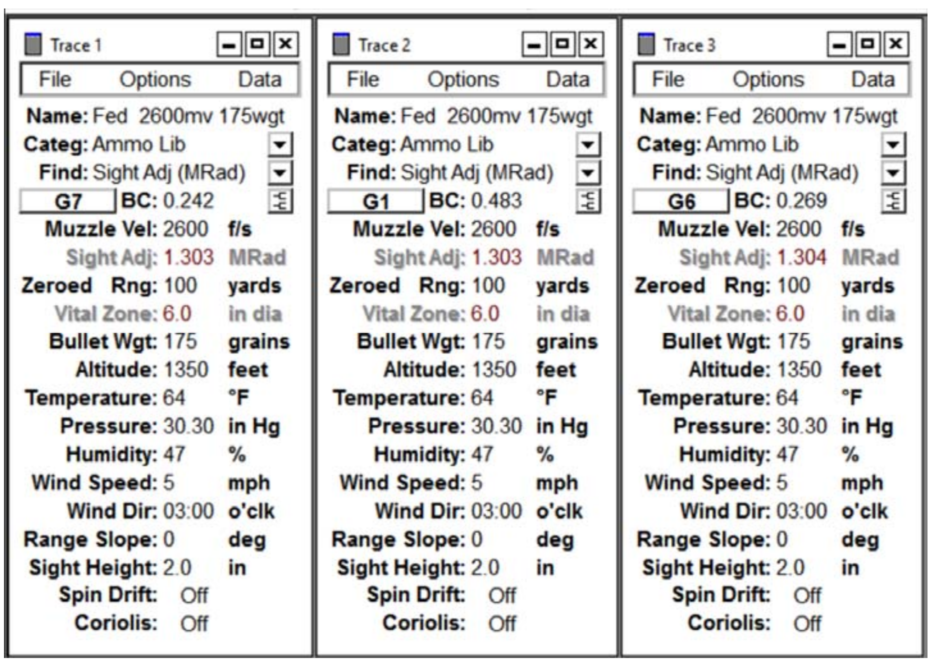
Testing with the System 88 can provide the information required to use existing drag functions to accurately predict ballistic performance at extended ranges. A brief description of the procedure is

1. Select an appropriate drag function and use the System 88 to measure the ballistic coefficient from gun to a range corresponding to approximately 1350 fps. This drag function and ballistic coefficient are appropriate from the gun to ranges slightly beyond measurement range. This drag function has been normalized to standard atmosphere.
2. Place a subsonic target at a range corresponding to approximately 1000 fps and measure ballistic coefficient. Note the time-of-flight. With Ballistic Explorer, set ballistic coefficient break point at 1350 fps and use the previously measured ballistic coefficient above this point. With successive approximations, adjust only the ballistic coefficient used below 1350 fps until predicted time-of-flight at target matches experimental time-of-flight. You now have predictions valid down to 1000 fps and slightly below.

3. Place subsonic target at a range corresponding to velocities that are well below 1000 fps. After the test has been fired, repeat the above procedure with a second break point set at 1000 fps. Keep the two previously determined ballistic coefficients in place. After determining the third ballistic coefficient, you now have a means of properly predicting ballistic performance down well into the subsonic range.
4. The velocities of 1350 and 1000 fps are not sacred. They are considered representative. The number of break points may be increased.

The test and computation process is illustrated as follows. As an example, we will use a common load (Federal 308 Winchester with 175 grain Sierra). Instead of using firing data from the System 88, we will use the parameters predicted by G7. We will attempt to match the G7 performance using both the common G1 drag function and the less-used G6 drag function applied in the three stepped velocity ranges. The concept of stepped ballistic coefficients is not new, but this procedure allows you to determine the appropriate ballistic coefficients that fit your bullet and allows use of existing exterior ballistics software.

The Ballistic Explorer program allows simultaneous consideration of three "traces" or three ballistic problems at once. We first set all three traces to identical conditions but using G7 for Trace 1, G1 for Trace 2 and G6 for Trace 3. We will leave Trace 1 as our input data and use Traces 2 and 3 for our fitted traces. We will fit Traces 2 and 3 to the fired bullet using pseudo data from Trace 1. Input parameters are shown below.



Examine the time-of-flight of the three traces. Trace 1 is the "truth" as described by G7. The times are similar for short ranges, but diverge for longer ranges. Note significant differences between G1 and G6.

Examine T.O.F: seconds

Range:	0 Y	100 Y	200 Y	300 Y	400 Y	500 Y	600 Y	700 Y	800 Y	900 Y	1000 Y	1100 Y	1200 Y	1300 Y	1400 Y	1500 Y	1600 Y	1700 Y	1800 Y	1900 Y	2000 Y
Trace 1:	0.00000	0.11948	0.24772	0.38566	0.53442	0.69531	0.86993	1.06021	1.26849	1.49746	1.75004	2.02553	2.31570	2.61704	2.92876	3.25065	3.58277	3.92523	4.27823	4.64205	5.01694
Trace 2:	0.00000	0.11973	0.24879	0.38829	0.53946	0.70372	0.88257	1.07753	1.29000	1.52093	1.77043	2.03749	2.32030	2.61715	2.92678	3.24836	3.58140	3.92559	4.28074	4.64684	5.02387
Trace 3:	0.00000	0.12002	0.25032	0.39257	0.54876	0.72114	0.91228	1.12508	1.36261	1.62601	1.91058	2.21258	2.53156	2.86806	3.22282	3.59675	3.99084	4.40621	4.84406	5.30573	5.79271

Examine the zero adjustment or holdover. There are significant differences between the three traces.

Examine Zero Adjustment: MRad

Range:	0 Y	100 Y	200 Y	300 Y	400 Y	500 Y	600 Y	700 Y	800 Y	900 Y	1000 Y	1100 Y	1200 Y	1300 Y	1400 Y	1500 Y	1600 Y	1700 Y	1800 Y	1900 Y	2000 Y
Trace 1:	----	0.00	0.54	1.36	2.32	3.41	4.63	6.02	7.59	9.39	11.44	13.81	16.49	19.49	22.78	26.35	30.19	34.29	38.66	43.30	48.20
Trace 2:	----	0.00	0.55	1.38	2.36	3.48	4.75	6.20	7.84	9.70	11.81	14.19	16.84	19.79	23.01	26.52	30.31	34.38	38.72	43.34	48.24
Trace 3:	----	0.00	0.56	1.41	2.43	3.62	5.01	6.62	8.51	10.73	13.32	16.27	19.59	23.29	27.38	31.87	36.78	42.16	48.02	54.40	61.35

Examine the velocity of Trace 1 to determine the preferred range to the test target.

Examine Velocity: f/s

Range:	0 Y	100 Y	200 Y	300 Y	400 Y	500 Y	600 Y	700 Y	800 Y	900 Y	1000 Y	1100 Y	1200 Y	1300 Y	1400 Y	1500 Y	1600 Y	1700 Y	1800 Y	1900 Y	2000 Y
Trace 1:	2600	2425	2257	2096	1941	1791	1648	1509	1376	1249	1132	1057	1015	980	949	921	893	868	843	820	797
Trace 2:	2600	2425	2257	2095	1941	1793	1654	1525	1406	1300	1208	1132	1071	1022	982	947	916	889	863	840	818
Trace 3:	2600	2422	2245	2072	1904	1742	1588	1442	1307	1185	1092	1029	979	933	890	849	811	775	741	708	677

Trace 1 shows our bullet going 1376 fps at 800 yards. Choose 800 yards for convenience and pretend that we actually made measurements with the System 88 at 800 yards.

Return to the time-of-flight display and vary the ballistic coefficients of Trace 2 and 3 until the 800 yard time-of-flight equals that of Trace 1. It requires a minor change from 0.483 to 0.477 for the G1 function and from 0.269 to 0.286 for the G6 function to obtain the approximate match of time to 800 yards.

Examine T.O.F: seconds

Range:	0 Y	100 Y	200 Y	300 Y	400 Y	500 Y	600 Y	700 Y	800 Y	900 Y	1000 Y	1100 Y	1200 Y	1300 Y	1400 Y	1500 Y	1600 Y	1700 Y	1800 Y	1900 Y	2000 Y
Trace 1:	0.00000	0.11948	0.24772	0.38566	0.53442	0.69531	0.86993	1.06021	1.26849	1.49746	1.75004	2.02553	2.31570	2.61704	2.92876	3.25065	3.58277	3.92523	4.27823	4.64205	5.01694
Trace 2:	0.00000	0.11953	0.24794	0.38623	0.53551	0.69705	0.87222	1.06242	1.26897	1.49292	1.73471	1.99386	2.26895	2.55828	2.86046	3.17452	3.49983	3.83598	4.18275	4.54002	4.90774
Trace 3:	0.00000	0.11928	0.24704	0.38445	0.53284	0.69374	0.86880	1.05990	1.26913	1.49872	1.75044	2.02280	2.31162	2.61498	2.93269	3.26515	3.61288	3.97649	4.35666	4.75415	5.16978

Examination of the zero adjustment table indicates the improved predictions made possible by measuring ballistic coefficients over the distance required for the velocity to drop to approximately Mach 1.2. Zero adjustment or "holdover" differences between the three drag functions remains less than 0.1 mil from gun to over 1000 yards.

Examine Zero Adjustment: MRad

Range:	0 Y	100 Y	200 Y	300 Y	400 Y	500 Y	600 Y	700 Y	800 Y	900 Y	1000 Y	1100 Y	1200 Y	1300 Y	1400 Y	1500 Y	1600 Y	1700 Y	1800 Y	1900 Y	2000 Y
Trace 1:	----	0.00	0.54	1.36	2.32	3.41	4.63	6.02	7.59	9.39	11.44	13.81	16.49	19.49	22.78	26.35	30.19	34.29	38.66	43.30	48.20
Trace 2:	----	0.00	0.55	1.36	2.33	3.42	4.66	6.05	7.63	9.40	11.41	13.66	16.17	18.96	22.02	25.35	28.95	32.81	36.94	41.34	46.00
Trace 3:	----	0.00	0.54	1.35	2.30	3.38	4.61	6.00	7.58	9.38	11.44	13.80	16.47	19.46	22.75	26.37	30.30	34.57	39.20	44.18	49.56

Again look at the velocity predictions. A 1200 yard test is indicated for approximately 1000 fps.

Examine Velocity: f/s

Range:	0 Y	100 Y	200 Y	300 Y	400 Y	500 Y	600 Y	700 Y	800 Y	900 Y	1000 Y	1100 Y	1200 Y	1300 Y	1400 Y	1500 Y	1600 Y	1700 Y	1800 Y	1900 Y	2000 Y
Trace 1:	2600	2425	2257	2096	1941	1791	1648	1509	1376	1249	1132	1057	1015	980	949	921	893	868	843	820	797
Trace 2:	2600	2423	2253	2089	1933	1784	1644	1514	1395	1289	1198	1123	1063	1015	975	941	910	883	858	834	812
Trace 3:	2600	2432	2266	2103	1943	1789	1642	1502	1370	1248	1142	1068	1014	968	925	885	848	812	778	746	715

Note the time-of-flight of 2.3157 seconds as indicated by Trace 1. Leave the ballistic coefficient of G1 Trace 2 at the previous 0.477 and set a break point at 1000 fps. Leave the ballistic coefficient of G6 Trace 3 at the previous 0.286 and set the break point at 1000 fps. Adjust the G1 and G6 ballistic coefficients for velocities below 1350 fps until they both predict a time-of-flight of approximately 2.3157 seconds at 1200 yards. This requires changing the G1 ballistic coefficient from 0.477 to 0.326 and changing the G6 ballistic coefficient from 0.286 to 0.277. These new ballistic coefficients are used for velocities between 1350 and 1000 fps.

Examine T.O.F: seconds

Range:	0 Y	100 Y	200 Y	300 Y	400 Y	500 Y	600 Y	700 Y	800 Y	900 Y	1000 Y	1100 Y	1200 Y	1300 Y	1400 Y	1500 Y	1600 Y	1700 Y	1800 Y	1900 Y	2000 Y
Trace 1:	0.00000	0.11948	0.24772	0.38566	0.53442	0.69531	0.86993	1.06021	1.26849	1.49746	1.75004	2.02553	2.31570	2.61704	2.92876	3.25065	3.58277	3.92523	4.27823	4.64205	5.01694
Trace 2:	0.00000	0.11953	0.24794	0.38623	0.53551	0.69705	0.87222	1.06242	1.26897	1.49464	1.74571	2.02060	2.31584	2.62885	2.95818	3.30310	3.66327	4.03863	4.42930	4.83555	5.25773
Trace 3:	0.00000	0.11928	0.24704	0.38445	0.53284	0.69374	0.86880	1.05990	1.26913	1.49900	1.75172	2.02547	2.31594	2.62132	2.94157	3.27715	3.62861	3.99666	4.38200	4.78548	5.20799

Examine the zero adjustments. The required zero adjustments agree within 0.1 mil to 1400 yards.

Examine Zero Adjustment: MRad

Range:	0 Y	100 Y	200 Y	300 Y	400 Y	500 Y	600 Y	700 Y	800 Y	900 Y	1000 Y	1100 Y	1200 Y	1300 Y	1400 Y	1500 Y	1600 Y	1700 Y	1800 Y	1900 Y	2000 Y
Trace 1:	----	0.00	0.54	1.36	2.32	3.41	4.63	6.02	7.59	9.39	11.44	13.81	16.49	19.49	22.78	26.35	30.19	34.29	38.66	43.30	48.20
Trace 2:	----	0.00	0.55	1.36	2.33	3.42	4.66	6.05	7.63	9.40	11.44	13.78	16.45	19.48	22.87	26.62	30.74	35.22	40.08	45.32	50.96
Trace 3:	----	0.00	0.54	1.35	2.30	3.38	4.61	6.00	7.58	9.38	11.44	13.81	16.50	19.51	22.83	26.49	30.47	34.81	39.50	44.59	50.07

A significant change in G1 BC was required for the sonic transition range. We expected that change because the three drag functions are drastically different over this velocity range. Notice however that the required holdover remains closely matched.

Repeat the process with the target located at approximately 1800 yards. Leave the derived coefficients for Traces 2 and 3 all the way down to 1000. Adjust the third ballistic coefficients of Traces 2 and 3 to give a time-of-flight of 4.278 at 1800 yards. Yes, this is stretching the 308! Observe the resulting times-of-flight shown below. They are closely matched at 800, 1200, and 1800 yards.

Examine T.O.F: seconds

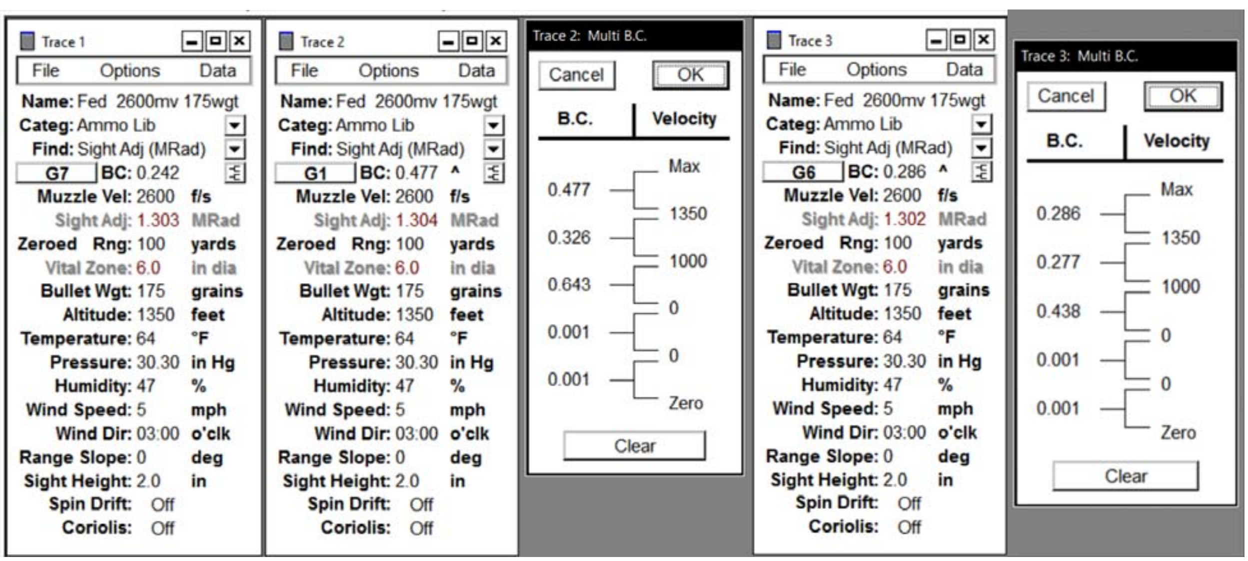
Range:	0 Y	100 Y	200 Y	300 Y	400 Y	500 Y	600 Y	700 Y	800 Y	900 Y	1000 Y	1100 Y	1200 Y	1300 Y	1400 Y	1500 Y	1600 Y	1700 Y	1800 Y	1900 Y	2000 Y
Trace 1:	0.00000	0.11948	0.24772	0.38566	0.53442	0.69531	0.86993	1.06021	1.26849	1.49746	1.75004	2.02553	2.31570	2.61704	2.92876	3.25065	3.58277	3.92523	4.27823	4.64205	5.01694
Trace 2:	0.00000	0.11953	0.24794	0.38623	0.53551	0.69705	0.87222	1.06242	1.26897	1.49464	1.74571	2.02060	2.31545	2.62176	2.93675	3.26008	3.59152	3.93092	4.27818	4.63325	4.99609
Trace 3:	0.00000	0.11928	0.24704	0.38445	0.53284	0.69374	0.86880	1.05990	1.26913	1.49900	1.75172	2.02547	2.31594	2.61901	2.93144	3.25335	3.58493	3.92640	4.27803	4.64007	5.01285

Now observe the predicted zero adjustments or holdovers.

Examine Zero Adjustment: MRad

Range:	0 Y	100 Y	200 Y	300 Y	400 Y	500 Y	600 Y	700 Y	800 Y	900 Y	1000 Y	1100 Y	1200 Y	1300 Y	1400 Y	1500 Y	1600 Y	1700 Y	1800 Y	1900 Y	2000 Y
Trace 1:	----	0.00	0.54	1.36	2.32	3.41	4.63	6.02	7.59	9.39	11.44	13.81	16.49	19.49	22.78	26.35	30.19	34.29	38.66	43.30	48.20
Trace 2:	----	0.00	0.55	1.36	2.33	3.42	4.66	6.05	7.63	9.40	11.44	13.78	16.45	19.47	22.79	26.40	30.28	34.41	38.78	43.39	48.23
Trace 3:	----	0.00	0.54	1.35	2.30	3.38	4.61	6.00	7.58	9.38	11.44	13.81	16.50	19.50	22.80	26.38	30.23	34.34	38.71	43.33	48.22

Using G1, the largest difference in predicted holdover is 0.12 mils at 1800 yards!
Using G6, the largest difference in predicted holdover is 0.05 mils at 1800 yards!



Shown above are the final conditions as displayed and used by the Ballistic Explorer program. The stepped ballistic coefficients shown vary greatly; they were chosen to match "experimental" times-of-flight at specific distances using the G1 and G6 drag functions to represent a bullet governed by G7. Had we used a G7 drag function to match the input data, the computed ballistic coefficient would have remained at the input 0.242 value for all velocity steps. The departure of the stepped drag functions from their initial values represents the degree of mismatch between the actual projectile and the drag function assumed to represent the projectile.

Here are the wind drift predictions.

Examine Wind Drift: MRad

Range:	0 Y	100 Y	200 Y	300 Y	400 Y	500 Y	600 Y	700 Y	800 Y	900 Y	1000 Y	1100 Y	1200 Y	1300 Y	1400 Y	1500 Y	1600 Y	1700 Y	1800 Y	1900 Y	2000 Y
Trace 1:	0.00	-0.10	-0.21	-0.32	-0.45	-0.58	-0.72	-0.88	-1.06	-1.25	-1.46	-1.68	-1.90	-2.10	-2.29	-2.48	-2.65	-2.82	-2.99	-3.15	-3.31
Trace 2:	0.00	-0.10	-0.21	-0.33	-0.45	-0.59	-0.73	-0.89	-1.06	-1.24	-1.45	-1.67	-1.90	-2.11	-2.31	-2.49	-2.67	-2.83	-2.99	-3.14	-3.29
Trace 3:	0.00	-0.10	-0.20	-0.31	-0.44	-0.57	-0.72	-0.88	-1.06	-1.25	-1.46	-1.68	-1.90	-2.10	-2.30	-2.48	-2.66	-2.83	-2.99	-3.15	-3.31

Here are the velocity predictions.

Examine Velocity: f/s

Range:	0 Y	100 Y	200 Y	300 Y	400 Y	500 Y	600 Y	700 Y	800 Y	900 Y	1000 Y	1100 Y	1200 Y	1300 Y	1400 Y	1500 Y	1600 Y	1700 Y	1800 Y	1900 Y	2000 Y
Trace 1:	2600	2425	2257	2096	1941	1791	1648	1509	1376	1249	1132	1057	1015	980	949	921	893	868	843	820	797
Trace 2:	2600	2423	2253	2089	1933	1784	1644	1514	1395	1260	1139	1051	995	967	942	919	898	879	860	843	827
Trace 3:	2600	2432	2266	2103	1943	1789	1642	1502	1370	1245	1137	1062	1008	977	948	921	895	871	847	824	802

The above procedure has not been confirmed with actual test firing. We are waiting to find a range that will accommodate the 300 Winchester Magnum and the 338 Lapua Magnum at distances corresponding to velocity decayed to well subsonic. The tested ranges were selected based on predicted velocities. In an actual test, the predicted distance to either Mach 1.2 or Mach 0.9 is not a critical parameter and placement of target is not critical; however, exact measurement from gun to target is critical. The chosen distances reflect approximate velocities where there are significant changes in the character of the usual drag functions and are provided for guidance. More steps and break points may be added as required for different bullets and drag functions. For example, the drag of a traced projectile will usually change after the trace fuel is burned; a change in ballistic coefficient at that break point is appropriate. Most ballistics programs expect ballistic coefficient steps or break points to be expressed in feet per second. We expect that the feet-per-second value can be directly translated to Mach number at the standard atmosphere conditions.

The forgoing procedure has several distinct advantages.

1. The procedure can be used without field experimentation to convert the function of one drag table to another.
2. It can use equipment such as the Oehler System 88 to characterize bullets when there is no published drag data available.
3. There is no requirement to estimate actual drop at longer ranges and errors from aiming and round-to-round muzzle velocity deviations are eliminated. Use of the System 88 allows you to quickly collect statistically significant samples. The procedure relies on accurately measured atmosphere, muzzle velocity, distances, and times-of-flight for each shot.
4. The experimental portion can be conducted at an unimproved site with portable instruments. The limiting factor is finding test locations to accommodate the large distances required to extend remaining velocities well down into the subsonic.

5. The procedure can be halted at any step. The first step provides accuracy to Mach 1.1, the second step to Mach 0.9, and the third step goes farther. The first step essentially represents the customary application of the Oehler System 88. The second and third steps extend the useful range of the System 88 or other measurements.
6. The software required is furnished with the System 88 and Ballistic Explorer. (If you use a System 88 and don't have Ballistic Explorer, send Oehler an e-mail and we'll send a complimentary copy.)
7. The procedure can use the universally recognizable G1 and G7 to provide an adequate fit to any unique bullet. Of course, the better the fit between assumed drag function and actual bullet, the more stable and precise are your results. If the first assumed drag function does not give good results, then you can repeat the analysis using a different drag function to fit the experimental data. A good fit between the assumed drag function and actual bullet behavior is indicated by minimal changes in the values of the stepped ballistic coefficients.
8. You can use a custom drag function to get the best fit. Fitting the predicted values to measured values on the distance versus time curve assures you that the custom drag function works properly. It does not say that the custom drag function is the only drag function that can provide an adequate fit to the measured values. The procedure can use a common drag function to make a stepped-ballistic-coefficient approximation to a custom drag function; this allows practical application of a custom drag function in a program which allows use of only common drag functions.
9. You can use a Doppler-radar-derived drag function (such as published by Lapua) to generate the distance versus time points. Conversion of the radar drag function to the familiar stepped G7 (or other) drag function will allow many of the benefits of the radar drag function to be accessed through simpler devices such as the Kestrel and various smart phones.

This procedure may appear complex and time consuming. In addition to collecting the actual firing data, the procedural step of determining the ballistic coefficients required to match the test data is tedious. This step presently requires determination of the ballistic coefficient over each velocity range beyond the first by successive approximations. This step could be aided by a computer program to automatically determine the correct ballistic coefficient for one or more following velocity ranges.