EMPIRICAL PRECISION

THE PRECISION RIFLE HANDBOOK — SHOOTING ACCURACY, BALLISTICS, AND CARTRIDGE EVALUATION

In This Book

Two standalone companion handbooks that can be read in any order:

- ***Empirical Precision: The Precision Rifle Handbook — Shooting Accuracy, Ballistics, and Cartridge Evaluation*** *(this book).* Rifle systems, optics, marksmanship, fieldcraft, cartridge evaluation, statistical group analysis, external ballistics, hit probability, and terminal performance.
- ***Empirical Precision: The Handloading Handbook — Ammunition Manufacturing and Function Testing.*** Workshop equipment, components, load research, assembly, safe work-ups, component quick reference, and simulated load ladders.

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LE Precision

Empirical Precision: The Precision Rifle Handbook — Shooting Accuracy, Ballistics, and Cartridge Evaluation

First Edition

The Easier on EP boxes in this edition refer to Empirical Precision as of November 2026.

Published by LE Precision

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Contents

Before You Begin ... vii
How to Use This Book ... viii

Part I. Foundations and the Empirical Mindset ... 1

Chapter 1. Accuracy, Precision, and Evidence ... 2
Chapter 2. Firearm, Range, and Field Safety ... 8
Chapter 3. Angular Units and Ballistic Math Basics ... 11

Part II. The Precision Rifle System ... 14

Chapter 4. The Rifle as a System ... 15
Chapter 5. Optics and Aiming Systems ... 29
Chapter 6. Scope Mounting, Leveling, and Mechanical Verification ... 34
Chapter 7. Range and Field Equipment ... 38

Part III. Marksmanship, Zeroing, and Fieldcraft ... 42

Chapter 8. Fundamentals of Precision Marksmanship ... 43
Chapter 9. Alternate and Positional Shooting ... 47
Chapter 10. Zeroing, Spotting, and Shot Calling ... 52
Chapter 11. Estimating Range, Wind, and Angles ... 57

Part IV. Cartridge Evaluation and Measurement Science ... 64

Chapter 12. Evaluating and Selecting a Cartridge ... 65
Chapter 13. Keeping Shooting and Evaluation Records ... 70
Chapter 14. The Range Testing Protocol ... 78
Chapter 15. Measurement Science for Shooters ... 84
Chapter 16. Comparing Cartridges, Loads, and Hardware ... 94
Chapter 17. Popular Load-Development and Tuning Methods Examined ... 107

Part V. Bullet Flight, External Ballistics, and Terminal Performance ... 112

Chapter 18. Bullet Stability ... 113
Chapter 19. External Ballistics Essentials ... 119
Chapter 20. Ballistic Solvers, Truing, and DOPE ... 127
Chapter 21. Hit Probability and Error Budgets ... 137
Chapter 22. Terminal Ballistics and Ethical Hunting Range ... 149

Part VI. Living With a Precision Rifle ... 153

Chapter 23. Barrel Lifecycle, Thermal Management, and Maintenance ... 154
Chapter 24. Range and Accuracy Troubleshooting ... 163

Reference ... 172

Conversions ... 172
Appendix A. Statistics, Ballistics, and Evaluation Formulas Reference Sheet ... 172
A.1 Mean point of impact and mean radius ... 172
A.2 The small-group correction ... 173
A.3 Rayleigh distribution of radial miss distances ... 173
A.4 Velocity mean, SD and ES ... 173
A.5 Confidence intervals and degrees of freedom ... 173
A.6 Comparing two loads' mean radii: F-test ... 174
A.7 Sequential testing and family-wise boundaries ... 174

A.8 Comparing velocity SDs: F-test 175
A.9 External ballistics and hit probability 175
Appendix B. Firearm and Range Safety Card 177
Notes 178
Glossary 181
Index 184

Before You Begin

These rules apply every time you handle or fire a rifle. Read them before your first range session. They are repeated as a card in Appendix B.

With every firearm

1. Treat every firearm as if it is loaded. Check the chamber yourself whenever you pick up or hand off a rifle.
2. Keep the muzzle pointed in a safe direction at all times.
3. Keep your finger off the trigger and outside the trigger guard until your sights are on the target and you have decided to fire.
4. Know your target, your backstop, and what lies beyond both.

At the range and in the field

5. Wear eye and ear protection whenever you are on an active firing line. Use double hearing protection near muzzle brakes.
6. Use a chamber flag whenever the rifle is cased, uncased, or on a cold firing line.
7. Confirm the rifle is clear of bore obstructions and that any suppressor is properly aligned and tight before firing.
8. Shoot only known-good ammunition that matches the cartridge stamped on the barrel. For handloads, fire only loads that have completed a safe work-up (see *The Handloading Handbook*).
9. Stop immediately at any pressure sign: stiff bolt lift, new or heavy ejector marks, or flattened, cratered, or pierced primers.
10. Keep ammunition out of direct sun and out of a hot chamber. Do not leave a live round sitting in a hot chamber while waiting to fire.
11. If a shot sounds or feels wrong, stop. Unload the rifle and inspect the bore for a stuck bullet before firing again. If a round fails to fire, keep the muzzle downrange for at least 30 seconds before opening the action.
12. Wash your hands and face after shooting or handling fired brass and targets. Do not eat, drink, or smoke until you have washed.

How to Use This Book

What you will learn

You will learn how to set up a precision rifle and optic, build repeatable marksmanship positions, read wind and distance, evaluate cartridges and ammunition with measured statistics, model external ballistics and hit probability, and set honest terminal-performance limits in the field.

This book starts with **known-good (safe, functional) ammunition**—whether commercial match ammunition or handloads. You do not need to handload to use this book. If measured analysis shows that a handload falls short of your goal, take that data back to the workshop (see *The Handloading Handbook*). If factory ammunition falls short, test another lot or cartridge using the same protocol.

What is covered and what is not

Centerfire and rimfire (.22 LR and other rimfire) rifles in bolt-action and semi-automatic platforms are covered. External ballistics and shooting workflows focus on **Benchrest, PRS and practical precision, Service Rifle, and ethical long-range hunting**. Measurement science applies equally to other accuracy disciplines such as bullseye pistol. Action-shooting formats that do not rely on external ballistics, such as 3-Gun, are out of scope. Ammunition manufacturing and reloading bench steps are covered in the standalone companion volume, *Empirical Precision: The Handloading Handbook — Ammunition Manufacturing and Function Testing*.

Where to start

You can read this handbook straight through, or follow the path that matches your goal:

- **New precision shooter:** Start at Chapter 1 and read straight through.
- **100-meter Benchrest shooter or factory-ammunition evaluator:** Focus on Chapters 1–8, 10–16, and 23–24.
- **Hunter with a verified load needing a DOPE card and ethical hunting range:** Focus on Chapters 2, 10–11, 18, 20, and 22 (plus Chapter 21 for hit-probability / WEZ math).
- **1,000-yard F-Class, PRS, or Service Rifle competitor:** Focus on Chapters 3–11, 14–21, and 23–24.
- **Rimfire (.22 LR) precision and trainers:** Focus on Chapters 1 to 16, 17 (barrel tuners), 19 to 21, and 23 to 24.

This is how it is done. This is how it is easier on EP.

Empirical Precision (EP) is a free and open-source reloading and ballistics app at empiricalprecision.com. It works offline and needs no account. Each method is taught in full first, with formulas and worked examples. Where EP does the same job, an *Easier on EP* box names the tool and gives a direct link.

Safety and evidence tags

A **Safety · See Chapter 2** box marks a step where a mistake can damage the rifle or hurt you. Every empirical claim with an open evidence question carries one of three tags: **Evidence · Supported by data**, **Evidence · Plausible but unproven**, or **Evidence · Folklore**. Contested topics follow one pattern: the claim, the physics, the test, the data, and the verdict.

Part I

Foundations and the Empirical Mindset

Chapter 1. Accuracy, Precision, and Evidence 2
Chapter 2. Firearm, Range, and Field Safety 8
Chapter 3. Angular Units and Ballistic Math Basics 11

Chapter 1

Accuracy, Precision, and Evidence

Key points

- Accuracy is how close your group center sits to the point of aim; precision is how tightly your shots cluster together.
- Every precision discipline—Benchrest, PRS, F-Class, Service Rifle, ethical hunting, rimfire precision competitions and trainers, and bullseye pistol—runs on the same measurement science.
- A 3-shot group is a tiny sample. It can make a poor cartridge or rifle look good and a good one look poor.
- The Law of Large Numbers: an average settles only as the number of shots grows.
- Evidence means enough recorded impacts from one rifle, measured by one method, and an honest statement of the uncertainty.

Why it matters

Every precision shooter asks the same basic question: where will the next bullet land? The answer looks slightly different across disciplines, yet the underlying problem is identical.

- **Benchrest and F-Class.** Shooters chase the smallest possible dispersion at known distances from stable rests or prone supports. Every tenth of an inch matters.
- **PRS and practical precision.** Shooters engage steel targets at varied ranges from barricades, tripods, and awkward positions under time pressure. First-round hit probability matters more than a single tiny group.
- **Service Rifle.** Shooters hold sling-supported positions across slow-fire and rapid-fire stages with iron sights or low-power optics, balancing position repeatability with mechanical precision.
- **Ethical long-range hunting.** Hunters need a cold-bore first-round hit inside a vital zone, paired with enough terminal velocity and energy to make a clean kill (see Chapter 22).
- **Rimfire precision competitions and trainers (NRL22, PRS Rimfire, smallbore) and bullseye pistol.** Precision .22 LR matches and trainers demand the same wind-reading skill, lot-testing rigor, and positional fundamentals at short range for a fraction of the cost. Even bullseye pistol shooting follows the same statistical laws of dispersion, shot calling, and sample size.

Whether you shoot commercial factory ammunition or handloads you assembled yourself (see *The Handloading Handbook*), precision shooting shares one weak spot. Modern rifles, optics, and ammunition invite constant tinkering, and every change invites a test. Many range tests are too small to answer the question they ask. A shooter changes one thing—a new box of ammunition, a different bipod, a torque setting—fires 3 shots, and sees a smaller group. The change seems to work. It may have done nothing. The group may have been small by chance.

Telling the difference takes measurement. Real-world analysis is neither cheap nor easy. Many mid-priced modern rifles already shoot very well with good factory ammunition. Improving on that takes time, discipline, and often a lot of money. There are no shortcuts,

gadgets, lucky charms, or rituals that allow you to skip the process. Treat measurement as an essential skill.

From three shots to evidence

My father had me zero my own rifle one afternoon. I remember that day fondly. We used a simple method that nobody questioned. Fire 3 shots. Adjust the scope. Repeat until the shots were "dead nuts on." Maybe throw out a few "flyers" I must have pulled. We left the range with a little less than half a box of .30-30 Winchester ammunition still in its yellow cardboard box. It was a rite of passage, and it "just worked."

For years I carried that tradition forward. I relied on 3-shot and 5-shot groups to tell me everything I thought I needed to know about a rifle. The process was cheap, it was simple and it "just worked." It was the way it had always been done.

Time passed. The targets stretched farther out and the rifles changed. The old ways began to show their cracks. But the process still "just worked." Didn't it?

Then the internet arrived. It brought a flood of forum posts, competing theories and endless arguments. Everyone had a system. Many claimed theirs was the only system that "just worked."

I met a competition shooter at the range. I was intrigued. I always knew those shooters existed (F-Class, benchrest and the like). I just thought they were good ol' boys with more money than sense, playing with shiny rifles and reloading to save money. It turned out they were much more serious than I could have imagined. They were the real deal. They all had a system too, and it "just worked."

That caused the first reckoning in me. Being told a process "just worked" was no longer good enough. I wanted to know exactly how well it worked. I wanted to know how well one process works compared to another. I wanted to know how to change my process so it works better. And I wanted to know whether a change actually made an improvement.

Then I had a second reckoning. I made a pan of cheap weeknight lasagna. I took a square from the corner. It was as close to perfect as any I have ever made. It was browned on top, with crispy cheese on the sides. It was not too sloppy and not too dry. It was just what I wanted. Then I got a second cut from near the center. It was still cold. The cheese was not even melted. How could this be? The answer was obvious. I had no right to call my lasagna perfect on the strength of one square cut from my favorite corner. A 3-shot group is that corner square.

Those early range days are a great memory. They are one of my favorites. But what worked for an old .30-30 with ammunition from the local hardware store was not working for me anymore. As the saying goes, "In God we trust; all others must bring data."[1] So let's go get some data.

How it is done

Accuracy versus precision

Shooters often use "accuracy" and "precision" as if they mean the same thing. In measurement science, they describe two separate properties of a group of shots.

- **Precision** is how tightly your shots cluster together, regardless of where they land on the target. Tight groups mean high precision (low dispersion).
- **Accuracy** is how close the center of your group sits to the point of aim. A zeroed rifle whose group center sits on the bullseye is accurate.

A rifle can be precise without being accurate: all 10 shots punch a tiny hole two inches left of the bullseye. You fix that with a turret adjustment (see Chapter 10). A rifle can also be accurate on average without being precise: 10 shots scatter across a four-inch circle centered on the bullseye. No turret click can shrink that spread. Shrinking dispersion takes better ammunition, better rifle hardware, or better marksmanship fundamentals.

Every long-range hit requires both. Precision keeps your cone of fire smaller than the target, and accuracy places the center of that cone on the target.

Anecdote versus evidence

An anecdote is an observation offered as proof. "This load shoots" after only one small group is an anecdote. Anecdotes are not lies. They are claims resting on samples too small to back them up.

Evidence has four marks: enough shots to answer the question asked, every shot recorded (including the ones you dislike), the same method of measurement for every load, and an honest statement of the uncertainty that remains.

Extraordinary claims require extraordinary evidence. "My rifle groups well at 100 yards" is a modest claim that only needs a modest sample of shots. "This 0.1 gr change halved my group size" is an extraordinary claim. Large tests rarely find effects that big from changes that small (see Chapter 17). Before you believe it, you need enough shots to rule out everything else, including luck (see Chapters 14, 15 and 16).

The Law of Large Numbers

The Law of Large Numbers says that the average of a sample moves toward the true average as the sample grows. Short runs are noisy and obscure the truth. Long runs settle toward the truth. Three examples from outside shooting show how strong the effect is.

The casino. A gambler bets on black at a roulette table and wins three times in a row. In that sample of three, black has won every time. Should the gambler assume he has found a winning method? The casino is not worried. An American wheel has 38 pockets, and 18 of them are black. Over the long run, black wins 47.4 percent of spins. Over 10,000 spins, the share of black settles close to that figure. The house keeps its edge of about 5.26 percent on every even-money bet.

The shooting parallel. A 3-shot group is the gambler's three wins. It feels like a winning method. It may be a lucky cluster of noise.

The coin. Flip a fair coin 10 times. Eight heads and two tails is an ordinary result. A split of 8 to 2 or worse, in either direction, happens about 11 times in 100. Stop there, and your data says the coin lands heads 80 percent of the time. Flip the same coin 10,000 times. The share of heads will land between 49 and 51 percent about 9,500 times in 10,000.

The shooting parallel. A rifle shoots one tiny group, with 2 shots outside it written off as "flyers." One group, and especially one group with the "flyers" removed, cannot separate a good rifle from good luck. Only more shots and honest shots can prove a rifle.

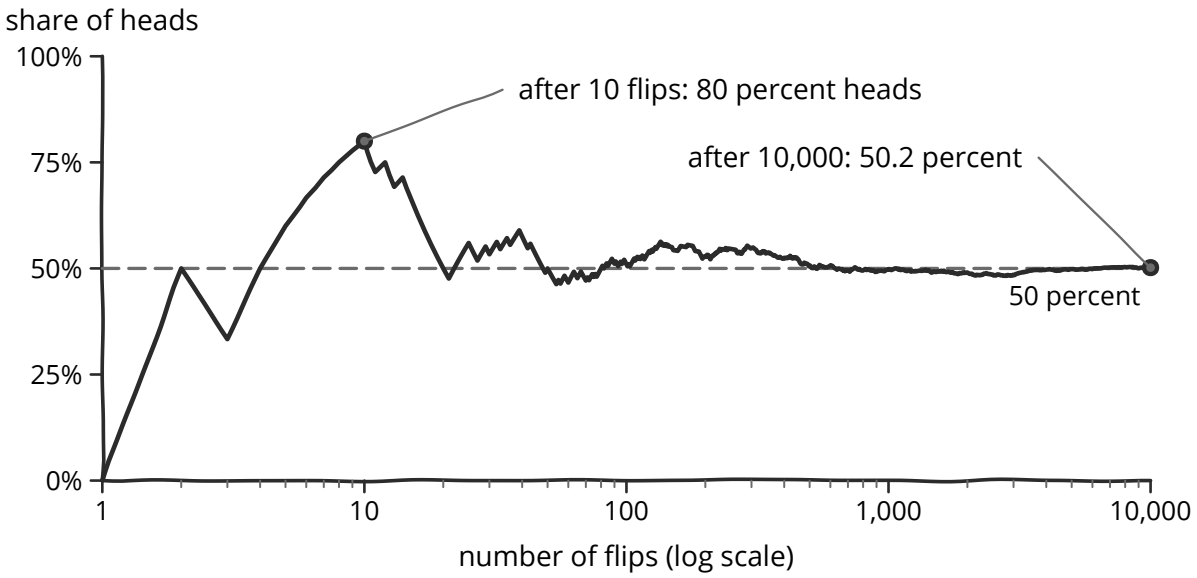


Figure 1-1. The share of heads in a long run of coin flips. It wanders early and settles near 50 percent.

The medical trial. A drug company gives a new heart medicine to five patients. Each patient gets a different dose. Patients 3 and 4 improve. Has the company found the perfect dose? No regulator would approve the drug on that evidence. Five patients cannot separate the drug's effect from chance. Regulators want large trials to wash out that noise. A late-stage trial typically enrolls 300 to 3,000 patients.[2]

The shooting parallel. A ladder test fires one shot at each charge. Two neighboring charges that land close together are patients 3 and 4 (see Chapter 17). Two bad results do not condemn a load, and two good results do not prove one.

The problem with small groups

Small groups mislead in three major ways.

1. **High volatility ("They swing widely").** Two small groups fired from the same rifle and ammunition often look completely different by chance alone. Fire two 5-shot groups from the same load, and one will be at least 1.5 times the size of the other about 30 times in 100. With 3-shot groups, that happens 46 times in 100.
2. **Selection bias ("The best of several is flattering").** Picking the best group and ignoring the rest gives a false picture of precision. Across seven 5-shot groups from the same load, the smallest group averages 0.66 times the load's true 5-shot average. The

largest averages 1.38 times that average. The smallest group is usually just the luckiest of the seven.

3. **Statistical center bias ("They read small").** You measure a group from the center of the shots on the target, not the true center the load would show over many shots. Because that center is pulled toward the shots you just fired, the group reads smaller than the load's true spread. Mean radius (the average distance of shots from the center) reads low by:
   - about 18 percent for a 3-shot group
   - about 11 percent for a 5-shot group
   - about 5 percent for a 10-shot group

The fewer shots in the group, the more it understates your true spread (see Chapter 15).

All three sets of figures are calculations that assume normally distributed shots.

It is not just groups. A velocity standard deviation (SD) from a 5-shot string swings from one string to the next even more widely than a 5-shot group does (see Chapter 15).

A larger sample fixes all three problems. It also tells you when two loads really differ.

Small samples are not useless. A few shots can reject a gross fault, such as a loose scope (see Chapter 4). They cannot prove a small gain.

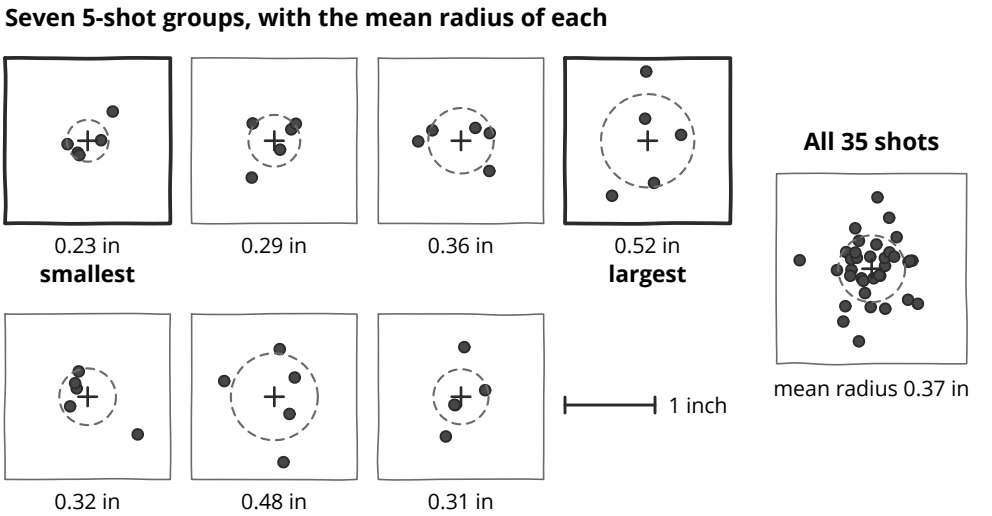


Figure 1-2. Seven 5-shot groups from one load, and the same 35 shots plotted about one center. The best and worst small groups differ by luck alone.

The price of certainty

The shots you need depend on the size of the difference you want to detect, not on whether you want to prove a load good or reject it as poor. A gross fault shows in a few shots. A small gain or loss takes dozens. The usual statistical standards allow a false alarm 1 time in 20 and ask for an 80 percent chance of catching a real difference. By those standards, you need about 35 shots per load (seven 5-shot groups) to tell apart two loads

whose true group sizes differ by 1.5 to 1. A 1.25 to 1 difference takes about 110 shots per load (see Chapter 16).

Uncertainty does not shrink in a straight line. It shrinks with the square root of the shot count. To cut your uncertainty in half, you must fire four times as many shots (for example, 40 shots instead of 10). Going from 3 shots to 30 cuts your uncertainty to less than a third. Going from 30 shots to 60 cuts it by only about 30 percent more, so the extra time and ammunition buy a much smaller gain.

The workflow on one page

The work follows a continuous path that loops from the rifle to the final application:

1. **Firearm and optic.** Record the rifle specifications, mount and level the scope, verify mechanical tracking, and lock the hardware baseline (Part II).
2. **Safety and verified ammunition.** Confirm the ammunition is safe and functional for your chamber, whether commercial factory ammunition or a handload that completed a safe work-up (Chapter 2 and *The Handloading Handbook*).
3. **Fundamentals and zero.** Build a repeatable shooting position, establish a verified zero, and practice honest shot calling (Part III).
4. **Testing and records.** Measure velocity and group dispersion with enough shots to separate signal from chance, and log every shot and environmental condition (Part IV).
5. **Comparison and selection.** Compare cartridges, lots, or hardware changes with proper statistical tests. If a handload falls short, take that data back to the workshop (see *The Handloading Handbook*); if factory ammunition falls short, test another cartridge or lot.
6. **Ballistics and truing.** Check bullet stability, build a ballistic solution, and true it against measured impacts at distance (Part V).
7. **Shoot for record.** Build your drop chart and error budget, know your hit probability, and take your verified system to a match or a hunt.
8. **Maintain and re-verify.** Track barrel wear, seasonal shifts, and lot changes, and re-verify when the system drifts (Part VI).

Even a proven setup comes back round. Barrels wear, seasons change, and ammunition lots run out (see Chapter 23).

Chapter 2

Firearm, Range, and Field Safety

Key points

- The four universal firearm safety rules block every negligent-discharge failure mode.
- Precision rifles add specific hazards: muzzle brake blast, suppressor alignment and heat, and hot-chamber cook-off.
- Only test known-good ammunition verified safe for your chamber; stop immediately on pressure signs.
- Squibs and hangfires require disciplined stop-and-wait procedures.

Why it matters

A precision rifle generates 50,000 to 65,000 psi inches from your face and sends projectiles miles downrange. Safe habits protect everyone on the line and keep every test session calm and repeatable.

How it is done

The four universal rules and what each prevents

Negligent discharges almost never come from a single mistake. They happen when two or more safety habits fail at the same time. The four universal firearm safety rules act as overlapping barriers so that one lapse does not injure anyone.

Rule	Failure mode blocked	Precision rifle application
1. Treat every firearm as if it is loaded.	Complacency after "clearing" a gun or trusting someone else's word.	Visually and physically inspect the chamber every time you pick up a rifle, even after dry fire or cleaning.
2. Never point the muzzle at anything you are not willing to destroy.	Injury from a mechanical failure, slam-fire, or unintended trigger press.	Keep the muzzle pointed downrange or safely vertical when moving between props, adjusting a bipod, or clearing a malfunction.
3. Keep your finger off the trigger until your sights are on the target and you have decided to shoot.	Startle reflex, stumble, or premature press on a light match trigger.	Precision triggers often break under 2 pounds. Keep your finger straight along the chassis or stock until the reticle settles on target.
4. Be sure of your target, what is in front of it, and what is beyond it.	Ricochets, pass-throughs, or striking foreground cover because of sight height.	High-velocity rifle bullets travel several miles if they clear a berm. Remember that the bore sits 1.5 to 2.5 inches below the scope, so a clear sight picture can still strike a barricade edge or hilltop.

Precision rifle hardware hazards

Precision rifles carry hardware that introduces hazards beyond ordinary range handling.

- **Chamber flags.** An open bolt is hard to verify from ten feet away. Insert a bright chamber flag (empty chamber indicator) whenever the rifle is not on the firing line or when the range goes cold. During positional matches, a chamber flag lets range officers and squadmates confirm a safe rifle at a glance while you move between stages.

- **Muzzle brakes and blast zones.** A muzzle brake vents high-pressure propellant gas—often 4,000 to 10,000 psi or more at the muzzle—outward to the sides and slightly rearward to cut recoil.[1] That blast throws dirt and gravel sideways and delivers sharp concussion to anyone beside the muzzle. Keep spotters and bystanders behind the shooter, never abreast of the muzzle. Wear double hearing protection (foam plugs under earmuffs) whenever firing or spotting near braked rifles, especially under covered firing lines.
- **Suppressor alignment and heat.** A suppressor that sits slightly off the bore axis risks a baffle strike, which can destroy the tube and launch jacket fragments off line. Check alignment with a calibrated bore alignment rod whenever mounting a suppressor on a new barrel or muzzle mount. Check tightness periodically during a session, because vibration and thermal expansion can back a direct-thread or quick-detach mount loose. Suppressors also trap intense heat. A few rapid strings can heat the outer tube hot enough to cause severe burns and melt nylon rifle cases or shooting mats. Let the suppressor cool before packing it, and use a heat-resistant cover if heat mirage obscures your sight picture.
- **Hot-chamber cook-off.** Leaving a live cartridge sitting inside a hot chamber transfers heat directly into the powder charge. Even before cook-off, a heated round burns faster, spiking chamber pressure and muzzle velocity and ruining group data. In an overheated chamber, a round can ignite on its own without a trigger press. Keep the bolt open between strings so air cools the bore, and chamber a round only when you are ready to fire.

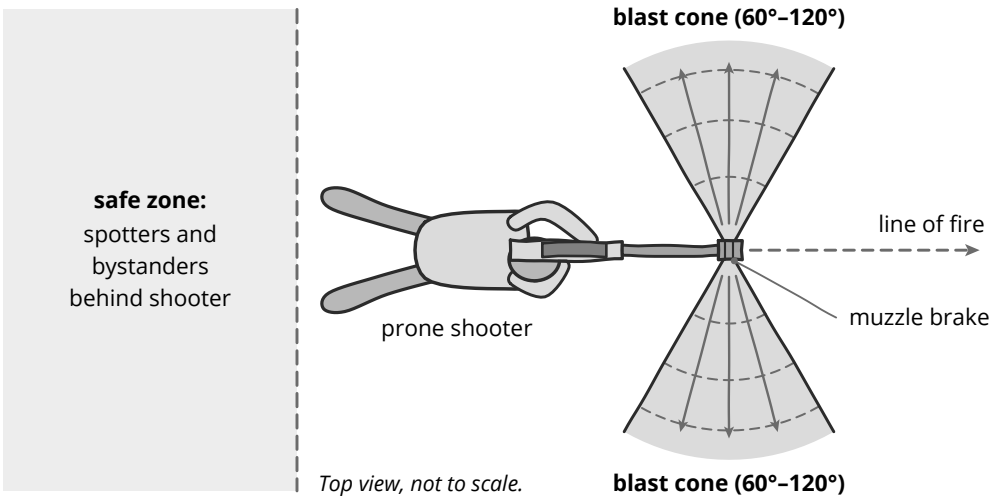


Figure 2-1. Muzzle brake blast zones from above. The side-blast cones extend outward and slightly rearward from the muzzle; spotters and bystanders belong behind the shooter.

Verifying known-good ammunition

Precision evaluation begins with ammunition already proven safe and functional for the specific rifle.

1. **Match the headstamp to the barrel stamp.** Read the chambering stamped on the rifle barrel and verify that every box and every cartridge headstamp matches it. Do not trust loose ammunition from an unlabeled box. Similar cartridges can chamber in the wrong rifle—for example, a smaller-diameter bullet firing loosely down a larger bore,

or a shorter case chambering into a longer throat—causing dangerous pressure spikes or case failure.

2. **Inspect factory ammunition.** Before loading a magazine, scan the rounds for crushed shoulders, deeply seated or crooked bullets, high or inverted primers, and mixed headstamps. Record the factory lot number in your log so you can trace any malfunction or performance shift back to that lot (see Chapter 13).
3. **Verify handloaded ammunition.** If you shoot handloads, confirm the recipe completed a safe work-up from a published start load in that specific rifle without exceeding published maximums (see *The Handloading Handbook*). Never shoot someone else's unverified handloads.
4. **Stop immediately on pressure signs.** Watch fired brass and bolt feel on every string. In centerfire rifles, heavy bolt lift, flattened or cratered primers, shiny ejector smears on the case head, pierced or blown primers, split necks or case bodies, and sudden unexplained velocity jumps are warning signs of excessive pressure. In rimfire rifles, watch for split rims, ruptured case heads, or hot gas escaping back from the breech. Pressure rises far faster than velocity, and some overpressure loads show few external signs until a case fails.[2]

Safety · See Chapter 2
If you observe heavy bolt lift, pierced primers, ejector smears, split brass or rimfire rims, escaping breech gas, or an unexplained velocity spike, stop firing immediately. Set the remaining rounds aside and do not fire them until you find the cause (for reloading-bench causes, see *The Handloading Handbook*).

Squibs, hangfires, and range discipline

Abnormal ignition requires calm, practiced reactions rather than haste.

- **Hangfires (the 30-second rule).** If the firing pin falls without firing, keep the muzzle downrange and wait at least 30 seconds before opening the action.[3] A delayed primer or powder burn can detonate out of battery if you open the bolt early, venting gas and brass toward your face and hands.
- **Squib loads and bore obstructions.** In a squib, the primer fires without a full powder burn, lodging the bullet in the bore; the report is muffled, recoil is light, and nothing hits the target. Stop, unload, remove the bolt, and inspect from the breech or run a cleaning rod through the bore. Firing into a lodged bullet, mud, snow, patch, or bore-sighting tool can rupture the barrel.
- **Eye and ear protection.** Wear impact-rated eye protection (ANSI Z87.1 or equivalent) and hearing protection whenever uncased rifles are on a live line. Hearing damage is cumulative and permanent; a single unmuffled centerfire rifle shot can cause lasting loss.
- **Lead hygiene.** Primers, exposed bullet bases, and steel splatter leave lead dust on hands, brass, and gear. Keep food and open drinks off the bench, and wash hands and face with cold water and soap before eating or drinking (cold water keeps pores closed). Wash range clothes separately and keep range shoes out of living areas, especially around children.[4]

Chapter 3

Angular Units and Ballistic Math Basics

Key points

- MIL (mrad) and MOA are angular units, not linear inches; their linear size grows with distance.
- 1 MIL equals 1/1,000 of the distance (3.6 inches at 100 yards; 10 cm at 100 meters).
- True MOA is 1.047 inches at 100 yards; Shooter's MOA (IPHY) is 1.000 inch at 100 yards.
- Using your reticle as a ruler removes guesswork when measuring impacts, holding wind, and dialing corrections.

Why it matters

External ballistics, scope turrets, group dispersion, and wind calls all speak in angles. Fluent angular math turns every shot impact into an exact correction.

How it is done

What an angle is and why shooters use angles

Linear units—inches, feet, centimeters—measure physical size on a target. They fail as a universal shooting language because the rifle pivots around you in an angle, not in inches.

A 2-inch group at 100 yards is mediocre for a precision rifle. A 2-inch group at 1,000 yards is extraordinary. The physical size is the same, yet the angular dispersion at 1,000 yards is ten times smaller. The same rule governs your riflescope. Turning an elevation turret by one click tilts the scope's internal erector assembly by a fixed angle. At 100 yards, that angle moves the point of impact a fraction of an inch. At 1,000 yards, the exact same click moves the point of impact ten times as many inches.

Working in angles solves this problem. Drop charts, wind calls, scope turrets, reticle hashes, and group dispersion all share one angular language that scales automatically with distance.

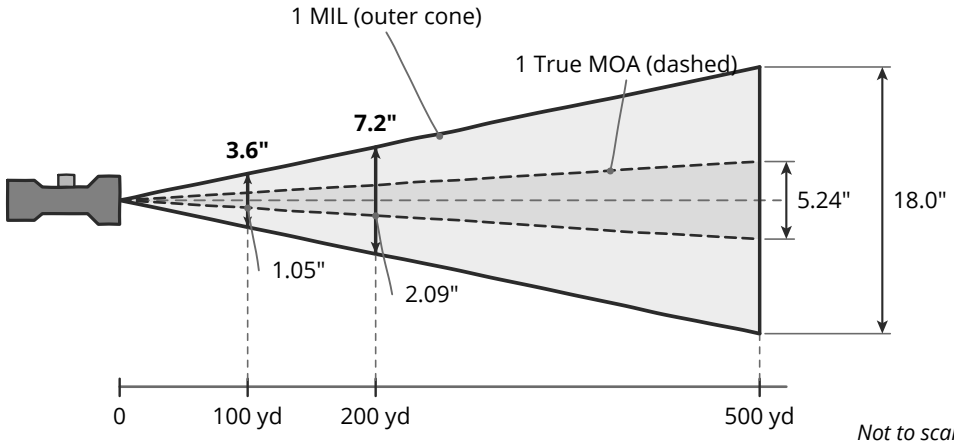


Figure 3-1. An angle expands linearly with distance. A 1 MIL cone spans 3.6 inches at 100 yards, 7.2 inches at 200 yards, and 18.0 inches at 500 yards.

MIL (milliradians)

A radian is the angle formed when an arc along a circle equals the circle's radius. One milliradian (1 mrad, written **1 MIL** in shooting) is 1/1,000 of a radian.

Because MIL is base-10, its math is simple in any unit of distance. For the small angles used in shooting, 1 MIL subtends (covers) 1/1,000 of the distance to the target:

- At **100 yards** (3,600 inches), 1 MIL = **3.6 inches**.
- At **1,000 yards**, 1 MIL = **36 inches** (1 yard).
- At **100 meters** (100,000 mm), 1 MIL = **10 cm** (100 mm).
- At **1,000 meters**, 1 MIL = **1 meter**.

Most MIL riflescopes adjust in **0.1 MIL** clicks. One click moves the point of impact 0.36 inch at 100 yards (1 cm at 100 meters).

```
1 MIL in inches = 3.6 × (distance_yd / 100)
1 MIL in cm     = 10 × (distance_m / 100)
MIL correction  = linear_offset_in / (3.6 × distance_yd / 100)
```

Worked example. Example numbers.

You fire at a steel plate at 400 yards and measure your impact 7.2 inches low.

```
1 MIL at 400 yards = 3.6 × (400 / 100) = 14.4 inches
MIL correction     = 7.2 / 14.4        = 0.5 MIL (5 clicks of 0.1 MIL)
```

Dial up 0.5 MIL to bring the point of impact onto the center of the plate.

MOA (True MOA vs. IPHY)

A full circle contains 360 degrees, and each degree divides into 60 minutes. One Minute of Angle (**1 MOA**) is 1/60 of a degree, or 1/21,600 of a full circle.

At a radius of 100 yards (3,600 inches), the circumference of a full circle is `2 × pi × 3,600 = 22,619.5 inches`. Dividing by 21,600 gives **1.0472 inches per 100 yards**, usually rounded to **1.047 inches**. This exact geometric value is **True MOA**. In metric units, **1 True MOA = 2.91 cm (29.1 mm) at 100 meters**.

Many shooters approximate 1 MOA as **1.000 inch per 100 yards** for quick mental arithmetic. That rounded unit is called **Shooter's MOA** or **IPHY** (Inches Per Hundred Yards).

At 100 yards, the 4.7 percent difference between True MOA and IPHY is tiny (0.047 inch on a 1-inch group). At long range, it adds up fast. Suppose a ballistic solver calculates a drop of 30.0 True MOA at 1,000 yards (314.2 inches). If your scope actually tracks in IPHY (1.000 inch per 100 yards per click) and you dial 30.0 MOA, the scope moves only 300.0 inches. You miss 14.2 inches low—about 1.35 MOA—purely from mixing True MOA and IPHY. Know whether your scope and your solver use True MOA or IPHY, and verify your scope's real click value with a Tall Target Test (see Chapter 6).

Most MOA riflescopes adjust in **1/4 MOA** clicks (0.262 inch at 100 yards; 7.3 mm at 100 meters). Benchrest and F-Class scopes often use **1/8 MOA** clicks (0.131 inch at 100 yards; 3.6 mm at 100 meters) for finer zeroing on tiny scoring rings.

Converting between MIL, MOA, and linear units

Use these plain-text formulas to move between MIL, True MOA, and linear measurements at any distance:

```
1 MIL        = 3.4377 True MOA (about 3.44 MOA)
1 True MOA   = 0.2909 MIL      (about 0.291 MIL)

Linear size (in) = MIL × 3.6 × (distance_yd / 100)
Linear size (in) = True_MOA × 1.0472 × (distance_yd / 100)
Linear size (cm) = MIL × 10 × (distance_m / 100)
Linear size (cm) = True_MOA × 2.909 × (distance_m / 100)

MIL      = linear_in / (3.6 × distance_yd / 100)
True MOA = linear_in / (1.0472 × distance_yd / 100)
True MOA = linear_cm / (2.909 × distance_m / 100)
```

Distance	1 MIL	0.1 MIL click	1 True MOA	1/4 True MOA click	1/8 True MOA click
50 yards	1.80"	0.18"	0.52"	0.13"	0.065"
100 yards	3.60"	0.36"	1.05"	0.26"	0.13"
100 meters	10.0 cm	1.0 cm	2.91 cm	7.3 mm	3.6 mm
200 yards	7.20"	0.72"	2.09"	0.52"	0.26"
300 yards	10.80"	1.08"	3.14"	0.79"	0.39"
500 yards	18.00"	1.80"	5.24"	1.31"	0.65"
1,000 yards	36.00"	3.60"	10.47"	2.62"	1.31"

Worked example. Example numbers.

You fire a group at 300 yards and measure its size on paper as 2.10 inches.

```
True MOA = 2.10 / (1.0472 × 3) = 2.10 / 3.1416 = 0.67 True MOA
MIL      = 2.10 / (3.6 × 3)    = 2.10 / 10.8   = 0.19 MIL
```

Notice that `0.67 × 0.2909 = 0.195 MIL`, matching the direct calculation.

Using the reticle as a ruler

With a matched scope (MIL reticle with MIL turrets, or MOA with MOA), you can skip inches and use the reticle as a calibrated ruler; mixing units forces you to multiply or divide by 3.44 under time pressure, inviting mistakes.

1. **Measure impacts directly.** If a 600-yard splash lands 0.8 MIL low and 0.4 MIL left, skip inches: dial up 0.8 MIL and right 0.4 MIL, or hold 0.8 MIL high and 0.4 MIL right.
2. **Dial vs. hold.** Dialing centers the crosshair for elevation changes, deliberate shots, and small targets; holding is faster under time pressure, follow-ups, and shifting wind. Many shooters dial elevation and hold wind.
3. **Estimate range.** Measuring a known-size target (such as an 18-inch steel plate) in MIL or MOA lets you compute distance without a laser rangefinder (see Chapter 11).

Part II

The Precision Rifle System

Chapter 4. The Rifle as a System 15
Chapter 5. Optics and Aiming Systems 29
Chapter 6. Scope Mounting, Leveling, and Mechanical Verification 34
Chapter 7. Range and Field Equipment 38

The Rifle as a System

Key points

- Every load—factory or handloaded—performs specifically to one rifle, and your baseline data only applies to the exact setup it was tested in.
- Cut, button and hammer-forged barrels can all shoot well. A heavier contour warms less, and heat moves the point of impact.
- A damaged crown or a new muzzle device moves the point of impact.
- Barrel length moves velocity. It barely moves peak pressure.
- Record twist, sight height, magazine length, and *(if handloading)* distance to the lands. The lands move forward as the throat wears.

Why it matters

Every result you measure comes from the rifle and the load together. Two rifles in the same chambering can fire the same load at different velocities because their bores, throats and finishes differ.[1] A shifting scope, a loose action screw or a new trigger changes your groups as surely as a new powder does. Until the rifle stays the same from one test to the next, you cannot tell what the load is doing.

How it is done

Learn the barrel first. Then measure the rifle, lock its hardware and record it.

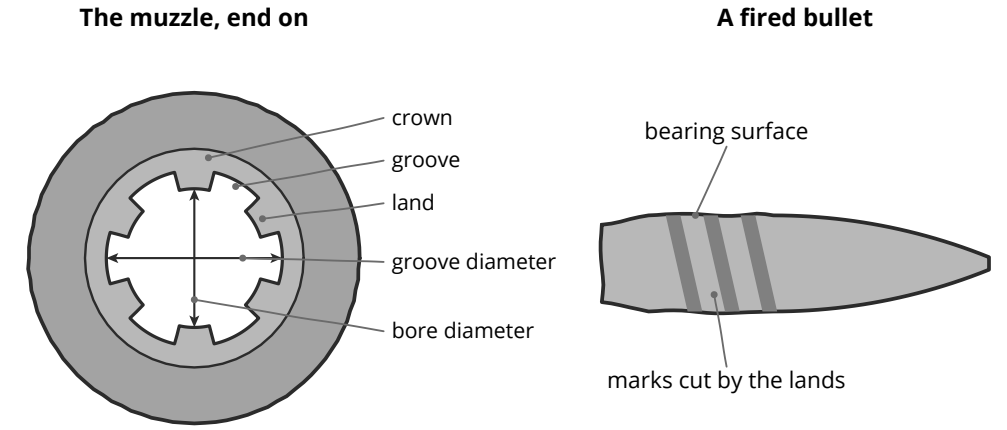
The barrel

A rifle barrel is a precisely made steel tube. The chamber is cut into the breech end, and the crown is cut at the muzzle. The bore joins the two. Spiral ridges called rifling line the bore. They grip the bullet and spin it so it stays stable in flight (Figure 4-1).

- **Lands** are the raised spiral ridges inside the bore. **Grooves** are the recessed channels cut between them.
- **Bore diameter** is measured across the tops of the opposing lands. **Groove diameter** is measured across the bottoms of the grooves. Bullets are made to the larger groove diameter, so the raised lands engrave the bullet as it enters the rifling. The engraved bullet seals the propellant gases behind it and takes up the spin.
- **The crown** is the machined exit of the bore at the muzzle. It is the last point the bullet touches before free flight. A burr or an uneven edge there deflects the escaping gas and moves the point of impact (see “The muzzle” below). Protect the crown from knocks, and keep a cleaning rod from wearing it.

Most modern rifle barrels are made from chrome-moly steel (such as 4140) or martensitic stainless steel (such as type 416).[2] The two differ in how well they resist rust and how easily they machine. Neither is more accurate than the other.[3] Whether stainless keeps its accuracy longer is not settled.[3]

At the breech end, the chamber supports the cartridge case. The rifling begins just ahead of the case mouth. The transition between them is the throat, where the loaded round meets the barrel (see *The Handloading Handbook*).



Rifling and engraving depth exaggerated.

Figure 4-1. The bore seen from the muzzle, with the lands, the grooves, the bore diameter and the groove diameter. Beside it, a fired bullet engraved by the rifling.

Contour and fluting

The contour, or profile, is the outside shape of the barrel along its length. The barrel blank is turned on a lathe centered on the bore. That keeps the outside of the barrel concentric with the bore.[2] Most contours have a straight shank just ahead of the action and then taper toward the muzzle. Makers give their profiles names such as sporter, varmint or heavy. They also publish drawings that give the diameters along the barrel. The names are not standard, so one maker's varmint contour differs from another's. Compare the drawings, not the names.

A heavier contour has more steel. That makes it stiffer. The extra steel also soaks up more heat, so each shot raises the barrel temperature less. In controlled tests over long firing strings, the point of impact shifted by more than 1 MOA as barrels heated. Heavier contours generally moved less.[4] One MOA (minute of angle) is about 1.047 inches at 100 yards. The price of a stiffer barrel that holds steadier under heat is more weight to carry and support.

Fluting cuts lengthwise grooves into the outside of the barrel. It saves weight and adds surface area, which aids cooling. A fluted barrel is stiffer than an unfluted barrel of equal weight, because the unfluted barrel needs a slimmer contour to weigh the same.[5] But a fluted barrel is always less stiff than an unfluted barrel of the same starting contour. Removing steel reduces stiffness.

A carbon-fiber barrel wraps a thin steel liner in structural carbon fiber. It is very stiff for its weight. In the same heat tests, a carbon-fiber barrel ranked among the most stable. Its point of impact shifted little as it heated.[6]

Heat in the barrel

Every shot puts heat into the barrel. The hot powder gas heats the bore hardest at the throat, where temperature and pressure peak. That heat moves outward through the steel to the outside of the barrel. The surface then sheds heat to the air by radiation and by convection, where moving air carries it away. A barrel takes in heat in seconds but needs many minutes to cool.

How fast a barrel warms depends on the powder charge compared with the weight of the barrel steel. A large case behind a small bore in a slim barrel heats the fastest. A small case in a heavy barrel heats the slowest.

Heat that builds up changes how the rifle and the load shoot.

- **Point of impact moves.** As a barrel heats, its shots can walk and its groups can open (see "Contour and fluting" above).
- **Velocity climbs.** Velocity can rise through a string as the chamber heats. A round left in a hot chamber warms, and its pressure rises. Never leave one there (see Chapter 14).
- **The throat wears faster.** Heat speeds the erosion that moves the lands forward (see "Throat erosion" below).

Pace your shots to keep heat from skewing a test. Start each test with a cool barrel and fire at a steady pace, so every load is shot at the same barrel heat (see Chapter 14). Open the action between strings so air can move through the bore. Keep the rifle in the shade.

Contested: a black barrel cools faster than a bright one

The claim. A black barrel sheds heat faster than a bright stainless one.

The physics. The finish does not change how much heat a shot puts in. It changes how well the surface radiates. A flat black finish radiates over 90 percent of the most any surface can. Cleaned stainless steel radiates about 30 percent, and polished stainless even less.[7] With the barrel at about 140 °F in 70 °F still air, radiation carries about as much heat as the air does. A black barrel can then shed roughly half again as much heat as a bright one. In a 10 mph breeze, the moving air carries most of the heat. A black barrel then sheds only about a tenth more heat than a bright one.[8] A coating is too thin to hold heat in. Sunlight works the other way. A black finish takes in more of the sun's heat, so in full sun a black barrel sits warmer between strings.

The test. Heat two barrels of one contour, one black and one bright, to the same temperature. Log their cooling with thermocouples. Do it in still air and in wind, and in shade and in sun. An infrared thermometer misleads here. It reads bright steel far cooler than it is, because bright steel radiates less.

The data. No controlled cooling test of black and bright rifle barrels has been published. The physics rests on measured surface values and standard heat-transfer methods.

The verdict. Plausible but unproven. Expect a real gain in still air and shade, little in wind and a loss in full sun. Time between strings cools a barrel more than any finish.

Throat erosion

Hot gas at high pressure wears the throat on every shot. The wear eats away the start of the rifling and moves the lands forward. In 6 mm and 6.5 mm barrels the lands move a few thousandths of an inch per 100 rounds. At a fixed seating length, the bullet's jump grows over time, so *(if handloading)* measure the distance to the lands from time to time (see *The Handloading Handbook*). Manage throat wear and velocity drift over the life of the barrel (see Chapter 23).

The muzzle

When the bullet leaves the muzzle, the gas behind it is still under high pressure. As the bullet clears the crown, that gas expands around its base and overtakes it. Even expansion pushes the bullet straight ahead. If gas escapes early on one side, it pushes unevenly on the bullet's base and tips the bullet slightly off line. That tilt is called yaw. In tests of large-caliber barrels, uneven pressure at the muzzle tracked the bullet's first yaw closely.[9]

Muzzle pressure is the gas pressure still behind the bullet as it leaves. It is far lower than the peak pressure reached early in the shot (see *The Handloading Handbook*). In a test of a 5.56x45mm NATO rifle, peak pressure near the chamber was about 55,700 psi. Muzzle pressure was about 4,800 psi from a 24-inch barrel, 8,150 psi at 14.5 inches and over 25,000 psi at 5 inches. It rose faster and faster as the barrel got shorter.[10] Slower powders and heavier charges also leave more pressure at the muzzle, with more blast and noise.[11]

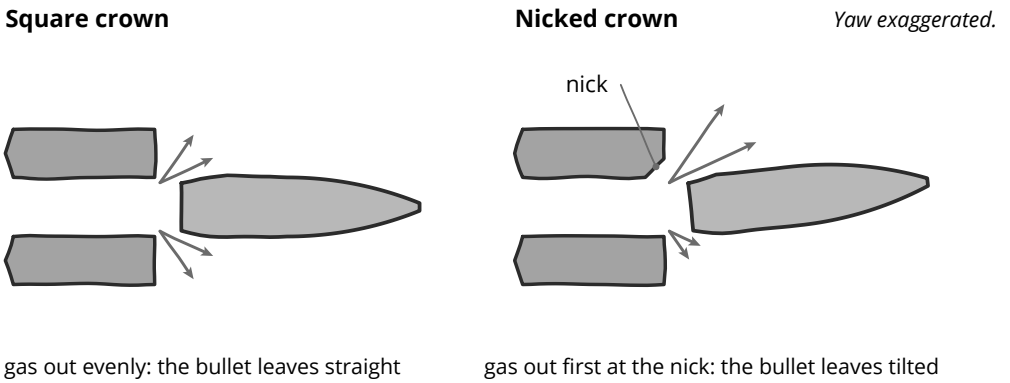


Figure 4-2. Gas leaving the muzzle behind the bullet. A square crown lets it out evenly all round. A nicked crown lets it out first on one side, and the bullet leaves tilted.

The crown. A crown cut square to the bore with a sharp, even edge lets gas escape evenly around the bullet base. A nick, a burr or wear from a cleaning rod lets gas out early on one side. Look over the crown from time to time under bright light and a magnifier. A gunsmith can recut a damaged crown square to the bore. Re-zero the rifle after any crown work.

Contested: a damaged crown ruins a rifle's precision

The claim. A nick in the crown permanently opens a rifle's groups.

The physics. A flaw in the crown lets gas out early on one side and tilts the bullet. A tilt that is the same on every shot moves the point of impact. A tilt that changes from shot to shot opens the group.

The test. Fire enough groups to find a reliable mean radius for the rifle (see Chapter 15). Damage the crown on purpose and fire the same number of shots. Then recut the crown square to the bore and fire a third set. Compare the three sets (see Chapter 16).

The data. Three published tests damaged rifle crowns on purpose to measure the effect. All three saw a clear shift in the point of impact. A crown cut with a grinder moved the point of impact about 16 MOA.[12] A crown struck with a hammer moved it well over a foot. Recutting the crown brought it back.[13] The effect on group size is less clear. The ground crown still shot six 5-shot groups that averaged about 1 MOA, against a single 0.55 MOA group before the damage.[12] The hammered crown averaged 2.26 inches over five 5-shot groups, against 1.55 inches before. Yet the same rifle averaged 1.40 inches after its muzzle was sawn off and deburred with a knife.[13] A third test damaged the crowns of four barrels, from mildly to severely. Every damaged barrel shot less accurately than before, and the first shots strayed the most. The report gave no group sizes.[14] None of these tests fired enough shots to tell a small change in group size from chance (see Chapter 1).

The verdict. Plausible but unproven. Every test shows that a damaged crown moves the point of impact. Whether crown damage reliably opens groups is not settled. Treat a damaged crown as a hardware change: recut it, re-zero the rifle and shoot a new baseline.

Muzzle devices

A muzzle brake vents gas to the sides to cut recoil. A suppressor traps the gas and lets it out slowly. Either one changes the blast the bullet flies through. Either one also adds weight at the muzzle, and that changes how the barrel vibrates (see Chapter 17). In one test, muzzle devices were threaded to run true to the bore within .002 inch.[9] A device that runs off the bore line lets the gas out unevenly.

- **Point of impact moves.** Expect the zero to move when you fit or remove a device. Zero with the device you will shoot with.
- **Velocity can change.** In one test, a suppressor lowered one load's velocity by about 30 fps (about 1 percent). It raised two others a little. Measure velocity with the device you will shoot with.[9]
- **Yaw can change.** In the same test, a .300 Winchester Magnum rifle fired four bullets with no device and with three suppressors. It fired 5 to 10 shots of each bullet in each setup. For three bullets, the drag changed by 4 percent or less. One bullet was prone to yaw. Its drag was highest with no device and fell with each suppressor, most with a two-stage design.[15]
- **Discipline rules.** Check your competition rules before fitting a muzzle brake. Both F-Open and F-TR F-Class rules ban muzzle brakes to protect neighboring prone shooters from side blast.

Evidence · Plausible but unproven

Brakes and suppressors are said both to open groups and to tighten them. In one published test, a rifle fired one 5-shot group with each of five brakes and one with none, too few to tell a real change from luck (see Chapter 1).[16] A device is part of the rifle's hardware. Fitting, removing or changing one voids the baseline (see "The hardware baseline" below).

How rifling is made

Every barrel begins as a solid round bar. A deep-hole drill bores a hole slightly under the final bore diameter. A reamer then brings the hole to size and smooths its surface.[2] The rifling is then formed by one of three main methods (Figure 4-3).

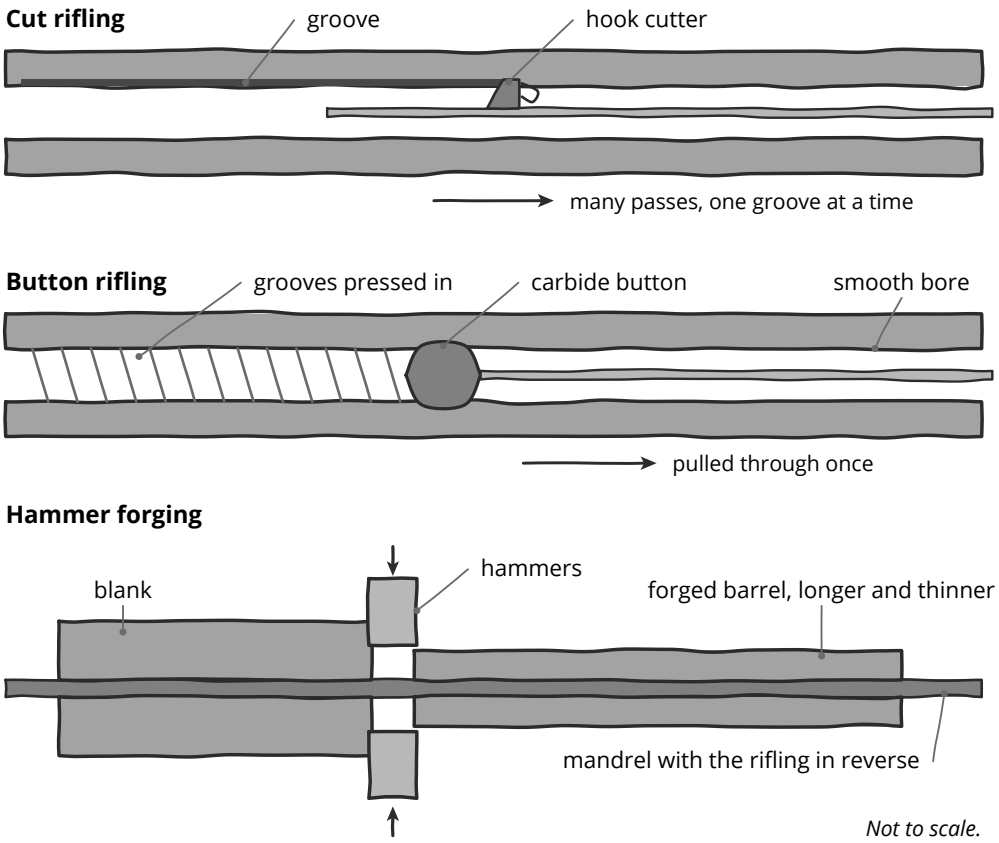


Figure 4-3. The three main rifling methods. Cut rifling cuts one groove at a time. Button rifling presses in all the grooves in one pass. Hammer forging beats the blank down onto a mandrel.

- **Cut rifling.** A hook-shaped cutter with a single point is drawn through the bore again and again. It turns as it travels, so the groove follows the twist rate. Each pass shaves a very thin layer of steel from one groove. The cutter removes steel without cold-working it, so it leaves very little stress in the barrel.[2] Cut rifling is the oldest method and the slowest.[17]
- **Button rifling.** A button is a hard carbide die ground with the reverse of the rifling. It is pulled or pushed through the reamed bore in one pass. The button does not cut metal. It presses the grooves in by pushing the steel aside. That cold-forming leaves a lot of stress in the steel, so the barrel must be heat-treated after rifling to relieve it. Without stress relief, the bore can open up or the barrel can warp when its outside is turned to contour.[2]
- **Hammer forging.** A short, thick-walled barrel blank is fitted over a hard mandrel that carries the reverse of the rifling. Opposing power hammers beat the outside of the blank down onto the mandrel. The steel stretches longer and thinner as the rifling forms inside the bore.[17] Done at room temperature, the process is called cold hammer forging. The machinery costs a great deal, but the cost per barrel is low. Many modern factory rifles use hammer-forged barrels.[17]

The method a maker uses tends to follow its size. The largest makers mostly hammer forge, mid-sized makers button rifle and small shops cut.[18]

Whatever the method, a match bore needs the same bore and groove diameters along its full length. Its twist must also follow its design from breech to muzzle. Most barrels have a constant twist. Some match barrels use a gain, or progressive, twist that quickens toward the muzzle. A flaw in the bore can be pressed into each bullet that passes through it. A bullet marked that way can be less stable in flight.

Evidence · Plausible but unproven
Cut rifling is widely held to be the most accurate method. No controlled test of well-made barrels from each process has been published. All three methods can make an equally accurate barrel.[18] What counts is the finished bore, not the process that made it. Cut rifling is slow, and small shops favor it. A small shop can inspect each barrel closely. Button rifling and hammer forging are faster and suit mass production. Judge a barrel by its maker's quality control and the groups it shoots.

Barrel length and velocity

Unload the rifle and check that the chamber is empty before you take any measurement.

To measure barrel length, take off any muzzle brake, suppressor or thread protector so the crown is bare. Close the bolt on the empty chamber. Slide a cleaning rod in from the muzzle until it stops against the bolt face. Mark the rod flush with the crown. Pull the rod out and measure from its tip to the mark (see Figure 4-4).

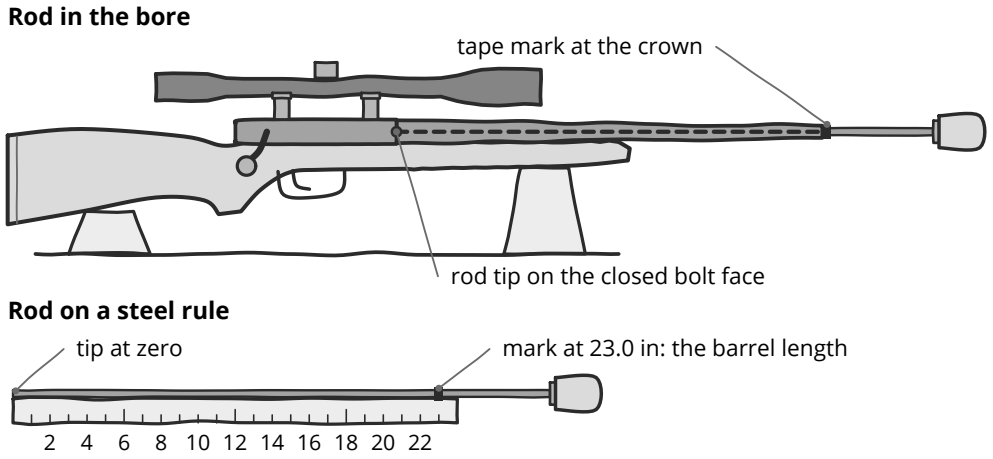


Figure 4-4. Measuring barrel length with a cleaning rod against the closed bolt face.

Published load data comes from test barrels that your rifle will rarely match. A shorter barrel gives less muzzle velocity. A longer barrel gives more, but each added inch gains less. Published barrel tests show a change of about 17 to 43 fps per inch, depending on the cartridge.[19] Test barrels also often give higher velocities than sporting rifles.[20] Treat a published velocity as a reference, not a promise. Rimfire .22 LR is an exception: its small, fast-burning powder charge finishes accelerating the bullet early, so velocity typically peaks around 16 to 18 inches and may drop slightly in longer barrels due to bore friction.

Barrel length has almost no effect on peak pressure. Pressure peaks in the first few inches of bullet travel, long before the bullet reaches the muzzle (see *The Handloading Handbook*).[21]

To estimate how barrel length changes velocity, multiply the difference in length by the change per inch. For a shorter barrel *(if handloading)*, lower your work-up velocity ceiling by 43 fps per inch unless you have a published test for your cartridge. The 43 fps figure gives the lower, safer ceiling. Do not raise the velocity ceiling for a longer barrel, because the gain from extra length is only an estimate (see *The Handloading Handbook*).

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Ignition shows how predicted velocity changes with barrel length. Like every prediction, it is for learning.

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Twist and stability

A rifled barrel spins the bullet so it stays stable and flies point first. Twist rate is the length of bore in which the rifling makes one full turn. One turn in 8 inches is written as 1:8. A shorter length is a faster twist, and it gives the bullet more spin.

Longer bullets need a faster twist. Check that your barrel's twist will stabilize a bullet before you buy it (see Chapter 18).

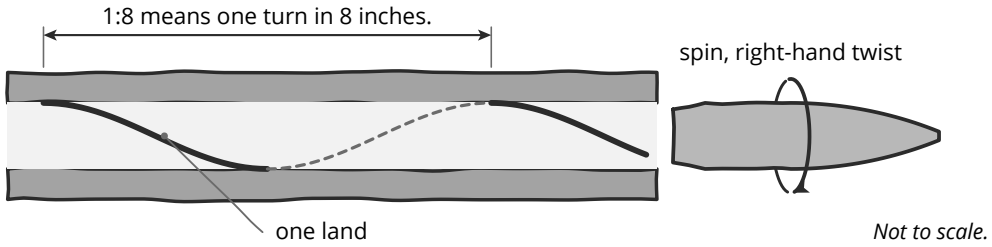


Figure 4-5. Twist rate. The rifling makes one full turn over the twist length, and the bullet leaves the muzzle spinning.

Use the maker's figure for the twist or measure it yourself. Push a tight patch on a free-spinning cleaning rod a short way into the bore, so the patch grips the rifling. Mark the rod at the muzzle and stick a tape flag on it near the handle. Push the rod in until the flag has made one full turn, then mark the rod at the muzzle again (see Figure 4-6). The distance between the two marks is the twist rate. Watch which way the rod turns from the handle end as you push it forward. Clockwise is a right-hand twist, and counterclockwise is a left-hand twist. Record both the rate and the direction (such as 1:8 right-hand), because spin drift depends on both (see Chapters 19 and 20).

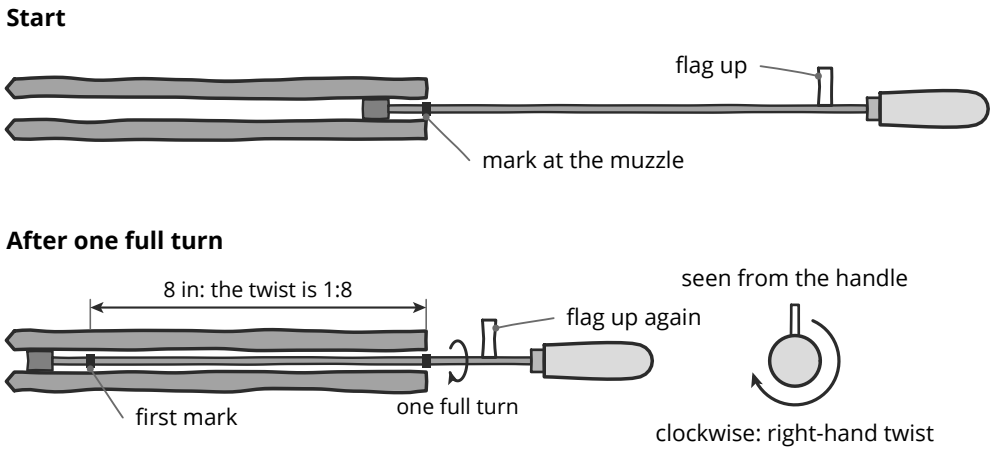


Figure 4-6. Measuring twist rate and direction with a patched rod and a flag on the rod. Seen from the handle, the rod turns clockwise in a right-hand twist.

Sight height and trajectory

The scope sits above the bore, so the line of sight and the bullet's path start apart. The bullet leaves the muzzle below the line of sight. It rises through the line of sight to its highest point and drops back through it at the zero distance. Sight height is the distance from the center of the bore to the center of the scope. It sets where the two lines cross, and every drop chart needs it. Inside the zero distance, an error in sight height can move the predicted point of impact by more than an inch.[22] Beyond the zero distance, the error grows with distance. With a 100-yard zero, it reaches about 0.9 MOA per inch of error at 1,000 yards. A drop chart trued at long range absorbs that far error. A wrong sight height then shows up at close range (see Chapter 20).

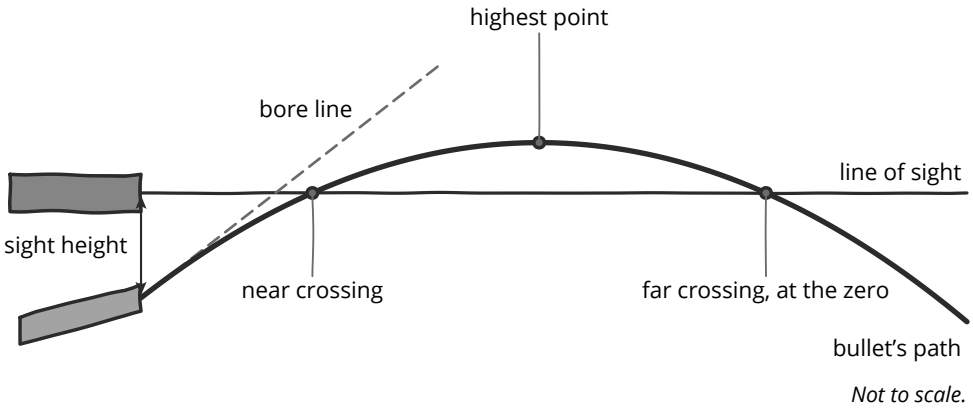


Figure 4-7. Sight height, and the line of sight crossing the bullet's path near the muzzle and again at the zero distance.

Worked example. Example numbers. Not load data.

To find sight height, use calipers that read to .001 inch. Measure the gap between the bottom of the scope's main tube and the round receiver or barrel below it. Measure that part's diameter at the same spot. Then add half of each diameter to the gap. This assumes the receiver or barrel is round and centered on the bore.

```
sight height = gap + (tube diameter ÷ 2)
                   + (receiver or barrel diameter ÷ 2)

gap                                    = .290 inch
30 mm tube = 1.181 inch, so half       = .591 inch
receiver   = 1.350 inch, so half       = .675 inch

sight height = .290 + .591 + .675      = 1.556 inch, about 1.56 inch
```


Magazine length and seating

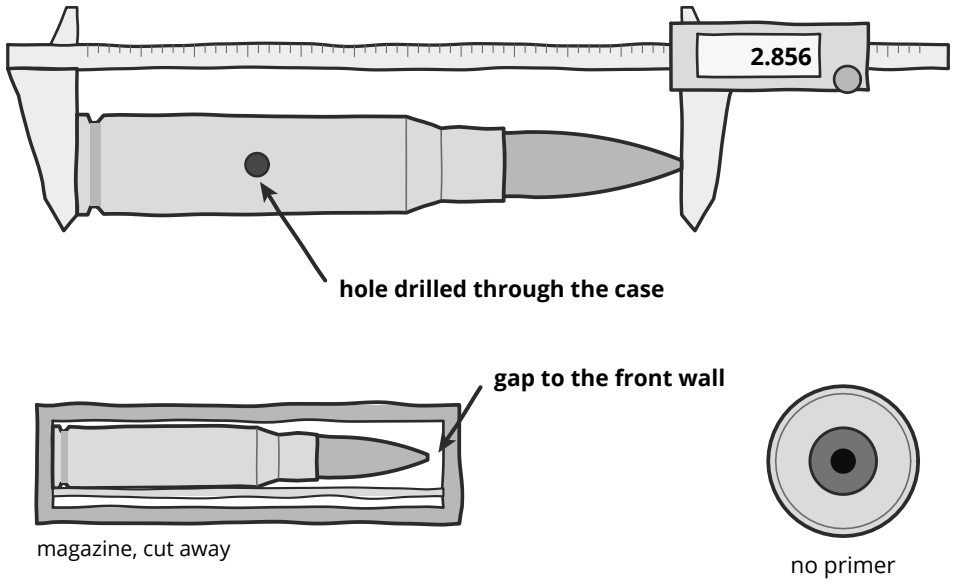
A round that feeds from a repeating rifle's magazine must fit inside it. The longest round that feeds reliably is the rifle's magazine length. It can be shorter than the cartridge's maximum COAL (cartridge overall length, measured from the case head to the bullet tip). For rounds that must feed from the magazine, magazine length caps how far out you can seat a bullet. If the lands sit beyond that limit, those bullets must jump to reach the rifling.

A repeater can also be single-fed. A round too long for the magazine can be loaded by hand, one round at a time. Some Highpower service rifle shooters do this with semi-automatic rifles (see *The Handloading Handbook*, Chapter 26). In the slow-fire stages they load each round by hand, so they seat their bullets long, past magazine length. They keep magazine-length rounds for the rapid-fire stages.

If you shoot factory ammunition, any factory round that feeds and chambers reliably already gives you a length known to fit. Measure maximum magazine length with dummy rounds *(if handloading)* once you have a seating die, sized cases, and bullets (see *The Handloading Handbook*).

1. Make dummy rounds with no primer and no powder. Mark them for good so they can never mix with live ammunition. Coloring the case or drilling a hole through the case wall works well (see Figure 4-8).
2. Seat a bullet long on purpose and try the round in the magazine. Seat the bullet deeper in small steps until the round fits inside the magazine.
3. Cycle the dummy round from the magazine through the action several times. Check that the bullet tip clears the front of the magazine without binding and that the round chambers smoothly.
4. Record the longest overall length that feeds reliably every time. That length is your magazine length.

Three limits cap how long you can load a round *(if handloading)*: magazine length (for magazine-fed rounds), distance to the lands, and neck grip. Seat the bullet at least one caliber deep in the neck so the case holds it securely. The published COAL is the lower limit. If you seat a bullet deeper than the published COAL or deeper than your tested recipe, work up the load again from the start load (see *The Handloading Handbook*). Choose an overall length between these upper and lower limits (see *The Handloading Handbook*).



Example numbers. Not load data.

Figure 4-8. A clearly marked dummy round beside the magazine, with its length measured.

Platforms: bolt-action, semi-automatic, and rimfire

Different rifle actions impose different constraints on precision, recoil control, and ammunition selection.

- **Bolt-action centerfire.** A bolt action locks the cartridge into a rigid, closed receiver with no reciprocating parts moving while the bullet travels down the bore. Manual cycling gives consistent chambering and lets you tune bullet seating length freely. Bolt actions are the standard platform for Benchrest, F-Class, PRS, and most long-range hunting.
- **Semi-automatic (gas guns and Service Rifles).** A semi-automatic rifle taps propellant gas to cycle a heavy bolt carrier group. Moving mass, gas-port timing, and automatic feeding add mechanical variables that a bolt action lacks. A free-floated handguard is essential so sling tension or bipod pressure cannot flex the barrel and shift the zero. In Highpower Service Rifle, shooters balance magazine-fed rapid-fire reliability with slow-fire single-loading precision, and verify that primers sit safely below flush to prevent slam-fires (see *The Handloading Handbook*, Chapter 26).[23]
- **Rimfire (.22 LR) precision rifles and trainers.** A bolt-action or match semi-automatic .22 LR rifle serves both as a dedicated precision competition rifle (NRL22, PRS Rimfire, smallbore) and as a low-recoil, modest-cost trainer for realistic wind-reading practice on short ranges. Because a standard-velocity .22 LR bullet leaves the muzzle around 1,050 to 1,100 fps, wind pushes it at 100 to 200 yards much like wind pushes a centerfire match bullet at 600 to 1,000 yards. Rimfire cartridges cannot be handloaded by the shooter, so ammunition selection relies on testing multiple factory brands and lot numbers to find the lot that shoots best in your specific barrel (see Chapter 12).

Factory rifles, staged upgrades, and custom actions

Precision rifles fall into four build tiers. Comparing them up front keeps you from paying twice for the same rifle.

- **Factory rifle (as-issued).** Ready to shoot out of the box at the lowest entry cost. Many shoot well enough for hunting, club matches, and learning marksmanship when paired with a reliable optic and known-good ammunition. Common limits are thin sporter barrels that heat quickly, flexible stocks, and heavier factory triggers.
- **Factory rifle with stock and trigger upgrades.** Fitting a rigid, adjustable stock or chassis and a crisp aftermarket trigger immediately improves cheek weld, length of pull, balance, and trigger break without touching the barrel. If you choose a common action footprint, these parts transfer to a custom action later.
- **Upgraded factory rifle with an aftermarket prefit barrel.** When a factory barrel wears out or limits precision, a match-grade barrel-nut or shouldered prefit brings custom-grade bore uniformity to an existing receiver. Always verify headspace with go and no-go gauges after any barrel change before firing (Safety · See Chapter 2).
- **Custom action build.** Machined to tight concentricity tolerances, usually on a standard footprint (such as the Remington 700 pattern) with an integral recoil lug, integral scope rail, smooth bolt lift, and reliable extraction. Tight receiver tolerances allow true shouldered prefit barrels you can swap at home with an action wrench and barrel vise.

Decide early: upgrade a factory rifle or buy a custom action. Tally the full cost of the finished rifle before buying your first part. Upgrading a factory rifle with a chassis, match trigger, bottom metal, rail, and prefit barrel often matches or exceeds the cost of starting with a custom action, while leaving you with a factory receiver that lacks integral features and strong resale value. If you plan to shoot a factory rifle as-is or stop at a stock and trigger, start with a factory rifle on a widely supported footprint. If you already know you want a match chassis, competition trigger, and heavy prefit barrel, buying a custom action from the start usually saves money and avoids building the same rifle twice.

Chassis and stock ergonomics

The stock or aluminum chassis links the barreled action to your body and to your support gear. A poorly fitted stock forces muscle tension into every shot, opening groups and hiding what the ammunition can do.

- **Length of pull (LOP).** LOP is the distance from the face of the trigger to the center of the buttpad. If LOP is too long, you stretch your neck and cant the rifle; if too short, your face crowds the scope ocular. Set LOP in your primary shooting position (usually prone) so your firing hand reaches the trigger straight back without strain.
- **Cheek weld (comb height).** Adjust the cheek piece so your cheekbone rests firmly on the stock with your eye naturally centered behind the scope. You should see a full, clear sight picture the moment your head settles, without craning your neck up or scrunching down.
- **Balance point and discipline stock rules.** How weight and forend shape are configured depends on the discipline. Benchrest and **F-Open** rifles (up to 22 lb, with a 3-inch flat forend riding on a coaxial mechanical front rest and an eared rear bag; muzzle brakes banned) are balanced to ride flat and track straight back in their bags. **F-TR** (F-Class Target Rifle) rifles are limited to 18.18 lb, chambered in .223 Remington or .308 Winchester,

supported by a front bipod and rear bag (muzzle brakes also banned), and balanced to recoil straight back into the shoulder. PRS and positional rifles are often weighted along the forend so the balance point sits two to four inches ahead of the magazine well. A rifle balanced there rests neutrally on a barricade bag without tipping muzzle-high or muzzle-low.

- **Mounting interfaces (Arca-Swiss and M-LOK).** A full-length Arca-Swiss dovetail rail along the bottom of the forend lets a bipod, tripod clamp, or bag rider slide quickly to the exact point needed for a barricade or terrain slope. M-LOK slots along the sides and bottom of the forend let you add internal or external weights, sling mounts, or short rail sections cleanly without clamping onto the barrel.

Rifle mass and the TOP Gun Principle

Heavy rifles are easier to shoot precisely than light rifles. More mass slows recoil velocity, reducing how far the rifle moves during the millisecond the bullet travels down the bore and making small flaws in follow-through less punishing.

The **TOP Gun Principle** (Theory of Precision) expresses this relationship as a simple rule of thumb linking a rifle's expected average group size to the ratio of cartridge muzzle kinetic energy to rifle weight:

```
Muzzle KE (ft-lbs) = (bullet_weight_gr × MV_fps²) / 450,437
Expected group size (MOA) ≈ Muzzle KE (ft-lbs) / (200 × rifle_weight_lbs)
```

Worked example. Example numbers.

Compare a 7-pound hunting rifle and a 16-pound match rifle, both firing a 140 gr bullet at 2,750 fps.

```
Muzzle KE = (140 × 2,750²) / 450,437 = 2,350 ft-lbs

7-pound rifle:  2,350 / (200 × 7)  = 1.68 MOA
16-pound rifle: 2,350 / (200 × 16) = 0.73 MOA
```

The lighter rifle carries more easily in the mountains, yet physics gives the heavier rifle a clear precision advantage with the exact same cartridge. Note that the TOP Gun Principle models centerfire recoil-limited systems and does not apply to .22 LR rimfire rifles, where recoil energy is negligible and precision is dominated by ammunition lot quality and chamber fit.

> **Evidence · Supported by data**
> Large-sample firing data across hundreds of rifles and cartridges confirms that heavier rifles firing lower-recoil cartridges consistently average smaller groups than lightweight rifles firing heavy magnums.[24] Treat the formula as a baseline expectation for multi-group average precision rather than a hard physical limit; barrel quality, ammunition consistency, and shooter skill still move any individual rifle above or below the estimate.

Bedding, rings and trigger

The action, stock, scope, and trigger work as one system, and every joint is a place where something can shift. A thin witness line of paint across each screw head onto its seat

reveals movement at a glance. Check that a free-floating barrel clears the stock along its full length under load, and record the trigger pull weight if you have a gauge.

A loose scope shows up quickly on target. If a rifle prints a 6-inch 3-shot group at 100 yards, fix the hardware or ammunition fault before testing loads; if replacing rings still leaves a 5-inch spread, the rings were not the cause. Example numbers. Not load data.

The hardware baseline

A baseline records how the rifle shoots in one fixed setup. Changing the scope, rings, stock, trigger, or muzzle device voids the baseline—never swap hardware mid-test, or you cannot tell whether the hardware or the ammunition moved the group.

1. Finish all hardware work (scope, rings, base, stock, bedding, trigger, muzzle device) before testing.
2. Torque every fastener to spec with a torque driver (see Chapter 7), mark each screw with witness paint, and record the values.
3. Log the full setup and date in the rifle record, then shoot a baseline (see Chapter 14).
4. Leave the hardware untouched until the test ends; if anything changes or shifts, close the old entry and shoot a new baseline (see Chapter 13).

Record the rifle

Record every detail in the rifle log (see Chapter 13): cartridge stamped on the barrel; barrel length, twist rate and direction, sight height, and magazine length; distance to the lands *(if handloading)* for each bullet (see *The Handloading Handbook*); barrel maker, rifling method, contour, finish, and round count; and scope, rings, base, stock, trigger, muzzle device, and torque values.

Optics and Aiming Systems

Key points

- A riflescope's most important job is holding zero and tracking repeatably, not maximum magnification.
- First Focal Plane (FFP) keeps reticle subtensions true at every power; Second Focal Plane (SFP) keeps reticle thickness constant.
- Unadjusted parallax moves the reticle relative to the target whenever your eye shifts off center.
- Match your scope's internal elevation travel and canted base (0, 20, or 30 MOA) to your cartridge's reach.

Why it matters

You cannot evaluate a cartridge or hold an accurate wind call through an optic that drifts, tracks unevenly, or induces parallax error.

How it is done

How a riflescope works

A riflescope is a precision mechanical instrument with glass inside. Its primary job is holding zero under recoil and moving the point of aim by an exact, repeatable angle when you turn the dials. Crisp glass helps you spot bullet splash and read mirage, yet bright glass cannot compensate for turrets that drift or fail to return to zero.

Six main assemblies do the work (see Figure 5-1):

- **Objective lens.** The front lens gathers light from the target and forms an inverted image at the first focal plane. Larger objective lenses gather more light and offer a wider exit pupil at high power, at the cost of extra weight and higher rings.
- **Main tube.** The outer aluminum housing—commonly 30 mm or 34 mm in diameter on precision scopes—holds the internal parts aligned. A larger tube does not transmit more light; it provides more physical room inside for the erector assembly to travel, giving greater total elevation adjustment.
- **Erector assembly.** An internal tube holding the lenses that turn the image right side up and change magnification. The elevation and windage turret screws push against the erector tube while an opposing spring pushes back. Every click pivots the erector tube by a fixed angle.
- **Ocular lens and diopter.** The rear lens assembly magnifies the reticle and image for your eye. Rotating the diopter ring focuses the reticle specifically for your vision.
- **Turrets.** Calibrated external dials marked in MIL (typically 0.1 MIL per click) or MOA (typically 1/4 or 1/8 MOA per click). Tactile, repeatable detents let you dial elevation and windage without looking away from the target.
- **Zero stop.** A mechanical collar or set-screw system inside the elevation turret that halts downward rotation right at (or slightly below) your zero distance. A zero stop lets you dial

back to zero quickly in low light or under match pressure without losing track of full revolutions.

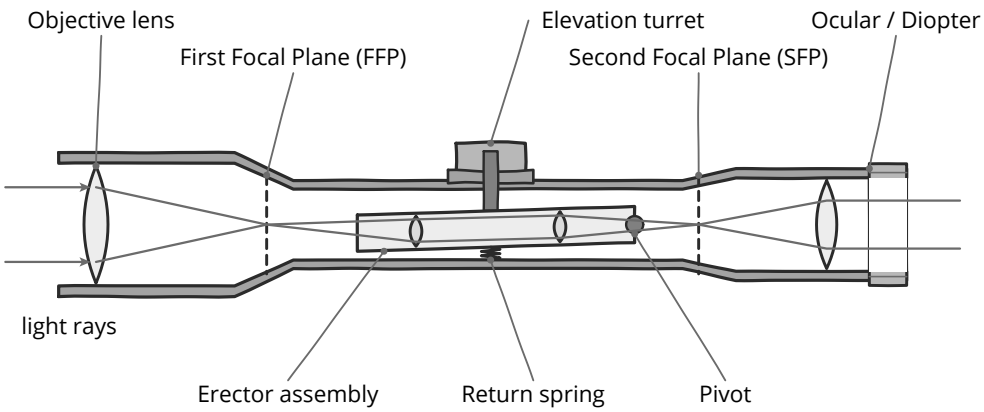


Figure 5-1. Cutaway of a variable-power riflescope showing the objective lens, first focal plane, erector assembly with elevation turret and return spring, second focal plane, and ocular lens with diopter.

Iron sights (Service Rifle context). Traditional Service Rifle and smallbore matches often use metallic aperture ("peep") sights instead of scopes. The rear sight is a small circular aperture close to the eye; the front sight is a vertical post or ring inside a protective hood. The human eye naturally centers the front sight in the brightest center of the rear aperture. Match rear sights use micrometer clicks—commonly 1/4 or 1/2 MOA—and obey the same mechanical verification rules as scope turrets.

CMP/NRA Service Rifle optics. Modern Civilian Marksmanship Program (CMP) and NRA Service Rifle rules allow riflescopes in place of iron sights, subject to strict limits: a maximum magnification of 4.5× and a maximum objective lens diameter of 34 mm. Competitors typically use either a fixed-power 4.5× scope or a 1–4.5× low-power variable optic (LPVO) with repeatable 1/4 MOA turrets and a post or simple crosshair reticle suited to round bullseye targets. Because an AR-15 upper receiver sits straight in line with the buttstock, Service Rifle scopes mount high above the bore—typically around 2.6 to 2.8 inches of sight height—which must be measured accurately and entered into any ballistic solver (see Chapter 4).

First Focal Plane (FFP) vs. Second Focal Plane (SFP)

A variable-power scope has two optical planes where the reticle can sit. Which plane the maker chooses changes how the reticle behaves when you zoom in or out.

- **First Focal Plane (FFP).** The reticle sits ahead of the magnification lenses. As you zoom in, the reticle grows in exact proportion to the target. A 1 MIL hash mark spans 1 MIL at 5x, 12x, and 25x alike. That lets you measure targets, call misses, and hold wind or elevation at any magnification without doing mental scaling. The trade-off is reticle thickness: a reticle thin enough for fine aiming at 25x can look very faint at 5x.
- **Second Focal Plane (SFP).** The reticle sits behind the magnification lenses. The target grows and shrinks as you zoom, while the reticle stays the exact same apparent thickness at every power. Because the target size changes relative to the fixed reticle, the reticle's hash marks are accurate at only one designated magnification (usually maximum power, or

a marked dot on the power ring). At half that power, every hash mark covers twice its labeled angle.

Feature	First Focal Plane (FFP)	Second Focal Plane (SFP)
Subtension accuracy	True at every magnification.	True at one calibrated magnification only.
Apparent reticle size	Scales with zoom; can look thin at low power.	Constant thickness across all powers.
Best suited for	PRS, positional matches, field shooting, varied-range hunting.	Benchrest, F-Class, known-distance target shooting.
Main watch-out	Fine reticles can fade against dark timber at low power.	Holding wind or drop at the wrong magnification causes large errors.

Reticle design

Choose a reticle that matches how you actually aim and correct shots.

- **Duplex and fine crosshair.** Thick outer bars narrow to a thin center crosshair or tiny dot. It offers an uncluttered sight picture for Benchrest, F-Class, and short-range hunting where you dial every correction or aim dead center, but it provides no built-in measuring ruler.
- **Bullet Drop Compensator (BDC).** Fixed drop marks calibrated for one assumed cartridge, muzzle velocity, and atmospheric density. BDC reticles are fast at moderate ranges, yet their marks lose accuracy as soon as your bullet, barrel length, or elevation differs from the factory assumptions.
- **MIL or MOA hash (stadia) reticle.** Evenly spaced angular marks along the vertical and horizontal axes—typically every 0.2 or 0.5 MIL, or every 1 or 2 MOA. A hash reticle works with any cartridge, any velocity, and any ballistic solver.
- **Christmas-tree (grid) reticle.** Extends a grid of windage dots below the horizontal crosshair so you can hold both elevation and wind simultaneously without touching a turret. Grid reticles shine in timed PRS stages and fast follow-up shots, though the extra markings can clutter the view when spotting subtle mirage or tiny paper bullet holes.

Parallax and eye-box discipline

Parallax is an optical error that occurs when the target's image does not fall on the exact same focal plane as the reticle. When those two planes sit apart, shifting your eye slightly off the center of the scope's exit pupil makes the reticle appear to slide across the target even though the rifle has not moved (see Figure 5-2). At 100 yards, severe unadjusted parallax can shift your point of aim by half an inch or more—enough to ruin a group test.

Remove parallax every time you change target distance:

1. Confirm the ocular diopter is already focused for your eye (see Chapter 6). Never use the parallax knob to sharpen a blurry reticle.
2. Aim at the target and turn the side-focus knob (or adjustable objective ring) until the target image looks crisp. Ignore the yardage numbers printed on the knob; they are only rough guides.
3. Rest the rifle steadily on bags so it cannot move, then bob your head slightly up, down, left, and right behind the ocular lens while watching the crosshair on the target.

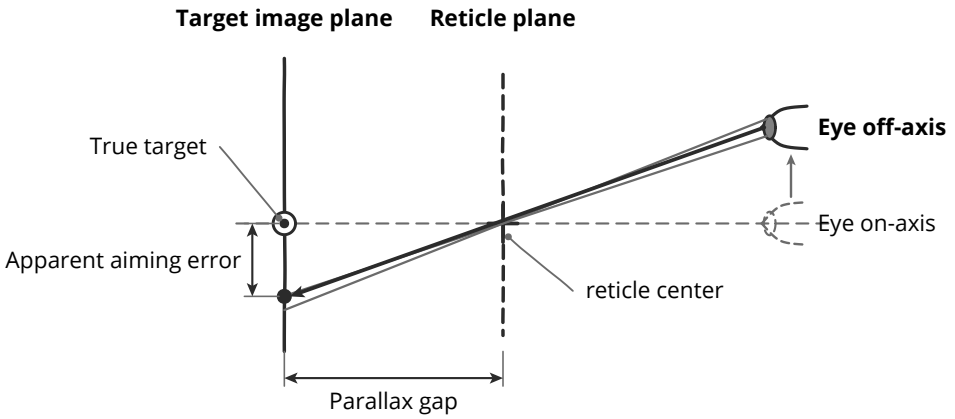


Figure 5-2. Optical parallax error. When the target image forms ahead of the reticle plane, moving the eye off-axis shifts where the reticle projects onto the target.

4. If the crosshair appears to drift across the target, adjust the parallax knob in small increments and test again until the crosshair stays pinned to one spot regardless of eye movement.

Even after parallax is removed, maintain consistent **eye-box discipline**. Center your eye behind the ocular lens so no dark crescents (scope shadow) appear around the edges of the view. A repeatable cheek weld keeps your eye centered from shot to shot.

Close-range rimfire parallax. Many centerfire scopes only focus parallax down to 50 yards, which leaves significant parallax error on close targets. NRL22 and PRS Rimfire matches routinely place targets as close as 15 to 50 yards. If you shoot rimfire precision matches, choose a scope whose side-focus or adjustable-objective parallax focuses down to 15 to 25 yards so your reticle stays pinned on small close-range targets even from awkward barricade positions.

Rings, bases, and canted rails

A scope mount must hold the optic rigidly parallel to the action and provide enough internal elevation travel for your cartridge's reach.

0 MOA versus 20 or 30 MOA bases. Every riflescope has a fixed total internal elevation travel—for example, 24 MIL (about 82 MOA). Mounted on a flat **0 MOA** base, a 100-yard zero sits roughly near the center of the erector's travel, leaving only about half the total travel (roughly 12 MIL) available to dial up for long-range shots.

A canted base—commonly **20 MOA** (about 5.8 MIL) or **30 MOA** (about 8.7 MIL)—tilts the scope downward relative to the bore. When you zero at 100 yards, the erector tube sits lower inside the main tube, freeing extra upward travel for distant targets.

Worked example. Example numbers.

A riflescope has 24.0 MIL of total internal elevation travel.

```
Flat 0 MOA base:
  Available up travel ≈ 24.0 / 2 = 12.0 MIL (12.0 MIL down remaining)
```

```
20 MOA canted base (20 / 3.438 = 5.8 MIL):
  Available up travel ≈ 12.0 + 5.8 = 17.8 MIL (6.2 MIL down remaining)

30 MOA canted base (30 / 3.438 = 8.7 MIL):
  Available up travel ≈ 12.0 + 8.7 = 20.7 MIL (3.3 MIL down remaining)
```

Do not add more base cant than your scope can absorb. If a scope has only 50 MOA of total travel (25 MOA from center to bottom), a 30 MOA rail can bottom out the erector tube before you can reach a 100-yard zero. As a rule of thumb, keep at least 3 to 5 MIL (10 to 15 MOA) of downward travel below your 100-yard zero so the erector does not press against the wall of the main tube.

Rimfire (.22 LR) canted rails. Subsonic .22 LR drops steeply past 100 yards, requiring roughly 12 to 14 MIL (42 to 48 MOA) of elevation to reach 300 yards from a 50-yard zero. Rimfire precision shooters who engage 200- to 300-yard targets commonly use **30 to 50 MOA** canted rails or mounts to keep enough upward turret travel. Keep in mind that a 50-yard .22 LR zero uses roughly 2 MIL (about 7 MOA) more downward erector travel than a 100-yard zero—so confirm your scope has enough total internal travel to zero at 50 yards on a steep rail without bottoming out the erector.

Ring height and alignment. Select the lowest ring height that clears the objective bell (with lens caps) above the barrel while giving you a relaxed, natural cheek weld. Modern one-piece mounts and CNC-machined rings on a true one-piece Picatinny rail rarely need lapping. On older two-piece bases, check alignment with machined alignment bars before clamping the scope. Tightening rings onto misaligned bases bends the main tube, binding the erector assembly and causing erratic turret tracking.

Scope Mounting, Leveling, and Mechanical Verification

Key points

- Mount the scope to your natural shooting position, not the other way around.
- Level the reticle to gravity using a plumb line; cant turns elevation into horizontal error at distance.
- Torque fasteners to spec and mark them with witness paint.
- Run a Tall Target Test to measure your scope's true click value (tracking factor) before truing a solver.

Why it matters

A 2-degree cant or a 3-percent turret tracking error looks invisible at 100 yards and causes systematic misses at 800 yards.

How it is done

Step-by-step mounting and torque

> **Safety · See Chapter 2**
> Unload the rifle, remove the magazine, and visually and physically verify the chamber is empty before mounting or adjusting an optic.

Mount the scope to your natural shooting position rather than forcing your neck to adapt to a poorly placed scope.

1. **Degrease threads and contact surfaces.** Wipe the receiver's mounting holes, base screws, and ring surfaces with isopropyl alcohol or acetone. Oil on threads acts as a lubricant and raises clamping force for a given torque reading, which can strip screws or stress the tube.
2. **Install the base or rail.** Set the rail onto the receiver and press down on each end in turn. If the rail rocks, have it bedded so tightening does not warp the action. Use blue removable threadlocker only if the maker calls for it, and follow their dry or wet torque specification. Tighten base screws evenly from the center outward with a calibrated torque driver.
3. **Seat the lower ring halves.** Place the lower rings into their Picatinny slots and push each ring firmly forward against the front shoulder of its slot while tightening the cross-bolts to spec. Pushing the rings forward prevents recoil from sliding the mount forward during firing.
4. **Set eye relief in your natural position.** Lay the scope in the lower rings and snug the top caps just tight enough that the scope can slide and rotate under gentle hand pressure. Set the scope to maximum magnification, where the eye box is tightest. Get into your primary shooting position (usually prone), close your eyes, settle your cheek

naturally on the comb, and open your eyes. Slide the scope forward or backward until you see a full, edge-to-edge sight picture with no black shadow ring.

5. **Focus the ocular diopter.** Turn the parallax knob to infinity and point the unloaded rifle at a plain overcast sky or bright blank wall. Glance through the scope for one to two seconds at a time and adjust the diopter ring until the reticle snaps into razor-sharp focus the instant your eye opens. Do not stare continuously while turning the ring; your eye muscles will strain to focus a blurry reticle and mask the true setting. Lock or witness-mark the diopter ring.
6. **Level the reticle to gravity** (see "Leveling the reticle to gravity" below).
7. **Torque the ring caps evenly.** Tighten the cap screws in an X-pattern in small alternating increments while keeping the gaps on the left and right sides of each ring equal. Stop at the scope maker's specification (commonly 15 to 20 inch-pounds). Over-torquing crushes the main tube, pinches the erector assembly, and causes erratic tracking.
8. **Apply witness paint.** Draw a thin line of paint across every base screw, cross-bolt, and ring cap screw onto its adjacent metal seat (see Chapter 4). Check those lines before every range session.

Leveling the reticle to gravity

Gravity pulls a bullet straight down toward the earth. If your reticle is canted (tilted sideways) relative to gravity, dialing elevation tilts the barrel slightly sideways as well as upward. At 100 yards, a small cant is invisible. At 800 to 1,000 yards, it walks impacts systematically off the side of the target.

Do not rely solely on laying a small level across the top elevation turret cap or wedging feeler gauges under the flat bottom of the scope saddle. Outer housings and turret caps are not always machined perfectly square to the internal reticle. Leveling the reticle directly against a gravity plumb line eliminates that error.

1. **Hang a plumb line.** Suspend a weighted string (a dark cord against a bright background, or a bright cord against a dark wall) 25 to 50 yards away so it hangs true to gravity.
2. **Level the rifle.** Clamp the unloaded rifle in a steady vise or cradle and level the action using a machined flat surface on the receiver or Picatinny rail.
3. **Align the vertical crosshair.** Look through the scope at the plumb line and rotate the scope tube until the vertical crosshair overlays the string cleanly from top to bottom.
4. **Torque and re-check.** Tighten the ring caps in small alternating steps, checking the plumb line after each pass so tightening does not roll the tube.
5. **Zero your scope bubble level.** Attach a rail- or tube-mounted anti-cant bubble level where you can see it with your non-aiming eye (or peripheral vision). Center the bubble while the reticle is locked onto the plumb line, then tighten the level mount and verify nothing shifted.

The math of cant error. When you dial elevation with a canted rifle, the bullet's drop splits into a horizontal error and a small vertical error (see Figure 6-1):

```
horizontal_error = total_drop × sin(cant_angle)
vertical_error   = total_drop × (1 − cos(cant_angle))
```

Worked example. Example numbers.

A cartridge drops 10.0 MIL (360 inches) at 1,000 yards. The shooter cants the rifle by 3 degrees (`sin(3°) = 0.0523`, `cos(3°) = 0.9986`).

```
horizontal_error = 10.0 MIL × 0.0523       = 0.52 MIL (about 18.8 inches)
vertical_error   = 10.0 MIL × (1 − 0.9986) = 0.014 MIL (about 0.5 inch)
```

A 3-degree cant—barely perceptible without a bubble level—pushes the bullet nearly 19 inches sideways at 1,000 yards, enough to miss an 18-inch steel plate cleanly.

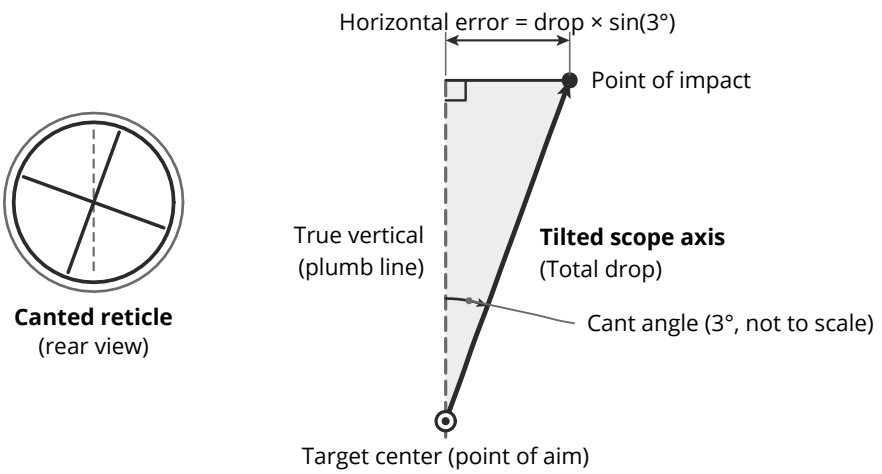


Figure 6-1. Cant geometry at distance. Dialing elevation along a vertical crosshair tilted by 3 degrees shifts the point of impact sideways by `drop × sin(3°)`.

The Tall Target Test

A scope's labeled click value (0.1 MIL or 1/4 MOA) is nominal; thread and erector tolerances commonly cause 1 to 4 percent tracking error. At 3 percent under-tracking, a 10.0 MIL dial at 1,000 yards moves only 9.7 MIL (nearly 11 inches low), which can mislead solver truing of MV or BC (see Chapter 20).

Run a **Tall Target Test** at 100 yards with a verified zero and a steady rest:

1. **Measure exact distance.** Tape or LRF-measure from the elevation turret to the target face; assuming 100.0 yards when the berm is 2 yards off adds 2 percent error.
2. **Hang a plumb tall target.** Staple a rigid target at least 40 inches tall, draw a vertical centerline, and plumb it with a level or plumb bob.
3. **Fire the lower group.** Place an aiming dot near the bottom of the plumb line, center the bubble level, and fire 3 to 5 shots at zero.
4. **Dial up and fire the upper group.** Dial **10.0 MIL** (36.00" at 100.0 yd) or **30.0 True MOA** (31.42" at 100.0 yd; 240 clicks on a **1/8 MOA** F-Class/Benchrest scope, or **20.0 True**

MOA / 160 clicks / 20.94" if travel is limited). Aim at the **same bottom dot**, center the bubble level, and fire 3 to 5 shots.

5. **Verify return to zero.** Dial back to zero and fire 3 shots at the bottom dot; if they do not overlap the first group, the erector is sticking or the mount is slipping.
6. **Measure the shift.** Measure the vertical distance (`actual_shift`) between lower and upper group centers along the plumb line, plus any sideways offset (`horizontal_drift`).

Compute the expected shift, the **tracking factor**, and any residual **cant angle**:

```
expected_shift (in) = dialed_MIL × 3.6 × (distance_yd / 100)
expected_shift (in) = dialed_True_MOA × 1.0472 × (distance_yd / 100)

tracking_factor = actual_shift / expected_shift
corrected_dial  = desired_correction / tracking_factor
cant_angle (deg) = arctan(horizontal_drift / actual_shift)
```

Worked example. Example numbers.

At a tape-measured distance of 100.0 yards, you dial up 10.0 MIL. The upper group center measures 34.92 inches above the lower group center and 0.60 inch to the right of the plumb line.

```
expected_shift  = 10.0 × 3.6 × (100.0 / 100) = 36.00 inches
tracking_factor = 34.92 / 36.00              = 0.970 (3.0% under-tracking)
cant_angle      = arctan(0.60 / 34.92)       = 0.98 degrees (about 1°)
```

For a 9.0 MIL solver drop, divide by the tracking factor: `9.0 / 0.970 = 9.28 MIL` (dial 9.3 MIL). If cant exceeds 1 degree, re-check reticle and bubble-level alignment.

Rimfire (.22 LR) at 50 yards. Subsonic .22 LR wind drift at 100 yards can blur group centers and cant checks. Run the same test at a tape-measured **50.0 yards**, where **10.0 MIL** equals **18.00 inches** and **30.0 True MOA** equals **15.71 inches**—cutting wind error and backer height while still testing full erector travel.

EASIER ON EP · FIREARMS · RIFLE PROFILES

Firearms stores your scope's measured tracking factor so Varytita applies it to every drop solution.

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Chapter 7

Range and Field Equipment

Key points

- Every chronograph adds its own noise to each reading. A noisy unit can hide a real difference between loads.
- For load testing, prefer Doppler radar. Light and weather do not affect it.
- A barrel-mounted magnetic unit can shift point of impact. Test it before you shoot groups with it on.
- A steady rest keeps the shooter out of the groups. A spotting scope or a target camera pairs each hole with its reading.
- A pocket weather meter and a thermometer in the ammunition box record the conditions that move velocity and drop.

Why it matters

You judge every load by the data you collect at the range. Your range gear decides how much of each result comes from the load and how much comes from outside noise. A noisy chronograph blurs the velocity spread. An unsteady rest blurs the group.

Conditions you cannot control still have to be recorded. Air temperature, station pressure and ammunition temperature all change from one range trip to the next. Readings taken at every session let you see their effect later.

How it is done

Chronographs

Velocity data is only as good as the instrument. Every chronograph adds its own error to each reading. That error adds to the true spread of your ammunition. The two combine like the sides of a right triangle.

$$\text{measured SD} = \sqrt{(\text{true SD}^2 + \text{instrument SD}^2)}$$

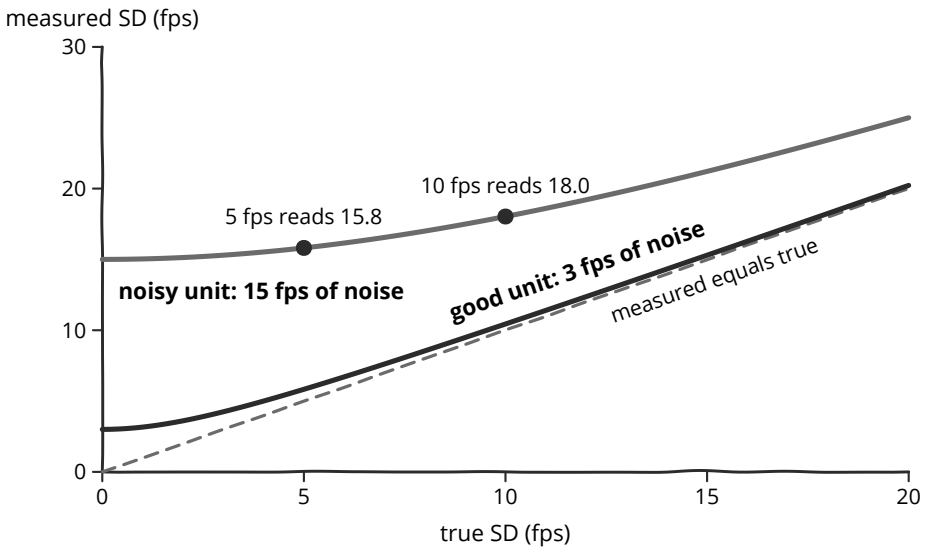
For example, ammunition with a true SD of 5 fps shows 15.8 fps when read through 15 fps of instrument noise.[1]

Worked example. Example numbers. Not load data.

Your load has a true SD of 10 fps.

$$\text{Noisy unit, 15 fps of noise: } \sqrt{(10^2 + 15^2)} = \sqrt{325} = 18.0 \text{ fps}$$
$$\text{Good unit, 3 fps of noise: } \sqrt{(10^2 + 3^2)} = \sqrt{109} = 10.4 \text{ fps}$$

Through the noisy unit, a 5 fps load reads 15.8 fps and a 10 fps load reads 18.0 fps. The true SD doubled, but the reading moved about 2 fps. A noisy chronograph cannot tell a good load from an ordinary one (see Figure 7-1).



Example numbers. Not load data.

Figure 7-1. Measured SD against true SD for two chronographs. The noisy unit hides the difference between good and ordinary ammunition.

If you know your instrument's noise, you can take it back out.

```
true SD = √(measured SD² − instrument SD²)
Example: √(12² − 3²) = √135 = 11.6 fps
```

Use this only with a noise figure you trust. A guessed figure gives a guessed answer.

There are three common chronograph types used in precision shooting. For load testing, prefer Doppler radar.

Type	How it reads	Practical considerations
Doppler radar	Tracks the bullet by radar from beside the muzzle	Points along the bullet's path. Light and weather do not affect it.
Optical	The bullet passes over light sensors in front of the muzzle	Sunlight, cloud shadows, poor alignment and muzzle blast all change readings.
Magnetic	Senses the bullet from a bayonet mounted on the barrel	Hangs extra weight off the barrel.

A barrel-mounted magnetic unit can shift your point of impact and change barrel harmonics and group size. The effect varies from rifle to rifle.[2] You can leave the unit on during a work-up, because a work-up checks velocity, not group size. Before you shoot groups with a barrel-mounted unit attached, test the rifle with the unit on and off in interleaved strings (see Chapter 16, "Testing any claim yourself").[3] Until you prove it does not change your groups, remove it for group shooting and chronograph separate strings. When you shoot groups and velocities in separate strings, you cannot pair each bullet hole with its velocity to check vertical spread against speed (see Chapter 24).

Evidence · Supported by data
In one test, optical units with screens less than 2 feet apart had average errors of 13 to 55 fps. An average error moves a drop chart and the charge at which you reach the velocity ceiling, not the SD. Two of those units added only about 4 fps of noise, and the other two added far more.[1] In another test, two Doppler units agreed within about 1 to 5 fps.[4]

Set up and check the unit at every session (see Chapter 14).

Rests, bags, tripods, and slings

A steady support isolates the rifle and ammunition from shooter wobble. Match your support gear to the job you are doing—pure cartridge evaluation demands different hardware than positional match shooting.

- **Benchrest front rests and rear bags.** A heavy cast-iron or aluminum pedestal front rest with a coaxial or windage-adjustable top, paired with a heavy sand-filled rabbit-ear rear bag, lets the rifle ride straight back under recoil with minimal shooter input. This is the cleanest setup on a shooting bench for testing ammunition dispersion and comparing loads (see Chapter 14).
- **Bipods.** A bipod mounts to the forend via a swivel stud, Picatinny rail, or Arca-Swiss clamp and supports the front of the rifle in prone and field positions. Look for rigid legs with minimal play, a cant lock you can tighten easily, and interchangeable feet (rubber for concrete benches, spiked or clawed feet for dirt and grass). Load the bipod forward lightly and consistently so the rifle recoils straight back rather than hopping sideways (see Chapter 8).
- **Rear bags and barricade bags.** In prone shooting, a compressible rear squeeze bag under the toe of the stock lets your support hand adjust elevation smoothly without muscling the rifle. For PRS stages and hunting over natural cover, a flat or waxed-canvas barricade bag filled with heavy sand or polymer beads drapes over fence posts, boulders, or props, absorbing vibration and giving a dead, non-bouncing platform (see Chapter 9).
- **Tripods.** A sturdy carbon-fiber or aluminum tripod fitted with a ball head or leveling base and an Arca-Swiss clamp lets you shoot standing, kneeling, or seated over tall grass and uneven terrain. The same tripod stabilizes spotting scopes, binoculars, and laser rangefinders for steady long-range observation.
- **Service Rifle slings.** In Highpower Service Rifle and traditional positional matches, a leather or web loop sling links your upper support arm to the forend swivel, transferring the rifle's weight onto bone structure rather than muscle. Use a free-floated handguard so tight sling tension cannot bend the barrel and shift your zero.

Spotting scopes and target cameras

A spotting scope or target camera lets you see each bullet hole from the firing line. Use it to match each impact on paper with its chronograph reading in your log (see Chapter 14). If you call a bad shot, write down your call before you look at the target (see Chapter 15).

Laser rangefinders

An accurate distance is essential before you dial elevation, especially past 400 yards where a 20-yard range error can cause a clean miss. A laser rangefinder (LRF) emits pulses of infrared light and times their return to calculate distance.

Every LRF has **beam divergence**—the beam widens into a rectangle or oval, commonly 1 to 3 MIL wide by 0.5 to 1.5 MIL tall (6 feet wide at 1,000 yards for a 2 MIL beam). Overlapping foreground brush or a background hillside can return a false distance.

- **Brace the unit.** Rest the rangefinder on a tripod, shooting bag, or rifle forend when ranging small targets past 500 yards. Handheld wobble spreads the beam across background terrain.
- **Know your beam alignment.** The beam may not sit dead center in the aiming box; sweep slowly across an isolated pole or sign at 300 to 500 yards from all four sides to map where it triggers.
- **Verify suspect readings.** Take three readings on the target and compare them. If readings jump between two distances, switch to near/first-target mode if available, or cross-check the distance by milling the target with your scope reticle (see Chapter 11).

Weather meters, pressure, and density altitude

A pocket weather meter records the air conditions that control aerodynamic drag and bullet drop (see Chapter 14 and Chapter 19).

- **Station vs. barometric pressure. Station pressure** is the actual uncorrected pressure where you stand, dropping with altitude to reflect true air density. **Barometric pressure** (from airports and forecasts) is adjusted to sea level. Mixing the two in a ballistic solver causes large high-altitude elevation errors (see Chapter 20); always match meter and solver pressure modes.
- **Density altitude (DA).** DA combines station pressure, temperature, and humidity into one standard-atmosphere altitude: high DA (hot, high, low pressure) means thinner air and less drop; low DA (cold, low, high pressure) means denser air and more drop. DA suits printed range cards, though raw inputs are more exact in a solver.
- **Ammunition temperature.** Air temperature moves drag, while powder temperature moves muzzle velocity. Keep your test ammunition in an insulated box with a thermometer inside, and log its temperature at every session (see Chapter 23).

Torque drivers, witness paint and scope levels

A torque driver sets fasteners to spec, and a paint-pen witness line across each screw head onto its seat shows instantly if a screw turns—keeping the hardware baseline fixed (see Chapter 4). Level the reticle to a plumb line at mounting, then check the scope level on every shot (see Chapters 6 and 20).

Part III

Marksmanship, Zeroing, and Fieldcraft

Chapter 8. Fundamentals of Precision Marksmanship 43
Chapter 9. Alternate and Positional Shooting 47
Chapter 10. Zeroing, Spotting, and Shot Calling 52
Chapter 11. Estimating Range, Wind, and Angles 57

Fundamentals of Precision Marksmanship

Key points

- Stable positions rely on bone support and rifle fit, not muscle tension.
- Natural Point of Aim (NPOA) keeps the rifle returning to the target without muscling.
- Straight-line recoil management lets you stay in the scope and spot your own impacts.
- Clean trigger control breaks the shot without disturbing sight alignment.

Why it matters

Every shot on paper records three sources of dispersion at once: the rifle, the ammunition, and the shooter. If shooter error is larger than rifle and ammunition dispersion, group testing measures your hold instead of your load. Sound fundamentals shrink human dispersion until the target reflects the rifle system.

How it is done

Precision marksmanship is repeatable mechanics. Build a position that holds the rifle without strain, align your eye behind the optic, press the trigger straight back, and manage recoil straight to the rear.

Building a stable prone and bench position

Muscles fatigue and tremble under load. Bones do not. Every stable shooting position routes the weight of the rifle through your skeletal frame and your support gear into the ground or the shooting bench.

Start with rifle fit before you fire a round. Adjust the length of pull so your trigger finger reaches the trigger face comfortably without stretching your wrist or crowding your shoulder. Adjust the comb height so your cheek rests firmly on the stock while your eye lands directly behind the center of the scope (see Chapter 4).

> **Safety · See Chapter 2**
> Verify that the scope has proper eye relief for your position before firing live ammunition. Prone shooting moves your head closer to the eyepiece than sitting at a shooting bench. Insufficient eye relief causes recoil to drive the eyepiece into your brow.

Straight-behind-the-rifle alignment. Lie flat behind the rifle in the prone position so your spine runs straight along the line of the bore. Spread your legs comfortably with your heels flat or toes turned outward to relax your lower back and glutes. Do not angle your torso sharply to the side unless heavy recoil or terrain forces a bladed stance. When your body lies straight behind the bore, recoil pushes straight back into your shoulder pocket instead of twisting the rifle sideways.

Place the buttpad squarely in the pocket of your shoulder, inboard of the shoulder joint and below the collarbone. Keep both shoulders level with the ground. Your non-firing hand manages the rear bag, squeezing or shifting it to raise or lower the muzzle without straining your firing arm.

Natural Point of Aim (NPOA). A rifle held on target by muscle tension springs back toward its resting line the instant recoil breaks your hold. That spring-back shifts the bullet off target before it clears the muzzle. Check your NPOA before every string:

1. Build your prone or shooting-bench position and settle the reticle on the center of the target.
2. Close your eyes for two to three seconds. Take a normal breath and let it out naturally.
3. Open your eyes and see where the reticle rests.
4. If the reticle drifted left or right, shift your hips and legs slightly in the opposite direction while keeping the bipod or front rest planted. If it drifted high or low, adjust your rear bag height or slide your body slightly forward or back.
5. Repeat until you can close your eyes, breathe, open your eyes, and find the reticle still centered on the target with zero muscular effort.

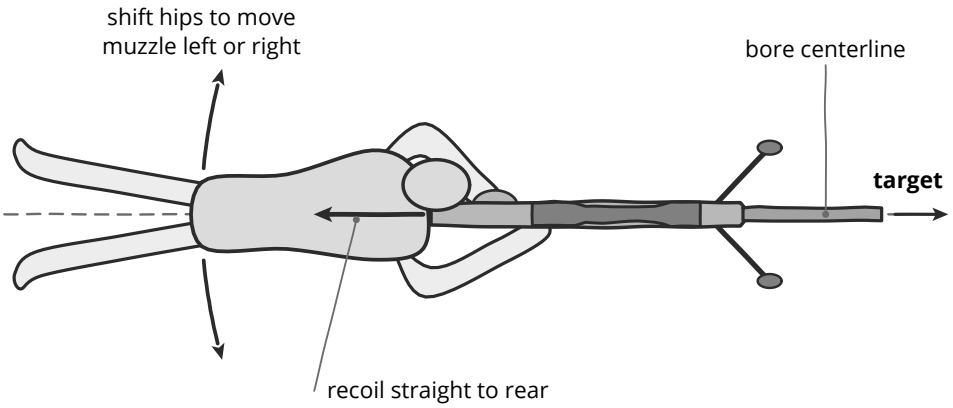


Figure 8-1. Overhead view of a prone shooter aligned straight behind the bore, showing straight-line recoil transfer and hip-shift corrections for Natural Point of Aim.

Shooting-bench setup. At a shooting bench, sit squarely behind the rifle rather than twisting sideways across the tabletop. Keep your chest off the sharp edge of the tabletop if it transmits your heartbeat into the rifle. Set the stool height so your elbows rest evenly on the shooting bench without hunching your shoulders.

Free recoil versus pinned and loaded bipod. Precision disciplines manage rifle contact in two distinct ways, depending on rifle weight, recoil, and support gear:

- **Free recoil and bag riding (Benchrest and F-Open).** Heavy Benchrest rifles and **F-Open** rifles ride on a wide, flat-bottomed forend (typically 3 inches wide) in a coaxial mechanical front rest and a heavy sand-filled rear bag with tall ears (no muzzle brake is allowed in F-Class). The rifle is balanced so it tracks straight back through the bags under recoil. Benchrest shooters often shoot pure free recoil—avoiding shoulder or cheek contact and touching only a very light trigger with the fingertip—while F-Open shooters use either free recoil or very light, consistent shoulder contact to manage heavier cartridges.

  Setting up a rifle to track cleanly in bags requires deliberate alignment. Position the front-rest forend stop so the rifle returns to the exact same longitudinal index after every shot, and adjust front-bag clamping and rear-bag ear tension so the stock glides smoothly without binding or rocking. Before firing, perform a **bag-tracking check**: center the crosshair on the target, then slide the rifle gently back and forth about two inches in the

bags while watching the reticle. If the crosshair climbs, drops, or drifts sideways during the slide, re-level the rest, square the rear bag to the line of fire, or adjust ear fill until the reticle tracks straight vertically without cant or hop. Standard sporter and tactical chassis stocks—with rounded forends, angled buttstocks, and higher recoil-to-weight ratios—rarely slide flat in bags and usually shoot far better when pinned firmly into the shoulder.

- **Pinned rifle and loaded bipod (F-TR, PRS, and field prone). F-TR** (F-Class Target Rifle) rifles shoot from a front bipod and rear bag with no muzzle brake, while practical precision and hunting rifles shoot from bipods, packs, or props rather than flat mechanical rests. A bipod has small amounts of mechanical play in its joints and feet. Before breaking the shot, lean your weight forward slightly into the rifle until the bipod legs take up all slack and stop moving. That steady forward pressure is called loading the bipod. It prevents the bipod feet from hopping backward and upward at ignition. Pair a steady bipod load with firm, consistent shoulder-pocket pressure and a hand on the rear bag.

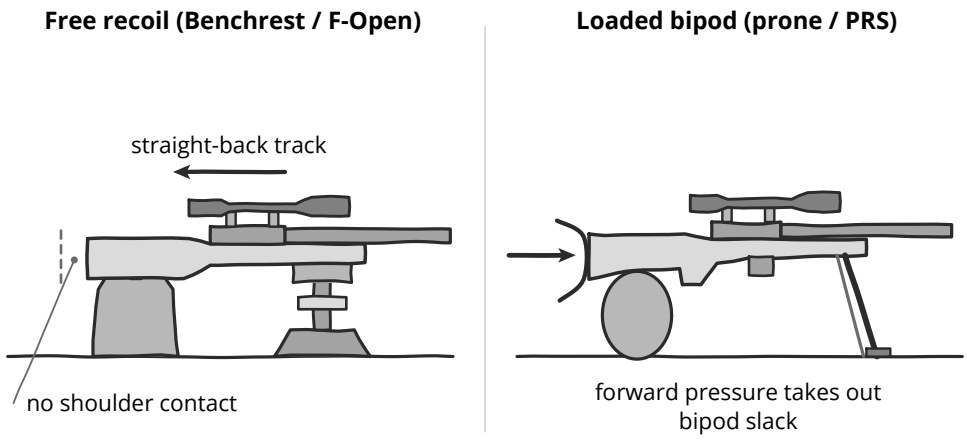


Figure 8-2. Side-by-side comparison of a free-recoil Benchrest setup on flat-tracking bags and a loaded-bipod prone setup with forward shoulder pressure.

Evidence · Plausible but unproven
Shooters often debate whether light shoulder pressure or heavy shoulder pressure produces tighter groups from a bipod. Controlled data separating hold weight across rifle weights and calibers is scarce. What matters most is keeping your shoulder pressure, bipod load, and rear-bag tension identical from shot to shot so the rifle recoils the same way every time.

Sight picture, breathing, and trigger control

Keep head position, breathing, and trigger press consistent so nothing disturbs alignment before the bullet clears the bore.

Cheek weld and eye box. Rest your cheek on the same comb spot with light, consistent pressure, looking straight through the scope's center for a full, shadow-free image. A dark crescent shadow means your eye is off-axis, adding parallax error if side focus is imperfect (see Chapters 5 and 6). Keep your head upright so cant is easy to judge.

Natural respiratory pause. Breathing moves the muzzle vertically and causes vertical stringing. Take a normal breath, exhale naturally, and break the shot during the relaxed

two- to four-second pause at the bottom of the exhale. Never force air out or hold your breath until your pulse thumps the reticle; if not settled within four seconds, breathe again.

Straight-back trigger control. Center the pad of your index finger on the trigger face with a small air gap beside the stock so finger motion cannot push it sideways. Keep the firing hand relaxed—squeezing the grip pulls the muzzle off target—and press straight rearward along the bore.

- **Single-stage:** Build steady rearward pressure until the sear breaks without anticipating the shot.
- **Two-stage:** Take up the lighter first stage to the stop, confirm sight picture, and press steadily through the break.

Follow-through. Several milliseconds pass between sear release and muzzle exit; lifting your head, relaxing your shoulder, or releasing the trigger early shifts impact. Keep the trigger pinned, cheek planted, and eye in the scope until recoil finishes and the rifle settles, then reset and cycle.

Recoil management and self-spotting

Self-spotting through the scope shows immediately whether a miss came from wind, elevation, or a poor break, allowing instant corrections without waiting on a spotter.

Staying in the scope. With straight-behind alignment and a square shoulder pocket, recoil lifts the reticle straight up and drops it back on target. A sharp jump up and right (for right-handed shooters) signals alignment, bipod-load, or grip-tension errors.

Keep your cheek on the comb rather than peeking over the scope. If recoil throws the target out of view, lower magnification—10x to 15x gives a wider field of view than 24x+ and makes spotting far easier. A muzzle brake, suppressor (see Chapter 4), or heavier rifle also cuts recoil velocity and muzzle jump.

Observing trace and splash. Staying in the scope at medium and long range reveals two cues:

- **Bullet trace:** The faint parabolic shimmer of disturbed air along the bullet's arc, clearest in bright light with mild humidity against a dark, uniform background.
- **Impact splash:** The puff of dirt, gravel spray, or steel paint flake on impact. Read the base of the splash where the bullet struck, not the dust drifting downwind (see Chapter 10).

Chapter 9

Alternate and Positional Shooting

Key points

- Positional shooting trades raw stability for speed and field adaptability.
- Triangulate support using slings, bags, packs, barricades, and tripods to shrink your wobble zone.
- Never rest a bare barrel directly on a hard prop; pad the forend to prevent recoil hop and zero shift.
- Dry-fire practice isolates trigger and position faults without burning barrel life.

Why it matters

Matches (PRS, Service Rifle) and ethical hunting rarely offer a flat concrete shooting bench or a level firing point. Every step off the ground raises your center of gravity and widens your wobble zone. Measuring and shrinking positional wobble tells you what targets you can hit reliably and expands your practical effective range.

How it is done

Positional shooting follows the same rules as prone shooting: use bone support instead of muscle, build triangles of contact, and accept your natural wobble instead of snatching the trigger.

Sitting, kneeling, and standing

Unsupported and sling-supported field positions follow a clear stability order: prone is most stable, followed by sitting, kneeling, and standing. Choose the lowest position that lets you clear grass, brush, and terrain while keeping a clean view of the target.

Sitting. Sitting provides a wide, low base with two contact points on the ground (your hips and feet) and two contact points supporting the rifle (both arms on your legs). Common variations include crossed-ankle, crossed-leg, and open-leg sitting. In every variation, avoid placing the bony point of your elbow directly on the bony tip of your kneecap. Bone-on-bone point contact rolls and wobbles. Instead, place the flat of your upper arm or triceps just behind the elbow against the flat inside of your shin or thigh, or rest your forearm across the top of your knee. Lean slightly forward so your torso weight locks the position into the ground.

Kneeling. Kneeling gets you above tall grass faster than sitting. In low kneeling, sit back on the heel or side of your rear boot while your support foot sits flat on the ground in front of you. Place the flat of your support arm just forward of your kneecap so the arm locks over the leg without bone-on-bone rolling. High kneeling (hips raised off the rear heel) is quicker to enter and higher for clearing obstacles, but it introduces much more horizontal sway.

Standing (offhand). Standing removes all lower-body bracing and leaves the largest wobble zone. Turn your body roughly 60 to 90 degrees off the target line (a bladed stance) with your feet about shoulder-width apart. Tuck your support elbow tightly against your

ribcage or hip so your forearm forms a vertical bone column under the forend. Shift your hips slightly toward the target to counterbalance the rifle's weight.

In standing, the reticle will never stop moving completely. Do not try to ambush the bullseye by jerking the trigger as the reticle flashes past center. Instead, settle into your natural wobble zone centered on the target, build steady rearward trigger pressure while the reticle drifts inside the scoring zone, and let the shot break smoothly.

Service Rifle sling support. A properly fitted loop sling turns your support arm, torso, and rifle into a rigid triangle. Put the sling loop high on your upper arm, above the bicep and tight enough that it cannot slip down toward the elbow. Twist the sling so it lies flat across the back of your support hand, then adjust the length until the sling carries the weight of the rifle without your bicep doing the work. Check your NPOA by closing your eyes and relaxing; adjust your whole body if the reticle settles off target.

For quick field shots where a loop sling is too slow, a hasty sling (wrapping the support arm once around a standard carry strap and pulling it snug against the back of the hand) adds meaningful stability in a few seconds.

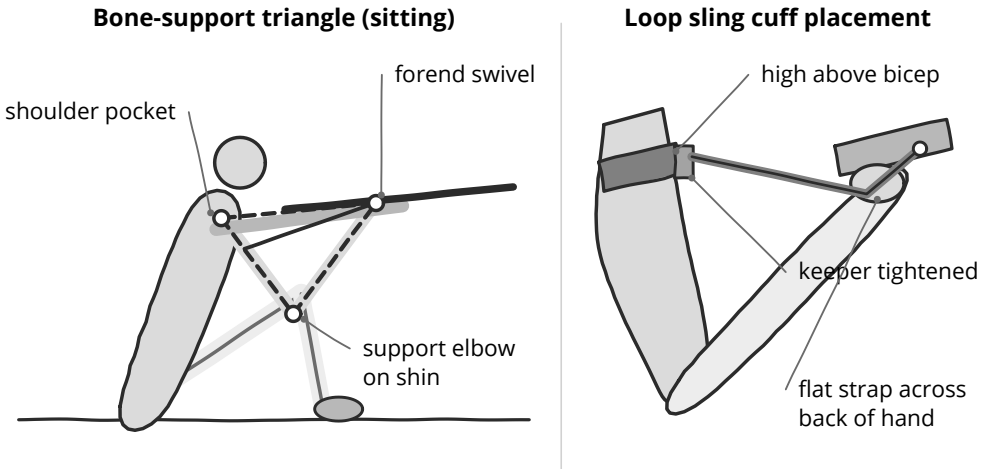


Figure 9-1. Bone-support triangles in sitting and kneeling positions, with a detail view of a Service Rifle loop sling seated high on the upper arm.

Rapid-fire positional cadence

Across-the-Course Highpower Service Rifle matches test your ability to drop from standing into a sling-supported position, verify NPOA, execute a clean reload under the clock, and fire 10 aimed shots without rushing the trigger:

- **200-yard rapid-fire sitting:** Start standing with a loaded 2-round magazine, drop into sitting (or kneeling), fire 2 rounds, reload an 8-round magazine, and fire the remaining 8 rounds—10 rounds total in **60 seconds**.
- **300-yard rapid-fire prone:** Start standing with a 2-round magazine, drop into prone, fire 2 rounds, reload an 8-round magazine, and fire the remaining 8 rounds—10 rounds total in **70 seconds**.

Consistency under time pressure comes from mechanical preparation rather than frantic speed. Before the command to load, pre-set your loop sling on your upper arm and index

your foot or mat placement so your body lands aligned with the target. Drop smoothly into position, take a brief beat to check NPOA and shift your hips if needed, and break the first 2 shots cleanly. Execute the 2+8 reload without breaking your support-elbow anchor or sling tension, re-acquire your sight picture, and settle into an even rhythm of roughly one shot every 3 to 4 seconds. Dry-firing the full drop, NPOA check, and 2+8 reload sequence builds a repeatable cadence that leaves 10 to 15 seconds to spare.

Barricades, props, packs, and tripods

Practical precision matches and field hunts often let you rest the rifle on a fence post, roof ridge, rock, tank trap, pack, or tripod. A prop improves stability only if you build a solid structure around it.

Building triangles of support. A rifle resting only on a front barricade pivots like a seesaw. Every twitch of your firing shoulder moves the muzzle. Add a second point of contact whenever time and terrain allow:

- Rest your firing elbow on a knee, hip, or lower rail of the barricade.
- Trap a rear bag between the buttstock and a lower prop surface, or between your firing arm and ribcage.
- Run a sling under tension from the forend to your body or foot to pull the rifle down into the prop.

Each added support point closes a triangle and shrinks your wobble zone.

Managing bag fill. A shooting bag bridges the gap between a hard, irregular prop and the rifle's forend. Heavy, dense fills (such as sand or fine glass beads) conform tightly to sharp edges and absorb recoil energy, reducing bounce. Lighter fills (such as polymer pellets) save weight when carrying gear in the mountains, though they shift slightly more under recoil.

Do not overfill a barricade bag until it feels like a hard brick. A bag filled to roughly 75 to 85 percent capacity drapes over rails, branches, and angled boards, forming a flat, wide shelf for the rifle stock to settle into.

Minimizing recoil hop on awkward props. Never rest a bare barrel directly on wood, steel, rock, or a hard pack frame. A barrel vibrates during firing and bounces sharply away from a hard contact point, causing erratic point-of-impact shifts and vertical stringing. Always keep the stock forend, or a padded bag between the stock and the prop, as the sole contact point.

Align your body as straight behind the rifle as the prop permits. Avoid leaning your full body weight sideways into an unstable barricade or pushing hard forward on a loose fence rail. Let the rifle's weight settle naturally into the bag, build even cheek and shoulder contact, and press the trigger straight back.

Packs and tripods. A firm field pack laid flat on the ground works well as an improvised prone or seated front rest. Cinch the straps tight so the pack does not roll under recoil, and rest the rifle's forend, never the barrel, across the center of the pack.

A sturdy tripod lets you shoot cleanly from standing, kneeling, or seated positions over tall brush or across steep slopes. You can clamp the rifle directly into a tripod head using a rail

adapter or saddle, or rest a flat support bag on top of a wide tripod platform. Set the tripod legs wide enough for stability, and point one leg directly toward the target so it braces straight against rearward recoil. Hang your pack lightly from the center hook only if wind is not swinging the pack like a pendulum.

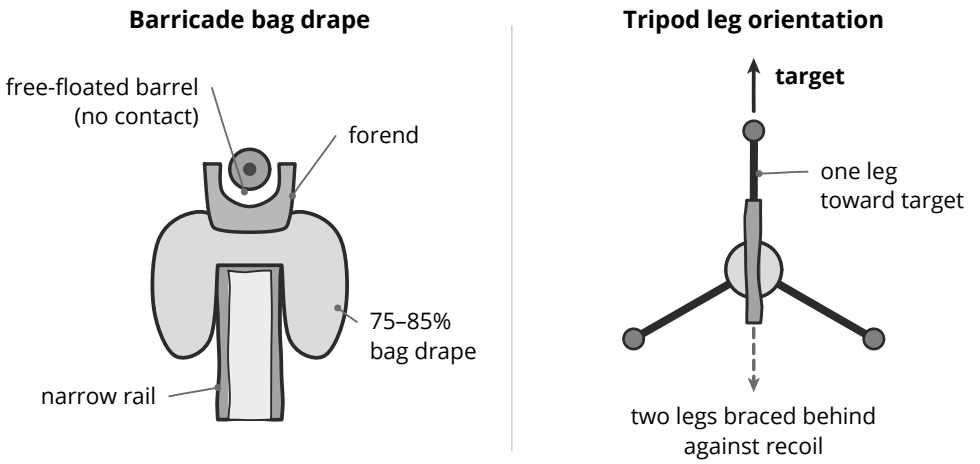


Figure 9-2. Proper barricade bag drape under a rifle forend and tripod leg orientation with one leg pointed toward the target.

Dry-fire diagnostic protocols

Dry fire lets you test your position, trigger press, and wobble zone hundreds of times at zero ammunition cost and zero barrel wear.

> **Safety · See Chapter 2**
> Before every dry-fire session, remove the magazine, open the action, and physically and visually inspect the chamber to confirm the rifle is empty. Remove all live ammunition from the room or shooting bench. Point the muzzle only at a safe backstop that can stop a bullet. On rimfire rifles, use an inert snap cap or dry-fire block if the maker warns that dry-firing on an empty chamber can peen the breech face.

Use four structured protocols to diagnose specific faults:

1. **NPOA and reticle settle check.** Build your prone, sitting, kneeling, or barricade position on a small, high-contrast aim point (such as a 1-inch dot on a wall or a downrange target). Close your eyes, exhale to your natural respiratory pause, and open your eyes. If the reticle moved off the dot, adjust your body or support gear, not your arms, until it returns to the dot automatically.
2. **Trigger break isolation.** Watch the reticle closely as you press the trigger through the break. In a clean break, the reticle does not twitch when the firing pin falls. A twitch down and left (for a right-handed shooter) usually signals anticipation (flinch) or tightening the whole firing hand. A twitch right or left signals side pressure from the trigger finger or a loose rear bag. Repeat until ten consecutive dry breaks show zero reticle jump.
3. **Wobble-zone measurement.** Get into a positional hold (sitting, kneeling, standing, or on a barricade) and look through your scope at a target of known distance or a scaled

dry-fire target. Use your reticle's MIL or MOA hash marks to measure the full width and height of your reticle's movement during your natural respiratory pause. Record that angular wobble diameter in your log (see Chapter 13). Comparing your measured wobble zone to the angular size of a target tells you honestly whether a shot is high-percentage or a gamble (see Chapter 21).

4. **Ball-and-dummy live-fire check.** At the range, have a partner mix one inert dummy round randomly into a magazine of live rounds (or single-feed rounds into the chamber without letting you see which one is inert). Fire the string normally. When the firing pin clicks on the dummy round instead of firing, any flinch, shoulder dip, or blink shows up immediately in the scope.

Evidence · Supported by data
Dry-fire diagnostics and ball-and-dummy drills separate mechanical rifle dispersion from shooter-induced trigger and flinch errors. Tracking positional wobble in angular units gives an objective measure of positional skill before live ammunition is fired.[1]

Zeroing, Spotting, and Shot Calling

Key points

- A three-shot zero leaves large mean-point-of-impact uncertainty; verify zero with 5 to 10 shots.
- Distinguish cold-bore shots from cold-clean-bore shots and measure any shift with repeated sessions.
- Calling your own shot before impact separates shooter error from wind or ammunition error.
- Give spotter corrections in angular units (MIL or MOA), never linear inches.

Why it matters

Every ballistic table and drop chart assumes your zero is centered on the aim point at your zero distance. An off-center zero does not average out downrange. A 0.3 MIL zero error at 100 yards remains a 0.3 MIL bias at 600 yards and 1,000 yards, shifting your entire group off the edge of the target before wind or drag even act.

How it is done

Zeroing is a two-step job: get on paper mechanically, then center the mean point of impact statistically so you do not chase random noise.

Bore-sighting and mechanical zero

Bore-sighting aligns the scope closely enough to the bore that your first live shot lands on paper.

> **Safety · See Chapter 2**
> Confirm the rifle is completely unloaded before looking through the bore or inserting any bore-sighting tool. If you use a muzzle-mounted laser or optical bore-sighter, remove the arbor from the muzzle before chambering any ammunition. Firing a round with a bore-sighter left in the barrel causes a bore obstruction and catastrophic barrel damage.

Optical bore-sighting (bolt-action rifles). Place the rifle firmly in sandbags or a rest at the range, pointed at a large target at 50 or 100 yards. Remove the bolt. Look straight through the rear of the receiver and down the bore, shifting the bags until the target sits centered in the circular opening of the muzzle. Without bumping the rifle, look through the scope and dial the elevation and windage turrets until the reticle centers on the same target. Reinstall the bolt.

Semi-automatic rifles. Where the receiver design prevents looking straight through the bore, use a chamber-inserted laser cartridge, a muzzle collimator (removed immediately after alignment), or fire your first check shot at 25 yards on a large paper backer. Confirm impact, adjust onto the bullseye at 25 yards, and move back to your true zero distance (commonly 100 yards for centerfire rifles and 50 yards for .22 LR rimfire).

Setting mechanical zero and zero stops. Do not slip your turrets to "0" after a single three-shot group. First verify your zero with 5 to 10 shots (see "Statistical zeroing" below). Once the mean point of impact is centered on the aim point:

1. Follow the scope maker's instructions to loosen the turret cap screws or lift the locking cap.
2. Rotate the outer turret dial so the "0" mark lines up cleanly with the index line on the scope tube, without turning the internal adjustment shaft.
3. Set the mechanical zero stop if your elevation turret has one. Most shooters set the zero stop 0.2 to 0.5 MIL (or 1 to 2 MOA) below true zero. Leaving that small margin below zero lets you dial slightly downward if cold air, a new ammunition lot, or a closer target requires a minor negative correction, while still stopping you reliably near zero when dialing down in the dark or under time pressure.
4. Tighten the turret screws to the maker's torque specification and fire two confirmation shots to verify nothing slipped. Record your zero distance, sight height, and environmental conditions (see Chapters 4, 6, and 13).

Service Rifle 200-yard zero and two-load offsets. Highpower Across-the-Course Service Rifle competitors commonly zero at **200 yards** (the closest match stage) and record verified elevation come-ups for **300 yards** and **600 yards** rather than zeroing at 100 yards. Because many shooters run magazine-length 77 gr match ammunition at 200 and 300 yards and switch to longer, single-loaded 80 gr match ammunition at 600 yards (see Chapter 4), verify and record the separate elevation and windage zero offset between the two loads instead of assuming they share the same 200-yard zero.

Statistical zeroing

Every rifle and load shoots a pattern of random scatter around its true center, called the mean point of impact (MPOI). Because individual shots land randomly inside that cone of dispersion, the average center of a small group rarely matches the true center of the rifle.

The uncertainty of a sample's mean point of impact on either the horizontal or vertical axis depends on the rifle's one-axis standard deviation (`sigma`) and the number of shots (`n`):

```
SE_MPOI = sigma / sqrt(n)
```

Here `SE_MPOI` is the standard error of the mean point of impact on one axis (in MIL or MOA), `sigma` is the true one-axis standard deviation of the rifle-and-ammunition system, and `n` is the number of shots fired. For a rough 95 percent confidence band on each axis, multiply `SE_MPOI` by 2 (`+/- 2 * sigma / sqrt(n)`).

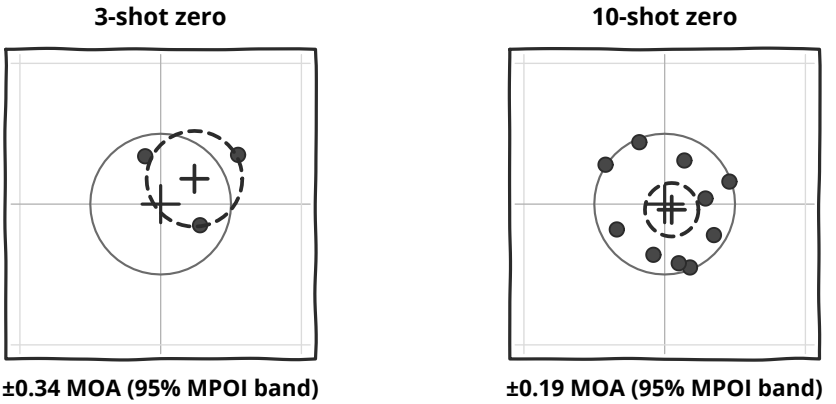
Shots (n)	Multiplier (`1 / sqrt(n)`)	95% axis band (`+/- 2 / sqrt(n)`)	Practical use
3	0.58	+/- 1.15 * sigma	Rough bore-sight check only; too noisy for final zero
5	0.45	+/- 0.89 * sigma	Minimum check; pair two 5-shot groups for final zero
10	0.32	+/- 0.63 * sigma	Reliable zero verification for precision rifles
20	0.22	+/- 0.45 * sigma	High-confidence baseline zero (see Chapter 15)

Example numbers. Suppose a rifle averages about 1.0 MOA extreme spread across 5-shot groups, which corresponds roughly to a one-axis standard deviation of `sigma = 0.30 MOA` (about 0.09 MIL).

- After **3 shots**, `SE_MPOI = 0.30 / sqrt(3) = 0.30 / 1.732 = 0.17 MOA`. The 95 percent uncertainty band on each axis is about `+/- 0.34 MOA`. Your 3-shot group center can easily print a third of an MOA high or left purely by chance, even when the true zero is dead center.
- After **5 shots**, `SE_MPOI = 0.30 / sqrt(5) = 0.30 / 2.236 = 0.13 MOA`, giving a 95 percent band of `+/- 0.27 MOA`.
- After **10 shots**, `SE_MPOI = 0.30 / sqrt(10) = 0.30 / 3.162 = 0.095 MOA`, cutting the 95 percent band down to `+/- 0.19 MOA`.

Chasing every 3-shot group with turret clicks is called chasing your zero. When you click 0.25 MOA right to fix a random 3-shot offset, you often push your true zero 0.25 MOA off center. On the next trip, another 3-shot group prints right, and you click back left.

When a shift is real versus noise. Verify a final zero with a 5-to-10 shot group, or two 5-shot groups fired at a steady pace so barrel heat stays controlled (see Chapter 14). Measure the exact horizontal and vertical offset from your aim point to the center of the group. Adjust your turrets only when the measured offset is larger than roughly `2 * SE_MPOI` (or clearly exceeds one turret click plus normal scatter). If a 5-shot confirmation group sits within 0.1 MIL or 0.25 MOA of center on a 1.0 MOA rifle, leave the turrets alone and verify again on your next range trip.



Example numbers.

Figure 10-1. Comparison of mean-point-of-impact uncertainty for a 3-shot zero versus a 10-shot zero on the same 1.0 MOA rifle.

Evidence · Supported by data
Small-sample groups produce wide random swings in both apparent group size and apparent point of impact. Using 5 to 10 shots (or pooled groups across sessions) reduces mean-point-of-impact uncertainty by the square root of the sample size.[1]

Contested: cold-bore shift

The claim. The first shot fired from a cold barrel strikes away from the rest of the group, requiring a dedicated cold-bore hold or turret offset in your shooting log.

The physics. Two very different bore conditions are often lumped together under one name. A **cold-clean-bore** shot is fired through a freshly scrubbed barrel stripped of copper and carbon fouling, often with trace amounts of cleaning solvent or oil left in the grooves. Stripping the bore changes friction, engraving resistance, and muzzle velocity until the first one to five shots lay down a fresh fouling layer (see Chapter 23). A **cold-fouled-bore** shot is fired through an ambient-temperature barrel that already carries normal fouling from previous shooting. Between shot 1 and shot 2 in a fouled barrel, bore friction barely changes, though a small thermal step, stock-bedding pressure, or the shooter settling into position on the first shot can still move impact in some rifles.

The test. Separate the two conditions completely. To test a cold-fouled bore, leave the bore fouled and fire one cold shot at a dedicated 100-yard bullseye across 5 to 10 separate range trips, allowing the rifle to cool fully to ambient air temperature between shots. Record each cold shot's horizontal and vertical offset from your established 10-shot zero. Run a second, separate test where you clean the bore to bare steel before each first shot and log its offset. Compare the average offset of each series against the rifle's normal shot-to-shot standard deviation (see Chapters 15 and 16).

The data. Repeated testing shows that cold-clean-bore shifts are common and often measurable, with velocity and point of impact stabilizing only after several fouling shots (see Chapter 23). Cold-fouled-bore shifts are far less consistent. When shooters track 10 or more true cold-fouled shots on a single composite target, many perceived "cold-bore flyers" turn out to sit squarely inside the rifle's normal dispersion cone, or disappear once the shooter runs a dry-fire settle routine before shot 1. A subset of rifles, often slim sporter barrels or rifles with uneven bedding contact, do display a repeatable directional shift on the first cold shot.

The verdict. Plausible but unproven as a universal rule; rifle-specific. Treat cold-clean-bore shifts as real and fire fouling shots after cleaning before hunting or competing. For a cold-fouled bore, never invent a correction from one stray first shot. Measure your first cold shot across 5 to 10 sessions, and apply a cold-bore offset only if the mean shift is consistent and larger than your rifle's normal scatter.

Spotting and shot calling

Good shooting does not end when the trigger breaks. Calling your shot and reading downrange feedback tell you why a bullet landed where it did.

Calling your shot before impact. Keep your eye in the scope through the trigger break and note the exact spot on the target where the reticle sat the instant the firing pin fell. State your call mentally or aloud before you look for the bullet hole or splash: "Good break, center," or "Pulled 0.2 MIL low-right."

Shot calling separates shooter error from external error:

- If you called "0.2 MIL low-right" and the bullet struck 0.2 MIL low-right, your zero, rifle, and wind call are correct. Fix your position or trigger press, not your turrets.

- If you called a dead-center break and the bullet landed 0.4 MIL left, you have real information about wind, zero, or ammunition.

Reading bullet trace and impact splash. When spotting for yourself or a partner, position the spotting scope as close to the rifle's bore line as practical, directly behind and slightly above the shooter's shoulder. Seeing trace requires looking nearly along the bullet's flight path. Focus the spotting scope sharply on the target, then back the focus slightly toward the shooter (roughly two-thirds to three-quarters of the way to the target). That focal plane puts the descending arc of the bullet's air disturbance into sharp relief.

When a bullet strikes dirt or gravel, watch the exact point where the splash starts, not the plume of dust blowing downwind a moment later. On painted steel, look for the dark lead mark or bright chipped paint, and listen for the delayed metallic ring (sound travels roughly 1,125 feet per second, so a 600-yard steel hit rings back more than one and a half seconds after impact).

Shooter-spotter communication. Agree on a shared language before the first shot is fired. Always speak in angular units matching the shooter's reticle (MIL or MOA), never linear inches. A spotter who calls "12 inches left" forces the shooter to do mental division under time pressure, and 12 inches means completely different corrections at 300 yards versus 800 yards (see Chapter 3).

Keep calls short, standard, and unambiguous. State either the impact or the correction consistently, never mixing the two without saying which one you mean:

- **Correction call (preferred in matches):** "Right 0.4, up 0.2."
- **Impact plus correction:** "Impact 0.4 MIL left, 0.2 low. Hold right 0.4, up 0.2."

Confirm beforehand whether the shooter is dialing turrets or holding in the reticle so both people stay synchronized on follow-up shots.

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Targets prints a Sight-In Target and Marking computes the exact angular offset from aim point to mean point of impact.

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Chapter 11

Estimating Range, Wind, and Angles

Key points

- Wind-call error is the largest uncertainty in almost every long-range shot.
- Wind near the muzzle deflects the bullet far more than the same wind near the target.
- Range error grows in vertical cost as trajectory steepens at long range and with subsonic rimfire.
- Simple cosine rules approximate moderate angles, but steep long-range angles require a full ballistic solver.

Why it matters

Once your rifle, optic, zero, and ammunition are verified, the remaining misses come from the environment. Gravity pulls the bullet down faster as distance increases, wind pushes it sideways throughout flight, and steep slopes change how gravity acts across the line of sight. Measuring distance, wind, and incline accurately turns a proven rifle system into consistent first-round hits.

How it is done

Measure distance first, read the wind from muzzle to target, and correct for slope angle before dialing or holding.

Range estimation

As a bullet slows downrange, its trajectory curves downward more steeply. A 10-yard range error at 200 yards with a flat-shooting centerfire cartridge barely moves impact. A 10-yard error at 900 yards, or even a 5-yard error at 150 yards with subsonic .22 LR rimfire, can easily drop a shot underneath the target (see Chapter 19).

Laser rangefinder (LRF) best practices. A laser rangefinder measures distance quickly by timing a light pulse reflected off the target. Reliable readings require discipline:

- **Stabilize the unit.** Brace the rangefinder on a tripod, barricade, or shooting bag. Hand tremor at 800 yards can sweep the aiming reticle completely off a small steel plate.
- **Range multiple times and cross-check.** Take three readings on the target. Then range the ground or berm immediately beside or behind the target to verify the number makes sense.
- **Know reflective limits.** Published maximum range ratings usually apply to large, bright, reflective targets like buildings or road signs. Dark steel, soil, and game animals reflect far less laser energy and often cut effective range in half. Fog, rain, snow, and heavy dust scatter the beam and shorten range further.

Beam divergence pitfalls. A rangefinder laser is not an infinitely thin dot. The beam spreads out as a cone or rectangle, commonly 1 to 3 MIL wide or tall. At 800 yards, a 2 MIL beam is 1.6 yards (nearly 5 feet) wide. If you aim at a 12-inch steel plate sitting behind a brush line or in front of a tall berm, part of the beam may strike the brush or the berm instead of the plate and return the wrong distance. Use first-target mode when ranging an

isolated object in front of a distant hillside, and last-target mode when ranging through light grass or twigs. Always verify the reading against nearby terrain.

Reticle milling. When a rangefinder is unavailable, broken, or blocked by weather, you can calculate distance using your scope's reticle if you know the target's physical size (see Chapter 3). In a first-focal-plane (FFP) scope, reticle subtensions are accurate at any magnification. In a second-focal-plane (SFP) scope, you must set the magnification ring to the maker's calibrated power (see Chapter 5).

For a **MIL reticle** (target measured in inches, range in yards):

```
Range (yards) = (Target size in inches * 27.778) / Target size in MIL
```

For a **MIL reticle** in metric units (target in meters, range in meters):

```
Range (meters) = (Target size in meters * 1,000) / Target size in MIL
```

For a **True MOA reticle** (1.047 inches per 100 yards; target in inches, range in yards):

```
Range (yards) = (Target size in inches * 95.5) / Target size in MOA
```

(If your reticle is calibrated in Shooter's MOA / IPHY at 1.000 inch per 100 yards, replace `95.5` with `100`.)

Example numbers. You spot an 18-inch-tall steel target and measure it carefully with your FFP MIL reticle. It spans `0.90 MIL` from top edge to bottom edge.

```
Range (yards) = (18 * 27.778) / 0.90 = 500.0 / 0.90 = 556 yards
```

Notice how sensitive reticle milling is to small reading errors. If you misread the same 18-inch plate by just `0.05 MIL`, calling it `0.85 MIL` instead of `0.90 MIL`, the formula gives `500.0 / 0.85 = 588 yards`. That tiny reading error creates a 32-yard range error. Measure from the finest hash marks on your reticle, measure both height and width if both are known, and average your readings.

Using a True MOA reticle on the same 18-inch target, suppose it measures `3.10 MOA` tall:

```
Range (yards) = (18 * 95.5) / 3.10 = 1,719 / 3.10 = 555 yards
```

Wind reading fundamentals

Crosswind deflects a bullet sideways in proportion to the component of the wind blowing perpendicular to the line of fire (see Chapter 19). Wind blowing directly from the side (3 o'clock or 9 o'clock) gives 100 percent crosswind effect, called a full-value wind. Wind blowing straight down the line of fire from 12 o'clock (headwind) or 6 o'clock (tailwind) gives zero crosswind deflection, though strong headwinds and tailwinds slightly change vertical drop through aerodynamic drag.

Clock-face wind value (the sine rule). For any wind blowing at an angle from your line of fire, multiply wind speed by the sine of that angle:

```
Effective crosswind = Wind speed * sin(wind angle)
```

Clock position	Angle from line of fire	Exact `sin(angle)`	Practical field value
12:00 or 6:00	0 degrees	0.00	Zero crosswind
1:00, 5:00, 7:00, or 11:00	30 degrees	0.50	Half value (50%)
2:00, 4:00, 8:00, or 10:00	60 degrees	0.87	Near-full value (roughly 7/8 or 85–90%)
3:00 or 9:00	90 degrees	1.00	Full value (100%)

Notice that a 2 o'clock wind is already 87 percent of a full crosswind. Many shooters underestimate quartering winds by treating 2 o'clock as "half value," when it actually pushes the bullet nearly as hard as a 3 o'clock wind.

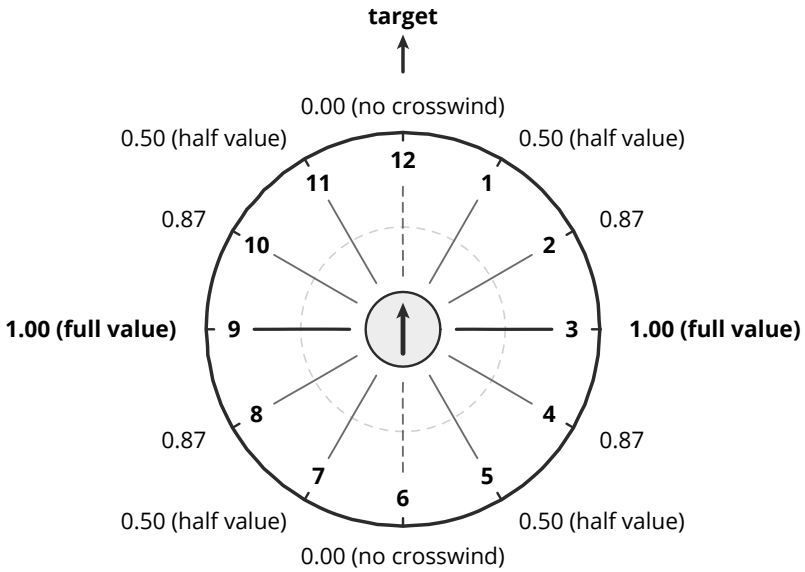


Figure 11-1. Clock-face wind-value diagram centered on the shooter, showing the exact sine-rule crosswind multiplier for each clock position.

Bracketing the wind. Wind rarely holds one steady speed. Instead of guessing a single exact speed, watch the environment for 15 to 30 seconds and bracket the wind's low end (lull) and high end (gust). For example, if the wind cycles between 6 mph and 10 mph, you have a 4 mph bracket centered on 8 mph. Decide before pressing the trigger whether to hold for the center of the bracket (8 mph) or wait for the predominant condition (say, the 6 mph lull) to return. Knowing how many mph of wind error fit across your target's width tells you immediately whether a bracket is shootable (see Chapter 21).

Reading mirage. Mirage is the visible shimmer of light bending through rising layers of warm air near the ground. Wind pushes those rising waves sideways, giving a direct look at wind downrange where your weather meter cannot reach:

- **Boil (vertical shimmer):** Waves rising straight up mean calm air or wind blowing straight along the line of fire (12 o'clock or 6 o'clock).
- **Light crosswind (2 to 4 mph):** Waves tilt slightly and drift lazily in the direction of the wind.
- **Moderate crosswind (5 to 8 mph):** Waves angle noticeably toward 45 degrees and move steadily across the glass.

- **Strong crosswind (10 to 12+ mph):** Mirage flattens into fast, nearly horizontal streaks. Above roughly 12 to 15 mph, mirage looks flat regardless of how much harder the wind blows, so pair mirage with flags or vegetation in strong winds.

  Remember that mirage shows the wind where your scope is focused. To read mid-range wind instead of target-backstop wind, back your spotting scope's focus off to roughly halfway downrange.

  Wind flags. Competitive Benchrest, F-Class, and Service Rifle ranges rely on wind flags because flags respond instantly to direction switches and speed changes. Benchrest shooters place multiple vane-and-tail flags from just past the muzzle to the target, watching all of them together so they can fire every shot of a group in the same repeating condition rather than chasing switches. Service Rifle and F-Class shooters read tall range flags hung along the firing lane. As a rough starting estimate on standard range flags, dividing the flag's angle from the vertical pole (in degrees) by 4 gives approximate wind speed in mph. For example, a 40-degree angle suggests roughly 10 mph, though heavy wet cloth hangs lower than light dry nylon.

  Vegetation and terrain. In field shooting without flags, read natural indicators along the flight path:

- **3 to 5 mph:** Felt lightly on the face; grass tips and tall weeds sway gently.
- **5 to 8 mph:** Leaves rustle steadily; light brush moves continuously.
- **8 to 12 mph:** Small twigs sway; dust begins to lift on dry ground.
- **12 to 15 mph:** Small tree branches move; loose grass and dry leaves blow steadily across open ground.

  Pay close attention to terrain. Ridges deflect wind upward and create swirling eddies on their leeward side. Valleys and draws funnel wind faster than open flats. Shooting berms shelter the firing line while full-strength wind blows across the open range 100 yards ahead.

Wind weight along the trajectory

Not all wind along the range matters equally. Wind near the muzzle deflects the bullet far more than the exact same wind near the target.

The reason is simple geometry. Crosswind pushes the bullet sideways and turns its velocity vector slightly downwind (see Chapter 19). An angular deflection introduced near the muzzle acts like steering a boat slightly off course at the start of a long crossing: the bullet carries that sideways angle across the entire remaining distance to the target. A deflection introduced in the last 100 yards has almost no remaining distance left in which to build lateral offset.[1]

For a uniform crosswind divided into equal thirds of the distance from muzzle to target:

- **First third (near the muzzle):** causes roughly **50 to 55 percent** of the total wind drift.
- **Middle third:** causes roughly **30 to 35 percent** of the total wind drift.
- **Final third (near the target):** causes only roughly **10 to 15 percent** of the total wind drift.

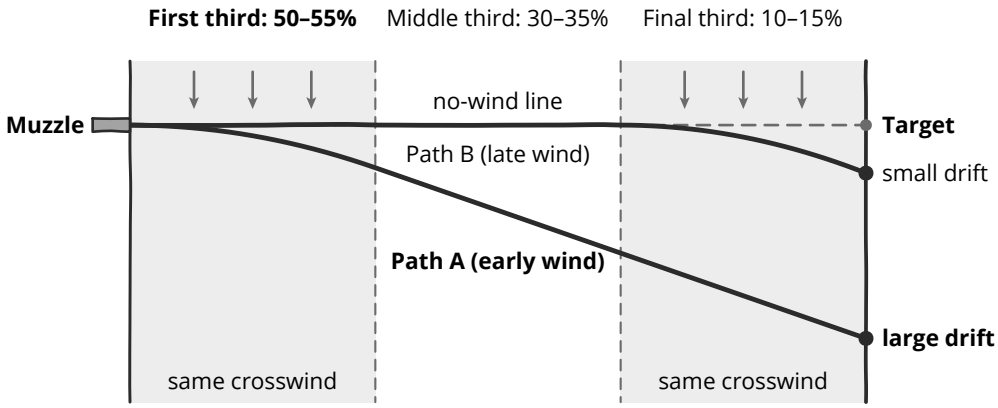


Figure 11-2. Overhead trajectory diagram showing why a crosswind near the muzzle produces far greater lateral displacement at the target than the same crosswind near the target.

In practice, give your closest attention to wind conditions in the first half of the trajectory. When shooting from a sheltered canyon rim or behind a high berm, look past your immediate shelter to see what the wind is doing as soon as the bullet clears cover, and never let a dramatic flag flapping right behind the target distract you from a quiet switch near the firing line.

Benchrest 100-meter wind-flag placement and condition-picking. On a 100-meter (or 100-yard) Benchrest range, place three to four vane-and-tail wind flags staggered along your firing lane and weighted toward the first half of flight—for example, near 15 to 20 meters, 35 to 40 meters, 60 to 65 meters, and close to the target—so your closest flags monitor the first third of flight that drives 50 to 55 percent of total wind drift. Align the flag heights slightly below your sight line so you can see all flags simultaneously through your peripheral vision or low-power spotter without breaking position. Rather than chasing rapid direction switches, watch the flags until you identify a repeating, steady condition, fire your sighters to confirm where that condition prints, and then fire every record shot of the group in that same condition.

F-Class and known-distance target wind craft

Long-range known-distance matches such as F-Class (typically 20-shot record strings at 600 to 1,000 yards) reward systematic wind tracking over raw guesswork:

- **Holding off versus dialing during a string.** Dial your windage turret to center your impacts on the predominant wind baseline so you are not holding far out in the outer rings on every shot. Once centered, use the target's scoring rings or reticle hash marks to hold off quickly for brief gusts and lulls during a 20-shot string—turning turrets on every minor puff invites click-counting errors and often leaves you chasing a switch that has already reversed. Re-dial only when the wind clearly settles into a new baseline.
- **Plotting every shot.** Record every shot's impact location and the wind condition you saw at the break—whether in a paper scorebook or on an electronic target (e-target) tablet. Plotting reveals whether a miss came from a missed flag switch, a gradual direction shift, or an uncorrected baseline drift, keeping you from over-correcting on a single stray shot.
- **Watching for vertical wind.** Wind blowing up or over side berms, ridges, or rolling terrain does not move purely horizontally. Updrafts lift the bullet and downdrafts push it

low—especially on crosswinds flowing over tall impact berms or range side walls—producing high and low impacts that easily masquerade as muzzle-velocity vertical spread. Compare vertical excursions against sudden flag or mirage changes before blaming your ammunition.

Shooting uphill and downhill

When you shoot steeply uphill or downhill, the bullet impacts higher on the target than your flat-fire drop chart predicts for the measured line-of-sight (slant) distance. Both uphill and downhill shots hit high if you dial for the full slant range.

The cause is the direction of gravity. Gravity always pulls straight down toward the center of the earth, perpendicular to horizontal ground, not perpendicular to a sloped line of sight. Over a sloped slant distance (`Slant range`) at an incline or decline `angle`, gravity acts perpendicular to the trajectory only across the horizontal run (`Horizontal distance`), which is shorter than the slant range. Less perpendicular gravity over the line of sight means less drop relative to your aim point.

The cosine (rifleman's) rule. For moderate angles and moderate ranges, multiply the laser-measured slant range by the cosine of the slope angle to find the horizontal equivalent distance, then dial the elevation for that shorter horizontal distance:

```
Horizontal distance = Slant range * cos(angle)
```

Slope angle (up or down)	`cos(angle)`	Horizontal distance at 500 yards slant
10 degrees	0.985	492 yards
20 degrees	0.940	470 yards
30 degrees	0.866	433 yards
40 degrees	0.766	383 yards
45 degrees	0.707	354 yards

Example numbers. Your laser rangefinder reads `500 yards` straight up a mountainside at a `30-degree` incline (`cos(30 degrees) = 0.866`).

```
Horizontal distance = 500 * 0.866 = 433 yards
```

Instead of dialing your 500-yard elevation, you dial your 433-yard elevation. On a typical 6.5 Creedmoor load, 500 yards might require `2.9 MIL` while 433 yards requires `2.2 MIL`. That `0.7 MIL` difference equals about 12.6 inches at 500 yards, which is easily the difference between a clean hit and shooting completely over the target.

Where the cosine rule breaks down. The rifleman's rule is an approximation, not exact physics. It ignores two real effects that grow with angle and distance:

1. **Aerodynamic drag still acts over the full slant distance.** Even though gravity pulls perpendicular to the path over the shorter horizontal distance, the bullet still flies through 500 yards of air, not 433 yards. It slows down more and stays in flight longer than a flat 433-yard shot, which makes the cosine rule slightly underestimate required elevation at long range.[1]

2. **Gravity also pulls along the line of fire.** Shooting uphill, a component of gravity (`g * sin(angle)`) slows the bullet slightly; shooting downhill, that same component speeds it up slightly. As a result, steep uphill and downhill shots at the exact same angle do not have identical drops at long range.

For moderate angles (under about 20 to 25 degrees) and moderate ranges (under about 400 to 500 yards), the cosine rule stays within roughly 0.1 to 0.2 MIL of the true answer. For steeper angles, longer ranges, or high-drag and subsonic rimfire bullets, use a ballistic solver that integrates the full gravity vector and air drag along the sloped path (see Chapter 20).

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Varytita calculates exact elevation and wind holds for uphill and downhill angles using full sloped-trajectory physics rather than the cosine approximation.

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IV

Part IV

Cartridge Evaluation and Measurement Science

Chapter 12. Evaluating and Selecting a Cartridge 65
Chapter 13. Keeping Shooting and Evaluation Records 70
Chapter 14. The Range Testing Protocol 78
Chapter 15. Measurement Science for Shooters 84
Chapter 16. Comparing Cartridges, Loads, and Hardware 94
Chapter 17. Popular Load-Development and Tuning Methods Examined 107

Chapter 12

Evaluating and Selecting a Cartridge

Key points

- Evaluate cartridges objectively across six dimensions: ballistic coefficient, muzzle velocity, recoil, supersonic reach, barrel life, and cost.
- At extended distance, a higher-BC bullet fired slightly slower almost always drifts less in wind than a lighter, faster bullet.
- Recoil limits practical accuracy by preventing self-spotting and inducing fatigue over long strings.
- Test factory match ammunition with the same statistical rigor as handloads; if it falls short, either test another lot or take the data to the reloading workshop.

Why it matters

Choosing a cartridge by marketing velocity or forum folklore locks you into excess recoil, short barrel life, or poor wind performance. An objective framework matches the cartridge to your actual targets and distances.

How it is done

The six-factor evaluation framework

Every cartridge trades one trait for another. A flat-shooting magnum extends supersonic reach, but it burns throats quickly and kicks hard enough to hide bullet impact in the scope. A small-bore trainer costs little to shoot and lasts for thousands of rounds, but crosswinds push it off target early. Judging a cartridge across six measurable factors keeps those trade-offs in plain view.

1. **Ballistic coefficient (BC).** Higher BC means less aerodynamic drag (see Chapter 19). Less drag means less wind drift and slower velocity loss downrange. Because wind call error dominates misses past about 500 yards (see Chapter 21), BC is usually the single strongest ballistic lever at distance.
2. **Muzzle velocity.** Higher launch speed flattens the trajectory and reduces time of flight. Flatter trajectories forgive range-estimation errors, which matters in field hunting and unknown-distance shooting. Velocity also raises impact velocity for terminal expansion (see Chapter 22).
3. **Recoil and self-spotting.** Free recoil energy rises with bullet weight, powder charge weight, and muzzle velocity, and falls as rifle weight increases. Heavy recoil causes shooter fatigue over long strings and lifts the muzzle off the target. If the scope jumps off the plate, you cannot watch your own trace or splash to make a fast wind correction. In practical rifle competition, being able to spot your own misses often adds more hits than a small gain in BC.
4. **Supersonic reach.** Standard ballistic predictions lose accuracy as a bullet slows into the transonic zone near Mach 1.2, roughly 1,340 fps on a standard day (see Chapter 19).[1] Some bullets also lose dynamic stability there.[2] Choose a cartridge whose

bullet stays above Mach 1.2 past your longest intended target distance, with margin for cold, dense air.

5. **Barrel life.** High powder charges forced through a small bore diameter erode the throat rapidly. An overbore cartridge can lose match-grade precision in 1,000 to 1,500 rounds, while a mild .308 Winchester or .223 Remington barrel can shoot well past 4,000 to 5,000 rounds. Barrel replacement is a real part of the cost per shot.
6. **Cost per round and availability.** Count the full cost of components or factory ammunition, plus barrel replacement divided by barrel life. A cartridge that costs half as much to feed lets you shoot twice as much practice. Practice reading wind and building steady positions usually buys far more hits than a marginal ballistic upgrade (see Chapter 21).

> **Safety · See Chapter 2**
> Always verify that the cartridge headstamp matches the chamber marking stamped on the barrel before loading a magazine or chambering a round. Several modern precision cartridges share similar case bodies and can chamber in the wrong rifle with dangerous results.

Ballistic coefficient vs. muzzle velocity

Shooters often equate high muzzle velocity with low wind drift. Physics disagrees. Wind drift depends on lag time, which is the extra time aerodynamic drag adds to the flight compared with a vacuum (see Chapter 19). A light bullet launched fast sheds speed quickly, builds lag time, and drifts heavily. A heavier, sleeker bullet launched slower holds its speed, builds less lag time, and drifts less.

Worked comparison. Example numbers. Not load data.

Table 12-1 compares four common loads on a standard sea-level day with a 100-yard zero, using the wind-drift figures from Chapter 19.[3] Example numbers. Not load data.

Table 12-1. Full-value crosswind drift in a 10 mph wind for four example loads.

Cartridge and bullet	Muzzle velocity	BC	300 yd	500 yd	700 yd	1,000 yd
.223 Remington, 55 gr	3,240 fps	G1 .243	11.8"	38.2"	87.8"	202.3"
.223 Remington, 77 gr	2,720 fps	G7 .195	8.5"	26.4"	58.4"	143.3"
.308 Winchester, 175 gr	2,600 fps	G7 .243	7.3"	21.9"	47.0"	111.7"
6.5 Creedmoor, 140 gr	2,700 fps	G7 .315	5.2"	15.3"	31.8"	71.9"

The 55 gr .223 Remington leaves the muzzle 540 fps faster than the 6.5 Creedmoor. By 300 yards, it already drifts more than twice as far in the same wind. At 1,000 yards, it drifts nearly three times as far. Even within the same cartridge, stepping up to a heavy 77 gr .223 Remington match bullet cuts 1,000-yard wind drift by nearly 60 inches despite starting 520 fps slower. The .308 Winchester, starting 640 fps slower than the 55 gr .223 Remington, cuts wind drift almost in half.

Between the .308 Winchester and the 6.5 Creedmoor, a 100 fps velocity edge combines with a 30 percent higher G7 BC to cut 1,000-yard wind drift by about 36 percent.

Higher muzzle velocity still has one clear advantage: less drop per yard of range error. When you range targets with a laser rangefinder or shoot at known distances, range error is small and BC wins. When you estimate distance by eye in the field, a flatter trajectory reduces vertical misses (see Chapter 21).[2]

Evidence · Supported by data
Wind-drift physics and Weapon Employment Zone modeling show that higher BC beats higher muzzle velocity whenever wind call error exceeds range-estimation error.[4]

Practical cartridge classes

Most precision rifles fall into four broad classes. Pick the mildest class that meets your supersonic reach, wind, and terminal energy requirements.

Rimfire precision and trainers (NRL22, PRS Rimfire, smallbore). Cartridges such as .22 Long Rifle (.22 LR), .17 Hornady Magnum Rimfire (.17 HMR), and .22 Winchester Magnum Rimfire (.22 WMR) offer the lowest cost per round, almost no recoil, and barrel life measured in tens of thousands of rounds. Standard-velocity .22 LR launches subsonic at roughly 1,050 to 1,100 fps with a low BC. At 100 to 300 yards, its drop and wind drift mimic a centerfire rifle at 600 to 1,000 yards. That makes .22 LR both a competitive precision discipline of its own and an efficient trainer for positional shooting, trigger control, and wind reading on short ranges. The faster .17 HMR and .22 WMR shoot flatter inside 150 yards for small game, though match-grade ammunition selection is broadest in .22 LR.

Small-bore centerfire. The .223 Remington (and 5.56x45mm NATO in rifles chambered for it) bridges rimfire training and full-size match cartridges. Recoil is light, components are widely available, and barrels last thousands of rounds. In a fast-twist barrel (1:7 or 1:8), heavy 69 to 80+ gr match bullets stay supersonic past 800 yards and serve well in Service Rifle competition, varmint work, and high-volume practice. Wind drift remains higher than in 6mm or 6.5mm cartridges, so it teaches disciplined wind calling without punishing your shoulder or budget.

Low-recoil match and mid-range. The 6mm class includes 6mm Benchrest (6mm BR), 6mm GT, 6mm Creedmoor, and the classic .243 Winchester (6mm-08 class). The 6.5mm class includes 6.5 Creedmoor and 6.5x47 Lapua. Together they dominate practical precision matches, mid-range target shooting, and deer-sized game hunting. High-BC bullets in 105 to 115 gr (6mm) and 130 to 147 gr (6.5mm) stay supersonic past 1,000 yards while producing mild recoil in a heavy match rifle. Shooters can spot their own impacts through the scope and stay fresh across a two-day match. Inside this class, the main trade-off is barrel life versus speed. Efficient short cases like 6mm BR and 6mm GT offer longer barrel life than faster 6mm Creedmoor or .243 Winchester loads. The 6.5 Creedmoor trades slightly more recoil for longer throat life and broad factory match ammunition support.

Extended-range and hunting. The .270 and 7mm classes include .270 Winchester, 7mm-08 Remington, 7mm Remington Short Action Ultra Magnum (7mm SAUM), and 7mm Precision Rifle Cartridge (7mm PRC). The .30-caliber class includes .308 Winchester, .30-06 Springfield, .300 Winchester Magnum, and .300 Precision Rifle Cartridge (.300 PRC). These cartridges serve F-Class long-range competition, extreme long-range shooting, and

big-game hunting. Heavy 7mm and .30-caliber bullets carry high BCs. They retain enough impact velocity and energy for ethical hunting at longer distances (see Chapter 22), or remain supersonic past 1,500 yards on steel. The milder .308 Winchester, 7mm-08 Remington, .270 Winchester, and .30-06 Springfield offer long barrel life and manageable recoil inside 800 to 1,000 yards (and flat hunting trajectories inside 400 to 500 yards). The magnum cartridges add supersonic reach and terminal energy at the cost of heavier recoil, higher ammunition expense, and shorter barrel life.

Class	Typical examples	Strengths	Trade-offs
Rimfire precision and trainers (NRL22, PRS Rimfire, smallbore)	.22 LR, .17 HMR, .22 WMR	Very low cost, minimal recoil, extreme barrel life, wind practice at short range	Short effective reach, sensitive to wind, cannot be handloaded
Small-bore centerfire	.223 Remington	Low recoil, long barrel life, affordable components	Higher wind drift past 500 yards, limited big-game energy
Low-recoil match & mid-range	6mm BR, 6mm GT, 6mm Creedmoor, .243 Winchester, 6.5 Creedmoor	High BC, easy self-spotting, supersonic past 1,000 yards	Moderate to short barrel life in faster 6mm designs
Extended-range & hunting	.270 Winchester, 7mm-08 Remington, 7mm SAUM, 7mm PRC, .308 Winchester, .30-06 Springfield, .300 PRC	High downrange energy, long supersonic reach	Higher recoil and cost; shorter barrel life in magnums

EASIER ON EP · KYVOS · DISPERSION SIMULATION

Kyvos compares candidate cartridges and bullets side by side on hit probability, wind drift, and supersonic limit under the same field uncertainties.

empiricalprecision.com/heurisko?tab=kyvos

Factory match ammunition vs. handloads

You do not have to handload to shoot a precision rifle well. Modern factory match ammunition is loaded with consistent bullets and powders, and in popular chamberings (.22 LR, .223 Remington, 6.5 Creedmoor, .308 Winchester, and 6mm Creedmoor) it often delivers tight groups and low velocity SD straight from the box. Specialty match chamberings like 6mm GT and 6mm BR have far fewer factory SKUs than 6.5 Creedmoor, making lot testing and buying in bulk especially important if you do not handload.

Test factory ammunition with the same statistical discipline you would use for handloads (see Chapters 14 through 16).

1. **Test by lot number.** Record the lot number printed on every box (see Chapter 13). Two lots of the same factory SKU can differ in muzzle velocity and group size, especially in .22 LR where rimfire ammunition cannot be handloaded and lot testing is the main tuning lever.
2. **Use real sample sizes.** Do not buy a case of ammunition because one 3-shot or 5-shot group looked tight. Screen two or three candidate SKUs or lots with 10 rounds each,

then confirm the leader with a 20- to 30-shot composite and chronograph string (see Chapter 16).

3. **Judge against your hit-probability goal.** Enter the factory load's measured mean radius and velocity SD into a Weapon Employment Zone model for your real target and distance (see Chapter 21). If the load clears your hit-probability goal, buy enough of that lot for the season and spend your time practicing.
4. **Know when to move to the workshop.** Factory ammunition falls short when no available lot meets your precision or velocity SD goal, when you shoot a cartridge with limited factory match support, or when high-volume shooting makes handloading more economical. When a handload falls short during range evaluation, do not guess at the range. Take your measured mean radius, velocity SD, and target diagnostics back to the reloading workshop (see *The Handloading Handbook*) and change a major variable such as bullet or powder.

Chapter 13

Keeping Shooting and Evaluation Records

Key points

- Each record links to the one above it, so any shot traces back to its session, batch, load, lots and rifle.
- A note written on the spot is evidence. A note written later is memory.
- You can always calculate a new summary from raw readings, but you can never recover raw readings from a summary.
- Never alter raw data. An exclusion is a note beside a shot that stays in the record.
- Failed loads, stopped work-ups and a retired barrel's logs belong in the record too.

Why it matters

Precision shooting generates useful numbers at every step, whether you shoot factory match ammunition or handloads. Scattered across notebooks, box labels, and target sheets, those facts answer nothing. Kept as one connected record, they answer three questions.

What is in this box? A slow string, an unexpected shift in zero, or a stiff bolt traces to one ammunition lot or one workshop step only if the box leads back to it.

Is this still the load I tested? Seasons change, lots run out and the throat wears (see Chapter 23). You can tell drift from noise only against a history.

What did the test really show? Most tests pool shots from several sessions, because small samples mislead (see Chapters 15 and 16). Pooling works only if every shot carries its load. A result can be checked only while every raw shot is still there.

How it is done

Choose one format and write at the time

Two formats work, and neither needs special tools.

- **A bound notebook.** Pages cannot fall out, and the order of the entries shows when each was written. Number the pages and date every entry.
- **A spreadsheet.** It sorts, filters and does the arithmetic (see Chapter 15).

Paper in the workshop and at the range, with a spreadsheet at home, works well. Pick one format for each kind of record and use it every time.

Write each entry when it happens. Note the lot number as you open the container and the scale check as you make it. At the range, write a shot's call before you look at the target (see Chapter 15). A note written later is memory. It cannot show that an error was noted before you saw where the shot went.

Build one ID chain

Give every record a short ID, and write on each record the ID of the one above it. The chain runs rifle, load, batch, session and shot. A session can fire several batches, so each shot names both its session and its batch.

Level	What it is	Example ID	Chapters
Rifle	One barrel on one action	Rifle 1	4, 23
Load	One factory SKU or handload recipe	FM-140 or B3	12, 16, 20
Batch	One factory lot number, or rounds loaded together from one lot of each component	Lot 41928 or B3-2	12, 16, 23
Session	One range trip with one rifle	14	14
Shot	One round fired	14-04	14, 15

> **Safety · See *The Handloading Handbook*.** Work up again from the published start load after any change of primer, case maker, bullet or powder. Do the same after seating deeper than the worked-up seating or into the lands, and with a new barrel or a changed barrel length. For a new lot of the same component, record the lot. Load 10 check rounds at your current charge, or one step lower if your charge is at or near the published maximum. Compare their velocity with your records before loading in bulk. If the new lot runs faster by more than twice the noise (see Chapter 23), reduce the charge and work up again from below.

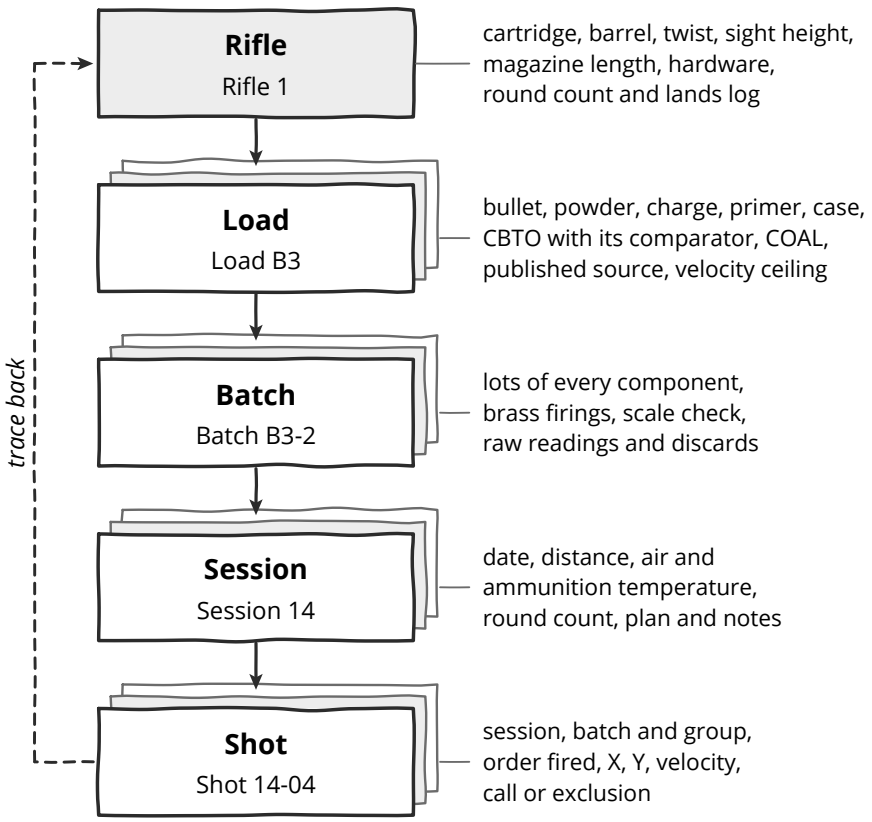
1. **Rifle.** Use a short name, such as Rifle 1. A new barrel starts a new rifle record with its round count at zero. Its lands, baseline and work-ups all start over (see Chapter 23).
2. **Load.** For factory ammunition, use the manufacturer's product SKU or a short code for the brand and bullet weight (such as FM-140). For handloads, use a letter for each work-up and a number for each step. Load B3 is step 3 of work-up B. Any change of charge or CBTO makes a new load ID. A change of primer, case maker, bullet or powder needs a new work-up. So does seating deeper or into the lands. Each starts a new work-up letter (see *The Handloading Handbook*). A change that does not require a new work-up, such as seating B3 slightly longer (while still off the lands), takes a letter suffix: B3a, then B3b.
3. **Batch.** For factory ammunition, use the lot number printed on the box flap or case (such as Lot 41928). Every new factory lot starts a new batch. For handloads, use the load ID and a running number: B3-1, then B3-2. Each loading session starts a new batch. A new lot of any component starts a new batch, even partway through a session.
4. **Session.** Number each rifle's sessions in order. Shoot two rifles on one trip and you have two sessions.
5. **Shot.** Use the session number and the order fired. Shot 14-04 is the fourth round fired in Session 14. Number every round, foulers and sighters included, so the numbers follow the chronograph string.
6. **Write the IDs everywhere.** Put them on the box label, the target sheet, the chronograph file name and the log page.

Worked example (factory ammunition). Example numbers. Not load data.

```
Rifle 1          24-inch barrel, 1:8 twist, 6.5 Creedmoor
Load FM-140      For Rifle 1. Factory Match 140 gr ELD-style SKU #81500
Batch Lot 41928  Factory lot 41928, case of 200 rounds purchased 10 May 2026
Session 14       19 May 2026, Rifle 1, 100 yards
                 Air 58 °F, ammunition 61 °F, round count 350 at start
                 Lot 41928 averaged 2,705 fps (SD 10 fps)
Shot 14-04       Batch Lot 41928, group 1, X 1.40 inch, Y 2.10 inch, 2,702 fps
```

Worked example (handloaded ammunition). Example numbers. Not load data.

```
Rifle 1      24-inch barrel, 1:8 twist, magazine length 2.800 inch
             Lands 2.252 inch CBTO at 350 rounds
             (comparator A, method A)
Load B3      For Rifle 1. Step 3 of work-up B. Bullet 1,
             powder 1, primer 1, case maker 1. CBTO 2.222 inch,
             comparator A. COAL 2.795 inch
Batch B3-2   Loaded 12 May 2026, 20 rounds
             Lots: bullet 221, powder 114, primer 07,
             brass batch D-3 at 3 firings
Session 14   19 May 2026, Rifle 1, 100 yards
             Air 58 °F, ammunition 61 °F
             Round count 350 at the start
             Batch B3-2 averaged 2,712 fps
Shot 14-04   Batch B3-2, group 1, X 1.45 inch, Y 2.15 inch, 2,709 fps
```



Example numbers. Not load data.

Figure 13-1. The record chain. Each record names the one above it, so every shot traces back to its rifle, load, batch and lots.

Now follow a lot check through the chain. Batch B3-3 is 10 check rounds for powder lot 120, new since B3-2. In Session 15, a week later at about the same temperature, they average 2,738 fps with an SD of 9 fps. B3-2's 15 test shots averaged 2,712 fps with an SD of 8 fps. Nothing else in the chain changed, so any real difference comes from the lot. A velocity rise at the same charge is a warning, so judge it against its noise (see Chapter 23).

```
noise = √(8² ÷ 15 + 9² ÷ 10) = √12.4 = 3.5 fps
rise  = 2,738 − 2,712 = 26 fps, more than 7 times the noise
```

The rise is far more than twice the noise, so it is real. Lower the charge and work up again from below with the new lot before you load it in bulk (see *The Handloading Handbook*). Example numbers. Not load data.

The rifle record

The rifle record holds the measurements from Chapter 4: cartridge, barrel length, twist, sight height and magazine length. Add the hardware, with its torque values and the date of the configuration.

Three parts of the rifle change, so give each one a dated log.

1. **Round count.** Update it before each session. Add every round fired through the barrel, foulers and sighters included (see Chapter 14).
2. **Lands log *(if handloading)*.** Write one line per sitting. Give the bullet, method and comparator, each reading with the average and spread, the date and the round count (see *The Handloading Handbook*).
3. **Baseline log.** Write each baseline with its date, the hardware it was shot with and its result. A hardware change closes the old baseline and opens a new one (see Chapter 4).

EASIER ON EP · FIREARMS · RIFLE PROFILES

Firearms keeps each rifle's record and its lands log, and gives how far the lands have moved per 100 rounds.

empiricalprecision.com/firearms

The load and batch records

(For handloaders only; skip if shooting factory ammunition—record the manufacturer, SKU, bullet weight, and lot number instead.)

The load record is your master recipe. Write it before you load the first batch, and keep it up to date. Record the components, charge weight, CBTO (with its comparator), COAL, published data source, book start and maximum charges, and your velocity ceiling.

The batch record is the workshop log page for one batch (see *The Handloading Handbook*). Each page holds:

- The batch ID, the load ID and the date.
- The bullet, powder and primer lots, copied from each box or container as you open it (see *The Handloading Handbook*).

- The brass batch, its lot, its firings and its measured capacity (see *The Handloading Handbook*).
- The scale check readings (see *The Handloading Handbook*).
- The die settings, the inserts, the fired base-to-shoulder average with the target sized reading, and the raw readings for shoulder bump, length and CBTO (see *The Handloading Handbook*).
- Each discarded case and why (see *The Handloading Handbook*).
- The number of rounds loaded, and anything unusual.

Brass carries its history from batch to batch: firings, growth per firing (see *The Handloading Handbook*), annealing settings (see *The Handloading Handbook*) and discards. That history shows when to trim and what ends your cases' lives.

> **EASIER ON EP · LOAD LIBRARY · MY LOADS**
>
> Load Library keeps each load's full recipe, down to the CBTO with its comparator and the brass with its firings.
>
> **empiricalprecision.com/loads?tab=mine**

The work-up record

(For handloaders only; skip if shooting factory ammunition.)

A work-up has a safety job, so its record carries more (see *The Handloading Handbook*).

1. Before you load, write the goal, the published source, the start and maximum charges with their velocities and your velocity ceiling. List the steps with each step's book velocity.
2. At the range, record every velocity in order, and each step's gain over the step before. Note the bolt lift, or in a semi-automatic how the action cycles, and what you saw on each case head and primer.
3. Write where you stopped and which stop rule stopped you (see *The Handloading Handbook*).
4. Write the working charge you chose and the step it sits below.

Keep a stopped work-up as carefully as a finished one. It shows where this rifle met a stop with those components and lots, though it never replaces a new work-up.

The range session record

Write the plan before you go. Give the session ID, the rifle, the loads and batches, the block order and the shot counts. Add how many foulers and sighters you will fire (see Chapters 14 and 16). Then record:

1. The date, the distance, the aim offset, the chronograph and the barrel round count at the start.
2. The air and ammunition temperature, the station pressure, the altitude and the wind (see Chapter 14).

3. Each shot in the order fired, with its group and any call, written before you look at the target.
4. Each fouler and sighter on its own line, marked as such. The chronograph caught them too, so this keeps the readings in step with the shots.
5. After every block, the count of chronograph readings against shots fired (see Chapter 14).
6. At home, each shot's X and Y from its aim mark, and its velocity.

Label each target sheet with the session and the load. Photograph it with a known length in the frame and keep it. Keep the chronograph file under the session ID.

EASIER ON EP · SESSIONS · RANGE SESSION LOG

Sessions keeps a record of every target you shoot, and each one traces back to the rifle, load and lots that made it.

empiricalprecision.com/sessions



Keep raw data, and never change it

Raw data are the readings themselves: every X, Y, velocity and shoulder reading. A mean radius, an SD or an average is worked from them. Keep the readings and you can work out any summary later, with more shots or a better method. Keep only the summary and the readings are gone (see Chapter 15). Once written, raw data never change.

1. **Correct by adding, never by erasing.** Cross out a wrong entry with a single line so it remains legible, then write the corrected value, the reason and the date beside it. If you mismeasure a bullet hole, re-measure it and add the corrected reading the same way.
2. **Keep raw data on its own sheet.** In a spreadsheet, do the arithmetic on another sheet that reads from it.
3. **Exclude by note, never by deletion.** Foulers and sighters are marked as such. Leave a test shot out of its group only for a shooter or equipment error noted when it happened (see Chapter 15). Mark the shot "excluded group", with the reason and when you noted it. Its velocity still counts, and the shot stays in the record. Run the analysis with and without it.
4. **Treat a chronograph misread the same way.** Keep the reading. Mark the shot "excluded velocity" and give the reason. Its hole still counts in the group.
5. **Keep failed loads and stopped work-ups.** Dropping the losers biases your records the way dropping shots biases a group. A rejected load also shows why the winner won, and it saves you from testing the same idea twice.

EASIER ON EP · CHRONOS · CHRONOGRAPH IMPORT

Chronos keeps each chronograph string with every reading and exports it for a spreadsheet. A reading you know the chronograph misread can be set aside. It stays in the string and drops out of the statistics.

empiricalprecision.com/chrono



One row per shot

A spreadsheet works best with one row for every round fired and one column for each fact. Keep a shot sheet with these columns.

Column	Holds
Session	The session ID
Load	The load ID
Batch	The batch ID
Group	The block or aim mark
Shot	The order fired in the session
Status	Test, fouler, sighter, excluded group or excluded velocity
X	Inches right of the aim mark
Y	Inches up from the aim mark
Velocity	fps, as read
Note	The call, or the reason for an exclusion and when you noted it

Keep a sheet for each level above it too: rifle, load, batch and session. Each sheet has one row per record, keyed by its ID. The session sheet holds the rifle, date, distance and conditions. No shot row repeats them.

To analyze one load, filter the shot sheet to that load. For composite mean radius, include all `test` shots and `excluded velocity` shots (since a chronograph misread does not affect where the bullet hit), measuring each shot from its own group's center. For velocity SD, include all `test` shots and `excluded group` shots (since a pulled aim does not affect muzzle velocity). Calculate both as shown in Chapter 15. You can also filter by batch or session to check whether one stands apart from the rest.

Worked example. Example numbers. Not load data.

Session	Load	Batch	Group	Shot	Status	X	Y	Velocity	Note
14	B3	B3-2	F	1	fouler			2,694	Separate aim mark
14	B3	B3-2	1	2	test	1.20	2.05	2,714	
14	B3	B3-2	1	3	test	1.70	1.75	2,706	
14	B3	B3-2	1	4	test	1.45	2.15	2,709	
14	C2	C2-1	2	9	excluded group	1.35	3.60	2,739	Felt the rifle jump off the rest. Noted before looking.

Results, decisions and long-term logs

Record each result with what it rests on. Give the sessions and shots it used, the shot count, the number of groups and the interval (see Chapter 15). Write the decision beside it, with the plan you fixed before the test, what you chose and the date (see Chapter 16).

Keep three running logs for each load you go on shooting (see Chapter 23).

- **Velocity history.** One line per session: the mean, SD and shot count, the ammunition temperature, the barrel round count and the lots.

- **Lot changes.** The date, the component, the old and new lots and the result of the velocity check.
- **Temperature response.** Any session where temperature shifted velocity beyond normal noise, along with any fps-per-degree slope calculated from your velocity history, the sessions used and the temperature span covered.

The drop chart and the DOPE card, the card of sight settings for each distance (see Chapter 20), belong to one rifle and one load too. Note the velocity and the sessions each was built from.

> **EASIER ON EP · ANALYSIS · STATISTICAL TOOLS**
>
> Analysis gives a text report of each result, with its numbers, conditions and notes, to keep with the decision it supports.
>
> **empiricalprecision.com/analysis**

Back up and keep the records

A lost record is a test you have to shoot again.

1. After each session, photograph or scan the new notebook pages.
2. Keep a second copy of the spreadsheet, the photographs and the chronograph files in a different place from the first.
3. Keep the target sheets in a folder marked with the session IDs.
4. Keep every record for at least the life of the barrel. The lands rate, the velocity history and any temperature slope come from records that span it (see Chapter 23).
5. When you retire a barrel, close its record with its final round count. Keep it with the rest.

> **EASIER ON EP · CUSTOM DATA · BACKUPS**
>
> Custom Data exports one backup file of your firearms, loads, sessions, chronograph strings and Analysis queues, to keep with your other copies after each session.
>
> **empiricalprecision.com/db-management**

Chapter 14

The Range Testing Protocol

Key points

- A rifle's first session shoots its baseline. A comparison holds only while its hardware stays the same.
- A target printed at true size doubles as a ruler. An aim mark the group never touches stays clean to aim at.
- Conditions change from one range trip to the next, so the record has to carry them.
- Interleaving spreads barrel heat, fatigue and weather evenly across the loads. Which shots count is settled before you fire.
- Each chronograph reading belongs on its own shot's line. Count readings against shots after every block.

Why it matters

Statistics can only work with what the range gives them. A careless session adds noise that no formula can remove. Worse, it can add bias. Bias makes one load look better for a reason that has nothing to do with the load. Bad data in gives bad results out.

The range protocol does three jobs. It holds the rifle and the shooter constant. It spreads the changes you cannot prevent evenly across the loads. It records everything else so you can see it later.

How it is done

Before the range: confirm the baseline

Before each session, confirm that the rifle's hardware is unchanged since its baseline (see Chapter 4 and "Shoot the hardware baseline" below). Check that the scope, rings and action screws are still at their torque. Keep the cleaning routine the same. Update the barrel round count. Any hardware change ends the comparison and starts a new baseline. That includes a new scope, rings, trigger, stock or muzzle device.

Shoot from the steadiest position you can. A solid rest on a shooting bench is best. Prone with sandbags is next (see Chapter 7). Control every variable you can. Between loads, change only the one thing under test.

Print targets at actual size

A printed target doubles as a ruler. If the printer shrinks the page, every measurement shrinks with it.

1. Choose a target that is easy to read and easy to carry home. Measuring at home is easier than measuring at the range.
2. Print at 100 percent, also called Actual Size. Never use "fit to page".
3. Measure a known feature on the printed sheet with a rule or calipers. A 6-inch bullseye must measure 6 inches (see Figure 14-1).

4. Use one sheet per load per session. Label it with the session ID, the date, the rifle and the load (see Chapter 13).
5. Give every block its own aim mark (see "Blocks: how many rounds per load per session" below).

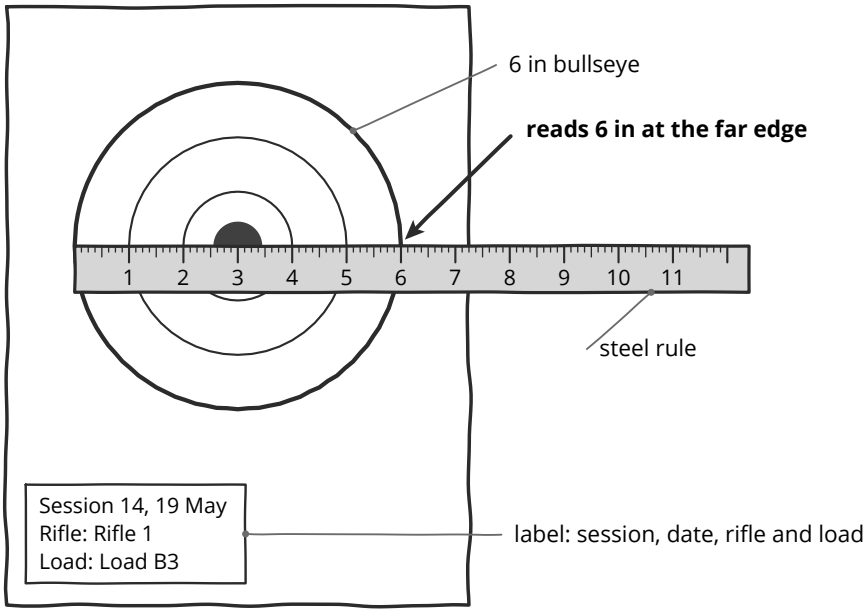


Figure 14-1. Checking a printed target before the range. A rule confirms that the bullseye printed at its stated size.

EASIER ON EP · TARGETS · TARGET DESIGN

Targets prints bullseye targets with a label naming the firearm and load. Print at 100 percent, so the grid stays a true ruler.

empiricalprecision.com/targets

Offset the aim mark

Do not aim at the spot where the group will land. A group that lands on its aim mark slowly shoots the mark away. Each later shot is then aimed at a ragged hole, and the hold gets worse.

Set the scope so the group lands above and to the right of the aim mark instead. On a grid, up and right can both be positive numbers. That keeps the arithmetic simple and avoids sign errors.

1. Zero the rifle at your test distance.
2. Dial the scope up and right by a fixed amount. Move it far enough that no hole can touch the aim mark, such as 2 MOA up and 2 MOA right at 100 yards. One MOA is about 1 inch at 100 yards, so that is about 2 inches each way. Example numbers. Not load data.
3. Write down the offset.
4. Leave it alone for the whole test.

The offset does not change the group's size. Mean radius is measured from the group's own center, not from the aim mark (see Chapter 15). It is not a zero error either. Fire a zero group with the turrets back at zero before you measure the zero (see Chapter 20).

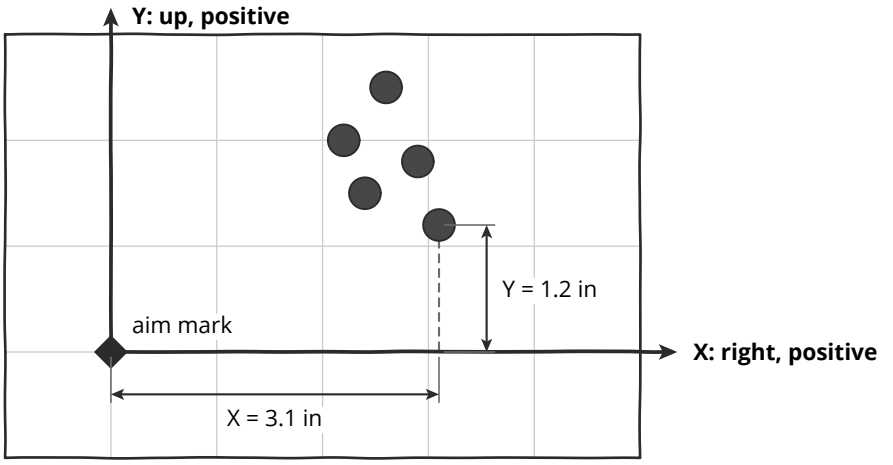


Figure 14-2. The aim mark sits at the origin. The group lands up and right of it, so every X and Y is positive.

Record every shot as raw coordinates

Record each shot's horizontal (X) and vertical (Y) distance from its aim mark. Keep these raw numbers for good, never only a group's average or size. Every later analysis starts from them.

1. Take the target home and lay it flat.
2. Measure from the center of the aim mark to the center of each hole. A grid target makes this quick.
3. Write each shot's X and Y on its own line in your shot record, beside its velocity (see Chapter 13).
4. Keep the sheet with your notes.

You turn those lines into a mean radius (see Chapter 15).

EASIER ON EP · MARKING · TARGET DIGITIZER

Marking turns a photo of the target into the X and Y of every shot. Set the scale from a known length in the photo, mark the aim mark, then mark each hole.

empiricalprecision.com/marking

Session variance: what changes between range trips

You need many shots per load, so most tests span several range trips. Conditions between trips do not affect every result equally. They rank like this.

Factor	Effect on muzzle velocity	Effect on the trajectory	What to do
Temperature	Critical. Powder temperature moves velocity and pressure.	Critical. Cold air is denser, so the bullet drops more.	Record air and ammunition temperature. Keep ammunition shaded.
Elevation and station pressure	None	Major. Thin air reduces drag.	Record altitude and pressure.
Storage humidity	Moderate to severe. Damp powder loses velocity, and powder stored drier than at the work-up gains it (see *The Handloading Handbook*).	Minor	Store powder and ammunition sealed. Note where they were kept.
Wind	None	Moves shots within a session only.	Hold for the wind you have. Test in the calmest conditions you can.

Read the air temperature and the station pressure from a pocket weather meter (see Chapter 7). Station pressure is the pressure where you stand, not the sea-level figure in weather reports (see Chapter 19). Read the ammunition temperature with a thermometer in the ammunition box.

Temperature leads the list. Ammunition left in a hot car, or a round left in a hot chamber, can raise pressure to a dangerous level. Keep ammunition out of the sun. Chamber a round only when you are ready to fire it.

How much velocity shifts with temperature depends on the powder. Suppose you develop a load at 90 °F and fire it at 30 °F. A powder that shifts by 0.14 fps per °F loses about 8 fps. A powder at 0.5 fps per °F (where temperature sensitivity starts to matter) loses about 30 fps. Both estimates assume a straight-line change, though many powders drop off faster in the cold. Example numbers. Not load data. Keep your ammunition at a steady temperature during a session, and temperature shift within the session largely disappears (see Chapter 23).

The most important control is simple. Shoot every load you are comparing in the same session, interleaved. Then the day's weather falls on all of them alike. A cold day may slow every load, but it will not favor one.

How the rounds were stored matters too. In one test, damp storage moved velocity more than heat or cold usually does (see *The Handloading Handbook*).[1] Temperature response also varies by cartridge, lot and rifle (see *The Handloading Handbook*).

Blocks: how many rounds per load per session

A block is a run of one load fired in a row, such as 5 rounds. A pass fires one block of every load, and a session holds one or more passes. Blocks add shots to a growing record for each load. The total number of shots sets most of your statistical power. The block size sets the practical trade-offs.

Small blocks carry one statistical cost. Each group's center comes from its own shots, so each separate group uses up a little of the information (see Chapter 15, "Composite groups").

Block	Strengths	Weaknesses
3 rounds	Fast. Little barrel heat. Saves components early.	Many small groups to track. A 30-shot record takes 10 sessions and mixes many days of weather.
5 rounds	The practical middle. Ammunition boxes hold rows of five. Six loads of five make a 30-round session.	Still needs several sessions, so some weather mixing remains.
10 rounds	Fewer sessions. Most of a load's data shares one day's conditions.	More barrel heat and fatigue. Spends more components on a load that loses.
20 rounds	A load's data shares one day's conditions.	The most heat and fatigue. Wastes components if the load was poor from the third shot.

To build a 30-shot record with one block per load per session takes 10 sessions with 3-round blocks. It takes 6 sessions with 5-round blocks, 3 with 10-round blocks and 2 with 20-round blocks.

For most testing a 5-round block is the best balance. Use 10-round blocks when weather between sessions worries you more than barrel heat. Rimfire (.22 LR) shooters using 50-round match boxes with minimal barrel heat often shoot 10-round blocks (five 10-shot groups per box) for better statistical efficiency.

Evidence · Plausible but unproven
Barrel heat and fatigue are the usual explanations for groups that open late in a long string. The effect varies by rifle and barrel. In one controlled test, 50-shot strings were slow-fired through steel and carbon-fiber barrels of several contours. Point of impact shifted by more than 1 MOA as a barrel heated, and heavier barrels generally shifted less.[2]

Interleave the loads

Never fire one load's entire allotment in a row—the last load would meet the hottest barrel and most tired shooter. Fire one block of each load in turn instead. Never interleave a work-up: fire its steps in order, lowest first (see *The Handloading Handbook*).

1. Box each load in blocks, in firing order, and fire every load at the same distance.
2. Fire one block of load A, then B, then C, rotating the starting load each pass (A B C, then B C A, then C A B) so no load always goes first or last.
3. Keep a steady pace and rest between blocks, noting each block's start time.

Exception for .22 LR bullet waxes. Interleaving 5- or 10-round blocks works across *different lots of the same .22 LR brand*. Do not interleave *different brands with incompatible waxes* (such as oil/wax blends versus beeswax/tallow), as mixing lubricants opens groups until the bore re-seasons. Test one brand per session, or patch out the old wax (dry and solvent patches) and fire 15 to 30 seasoning shots before recording the next brand (see Chapter 23).

Foulers and sighters

Fouling shots after cleaning and sighters that check aim offset are not test data. Exclude them, but decide in advance:

1. Write down your fouler and sighter count before the session, and fire them at a separate aim mark or sheet.

2. Log each on its own numbered line marked fouler or sighter, since the chronograph reads them too (see Chapter 13).
3. Once you fire at a test aim mark, every shot counts.

Never drop a bad-looking shot after the fact—a flyer is often just the edge of normal spread. Exclude a test shot only for a shooter or equipment error documented when fired, before looking at the target (see Chapter 15).

Chronographs: set up and check

Doppler radar is best for load testing (see Chapter 7). Do not shoot group tests with a barrel-mounted magnetic chronograph unless on-versus-off testing confirms it does not shift point of impact or group size (see Chapter 7). Every session:

1. Align the unit per its manual (point Doppler units along the line of fire) and verify readings on your foulers.
2. Count readings against shots after every block—a missed or extra reading shifts every pairing after it.
3. Call each shot before looking at the target, then spot its hole via spotting scope or target camera (see Chapter 7) so every reading—including foulers and sighters—lands on its own shot's line.
4. Never change chronographs mid-test; to compare two units, record the same shots on both and note the offset.

EASIER ON EP · CHRONOS · CHRONOGRAPH IMPORT

Chronos imports the chronograph file, and you pair each reading with the shot that made it.

empiricalprecision.com/chrono

Shoot the hardware baseline

Your first session establishes the rifle's hardware baseline with repeatable ammunition (see Chapter 4), against which every later load is judged:

1. Use a proven load or one lot of factory match ammunition, following the protocol above (actual-size targets, offset aim marks, separate foulers, every shot logged).
2. Fire five 5-shot groups—never trust a single group.[3]
3. Label the targets, pool the five groups into one composite mean radius (see Chapter 15), and record it in the baseline log with the barrel round count (see Chapter 13).
4. *(If handloading)* Save and label the fired cases for this rifle; their chamber-formed shape sets your sizing die (see *The Handloading Handbook*).

Chapter 15

Measurement Science for Shooters

Key points

- Mean radius uses every shot. Extreme spread uses two, and it grows with the number of shots.
- Distance from a group's center follows a Rayleigh curve. About 39, 86 and 99 percent of shots land within 1, 2 and 3 single-axis SDs of the center.
- Every number from a sample is an estimate. Its shot count and confidence interval show how far to trust it.
- One small group is mostly luck. A composite of many groups tells you far more.
- Every shot is data. Where a shot landed is never a reason to drop it.

Why it matters

A load decision is a measurement, and one 5-shot group is a very small sample. Suppose you shoot seven identical loads as one 5-shot group each. On average, the best group comes out at 0.66 times the load's average 5-shot group, and the worst at 1.38 times. Pick the best of seven and you have picked luck.

Judging a load by its best group is like judging a whole pan of lasagna by one perfect corner square (see Chapter 1). The load is the whole pan.

Without a few statistical tools you chase noise. You change a charge by 0.1 gr because one group looked better, and the "best" load never repeats. With them you can say how big a group really is, how sure you are and how many more shots would settle the question (see Chapter 16).

How it is done

The terms

Term	Meaning
POA	Point of aim: where you aimed.
POI	Point of impact: where a bullet struck, measured as x (right) and y (up) from the aim mark.
MPI	Mean point of impact: the average of all x values and of all y values. It is the group's center.
ES	Extreme spread: the center-to-center distance between the two shots farthest apart. For velocity, the fastest minus the slowest.
MR	Mean radius: the average distance of every shot from the MPI.
SD	Standard deviation: how far a typical value sits from the average. You measure it for velocity and for each axis of a group.
n	The number of shots.
CI	Confidence interval: the span the true value plausibly lies in, given the shots you have.
MOA	Minute of angle. One MOA is about 1.047 inches at 100 yards.

Extreme spread and mean radius

Extreme spread measures the two widest shots and ignores every other shot. Mean radius measures every shot.

```
MPI x = (x1 + x2 + ... + xn) ÷ n
MPI y = (y1 + y2 + ... + yn) ÷ n
r     = √((x − MPI x)² + (y − MPI y)²)        for each shot
MR    = (r1 + r2 + ... + rn) ÷ n
```

ES has a second flaw. It grows with the number of shots, because every added shot is another chance to land wider than the widest pair so far. On average, the same load gives a larger ES over 10 shots than over 5. Never compare ES across different shot counts. Table 15-1 shows how fast velocity ES grows.

Table 15-1. Expected velocity ES, in units of SD.

Shots	Expected ES	If the true SD is 10 fps
5	about 2.3 SD	about 23 fps
10	about 3.1 SD	about 31 fps
30	about 4.1 SD	about 41 fps

Example numbers. Not load data.

ES still has a job. It rules out a bad load or a broken rifle fast. If a rifle that should shoot 0.5 MOA groups prints a 6-inch 3-shot group at 100 yards, you need no more shots. Something is wrong. Check the scope mounts and the ammunition before you fire again. Adam MacDonald divides the labor this way: “Use extreme spread to rule out a bad load with 5 shots. Use standard deviation to prove a good load with confidence.”[1]

Velocity ES has a job too. One slow round can drop below a plate at long range. A shot far slower or faster than the rest of its string points at something mechanical, such as erratic ignition or uneven neck tension, or at a chronograph misread (see Chapter 24). Inspect that case. A blown primer is a pressure sign: stop (see *The Handloading Handbook*).

Evidence · Supported by data
Assuming normal scatter, group ES runs about 2.7 times the measured MR for 5 shots and 3.2 times for 10. Over more than 150 real groups, the measured ratio was 2.75.[2] In a single 5-shot group, ES and MR are about equally noisy. MR pulls ahead as shots add up, and it pools across groups where ES cannot.

How shots scatter: normal and Rayleigh

Velocity has one dimension. Over many shots, velocities form a bell curve, the normal distribution. About 68 percent fall within 1 SD of the average, 95 percent within 2 SD and 99.7 percent within 3 SD. The same holds for the heights of shots on their own, or for their left-right positions on their own.

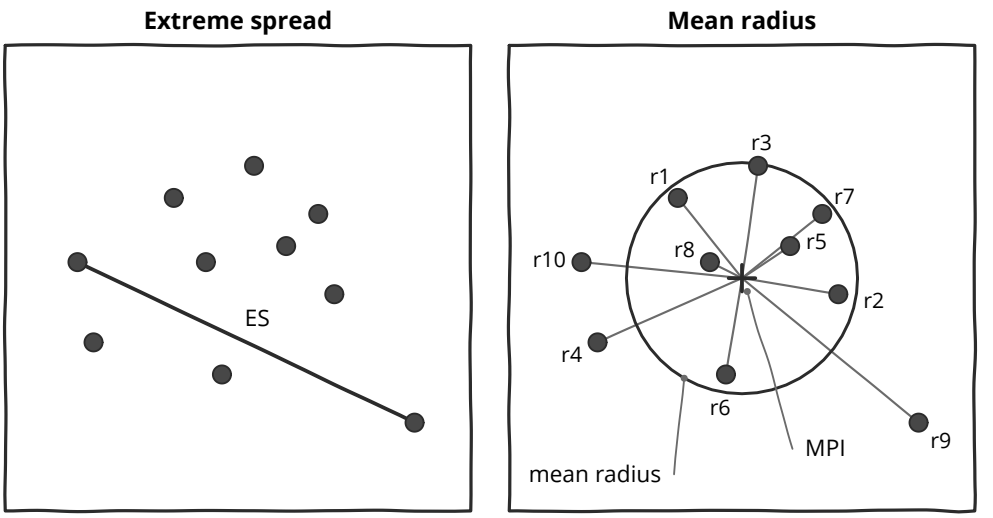


Figure 15-1. One group, two measures. Extreme spread uses the two widest shots, while mean radius averages the distance of every shot from the group's center.

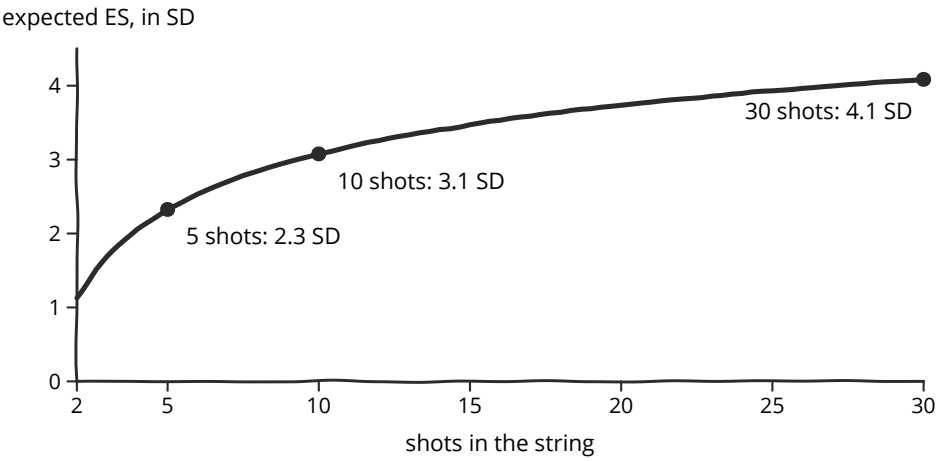


Figure 15-2. Expected velocity ES grows with the number of shots, from about 2.3 SD at 5 shots to about 4.1 SD at 30.

A group on paper has two dimensions. Each axis follows its own bell curve, but the distance from the center does not. A distance cannot be negative, so its curve starts at zero, rises to a peak and trails off to the right. This is the Rayleigh distribution, and its shares differ from the familiar ones. For a round group, with σ (sigma) the standard deviation along one axis:

Distance from the group's center	Share of shots inside it
1σ	about 39 percent
2σ	about 86 percent
3σ	about 99 percent

```
share of shots within z σ of the center = 1 − exp(−z² ÷ 2)
mean radius ≈ 1.25 × σ of one axis          (round group)
```

The 68, 95 and 99.7 percent rule does not apply to distance from the center. Applied there, it makes a normal group look as if it has flyers. About 14 percent of shots land beyond

2 SD, roughly one shot in seven. In a 10-shot group, one or two shots that far out are normal.

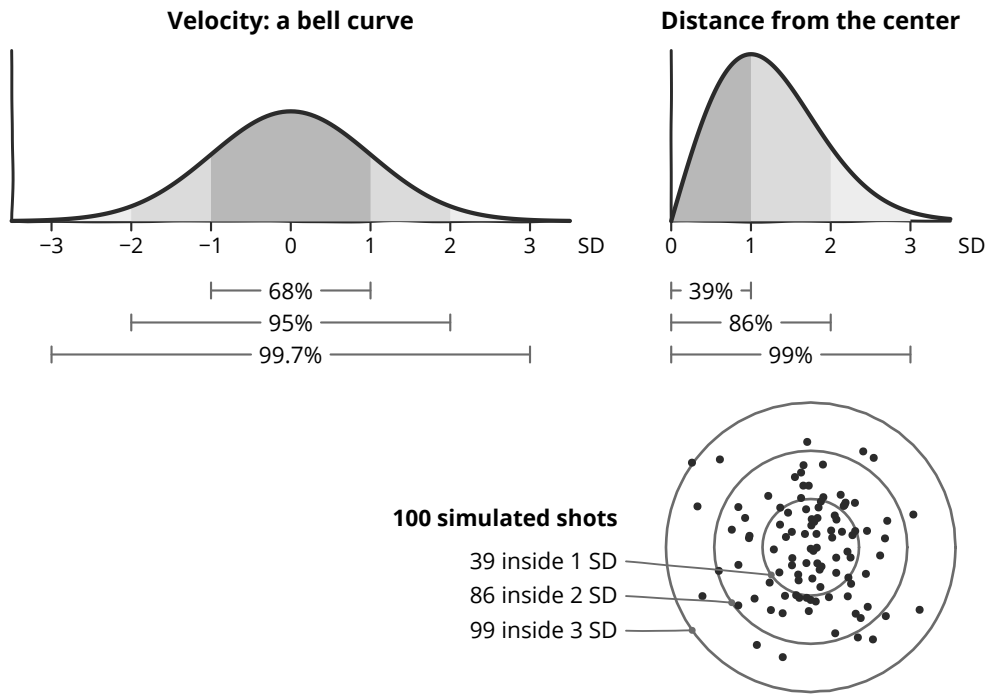


Figure 15-3. Two shapes of scatter. Velocity follows a bell curve, with 68, 95 and 99.7 percent of shots within 1, 2 and 3 SD. Distance from a group's center follows a Rayleigh curve, with 39, 86 and 99 percent.

Velocity SD

```
average = (v1 + v2 + ... + vn) ÷ n
SD      = √( [(v1 − average)² + (v2 − average)² + ...
             + (vn − average)²] ÷ (n − 1) )
```

Divide by n − 1, not n. Because the sample average is calculated from those same shots, the shots sit slightly closer to the sample average than to the load's true average. Dividing by n − 1 corrects that downward bias. The small-group correction below fixes the same bias for group size on paper.

Worked example. Five velocities: 2,795, 2,810, 2,802, 2,788 and 2,805 fps. Example numbers. Not load data.

1. Average: 14,000 ÷ 5 = 2,800 fps.
2. Differences from the average: −5, +10, +2, −12 and +5.
3. Squares: 25, 100, 4, 144 and 25. Their sum is 298.
4. Divide by n − 1, which is 4: 298 ÷ 4 = 74.5.
5. Take the square root: the SD is 8.6 fps.

The ES is 2,810 − 2,788 = 22 fps, or about 2.6 SD. That is close to the 2.3 SD expected for 5 shots.

Two things inflate a measured SD.

- **Instrument error.** The chronograph's own scatter adds to the true velocity SD (see Chapter 7).
- **Pooling across days.** Average velocity can shift from day to day, mostly with temperature. A single SD calculated across multiple days includes that day-to-day shift, so note if you report one. To measure within-session SD without day-to-day drift, subtract each session's average velocity from the shots fired in that session. Square all those differences, add them together, divide by `(total shots - number of sessions)` and take the square root. Use `(total shots - number of sessions)` as the degrees of freedom in place of `n - 1` in Appendix A.5.

There is no universal SD target. Set yours from hit probability at your distance (see Chapter 21).

Confidence intervals

Every SD or MR you measure is an estimate of the load's true figure. A confidence interval says how far off the estimate could plausibly be. A 90 percent interval is built so that, over many tests, about 90 of every 100 such intervals contain the true value.

The intervals below are 90 percent. Use them to judge one load against a goal: the upper end of a 90 percent interval is a 95 percent upper bound. To compare two loads, use the wider 95 percent interval, the 0.05 level of the tests in Chapter 16 (see Appendix A.5 for both).

Table 15-2 shows how wide that uncertainty is for velocity SD. Multiply your measured SD by the two numbers to get the interval.

Table 15-2. The 90 percent interval for the true velocity SD, as a multiple of the SD you measured.

Shots	Interval
5	0.65 to 2.37
10	0.73 to 1.65
20	0.79 to 1.37
30	0.83 to 1.28

The multiples come from the chi-square distribution. It describes how far the SD of n normally distributed values tends to wander from the true SD. For 5 shots, n − 1 is 4, and the two formulas give 0.65 and 2.37.

```
low multiple  = SQRT((n-1)/CHISQ.INV(0.95, n-1))
high multiple = SQRT((n-1)/CHISQ.INV(0.05, n-1))
```

Apply the table to the 5-shot example. With 90 percent confidence, the true SD lies between 8.6 × 0.65 = 5.6 fps and 8.6 × 2.37 = 20.4 fps. That string could have come from excellent ammunition or from poor ammunition. Ten shots that measure 10 fps narrow the interval to 7.3 to 16.5 fps. Example numbers. Not load data.

Group size behaves the same way. The true dispersion behind one 5-shot group lies between 0.71 and 1.77 times its corrected mean radius (see "The small-group correction" below). Behind six 5-shot groups composited, it lies between 0.85 and 1.22 times. Appendix A.5 gives other layouts at 90 and 95 percent.

Intervals also tell you whether two loads are separated. If the intervals do not overlap, you have good evidence that the loads differ. If they overlap almost completely, these shots have not separated them yet. If they overlap a little, run the F-test in Chapter 16, which can still separate them. Overlap does not prove the loads are the same. A load at an MR of .35 inch and one at .38 inch, each from six 5-shot groups, have 95 percent intervals of .29 to .44 and .32 to .48 inch. They cannot yet be ranked. Fire more rounds (see Appendix A.5). Example numbers. Not load data.

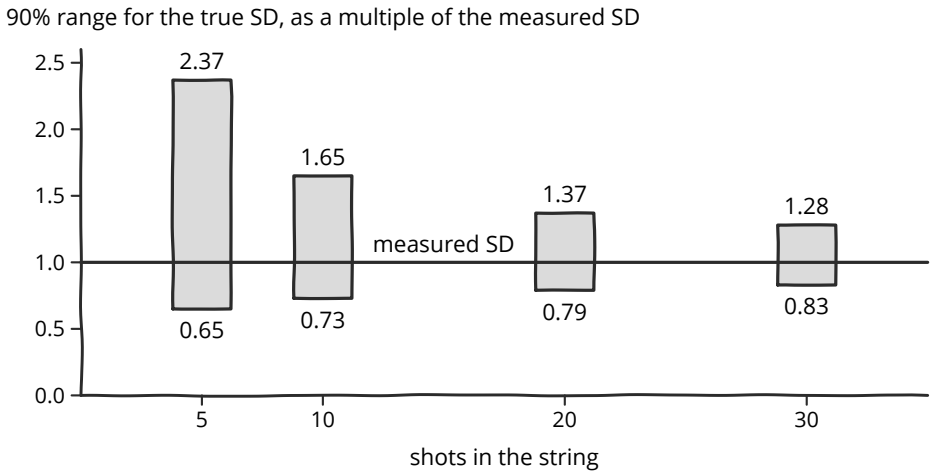


Figure 15-4. How sure is a velocity SD? The 90 percent interval for the true SD narrows from 0.65 to 2.37 times the measured value at 5 shots to 0.83 to 1.28 times at 30.

Composite groups

A composite pools several groups into one measurement. Build one this way.

1. Fire several groups of one load. Give each group its own aim mark.
2. Work out each group's own MPI from its own shots.
3. Measure every shot from its own group's MPI.
4. If the groups were shot at different ranges, convert each shot's distance from its MPI to an angle.

```
MOA = inches ÷ (1.047 × yards ÷ 100)
```

5. Correct each shot's distance for its own group's shot count (k), with the factor in "The small-group correction" below.
6. Pool all the corrected distances and average them. That is the composite MR.

Aligning the centers removes whatever moved each group as a whole, such as a change of zero or a steady wind. It keeps the spread, which is what you are measuring. Ten 5-shot groups composited give 50 shots, worth about 40 for measuring spread.

Keep every shot's raw x and y. Never average old averages. An average of averages hides how many shots stand behind each number, so a 3-shot group counts as much as a 10-shot one.

Each group costs a little. Its center comes from its own shots, so a group of k shots tells you about as much about spread as k − 1 shots would. Twenty shots in one group pin the MR more closely than 20 shots in 10 groups.

Composite only what belongs together: the same rifle, the same load and the same hardware. Any hardware change starts a new baseline (see Chapter 4).

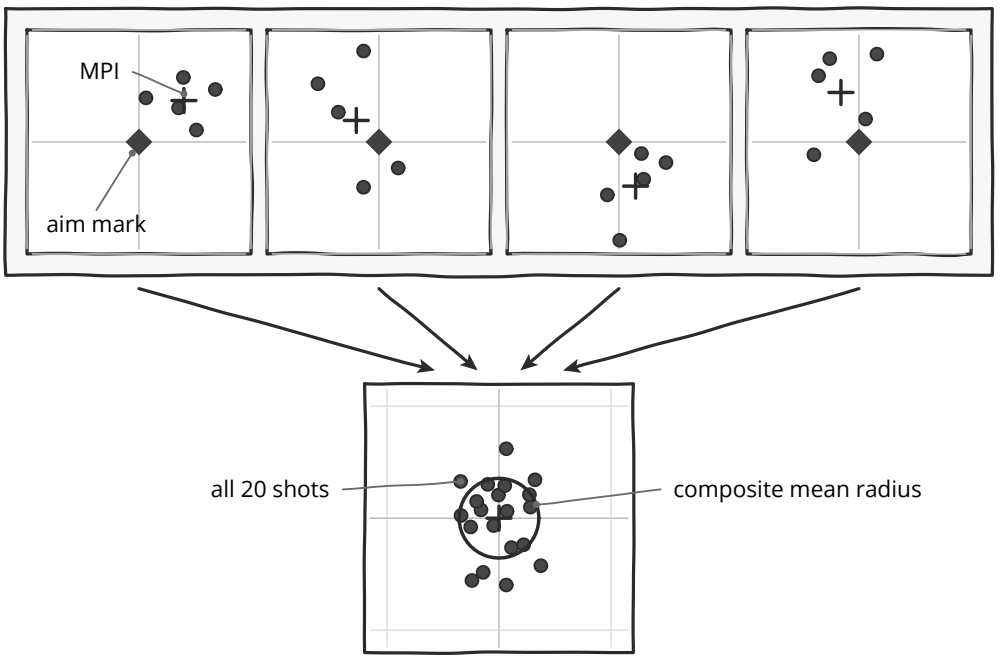


Figure 15-5. Building a composite. Each small group is centered on its own MPI. Then all the shots are overlaid in one frame.

The small-group correction

A small group's center comes from its own shots. So it sits closer to them than the load's true center does, and distances measured from it read small on average. The effect is 18.4 percent for 3-shot groups, 10.6 percent for 5-shot groups and 5.1 percent for 10-shot groups.

```
corrected MR = measured MR × √(k ÷ (k − 1))
k            = shots in the group
```

Table 15-3. How far a group's measured mean radius reads small, and the factor that corrects it.

Shots per group (k)	Measured MR reads small	Multiply by
3	18.4%	1.225
5	10.6%	1.118
10	5.1%	1.054

Without the correction, a load shot as many small groups looks tighter than the same load shot as a few large ones. The correction puts both on equal terms.

Every shot matters

Once you commit to the target, record every shot. Removing shots that spoil a group biases the result toward the answer you wanted. A wide shot can also carry information, such as a loose scope, a bad case or a hole marked in the wrong place. Every removed shot widens the interval. And exclusions that are not written down make your results impossible for anyone else to check or repeat.

Only two kinds of shot may be left out of the data.

Shots declared before firing. These include fouling shots after you clean the bore, sighters and warm-up rounds. Fire them at a separate aim mark or on a separate sheet, so they never mix with the test groups (see Chapter 14).

Shots with a documented shooter or equipment error. Examples are a rifle you felt jump off the rest, a shot that broke with the crosshair off the aim mark and a pulled trigger you called. Write the fault down as soon as you fire, before you look through a spotting scope or at the target.

Never leave out a shot because of where it landed. Calling an awkward shot an unexplained flyer only fools you.

To document an exclusion:

1. Write down the shot number, the reason and when you noted it.
2. Keep the shot in the raw record, marked with the part it leaves out: excluded group or excluded velocity (see Chapter 13).
3. Run the analysis with and without it. If the conclusion changes, you need more shots, not fewer.

> **Evidence · Folklore**
> The claim is that a shot far from the rest is a flyer and does not belong to the load. In a round group, some shots land wide by chance alone (see “How shots scatter: normal and Rayleigh”). Being wide does not, on its own, take a shot out of the load.

Worked example: mean radius by hand

Ten shots at 100 yards, measured from the aim mark. All values are in inches, and the squared columns are in square inches. Example numbers. Not load data.

Shot	x	y	dx	dy	dx²	dy²	r
1	1.20	2.05	−0.20	+0.25	0.0400	0.0625	0.320
2	1.70	1.75	+0.30	−0.05	0.0900	0.0025	0.304
3	1.45	2.15	+0.05	+0.35	0.0025	0.1225	0.354
4	0.95	1.60	−0.45	−0.20	0.2025	0.0400	0.492
5	1.55	1.90	+0.15	+0.10	0.0225	0.0100	0.180
6	1.35	1.50	−0.05	−0.30	0.0025	0.0900	0.304

Shot	x	y	dx	dy	dx²	dy²	r
7	1.65	2.00	+0.25	+0.20	0.0625	0.0400	0.320
8	1.30	1.85	−0.10	+0.05	0.0100	0.0025	0.112
9	1.95	1.35	+0.55	−0.45	0.3025	0.2025	0.711
10	0.90	1.85	−0.50	+0.05	0.2500	0.0025	0.502
Sum	14.00	18.00	0.00	0.00	0.9850	0.5750	3.599

1. **Measure each shot.** For each hole, measure x to the right and y up from the aim mark to the center of the hole. Dial the offset so the group lands up and right of the aim mark (see Chapter 14). Then every number is positive.
2. **Find the MPI.** The x values add to 14.00, and 14.00 ÷ 10 = 1.40. The y values add to 18.00, and 18.00 ÷ 10 = 1.80. The group's center is 1.40 inches right of the aim mark and 1.80 inches above it.
3. **Find each shot's offsets.** dx = x − 1.40 and dy = y − 1.80. Each column of offsets adds to zero, which is a useful check.
4. **Square the offsets and add them.** Work out $dx^2 + dy^2$ for each shot.
5. **Take the square root.** That is the shot's distance r from the center.
6. **Average the distances.** 3.599 ÷ 10 = .360 inch. That is the measured mean radius.
7. **Correct for group size.** This is one 10-shot group, so multiply by 1.054: .360 × 1.054 = .379 inch.
8. **Convert to an angle if you need one.** At 100 yards, .379 ÷ 1.047 = 0.36 MOA.
9. **Find the ES for comparison.** The two shots farthest apart are 9 and 10: $\sqrt{(1.05^2 + 0.50^2)} = \sqrt{1.3525} = 1.16$ inches. That is 3.2 times the measured MR, about average for 10 shots. Eight of the ten shots play no part in it.

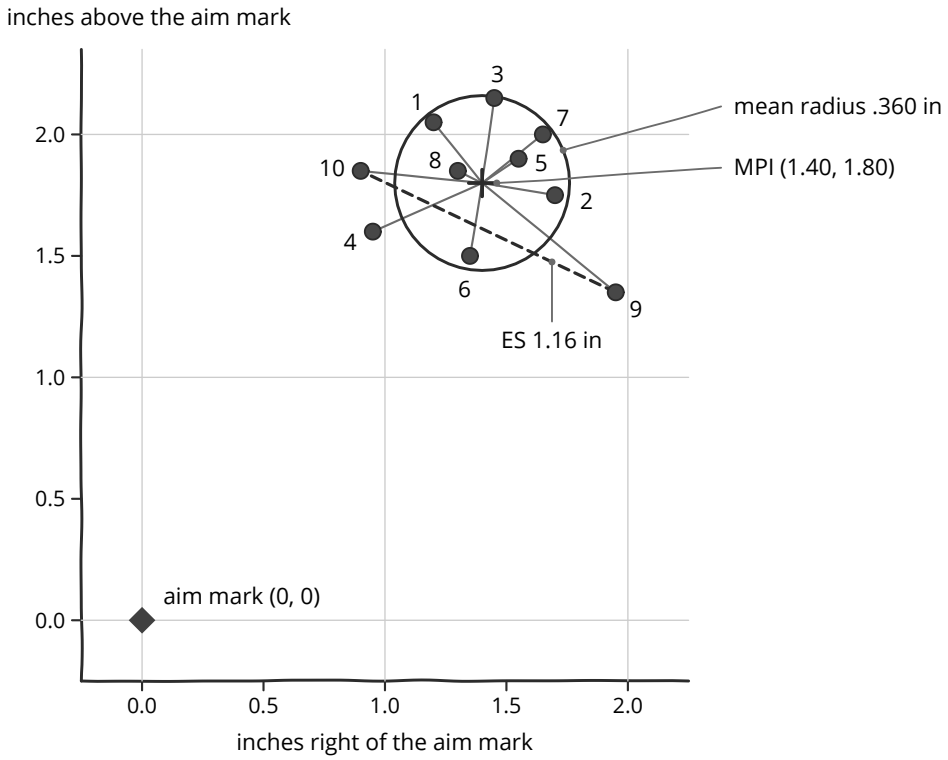
The same table gives the spread on each axis, which is where a stringing check starts (see Chapter 24, Table 24-1).

```
SD horizontal = √(0.9850 ÷ 9) = .33 inch
SD vertical   = √(0.5750 ÷ 9) = .25 inch
```

By spreadsheet

Any spreadsheet does the same work in seconds. Put the x values in column A, the y values in column B and any velocities in column D, in rows 2 to 11.

```
E1:  =AVERAGE(A2:A11)                MPI x
E2:  =AVERAGE(B2:B11)                MPI y
C2:  =SQRT((A2-$E$1)^2+(B2-$E$2)^2)  distance r, copy down to C11
E3:  =AVERAGE(C2:C11)                measured MR
E4:  =E3*SQRT(10/9)                  corrected MR, one 10-shot group
E5:  =STDEV.S(D2:D11)                velocity SD
```



Example numbers. Not load data.

Figure 15-6. The worked example plotted: ten shots, the aim mark and the MPI 1.40 inches right of it and 1.80 inches up, with each shot's distance r and the ES line between shots 9 and 10.

The ten example shots give .360 in E3 and .379 in E4.

For a composite, center each group on its own MPI. On the shot sheet (see Chapter 13), columns A to J run from Session to Note. Add six columns and copy each formula down.

```
K2:  =OR(F2="test",F2="excluded velocity")
L2:  =AVERAGEIFS(G:G,A:A,A2,B:B,B2,D:D,D2,K:K,TRUE)
M2:  =AVERAGEIFS(H:H,A:A,A2,B:B,B2,D:D,D2,K:K,TRUE)
N2:  =COUNTIFS(A:A,A2,B:B,B2,D:D,D2,K:K,TRUE)
O2:  =SQRT((G2-L2)^2+(H2-M2)^2)
P2:  =IF(AND(K2,N2>1),O2*SQRT(N2/(N2-1)),"")
```

Column K flags the shots whose bullet holes count in the group (`test` and `excluded velocity`). Columns L and M calculate that group's MPI, N counts the valid shots in that group (`k`), O calculates each shot's distance `r` from the group's MPI, and P applies the small-group correction. Fouler, sighter and `excluded` `group` rows remain blank in column P, so they drop out automatically. The composite MR for load B3 is then:

```
=AVERAGEIFS(P:P,B:B,"B3")
```

EASIER ON EP · ANALYSIS · STATISTICAL TOOLS

Analysis gathers one load's shots from any sessions into one composite and gives its mean radius and velocity SD, each with its 95 percent interval.

empiricalprecision.com/analysis?tab=queues

Chapter 16

Comparing Cartridges, Loads, and Hardware

Key points

- A plan fixed before the test keeps you from choosing luck after it.
- A fixed sample is simple and fair but costly. Two-phase screening saves rounds but can cut a good load. A sequential tournament can save the most when one load is much worse, but needs a stricter threshold.
- A small sample can reject a bad load but cannot rank good ones. The recommended default screens briefly and gives the large sample to one finalist.
- The big gains come from the bullet, the powder and the barrel, not from fine charge changes.
- Every extra load, and every extra look at the data, is one more chance for luck. The threshold tightens to match.

Why it matters

Small samples make identical loads look different. Shoot seven identical loads as one 5-shot group each, and the best group averages 0.66 times the load's average 5-shot group (see Chapter 15). Pick it and you have mostly picked luck. Real differences are expensive to prove. Separating two loads whose dispersion differs by 1.5 to 1 takes about 35 shots per load, and 1.25 to 1 takes about 110 (see Table 16-1).

Small samples can still answer big questions. A few shots are enough to show that something is badly wrong. The skill is matching the shot count to the size of the question.

> **Evidence · Supported by data**
> The figures above are calculations that assume normally scattered shots. Measured groups matched the calculated ratio of group size to mean radius.[1]

How it is done

For most testing, follow "The recommended default" below. Methods 1 to 3, after it, rank several loads at once.

Decide before you shoot

Write down the test plan before you prepare a single test round. Start with the question. Which of four loads groups best? Or does one load meet a 600-yard goal? Those are different tests.

Use mean radius for dispersion and velocity SD for consistency, and report each with its confidence interval. Keep extreme spread for spotting a gross fault. Set your goal as a maximum mean radius and maximum velocity SD for your target distance, such as 0.50 MOA and 12 fps. You can derive these limits from your desired hit probability using a drop chart (see Chapters 20 and 21). Until you have measured muzzle velocity, build a preliminary drop chart from the bullet maker's BC and the published velocity adjusted for your barrel length, then update the limits once you have chronograph data. Choose your

test method, shot counts and rejection threshold in advance so the goalposts cannot move after you see the targets.

What a p-value means

A statistical test of two loads returns a p-value. It is easy to misread.

- The p-value is the probability of seeing a gap at least this large if the two loads were really the same.
- It is not the probability that one load is better or worse. A p-value under 0.05 does not mean 95 percent certainty that the load with the smaller group is better.
- A p-value under 0.05 means identical loads would show a gap at least this large less than 1 time in 20. That is good evidence of a real difference. It is not proof.
- Each new test is a new chance for luck to fool you. Testing again after every block adds chances, and so does testing several loads at once. Both need a stricter threshold (see "Testing more than two loads" and "Method 3. The sequential tournament" below).

How many shots answer which question

Table 16-1. Shots per load needed to separate two loads, with a two-sided test at 0.05 and 80 percent power.

One load worse than the other by	For dispersion	For velocity SD
1.5 to 1	about 35 shots	about 50 shots
1.25 to 1	about 110 shots	about 160 shots

Dispersion is compared with an F-test on the two mean radii, shot as 5-shot groups (see Appendix A.6). Velocity SD is compared with an F-test on the two SDs (see Appendix A.8). Both tests are worked in "Comparing two loads by hand" below. Smaller groups cost more shots: in 3-shot groups the dispersion column becomes about 42 and 132. A two-sided test counts a gap in either direction. At 0.05 it raises a false alarm 1 time in 20 when the loads are really the same. A power of 80 percent means the test catches a real difference of that size 8 times in 10.

Table 16-2. The chance that two identical loads look different, with one group each and one group at least 1.5 times the size of the other.

Shots per group	Chance
3	46 percent
5	30 percent

Put together, the tables suggest how many shots each question needs.

Question	Shots
Is something broken?	3 to 5, and read the ES
Is this load clearly bad?	5 to 10 per load, as a screen
Is this load good?	A 20 to 30 shot composite
Is one load 1.5 times better than another?	About 35 each for groups, 50 each for velocity SD
Is it 1.25 times better?	About 110 and 160 each. Changing the bullet or powder is usually cheaper.

Careful testers disagree only about how many shots are enough. Their suggestions are 20 to 50 shots, five 5-shot groups and 10-shot groups.[2] That is a trade between cost and barrel life, not a dispute about the math.

EASIER ON EP · ANALYSIS · STATISTICAL TOOLS

Analysis gives the shots each load needs for the difference you want to find, your group size and the number of loads you will compare. It also says how many more shots the loads under test still need.

empiricalprecision.com/analysis

Evidence · Folklore

The claim is that one 3-shot or 5-shot group shows how a load shoots. Assuming normal scatter, two identical loads shot as one group each often look clearly different (see Table 16-2 and Figure 16-2). A small group can rule out a disaster, but it cannot rank loads.

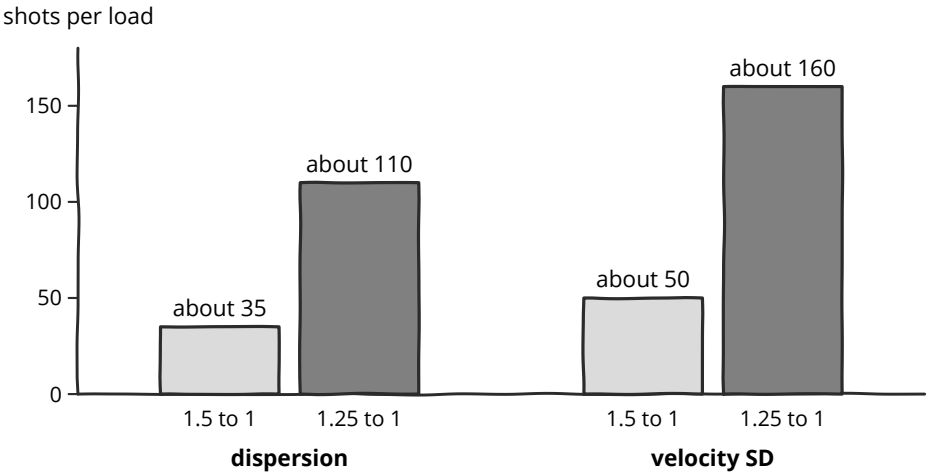


Figure 16-1. Shots needed per load to tell two loads apart. A 1.25 to 1 difference needs about 3 times the shots of a 1.5 to 1 difference.

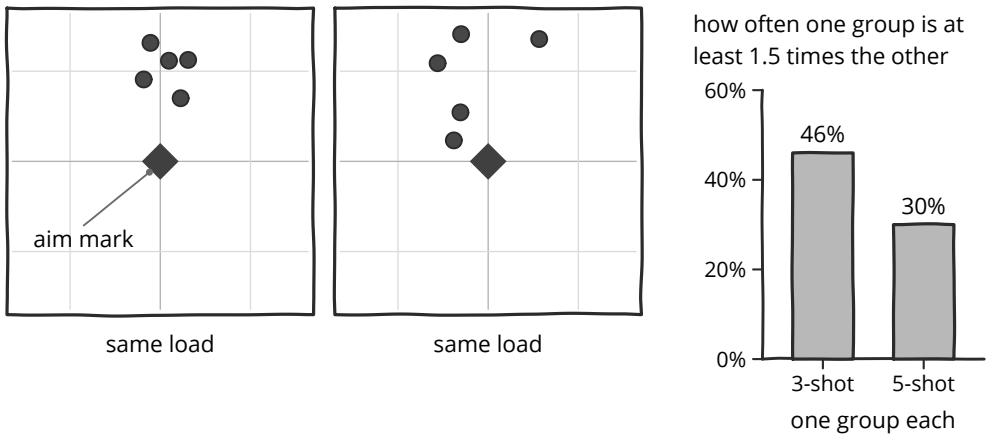


Figure 16-2. Same load, different groups. Shot as one group each, two identical loads show one group at least 1.5 times the other 46 percent of the time with 3-shot groups and 30 percent with 5-shot groups.

Comparing two loads by hand

Intervals give a quick first look (see Chapter 15). When two loads' intervals overlap almost completely, these shots cannot say which load is better. When the intervals do not overlap at all, the difference is very unlikely to be luck (see Figure 16-3). When they overlap a little, run a test.

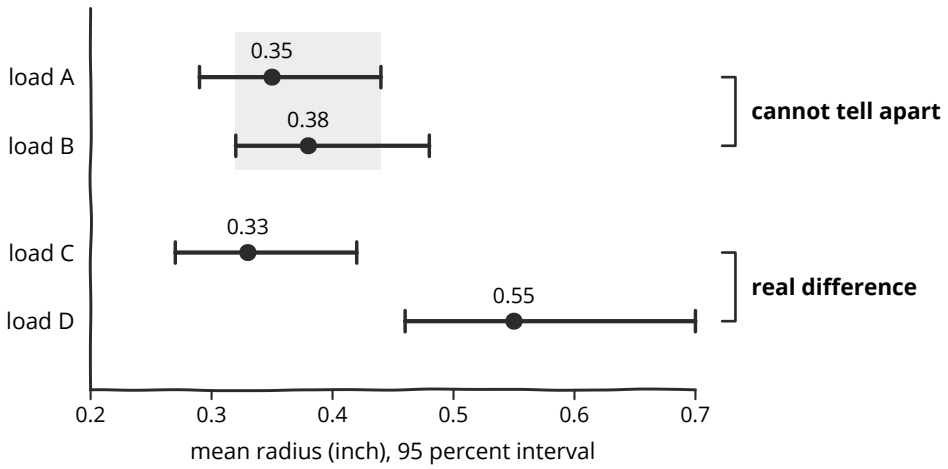


Figure 16-3. Two pairs of loads with their 95 percent intervals. One pair overlaps almost completely. The other pair is clearly separated.

With a calculator. When comparing two loads fired for the same number of shots in 5-shot groups, divide the larger mean radius by the smaller. Call the load with the larger mean radius worse if the ratio reaches or exceeds the threshold in Table 16-3 (which pre-calculates the F-test below). When comparing more than two loads, divide each load's mean radius by the smallest mean radius and use the column for the total number of loads tested (see "Testing more than two loads" below).

Table 16-3. The ratio of mean radii (larger divided by smaller) needed to call a load worse in a two-sided test when all loads have the same number of shots, fired in 5-shot groups. Two loads use 0.05. More loads use the thresholds in Table 16-5.

Shots per load	2 loads	3 loads	4 loads	5 loads	6 loads
10	1.70	1.94	2.08	2.18	2.27
20	1.45	1.58	1.65	1.71	1.75
30	1.35	1.45	1.50	1.54	1.57
35	1.32	1.41	1.45	1.49	1.52
50	1.26	1.33	1.37	1.39	1.42
100	1.18	1.22	1.25	1.26	1.28

With a spreadsheet. For any shot counts and group sizes, use an F-test on the two mean radii. It compares the square of their ratio with the F distribution, on each load's degrees of freedom (see Appendix A.5 for the degrees of freedom and A.6 for the test).

```
For each load: n = shots, g = groups, MR = mean radius,
corrected for small groups (see Chapter 15)

df = 2 × (n − g) × 0.915
F  = (larger MR ÷ smaller MR)²
two-sided p = 2 × F.DIST.RT(F, df of larger, df of smaller)
```

The 0.915 adjusts the degrees of freedom for mean radius (see Appendix A.5). Use the two-sided test, because only the data tell you which load looks worse. Spreadsheets round the degrees of freedom down, which changes p very little.

Worked example. Example numbers. Not load data.

Load A has 30 shots in six 5-shot groups and a mean radius of .42 inch. Load B has the same layout and a mean radius of .60 inch.

```
df          = 2 × (30 − 6) × 0.915 = 43.9 for each load
F           = (0.60 ÷ 0.42)² = 2.04
two-sided p = 2 × F.DIST.RT(2.04, 43.9, 43.9) = 0.020
```

Here a gap at least this large would turn up about 2 times in 100 if the two loads were really the same. That is not the chance that load B is worse (see "What a p-value means" above).

For one planned test of two loads, a p-value below 0.05 is the usual line. On that rule you would call load B worse. Table 16-3 agrees: the ratio is 1.43, past the line of 1.35 for 30 shots.

Two cautions apply to every comparison. First, a small sample has little power. With one 5-shot group per load, only a very large gap clears 0.05, and a p-value above it does not show the loads are the same (see Table 16-1). Second, radii measured from a group's own center read small, and more so in small groups. Apply the small-group correction to each load before testing (see Chapter 15).

Velocity SD. Compare two velocity SDs the same way, using an F-test. When both loads have the same number of shots, divide the larger SD by the smaller and compare the ratio against Table 16-4.

Table 16-4. The ratio of velocity SDs (larger divided by smaller) needed to call a load less consistent in a planned two-sided test at 0.05 when both loads have the same number of shots.

Shots per load	Larger SD, at least this many times the smaller
10	2.01
20	1.59
30	1.45
50	1.33
100	1.22

In a spreadsheet, F.TEST on the two loads' velocities gives the two-sided p-value. The same test by hand:

```
For each load: n = shots, SD = velocity SD

df = n − 1
F  = (larger SD ÷ smaller SD)²
two-sided p = 2 × F.DIST.RT(F, df of larger, df of smaller)
```

Worked example. Example numbers. Not load data.

Load A has 30 shots with a velocity SD of 9.0 fps. Load B has 30 shots with a velocity SD of 14.0 fps.

```
F           = (14.0 ÷ 9.0)² = 2.42
two-sided p = 2 × F.DIST.RT(2.42, 29, 29) = 0.020
```

On the 0.05 line you would call load B less consistent. The ratio, 1.56, is past the line of 1.45 in Table 16-4.

The recommended default

A short screen and one large confirmation answer most questions.

1. Choose the candidates. Start from proven factory SKUs or proven components, and make the candidates differ in something that matters, such as the bullet, powder, or ammunition brand/lot.
2. *(Handloaders only; factory-ammo shooters start at Step 4.)* Work up each candidate for pressure and velocity from its published start load (see *The Handloading Handbook*). One shot per step is fine for safety. It cannot find a node (see Chapter 17).
3. *(Handloaders only; factory-ammo shooters start at Step 4.)* Choose each candidate's charge for your velocity goal (see *The Handloading Handbook*), with margin below the step where its work-up stopped (see *The Handloading Handbook*).
4. Screen each candidate with 5 to 10 shots, interleaved in one session (for .22 LR testing across brands with different bullet waxes, do not interleave every 5 rounds—shoot one

brand per session or patch and season between brands; see Chapters 14 and 23). Reject the ones that are clearly bad. Extreme spread is good at catching a bad load.[3]

5. Pick one finalist.
6. Confirm the finalist with a 20 to 30 shot composite, ideally over two or more sessions.
7. Judge it against your goal using the upper end of its 90 percent interval (see Chapter 15). For a hit goal at distance, judge it by its hit chance (see Chapter 21). For velocity SD across multiple sessions, use the within-session SD (see Chapter 15, "Pooling across days") if your drop chart corrects velocity for temperature (see Chapter 23). Otherwise, use the pooled SD. Record which one you used.
8. If it passes, you are done. If it fails, go back to step 6 with the next candidate that passed the screen. Or change the bullet or the powder and go back to step 2. A new bullet or powder needs its own work-up. Do not adjust the charge by 0.1 gr.

The last step matters most. A 0.1 gr change is tiny next to a change of bullet or powder. Small-sample charge nodes rarely repeat in large tests (see Chapter 17). Proving the effect of a 0.1 gr change would take far more shots than even a 1.25 to 1 difference needs.

Worked example. Example numbers. Not load data.

Say your goal at 600 yards is a corrected mean radius of 0.50 MOA or less and a velocity SD of 12 fps or less (see Chapter 21). Four candidates use two bullets and two powders. Each was screened with 10 shots in one session.

Candidate	Mean radius, corrected (MOA)	Velocity SD (fps)	Velocity ES (fps)
1	0.38	11	35
2	0.47	9	30
3	0.79	14	52
4	0.43	24	81

Candidate 4 goes. Its 81 fps velocity ES is a red flag. A 10-shot SD has a 90 percent interval of 0.73 to 1.65 times the measured value. That puts its true SD between about 18 and 40 fps, wholly above the goal.

Candidate 3 goes too. Even a single 5-shot group has a 90 percent interval of 0.71 to 1.77 times, and 10 shots are tighter than that. At the low end, 0.71 × 0.79 = 0.56 MOA, which is still above the goal.

Ten shots cannot separate candidates 1 and 2. Pick one on whatever matters next, such as bullet supply, cost or ballistic coefficient. Say you pick candidate 1.

The confirmation is six 5-shot groups over two sessions. The measured mean radius is 0.36 MOA and the pooled velocity SD is 9 fps. First correct the mean radius for 5-shot groups.

```
corrected MR = measured MR × √(k ÷ (k − 1))
k = shots per group
0.36 × √(5 ÷ 4) = 0.36 × 1.118 = 0.40 MOA
```

For six 5-shot groups, the 90 percent interval for dispersion is 0.85 to 1.22 times. For 30 shots, velocity SD has a 90 percent interval of 0.83 to 1.28 times.

```
Mean radius:  0.40 × 0.85 = 0.34    to   0.40 × 1.22 = 0.49 MOA
Velocity SD:  9 × 0.83 = 7.5        to   9 × 1.28 = 11.5 fps
```

Both upper ends sit inside the goal, so candidate 1 passes. Suppose instead the corrected mean radius had come back at 0.62 MOA. Its whole 90 percent interval, 0.53 to 0.76 MOA, would sit above the goal. You would then move to candidate 2 or to a new bullet or powder, not to a 0.1 gr change.

Evidence · Supported by data
In large-sample tests, bullet, powder and barrel dominate precision.[4] Screening small and confirming large follows from those results.

EASIER ON EP · ANALYSIS · STATISTICAL TOOLS

Analysis ranks the loads under test for mean radius and velocity SD, calls any load shown worse than the leader and judges each against your goal. For a load tied with the leader, it gives the shots each would need to tell the two apart if the gap measured is real.

empiricalprecision.com/analysis

Testing more than two loads

Every extra load is one more chance for luck. You test the leader against each of the others, and the leader is the luckiest load of the group. That works like testing every pair. Take five loads that are truly the same and shoot 35 shots of each. Test the leader against the other four at a plain 0.05. At least one load will be called worse about 27 times in 100.

The fix is to divide 0.05 by the number of pairs. Five loads make 10 pairs, so the threshold is 0.005. The count is loads × (loads − 1) ÷ 2.

Table 16-5. Call a load worse when its two-sided p-value against the leader is below this threshold, in one test after all shots are fired.

Loads	Pairs	Threshold
2	1	0.05
3	3	0.016
4	6	0.0083
5	10	0.005
6	15	0.0033

Each threshold is rounded down, which errs on the strict side. This keeps the chance of wrongly calling any load worse at or below about 5 in 100. The price is power. With more loads in the test, it takes a larger gap or more shots to call one worse.

To rank several loads at once, use one of the three methods below. In every one, a load that shows pressure signs stops at once, whatever the numbers say.

Method 1. Fixed sample

Choose a large sample, prepare it all, shoot it all and then decide.

1. Choose a sample size per load: 30 to 35 rounds.
2. Prepare everything first. Five loads of 35 rounds is 175 rounds.
3. Fire in interleaved 5-round blocks (see Chapter 14).
4. Pool each load's shots and compute its mean radius.
5. The smallest mean radius leads. Test the leader against each other load at the threshold from Table 16-5. A load that does not clear it is not shown to be worse, so treat it as tied with the leader.

Worked example. Example numbers. Not load data.

Five loads, 35 shots each, all in 5-shot groups. Five loads make 10 pairs, so the threshold is 0.005.

Load	Mean radius (inch)	Two-sided p against A	Decision
A	0.41	Leader	Leader
D	0.44	0.62	Tied with A
B	0.47	0.33	Tied with A
E	0.55	0.038	Tied with A
C	0.62	0.0037	Worse

Thirty-five shots each were enough to reject C. They were not enough to rank A, D, B and E. E looks worse, and a plain 0.05 would call it worse. With five loads in the test, that line is too loose. Choose among the four on velocity SD, cost or supply. Or shoot more.

Cost. The most rounds of any method. Every load gets the full count, even one that was plainly poor after its first block.

Risk. Low. No load is cut early by bad luck, and there is no math to do at the range. Ties among the leaders are common, because a 1.25 to 1 difference needs far more than 35 shots per load to show.

Method 2. Two-phase screening

Screen every load with a small sample. Cut the worst. Spend the large sample only on the rest.

1. Phase 1. Before you prepare ammunition, write down the screening level, such as 0.05. Prepare 10 rounds of every load.
2. Fire them in interleaved blocks and compute each mean radius. Test each load against the Phase 1 leader. Cut a load only when its p-value falls below the screening level, or when it shows a gross fault such as a wild extreme spread. Carry every other load into Phase 2.
3. Phase 2. Prepare 25 more rounds of each survivor.
4. Fire them interleaved. Pool each survivor's two phases. Test each against the leader at the Table 16-5 threshold for the number of loads you screened.

5. Check that the Phase 2 shots alone tell the same story. If they do not, treat those loads as tied and shoot more before you choose.

Worked example. Example numbers. Not load data.

Six loads were screened with 10 shots each. All shots are in 5-shot groups. Mean radius is in inches at 100 yards.

Load	B	A	E	D	C	F
Phase 1 mean radius (inch)	0.39	0.44	0.47	0.52	0.71	0.83
p against B	Leader	0.65	0.48	0.28	0.028	0.0065

The screening level was 0.05, so C and F are cut. A, D and E are carried with B, and each gets 25 more shots.

Load	Phase 1, 10 shots	Phase 2, 25 shots	Pooled, 35 shots
A	0.44	0.45	0.447
B	0.39	0.49	0.461
D	0.52	0.48	0.491
E	0.47	0.50	0.491

The pooled figure is the average weighted by shots. For load B it is $(10 \times 0.39 + 25 \times 0.49) \div 35 = 0.461$. Weighting each phase by its shots gives the same figure as averaging every corrected distance (see Chapter 15). Tested against A, B has a p-value of 0.83, and D and E 0.50 each. None comes near even a plain 0.05. The four finalists are tied.

This table holds two lessons. First, B led the screen, but its next 25 shots were ordinary. Selection flatters the survivors, because a load that passes a screen was partly lucky. That is why step 5 checks the Phase 2 shots alone. Second, D trailed at 0.52. Its gap was well inside the noise of 10 shots, so the rule carried it. Its next 25 shots matched the leaders. A rule that cut the worst half would have lost it.

Cost. In this example 160 rounds, against 210 for a fixed sample of 35.

Risk. Cutting a load as good as the leader. With six equal loads, a 0.05 screen cuts at least one of them about 1 time in 3, and a 0.01 screen about 1 time in 12. A 10-shot screen cannot reliably separate even a 1.5 to 1 difference, which needs about 35 shots per load, so it saves rounds only when some loads are far worse.

Method 3. The sequential tournament

Test after every block. Each of these tests is a look. Drop a load as soon as the evidence says it is worse. Keep shooting the rest.

1. Before the first shot, write down the loads, the block size, the maximum shots per load and the threshold for every look.
2. Prepare one 5-round block of every load.
3. Fire the blocks. Record the raw X and Y of every shot.
4. Recompute each load's mean radius from all of its shots so far.
5. Find the leader, the load with the smallest mean radius.

6. Run the two-sided F-test of each other load's mean radius against the leader's.
7. Cut a load only when its p-value falls below the threshold for this look.
8. Prepare and fire the next block only for the survivors. Stop when one load remains or you reach the planned maximum.

The threshold must be stricter than 0.05, for two reasons. Each look is one more chance for luck to cut a good load. And the leader is the luckiest load of the group (see "Testing more than two loads" above). Take four loads that are truly the same. A plain 0.05 at each of six looks cuts at least one of them nearly half the time.

Use the O'Brien-Fleming thresholds, divided by the number of pairs as in Table 16-5.[5] They are very strict at the early looks, when each load has few shots. They ease toward 0.05 at the last look, when the most shots stand behind the decision. Over the whole tournament the chance of cutting a load as good as the leader stays at or below about 5 in 100.

Table 16-6. Cut a load when its two-sided p-value against the leader is below this threshold, with 5-shot blocks and up to 30 shots per load.

Shots per load	2 loads	3 loads	4 loads	5 loads	6 loads
5	No cut	No cut	No cut	No cut	No cut
10	0.00037	0.00012	No cut	No cut	No cut
15	0.0036	0.0012	0.00061	0.00036	0.00024
20	0.011	0.0039	0.0019	0.0011	0.00079
25	0.024	0.0081	0.0040	0.0024	0.0016
30	0.040	0.013	0.0066	0.0040	0.0026

No cut means the threshold is below 0.0001. So few shots almost never clear it. Skip the math at that look. The thresholds are rounded down, which errs on the strict side. Use the column for the number of loads you started with, even after some are cut. For another block size or maximum, see Appendix A.7.

Worked example. Example numbers. Not load data.

Four loads, 5-round blocks and a maximum of 30 shots each. The thresholds come from the 4 loads column of Table 16-6. The table gives each load's mean radius in inches. The two-sided p-value against the leader follows in parentheses.

Shots each	Threshold	A	B	C	D	Decision
5	No cut	0.38 (leader)	0.41 (p 0.84)	0.80 (p 0.062)	0.54 (p 0.36)	Keep all four
10	No cut	0.40 (leader)	0.42 (p 0.85)	0.85 (p 0.0066)	0.60 (p 0.13)	Keep all four
15	0.00061	0.41 (leader)	0.42 (p 0.91)	0.83 (p 0.0017)	0.64 (p 0.042)	Keep all four
20	0.0019	0.42 (leader)	0.43 (p 0.90)	0.84 (p 0.00034)	0.66 (p 0.017)	Cut C
25	0.0040	0.42 (leader)	0.44 (p 0.78)	Out	0.69 (p 0.0034)	Cut D
30	0.0066	0.43 (leader)	0.44 (p 0.88)	Out	Out	Stop. A and B tied

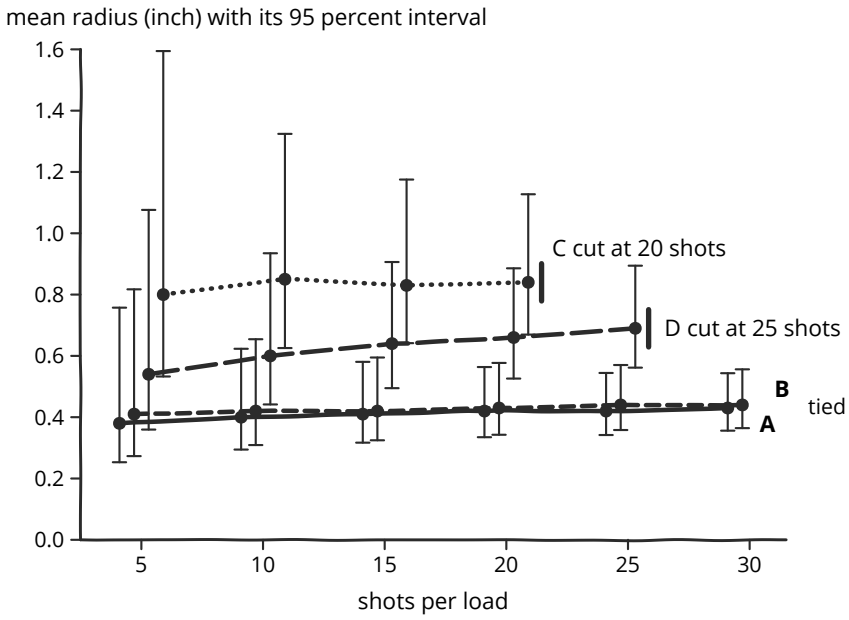
Here is the look that cut C, by hand.

```
df          = 2 × (20 − 4) × 0.915 = 29.3 for each load
F           = (0.84 ÷ 0.42)² = 4.00
two-sided p = 2 × F.DIST.RT(4.00, 29.3, 29.3) = 0.00034
```

Because 0.00034 falls below the 20-shot, four-load threshold of 0.0019, C is cut (rounding df down to 29 in a spreadsheet gives 0.00036, the same verdict). A plain 0.05 threshold would have cut C at 10 shots and D at 15, but that rule cuts a good load nearly half the time; Table 16-6 waits for stronger proof. The tournament used 105 rounds (30 each of A and B, 20 of C, 25 of D) versus 120 for a fixed 30-shot test, with A and B finishing tied.

Cost. Fewest rounds when one load is much worse, little saving when loads are close, and no cuts before 15 shots with four or more loads. Requires computing results between sessions before preparing the next block.

Risk. Low if thresholds are kept (≤5 in 100 chance of cutting an equal load), though multi-session testing introduces session-to-session weather.



Example numbers. Not load data.

Figure 16-4. The tournament example. Each load's mean radius with its interval after each block, with both cuts marked.

Barrel-life budgeting for overbore cartridges

Overbore cartridges (7mm SAUM, 6.5 PRC, hot 6mm designs) often deliver only 800 to 1,300 competitive rounds before throat erosion degrades precision, with lands advancing roughly .010 to .015 inch per 100 rounds (see Chapter 23). A 175- to 210-round five-load fixed test burns 15 to 25 percent of that life before a single match. On barrel-burners, use two-phase screening (Method 2) or a sequential tournament (Method 3), limit the initial slate to two or three proven pairings, drop clear losers early, and save 30-shot confirmation for your finalist.

Testing any claim yourself

Any precision claim can be tested by treating each setup as an arm:

1. State the claim numerically ("setting 3 groups a third smaller than setting 1," not "shoots better") and fix the shot count and decision rule beforehand.
2. Size each arm from Table 16-1 for two arms. With more arms, Table 16-5 tightens the threshold: finding a 1.5 to 1 group-size difference needs about 45, 55, and 60 shots per arm for three, four, and five arms (about 67, 77, and 84 for velocity SD).
3. Work up from the published start load for any arm that changes a component or seats bullets deeper or into the lands (see *The Handloading Handbook*).
4. Interleave and rotate arms each pass (see Chapter 14), blinding the shooter via a helper when possible.
5. Analyze with confidence intervals and F-tests on mean radius and velocity SD (above; Appendix A.6 and A.8), then repeat winner versus runner-up on another day to confirm.

Worked example. Example numbers. Not load data. Testing whether annealing every firing cuts velocity SD from 15 to 10 fps (1.5 to 1) requires about 50 interleaved shots per arm (50 annealed, 50 not). A smaller claim—15 to 12 fps (1.25 to 1)—needs about 160 shots per arm. When a test costs more than the gain is worth, that is a useful answer too.

Closing the loop

When a candidate misses your precision or velocity SD goals (see Chapter 21), act on the numbers rather than guessing:

- **Handloaders:** Take your composite mean radius, velocity SD, and intervals back to the bench (see *The Handloading Handbook*). Skip 0.1 gr tweaks—change a major variable (bullet, powder, or primer) and work up safely from the published start load.
- **Factory shooters:** Log the failing lot and test another lot, bullet weight, or match brand. For .22 LR rimfire, structured lot testing is the primary way to match ammunition to a barrel.

Keep failed tests in your log (see Chapter 13) so you never waste components or barrel life repeating a dead end.

Chapter 17

Popular Load-Development and Tuning Methods Examined

Key points

- Ladder tests, optimal charge weight and velocity nodes look for flat spots with a few shots per step. Random scatter makes flat spots in most tests.
- Nodes found with a few shots rarely hold up when the same loads are fired in large numbers.
- Seating depth matters more for some bullet shapes than others. A small-sample sweep cannot find a sweet spot reliably.
- A tuner does change how a barrel vibrates. Whether that helps by a useful, repeatable amount is still open.

Why it matters

Popular methods spend components and barrel life. Their appeal is speed, an answer from 20 or 30 rounds. Speed is not the problem. The problem is that small samples give confident answers that are often noise. A false node costs you twice. You load for it, and then it fails to repeat.

The verdicts below concern each method as it is usually practiced, with one to five shots per step. Run with enough shots, any of these becomes a fair experiment (see Chapter 16, “Testing any claim yourself”).

If you shoot factory ammunition, you can skim the charge-weight and seating-depth sections below and focus on **Contested: barrel tuners**, which applies to factory and handloaded rifles alike. The small-sample lessons in the earlier sections still help whenever someone recommends picking a factory lot from a single 3-shot group.

How it is done

> **Safety · See *The Handloading Handbook*.** A ladder or an optimal charge weight test fired to find a node is not a work-up. Fire no charge above one you have already reached in a work-up from the published start load (see *The Handloading Handbook*). Observe every pressure stop rule from *The Handloading Handbook* at every step.

Contested: ladder tests

The claim. Fire one shot at each of a series of rising charges, usually at long range. The bullets land at different heights. Where several steps in a row land at about the same height, the load is in a node. A charge in the middle of that node forgives small variations. Some shooters read each shot’s velocity instead of its height.

The physics. The usual explanation is barrel vibration. The muzzle moves while the bullet travels down the bore. A bullet that exits near a turning point of that motion should be less affected by small changes in exit time. Another proposed explanation is that slower bullets leave the muzzle a little higher, which offsets their extra drop.

The test. Each step has one shot, and each shot carries the load's normal scatter in height and in velocity. Whether a run of steps looks flat depends as much on that scatter as on any node. Here is how often scatter alone makes a step look flat.

Worked example. Example numbers. Not load data.

Take a velocity ladder of ten steps. Each step should add 10 fps. The load's shot-to-shot SD is 8 fps. There is no node at all. Call a step flat if it rises 5 fps or less.

Each step's rise is the gap between two shots that each wander about 8 fps. So the rise itself wanders about 11 fps (8 × √2). A rise that should be 10 fps reads 5 fps or less about one time in three.

A ten-step ladder has nine rises. A computer simulation of a million such ladders shows a flat step in nearly every one. Two flat steps in a row, three shots that look like a plateau, turn up in about 3 ladders in 10.

The data. A ladder that showed a flat spot did not show it again when it was fired a second time.[1] Fired in samples of 20 to 35 shots per step, the nodes disappeared.[2] Separate 30-shot tests in three rifles found no nodes.[3] Lighter charges tended to group tighter.[4]

The verdict. Folklore. One shot per step cannot find a node (see Figure 17-1). A ladder is still the right way to work up for pressure and velocity (see *The Handloading Handbook*).

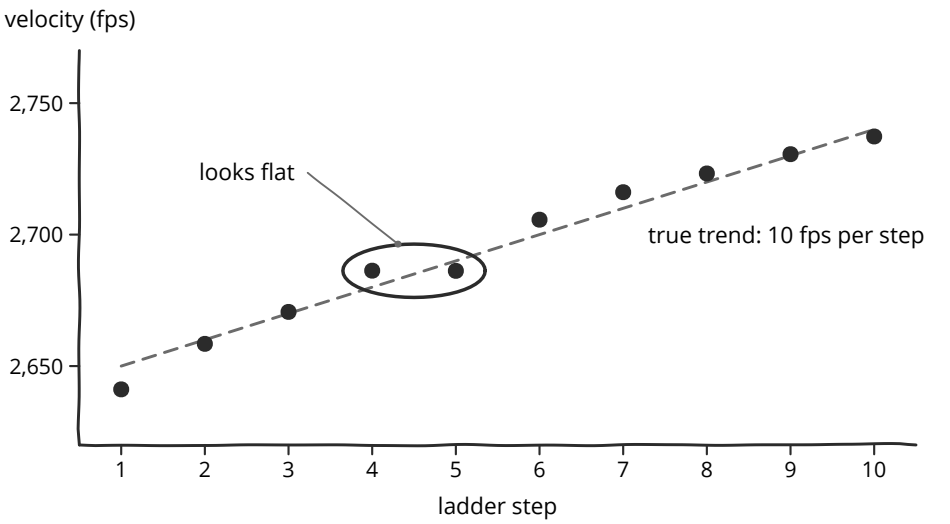


Figure 17-1. A simulated ten-step velocity ladder with no node. Random scatter alone makes a step that looks flat.

Contested: optimal charge weight

The claim. Fire 3-shot groups at a series of charges. Rotate through the charges so each group builds up a shot at a time. Look for three neighboring charges whose groups center on the same point. The middle charge is the optimal charge weight. Its point of impact should not move with small changes in velocity.

The physics. The same barrel-timing idea as the ladder. If the point of impact holds still across a range of charges, small charge and velocity variations should not move the shots.

The test. A 3-shot group's center is uncertain. It wanders from the true center by about the shot spread divided by the square root of three.

```
center wander on one axis = σ ÷ √n
σ on one axis             = mean radius ÷ 1.2533
```

Here is how far a center wanders for one load.

Worked example. Example numbers. Not load data.

A rifle and load with a true mean radius of 0.50 MOA have a σ of 0.50 ÷ 1.2533 = 0.40 MOA on each axis. A 3-shot group's center wanders by 0.40 ÷ √3 = 0.23 MOA. The centers of two groups of the same load then differ with an SD of about 0.33 MOA on each axis. Groups from different charges can line up by chance. Groups from the same charge can look apart.

Group sizes are just as noisy. The best of seven 5-shot groups from one load averages 0.66 times the load's average 5-shot group (see Chapter 15). Groups of 3 shots are noisier still.

The data. Large-sample testing found that optimal charge weight results disappeared, as charge nodes did (see "Contested: ladder tests" above).[3] Users of the method disagree. In their view, real effects are large enough to see with few shots.

The verdict. Folklore. You cannot choose a charge from the centers of 3-shot groups. Those centers wander by more than the effect sought (see Figure 17-2). A charge chosen for your velocity goal, with margin, does the same job with less ammunition.

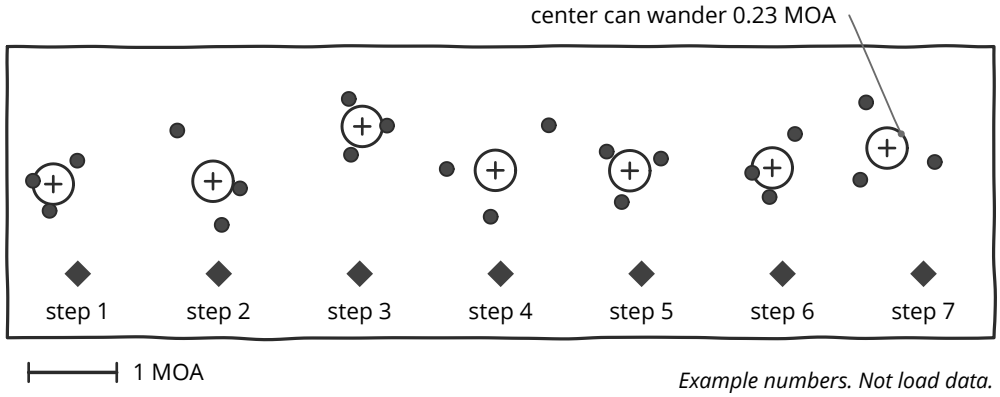


Figure 17-2. An optimal charge weight target. Each charge step has its own aim mark and 3-shot group, with a circle showing how far each group's center can wander.

Contested: velocity nodes

The claim. Somewhere in a load's charge range is a node where velocity barely changes with charge. Loads there give a low velocity SD. Shooters usually look for the node with one shot per step or with short strings.

The physics. Internal ballistics models show velocity rising smoothly as charge rises. A real plateau would need a cause these models do not include.

The test. One shot per step and short strings are both too noisy. In the ladder example above, chance alone makes a flat step in nearly every ladder and a three-shot plateau in

about 3 ladders in 10. A short string's SD is noisy too. A 5-shot SD has a 90 percent interval of 0.65 to 2.37 times the measured value. So a 5-shot SD of 6 fps fits a true SD anywhere from about 4 to 14 fps. Example numbers. Not load data.

The data. Two of the large-sample tests above went back to apparent velocity flat spots with 20 to 35 shots per charge. The flat spots did not hold, and average velocity rose in a nearly straight line with charge.[5]

The verdict. Folklore. One shot per step or a short string cannot find a velocity node. Choose the charge for the velocity you need. Measure its SD with 20 to 30 shots. If the SD is too high, look at ignition, neck tension and charge weighing rather than at 0.1 gr.

Contested: seating depth sweeps

The claim. Each bullet has a seating depth sweet spot. Seat the same load at a series of jumps to the lands, fire a small group at each and pick the best.

The physics. Jump does change things. It changes how the bullet meets the rifling and how hard it is to start moving. Ogive shape changes how much this matters. Some secant-ogive bullets have a sweet spot .030 to .040 inch wide, anywhere from jammed into the lands to .150 inch off them.[6] Hybrid-ogive bullets are much less sensitive.[7] Monolithic bullets need jump (see *The Handloading Handbook*).[8]

The target also moves: as the throat erodes, the lands move forward and jump grows (see Chapter 23 and *The Handloading Handbook*). Over a few hundred rounds, this movement can shift a bullet completely out of a narrow seating window.

The test. A sweep is a set of loads fired as small groups. It has the same problem as any small-group comparison. Seven settings shot as one 5-shot group each will show a best group about 0.66 times the load's average 5-shot group, even if seating does nothing.

The data. In one large-sample test with 20 to 30 shots per seating depth, the difference between the best and worst depths was small enough to be random noise.[9] Meanwhile, the .030 to .040 inch sweet-spot claim rests on shooter reports without published sample sizes, and its recommended test procedure fires only two 3-shot groups at each of four jumps.[6]

The verdict. Folklore. A small-sample sweep cannot find a sweet spot reliably. Start at the bullet maker's guidance. Never jam a hunting load. Prefer a jump band where groups change little, so throat erosion does not matter. Test seating only with adequate samples.

> **Safety · See *The Handloading Handbook*.** A seating change is a load change. Seating deeper takes space from the powder and raises pressure. Seating into the lands raises it too. Before a sweep goes deeper than the published COAL, deeper than your worked-up seating or into the lands, work up again from the start load at that seating (see *The Handloading Handbook*).

Contested: barrel tuners

The claim. A tuner is a weight on the muzzle that you can move in small steps. Moving it changes how the barrel vibrates, so the bullet leaves at a better moment. It tunes the barrel to the ammunition rather than the ammunition to the barrel. The effect is large enough to see with few shots.[10]

The physics. Mass at the muzzle does change how a barrel vibrates. That much is basic mechanics. The question is whether the change improves dispersion by a useful and repeatable amount.

The test. Tuner settings are compared by their groups. Settings that differ a little need many shots to separate. Settings tested with small groups suffer the same best-of-many luck as any sweep.

The data. One test fired more than 1,800 rounds through four tuners on four rifles.[11] The tuners showed no repeatable effect.[12] Critics fault the test protocol. The objections are that the tuners may have been too light, and that a tuner's weight, position and range of adjustment must suit the barrel and the load.[13] The test also did not check whether slower shots leave the muzzle higher and so offset their extra drop. That would take long-range shooting with every shot tracked by radar.[14] Added weight at the muzzle did seem to shrink groups, a result that needs more testing.[10]

The verdict. Plausible but unproven. The physics is real. Whether the effect is large and repeatable enough to matter is not settled. If you use a tuner, test it with the protocol in Chapter 16 ("Testing any claim yourself"). Each setting you compare is one arm. With more than two arms the threshold tightens (see Table 16-5), so each arm needs more shots. To find a 1.5 to 1 difference in group size, three arms need about 45 shots each. Four arms need about 55 and five about 60. For velocity SD, three, four and five arms need about 67, 77 and 84.

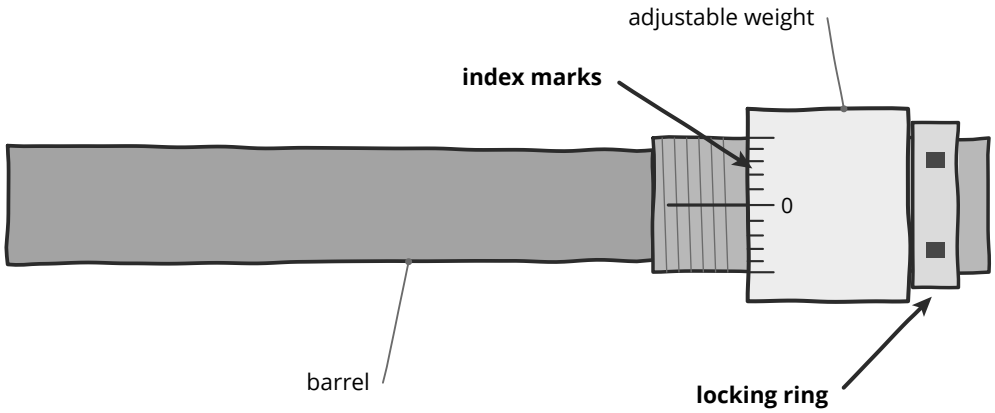


Figure 17-3. A barrel tuner on a rifle muzzle. The adjustable weight and its index marks are visible.

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Analysis queues let each ladder step, seating depth or tuner setting grow into a real sample across sessions.

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V

Part V

Bullet Flight, External Ballistics, and Terminal Performance

Chapter 18. Bullet Stability 113
Chapter 19. External Ballistics Essentials 119
Chapter 20. Ballistic Solvers, Truing, and DOPE 127
Chapter 21. Hit Probability and Error Budgets 137
Chapter 22. Terminal Ballistics and Ethical Hunting Range 149

Chapter 18

Bullet Stability

Key points

- The gyroscopic stability factor, Sg, compares the bullet's spin with the air's push to turn it over. Below 1.0 the bullet tumbles.
- An Sg of 1.5 or more gives full BC with a margin. From 1.1 to 1.5 the bullet flies but yaws, which costs BC and opens groups.
- Length decides stability far more than weight. A polymer tip adds length but almost no mass, so it needs its own correction.
- Cold, dense air is the hard case. Sg falls as the air gets denser, so the coldest, densest day sets the margin.
- A hotter load barely helps. A faster twist or a shorter bullet is the fix.

Why it matters

The powder's work ends at the muzzle. From there the bullet has to fly point first. An unstable bullet will not group. A marginal one flies but wobbles, so it loses part of its ballistic coefficient, or BC. A BC compares a bullet's drag with that of a standard projectile (see Chapter 19). A bullet below Sg 1.0 tumbles and leaves oblong holes. No amount of load tuning fixes that.

Stability is set by the barrel's twist, the bullet's length and weight, its velocity and the air. The twist is the costly part to change. So check stability before you buy bullets and before you build a load around them.

How it is done

What Sg measures

On a typical rifle bullet, the air's push centers ahead of the center of gravity. So the air tries to turn the nose away from the path. Spin resists that turning, much as a spinning top resists falling over. Sg is the ratio of the spin's resistance to the air's overturning push.

Sg depends on the bullet's mass, its moments of inertia, its spin rate, the air density, the aerodynamic overturning moment and the velocity. Simple formulas such as Greenhill's and Miller's are estimates. They are built on the bullet's diameter, length and weight or density. They cannot see how the mass is spread inside the bullet or exactly where the air's push centers.[1]

A bullet grows more stable as it flies. Its spin decays much more slowly than its forward speed. So the muzzle is where gyroscopic stability is lowest.

Sg measures gyroscopic stability only. A bullet can also be dynamically unstable, meaning its wobble grows in flight instead of settling out. Dynamic instability shows up mostly as the bullet slows through the transonic zone near the speed of sound (see Chapter 19).[2]

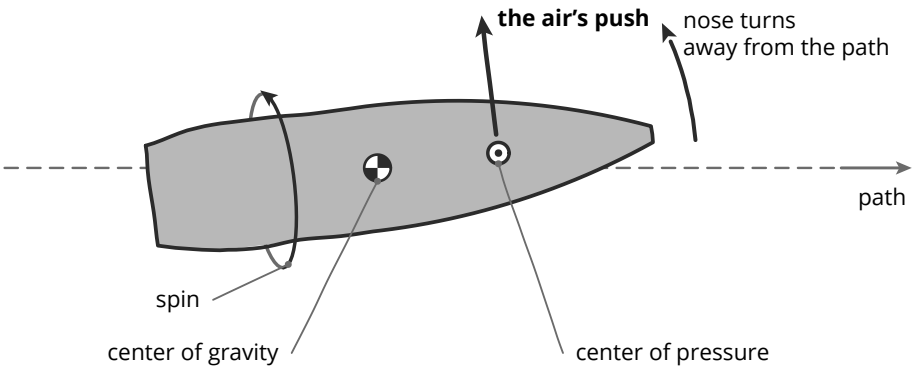


Figure 18-1. Why a bullet needs spin. The air's push centers ahead of the center of gravity and tries to turn the nose away from the path.

The thresholds

Table 18-1. How to read Sg.[3]

Sg	Reading	What it means
1.5 or more	Stable	Full BC, with margin for colder and denser air
1.1 to under 1.5	Marginal	The bullet flies but yaws. That can cost as much as 10 to 15% of its BC and open groups
1.0 to under 1.1	Insufficient	Flies point first for now, with no margin. Colder air or a slower load can take it below 1.0
Below 1.0	Insufficient, will not stabilize	The bullet tumbles and keyholes. No load tuning fixes it

Some sources set the threshold for full stability at 1.4 instead of 1.5. Either way, that margin covers formula error and cold, dense air.[1] The line at 1.0 is physics. The margin above it is insurance.

Spin, drag and the spin ceiling

More spin also lowers drag, up to a point. Mach 1.7 is 1.7 times the speed of sound. Doppler tests show that above about Mach 1.7 to 1.8, a bullet's drag is lowest at an Sg of about 2.0. Transonic drag keeps falling as Sg rises.[1]

Spin has a ceiling too. A bullet can spin fast enough to come apart in flight. From about 250,000 rpm, thin-jacketed bullets have been known to fail.[4]

```
Spin rate (rpm) = muzzle velocity (fps) × 720
                  ÷ twist (inches per turn)
```

Example numbers. Not load data. A bullet at 3,000 fps from a 1:8 twist spins at 3,000 × 720 ÷ 8 = 270,000 rpm. That is past the 250,000 rpm caution, so a thin-jacketed bullet could come apart.

The Miller twist rule by hand

The Miller twist rule is the usual estimate.[5]

```
Sg = 30 × m ÷ (t² × d³ × l × (1 + l²))

m   bullet weight in grains
d   bullet diameter in inches
l   bullet length in calibers = length ÷ d
t   twist in calibers per turn = twist in inches ÷ d
```

The base rule assumes 2,800 fps, 59 °F and 29.92 inHg. Two factors adjust it.

```
Velocity factor = (v ÷ 2,800)^(1/3)
                  v = muzzle velocity in fps

Air factor      = ((T + 460) ÷ 519) × (29.92 ÷ Pst)
                  T   = air temperature in °F
                  Pst = station pressure in inHg

Sg corrected    = Sg × velocity factor × air factor
```

Below 1,120 fps the velocity factor stops changing. The rule holds it at its 1,120 fps value. Station pressure is the air pressure a barometer reads where you stand, not the sea-level figure in weather reports (see Chapter 19).

1. Measure a few bullets with calipers and use the longest. Catalog lengths are often nominal.[4] For a polymer-tipped bullet, also measure the metal length (see "Bullet length and tips" below).
2. Convert the length and the twist to calibers.
3. Work out the base Sg. For a tipped bullet, use the tip formula.
4. Apply the velocity factor for your measured muzzle velocity. If you have not fired the load yet, use the published velocity (see *The Handloading Handbook*) adjusted for your barrel length (see Chapter 4).
5. Apply the air factor for the coldest, densest day you expect.
6. Read the result against the thresholds.

Worked example. Example numbers. Not load data.

A bullet of .264 inch diameter weighs 140 gr and measures 1.40 inches. The barrel has a 1:8 twist. The muzzle velocity is 2,700 fps.

```
l  = 1.40 ÷ 0.264 = 5.30 calibers
t  = 8 ÷ 0.264 = 30.3 calibers

Sg = 30 × 140 ÷ (30.3² × 0.264³ × 5.30 × (1 + 5.30²))
   = 4,200 ÷ (918 × 0.0184 × 154.2)
   = 1.61

Velocity factor      = (2,700 ÷ 2,800)^(1/3) = 0.988
Sg on a standard day = 1.61 × 0.988 = 1.59
```

On a mild sea-level day this bullet is stable, but only just.

Bullet length and tips

Length decides. In Miller's rule, Sg falls roughly with the cube of the bullet's length. Twist enters as a square, so a 1:7 barrel gives about 31 percent more Sg than a 1:8 barrel. Weight enters only once. Heavy bullets cause trouble mostly because they are long.

Several things make a bullet longer.

- A heavier bullet of the same design.
- A monolithic copper bullet. Copper bullets are longer than lead-core bullets of the same weight, so they may need a faster twist (see *The Handloading Handbook*).
- A polymer tip, which adds length but almost no mass.

A tip-corrected form of Miller's rule accounts for a polymer tip.[6] Use the metal length (total length minus tip length) in the $(1 + lm^2)$ term, which reflects how the bullet's mass is distributed. Keep the full length l outside the parentheses, because the tip still shapes the airflow.

```
Sg = 30 × m ÷ (t² × d³ × l × (1 + lm²))

l    full length in calibers
lm   metal length in calibers = (length − tip length) ÷ d
```

Example numbers. Not load data. Give the bullet in the worked example a .15 inch polymer tip. Its metal length is 1.25 inches, or 4.73 calibers. Its Sg on a standard day becomes 1.98 instead of 1.59. Leaving the tip out of the formula makes a tipped bullet look less stable than it is. That is the classic false "unstable" verdict.

The tip formula treats the tip as weightless, so it reads slightly high for an aluminum tip. By contrast, a lead-free bullet with a light powdered-metal core inside a copper jacket is more stable than the formula predicts.[3]

Measuring matters most when the answer is close. Whenever Sg lands between 1.3 and 1.6, a nominal catalog length can flip the verdict.[3] An estimated tip length is usually within .02 inch, which moves Sg about 3 percent.[7]

> **Evidence · Supported by data**
> In firing tests, tipped varmint bullets keyholed within a few percent of Sg 1.0 by the tip-corrected formula.[6] So the line at 1.0 is real.

Why cold, dense air is the hard case

Dense air pushes harder on the nose, but the spin does not change with the weather. So Sg falls as air density rises. Air is densest when it is cold, at low altitude and under high pressure.

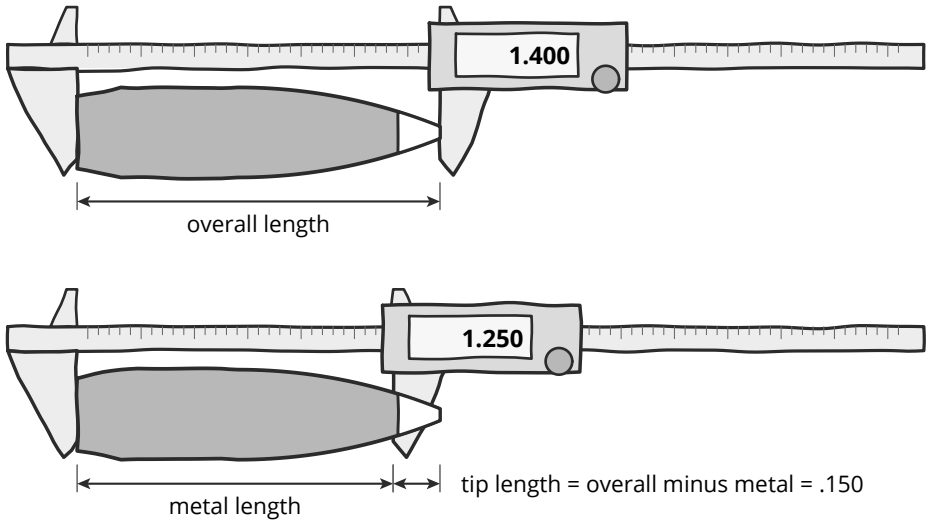


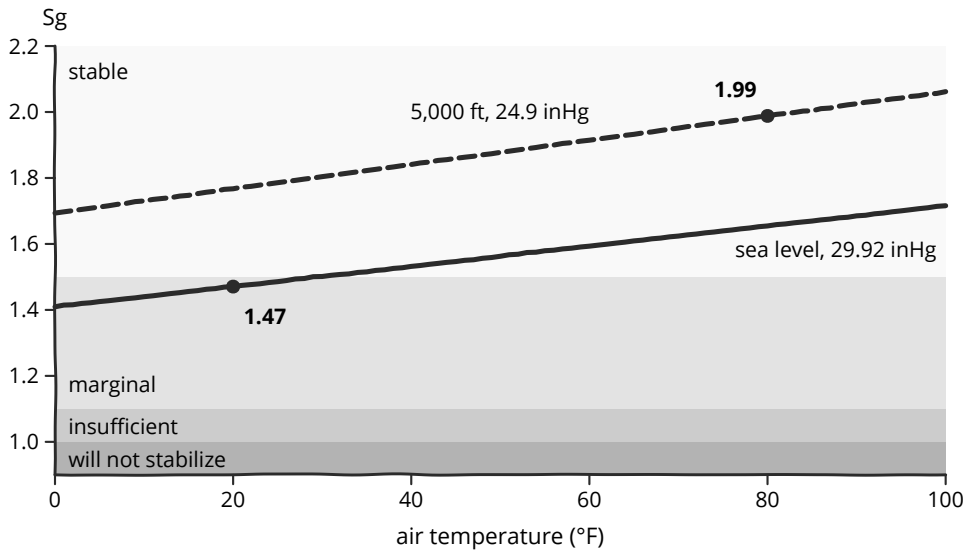
Figure 18-2. Measuring a tipped bullet: overall length, then metal length.

Carry the worked example into two kinds of weather.

```
20 °F at sea level, 29.92 inHg:
  Air factor = (20 + 460) ÷ 519 × 29.92 ÷ 29.92 = 0.925
  Sg = 1.59 × 0.925 = 1.47     Marginal

80 °F at 5,000 feet, station pressure about 24.9 inHg:
  Air factor = (80 + 460) ÷ 519 × 29.92 ÷ 24.9 = 1.25
  Sg = 1.59 × 1.25 = 1.99      Stable
```

The same bullet and load reads 1.99 on a warm day at altitude and 1.47 on a cold day at sea level (see Figure 18-3). In a similar case, a bullet at Sg 1.5 on an 80 °F afternoon at 5,000 feet is about 1.1 on a 20 °F day at sea level.[3] A rifle zeroed in summer and carried on a late-season hunt sees exactly this change.



Example numbers. Not load data.

Figure 18-3. Sg against air temperature for the worked-example bullet, at sea level and at 5,000 feet.

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Strovilos works out the stability factor from your bullet, twist, velocity and air, and names the band: stable, marginal or insufficient.

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Contested: a hotter load rescues a marginal bullet

The claim. If a bullet is marginal, drive it faster. The idea comes up often at the range.

The physics. A faster bullet spins faster from the same twist. But the air's overturning push also grows with speed. In Miller's rule, the net gain grows only with the cube root of velocity.

The test. Work the velocity factor at two speeds.

The data. In the worked example, 200 fps more velocity raises Sg from 1.59 to 1.63. That is about 2 percent. Changing the twist from 1:8 to 1:7.5 raises it to 1.81.

The verdict. Folklore. The effect is real but weak. A hotter load cannot rescue a marginal bullet. It does keep the bullet supersonic a little longer. It also raises the spin rate, which matters near the 250,000 rpm caution. The real fixes are a faster twist, which is a barrel decision, or a shorter bullet. For a tipped bullet, first make sure the tip is in the formula.

> **Safety · See *The Handloading Handbook*.** Never go past a published maximum to chase stability.

Signs at the target

A tumbling bullet hits the target sideways and leaves oblong holes (see Figure 18-4). That points to an Sg below 1.0. A marginal bullet usually cuts round holes at 100 yards, but its groups open up and it drops and drifts more at distance because yaw lowers its BC.

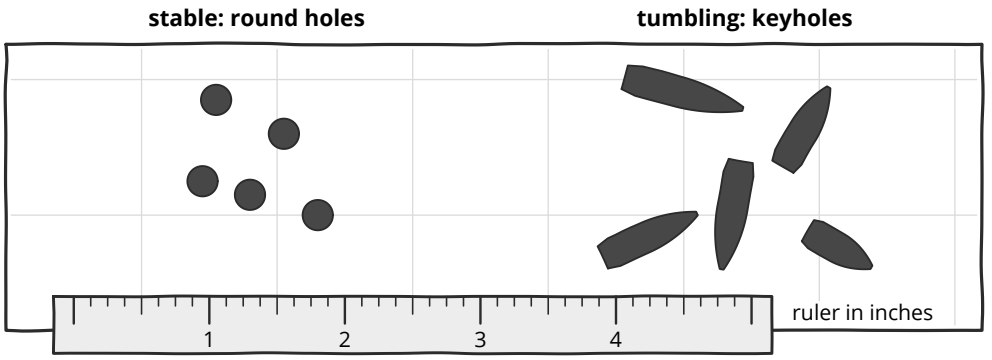


Figure 18-4. Round holes from a stable bullet beside oblong keyholes from a tumbling one.

Chapter 19

External Ballistics Essentials

Key points

- Drag shapes everything after the muzzle. It depends on air density, velocity and the bullet's shape. It changes fastest near the speed of sound.
- A ballistic coefficient (BC) compares your bullet with a standard shape. G7 fits long boat-tail bullets and G1 fits flat-base bullets. A BC means nothing without its own drag model.
- Wind drift depends on lag time, the time that drag costs the bullet. A fast bullet with a low BC can drift more than a slower bullet with a high BC.
- Spin causes spin drift, and a crosswind causes aerodynamic jump. Both are small and predictable, so a good drop chart includes them.
- The Earth's rotation matters only past roughly 800 to 1,000 yards. Air density matters at every distance.

Why it matters

Your load leaves the muzzle at a measured velocity. From then on, the air, gravity and the bullet's spin decide where it lands. Every drop chart rests on a few inputs: muzzle velocity, a BC and its drag model, the air, sight height and zero. When one of them is wrong, the miss looks like a load problem. Shooters then change the load to cure an input error.

Most of these effects have a short formula, so you can check a chart by hand.

How it is done

Drag and the Mach regimes

Air slows the bullet from the moment it leaves the muzzle. The drag force is:

```
Fd = 0.5 × ρ × v² × A × Cd(M)

Fd      drag force
ρ       air density (rho)
v       bullet velocity through the air
A       frontal area of the bullet
Cd(M)   drag coefficient at Mach number M
M       v ÷ speed of sound
```

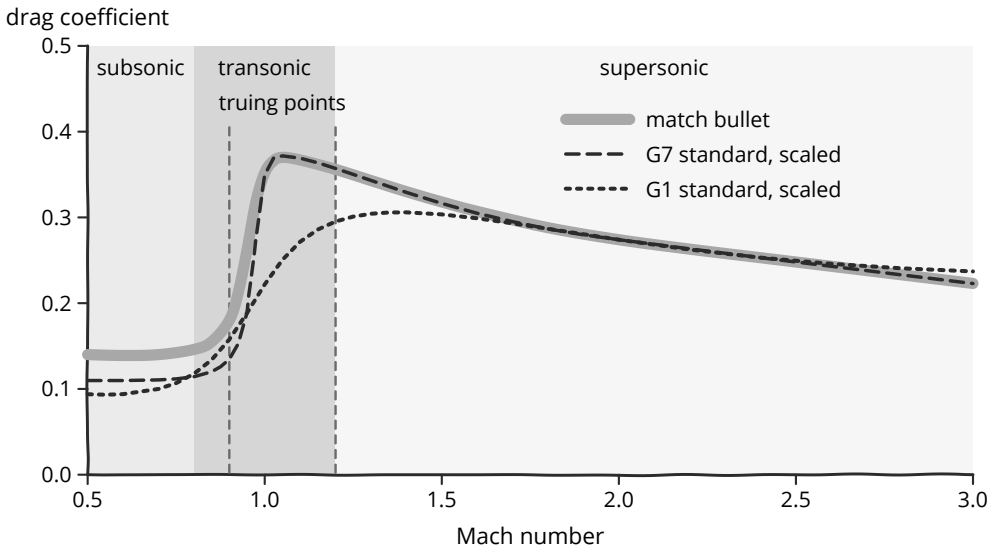
Drag rises with the square of velocity and in step with air density. The drag coefficient is not a constant. It changes with the Mach number, the bullet's velocity divided by the speed of sound.

The speed of sound depends on air temperature. It is about 1,116 fps on a standard sea-level day at 59 °F, so a bullet at 2,700 fps flies at about Mach 2.4. As the bullet slows, its Mach number falls and its drag coefficient changes.

Ballisticians divide the flight into three regimes.

Regime	Mach number	What happens
Supersonic	Above 1.2	A shock wave forms at the bullet's tip. Drag behaves predictably and models fit well
Transonic	About 0.8 to 1.2	Airflow partially detaches and buffets the bullet. Drag changes fastest, real bullets depart most from the standard drag curves, and some lose stability
Subsonic	Below about 0.8	Skin friction and base drag make up most of the drag, and the drag coefficient is lower than it is near Mach 1

For a typical rifle bullet, the drag coefficient rises as the bullet slows toward Mach 1 and peaks near it.



Illustration

Figure 19-1. Drag coefficient against Mach number for a typical long boat-tail match bullet, with the three flight regimes shaded. The G1 and G7 standard curves are drawn for comparison. The dashed lines at Mach 0.9 and 1.2 are the truing points, where a drop chart is checked against observed drops (see Chapter 20).

Predictions lose their grip in the transonic zone. Real drag curves differ most from the standards there.[1] Some bullets tumble as they slow through it.[2] So treat the range where your bullet slows to Mach 1.2 as the honest end of a predicted chart. That speed is near 1,340 fps, which for many cartridges is in the neighborhood of 1,000 yards.[1]

Subsonic and rimfire (.22 LR) flight. Standard-velocity .22 Long Rifle (.22 LR) match ammunition leaves the muzzle below the speed of sound, typically around 1,050 to 1,090 fps. Because the bullet stays subsonic for its entire flight, it avoids the transonic drag spike and buffeting that disturb faster rimfire loads. High-velocity .22 LR rounds launch near 1,200 to 1,280 fps and slow through Mach 1 within the first 40 to 60 yards, which often opens groups at longer rimfire distances.

Subsonic flight does not eliminate wind drift. A typical 40 gr lead round-nose .22 LR bullet has a low BC (roughly G1 .120 to .140) and a long time of flight. By the lag-time rule below, that long flight time produces large wind drift even in light breezes at 100 to 300 yards. Air temperature also matters more near Mach 1. A standard-velocity rimfire load that stays

cleanly subsonic at 75 °F (where Mach 1 is about 1,134 fps) can enter transonic airflow on a freezing morning (where Mach 1 drops to about 1,087 fps), changing both drag and point of impact.

Ballistic coefficient, G1 and G7

A BC is not a physical constant. It is an index that compares your bullet's drag with the drag of a standard reference projectile.

```
BC = sectional density ÷ i

sectional density   weight ÷ diameter² (see below)
i                   form factor = Cd of your bullet ÷ Cd of the
                    standard projectile at the same Mach number
```

A bullet shaped exactly like the standard has a form factor of 1. A sleeker bullet has a form factor below 1, so its BC is higher.

Three reference standards are in common use.

- **G1.** A flat-base projectile about 3.3 calibers long with a 2-caliber-radius ogive. It comes from artillery firing trials in Germany and France in the late 19th century, later turned into firing tables.[3]
- **G7.** A long boat-tail projectile with a 10-caliber-radius ogive and a 7.5-degree boat tail. Its shape is close to that of a modern long-range bullet.
- **RA4.** A rimfire-specific drag curve modeled on a standard 40 gr .22 LR lead round-nose projectile. It tracks subsonic rimfire deceleration far better than the artillery-derived G1 curve.

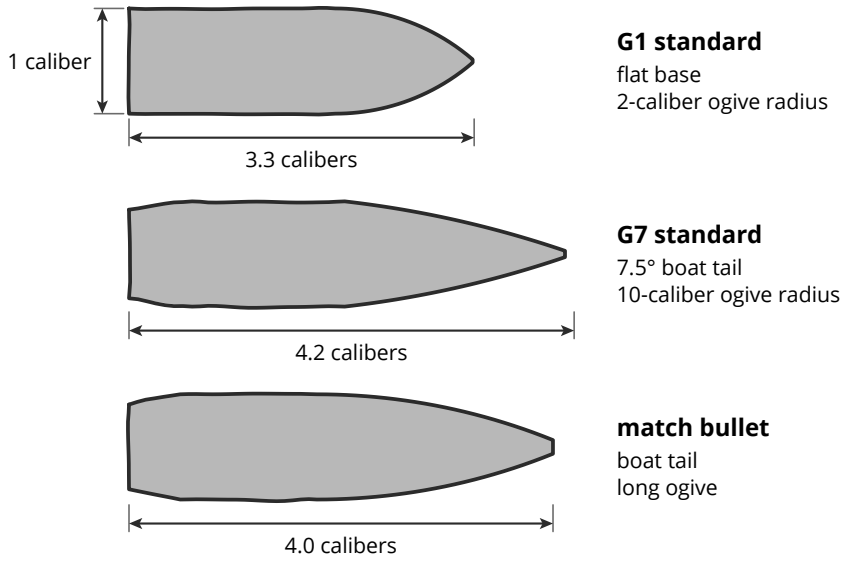


Figure 19-2. The G1 and G7 standard projectiles drawn at the same caliber, with a modern boat-tail match bullet beside them.

A G1 BC for a long boat-tail bullet does not hold steady. The G1 number that fits the trajectory falls as the bullet slows, which shooters call BC decay. Some makers publish

several G1 BCs, one per velocity band, to work around it. A G7 BC for the same bullet usually needs only one number.[4]

For the same bullet, the G7 number is roughly half the G1 number. The two are not interchangeable. Entering a G1 BC with the G7 drag model selected (or vice versa) produces a badly wrong trajectory that the solver cannot flag.[5]

Use G7 for long boat-tail bullets, G1 for centerfire flat-base and round-nose bullets, and **RA4** or a **custom Doppler drag model (CDM)** for .22 LR rimfire. With a standard that does not resemble your bullet, the drag can be right in the middle of the flight and wrong at both ends.[6] For subsonic .22 LR, a single G1 BC often diverges by 0.3 to 0.6+ MIL between 100 and 300 yards because the G1 curve does not match how a heeled, blunt-nosed lead bullet decelerates near Mach 0.95 down to Mach 0.70.

Neither G1 nor G7 matches a real bullet exactly. A bullet's own measured custom Doppler drag curve does better, most of all in the transonic zone and across subsonic .22 LR trajectories. For centerfire rifles, expect little or no gain from a custom curve if the bullet never slows below about 1,340 fps.[1]

A published BC is also referenced to a standard atmosphere: either the ICAO standard atmosphere or the Army Standard Metro.[4] Because their air densities differ by about 2 percent, using an Army Metro BC in a solver set to ICAO (or vice versa) starts with a 2 percent drag error. When the bullet maker specifies the atmosphere standard, match it in your solver.

> **Evidence · Supported by data**
> One Doppler radar test of several current bullets found only one that matched the G7 curve in both value and shape. Even so, G7 predicts these bullets better than G1 does.[7] G7 BCs predict well until the bullet nears transonic speed.[1]

Sectional density

Sectional density is the bullet's weight divided by the square of its diameter.

```
Sectional density = w ÷ (7,000 × d²)

w      bullet weight in grains
d      bullet diameter in inches
7,000  grains per pound
```

Example numbers. Not load data. A 140 gr bullet of .264 inch diameter has a sectional density of 0.287. A 175 gr bullet of .308 inch diameter has a sectional density of 0.264.

Drag pushes against the bullet's frontal area while mass resists slowing down. Between two bullets of the same shape, the one with higher sectional density retains velocity better. That is why BC equals sectional density divided by form factor: sectional density accounts for mass per frontal area, and form factor accounts for nose and base shape. Shape still matters heavily, so a heavy, blunt bullet can have a lower BC than a lighter, sleeker one.

Ogives and boat tails

The ogive is the bullet's curved nose, and its profile is tangent, secant or hybrid (see *The Handloading Handbook*, Chapter 14). A secant ogive gives a sleeker nose for its length, so very-low-drag designs use it. A boat tail tapers the base and reduces base drag. Small differences in the tip and the base from one bullet to the next change drag from shot to shot (see Chapter 21).

The ogive and the boat tail matter in the seating die too (see *The Handloading Handbook*).

Air density and density altitude

Drag rises in step with air density. Air density depends on pressure, temperature and humidity.

Pressure comes in two forms. Station pressure is what a barometer reads where you stand. Weather reports give pressure corrected to sea level. A ballistic solver must know which one you entered. Enter the wrong type and it applies the altitude correction twice or not at all.

Density altitude (DA) folds the air into one number. It is the altitude in the standard atmosphere that has the same air density as the air you are in. Higher temperature, lower pressure and higher elevation all raise DA. More humidity raises it slightly, because moist air is a little lighter than dry air.

Higher DA means thinner air, and thinner air means less drag, less drop and less drift. Cold, dense air at sea level means more of all three.

The sizes are worth knowing. A 3 percent error in air density moves the trajectory as much as a 3 percent error in BC. Each change below moves air density by about the amount shown.[8]

Change	Air density change
15 °F of temperature	3%
0.9 inHg of pressure	3%
1,000 feet of density altitude	3%
0 to 100% humidity at 60 °F	0.7%
0 to 100% humidity at 80 °F	1.3%
0 to 100% humidity at 100 °F	2.4%

Humidity matters least in mild air. Warm air holds far more water, so its effect grows with heat. The humidity figures are for sea-level pressure.

An older rule of thumb says each 2,000 feet of DA takes about 1 MOA off the drop at 1,000 yards. It fits a typical 6.5 mm match load. A faster, higher-BC bullet changes less. A slower bullet that nears the speed of sound by 1,000 yards changes more. Treat the rule as a rough check on your solver.

In practice, a drop chart from a hot August day will not hold in a cold December. A chart from a home range at 500 feet will not hold at 6,000 feet. Air temperature also sets the speed of sound, so it moves the range where your bullet goes transonic. Powder temperature is a separate effect on muzzle velocity (see Chapter 23).

Wind and lag time

Drag acts along the air flow the bullet feels. In a crosswind, that flow comes partly from the side. So part of the drag pushes the bullet downwind. A bullet with no drag would not drift at all.

The classical lag-time rule follows from this.

```
Deflection = W × (TOF − dist ÷ v0)

W                 crosswind speed in feet per second
TOF               actual time of flight to the target in seconds
dist              distance to the target in feet
v0                muzzle velocity in feet per second
dist ÷ v0         time of flight in a vacuum
TOF − dist ÷ v0   lag time
```

Lag time is the time drag costs the bullet. Less drag means less lag and less drift. Total time of flight does not set the drift. So a bullet that starts fast but sheds speed quickly can drift more than a slower bullet that holds its speed.

Worked example. Example numbers. Not load data. At 1,000 yards (3,000 feet), a bullet launched at 2,700 fps has a vacuum flight time of 3,000 ÷ 2,700 = 1.11 seconds. With a charted TOF of 1.52 seconds, lag time is 1.52 − 1.11 = 0.41 seconds. A 10 mph crosswind (10 × 5,280 ÷ 3,600 = 14.7 fps) therefore produces 14.7 × 0.41 = 6.0 feet (about 72 inches) of drift.

Only the crosswind part of the wind moves the bullet sideways.

```
Crosswind = wind speed × sin(wind angle)

wind angle = the angle between the wind and the line of fire
```

Winds from 3 or 9 o'clock are full value; 12 or 6 o'clock have no crosswind component. Winds at 1, 5, 7, and 11 o'clock (30 degrees off) are half value; 2, 4, 8, and 10 o'clock (60 degrees off) are about 87 percent value.

Table 19-1. Drift per 1 mph of full-value crosswind for four loads, computed on a standard day with a 100-yard zero.[6] Example numbers. Not load data.

Load	300 yd	500 yd	700 yd	1,000 yd
6.5 Creedmoor, 140 gr, G7 .315, 2,700 fps	.52"	1.53"	3.18"	7.19"
.308 Winchester, 175 gr, G7 .243, 2,600 fps	.73"	2.19"	4.70"	11.17"
.223 Remington, 77 gr, G7 .195, 2,720 fps	.85"	2.64"	5.84"	14.33"
.223 Remington, 55 gr, G1 .243, 3,240 fps	1.18"	3.82"	8.78"	20.23"

The 55 gr .223 starts fastest yet drifts most due to its low BC and long lag time; stepping up to the 77 gr match bullet cuts 1,000-yard drift by nearly 30 percent, while the 6.5 Creedmoor drifts about 36 percent less than the .308.

Spin drift

As gravity curves the trajectory downward, a spinning bullet's nose stays slightly above the path. Gyroscopic action turns this into a slight nose-right attitude (for right-hand twist), and

air pushes the bullet right—formally yaw-of-repose drift, or spin drift.[7] Right-hand twist drifts right and left-hand left, independent of wind, growing faster than distance to several inches by 1,000 yards.[9] A published estimate uses stability factor and time of flight:[10]

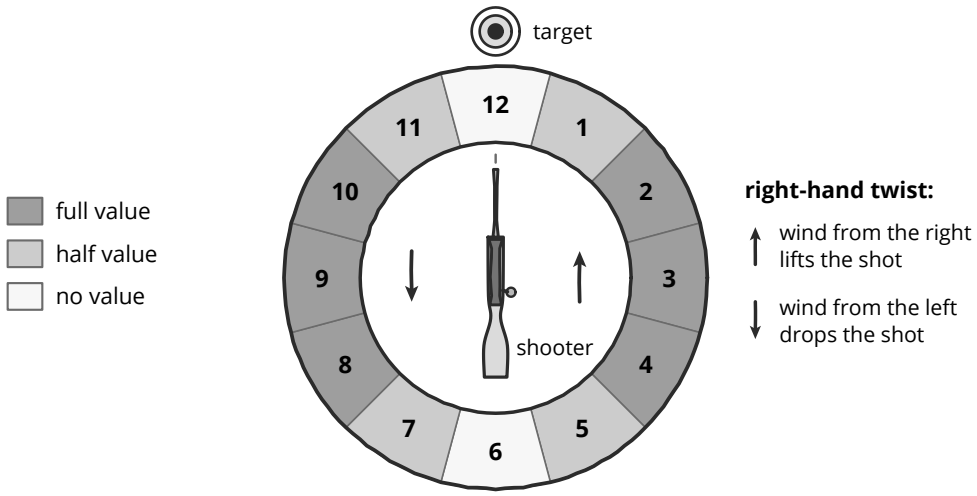
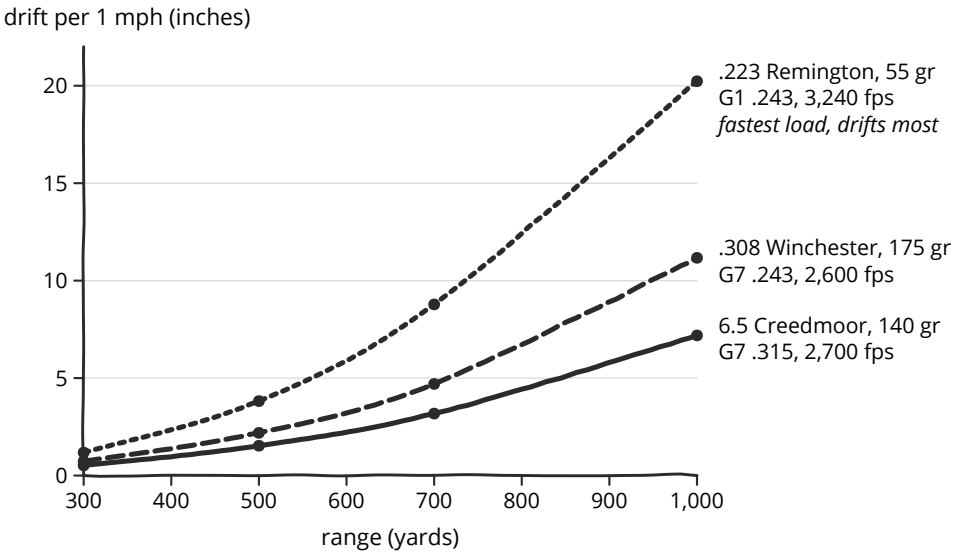


Figure 19-3. The wind clock seen from behind the shooter. It shows how much of each wind is crosswind and which way aerodynamic jump moves the shot.



Example numbers. Not load data.

Figure 19-4. Drift per 1 mph of full-value crosswind against range for the four example loads in Table 19-1.

```
Spin drift (inches) = 1.25 × (Sg + 1.2) × TOF^1.83

Sg    gyroscopic stability factor (see Chapter 18)
TOF   time of flight in seconds
```

Example numbers. Not load data. At Sg 1.6 and 1.5 s TOF, spin drift is 1.25 × 2.8 × 2.10 = 7.4 inches. Use this cautiously: a comparison across five bullets (Sg 1.6 to 2.2) found the formula tended to read high,[11] and short bullets in fast twists

extrapolate beyond that band.[9] Spin drift adds to wind drift in the same direction (e.g., left-to-right wind with right-hand twist) and subtracts from opposing wind.

Aerodynamic jump

A crosswind also deflects a spinning bullet vertically—aerodynamic jump. With right-hand twist, wind from the right lifts the shot and wind from the left drops it (left-hand twist reverses both); jump scales linearly with crosswind speed and vanishes in a pure headwind or tailwind.

In a full-value crosswind, the Table 19-1 6.5 Creedmoor jumps about .28 inch/mph at 700 yards and .39 inch/mph at 1,000 yards.[6] A right-hand-twist card built for a 3 o'clock wind under-holds elevation in a 9 o'clock wind by twice the jump—about 1 MOA for a 175 gr .308 in a 10 mph wind.[9] Misreading crosswind therefore costs both windage and a little elevation (see Chapter 21).

Coriolis and Eötvös

Earth's rotation adds two small effects: **horizontal Coriolis** deflects bullets right in the Northern Hemisphere and left in the Southern (growing with range and latitude), while **Eötvös** shifts eastbound shots high and westbound shots low (zero due north or south). Out to 1,000–1,500 yards both remain smaller than normal shot-to-shot velocity, drag, and wind variation,[7] but they still shift group center a few inches at 1,000 yards—enter latitude and azimuth past about 800 yards[6] and always when truing a solver (see Chapter 20).

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Varytita works out the trajectory for the day's air, with spin drift, Coriolis and aerodynamic jump included.

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Chapter 20

Ballistic Solvers, Truing, and DOPE

Key points

- In the supersonic part of the flight, drop error is mostly velocity error. So velocity comes before drag.
- Velocity and drag each have their own truing range: supersonic for velocity, near the transonic zone for drag. A large adjustment points to a wrong input, not a better fit.
- A zero error is an angle, so it grows with range. A tenth of an inch at 100 yards becomes about an inch at 1,000.
- Maximum point blank range picks the zero that keeps the bullet inside a vital zone for the longest span.
- You can set a far zero at a short range by aiming for a computed offset.

Why it matters

A zero that is dead on for a .30-30 at 100 yards is good enough there (see Chapter 1). At long range, every small error in the zero grows with distance. The task is to get the zero, and everything built on it, right enough for that.

A DOPE card (data on previous engagements) turns a trajectory into numbers you dial or hold. It is only as good as its inputs. A wrong velocity, sight height or zero gives a card that looks precise and still misses.

The chart comes from a ballistic solver, a program that works out the trajectory from your inputs. Working a full trajectory by hand is not practical.

Setting up a ballistic solver follows a common order of work. The inputs come first, then muzzle velocity, then drag, within limits.[1] Many apparent errors in ballistic predictions are really errors in how the scope adjusts.[2]

How it is done

Building the card takes six steps.

1. Gather the inputs.
2. Chronograph 10 or more shots for the muzzle velocity.
3. Zero the rifle and measure the zero offset.
4. Enter it all in the solver.
5. Check the chart, or true it, at your longest distance.
6. Print the card (see “The DOPE card and the field”).

Gather the inputs

Choose a solver that takes every input in the table below, including the drag model and the pressure type. It should let you true the velocity and scale the drag near Mach 0.9. At each distance, it should give the elevation, the wind per mph, the velocity and the time of flight.

Input	How to get it	What a wrong value does
Muzzle velocity	Chronograph mean of 10 or more shots, corrected to the muzzle, with the powder temperature	Small error up close that grows with range
BC and drag model	The bullet maker, in the matching drag model	Right up close, wrong far out
Sight height	Measured from bore center to scope center	Largest inside the zero. Beyond it, an angle error that grows to about 0.9 MOA per inch of error at 1,000 yards with a 100-yard zero
Zero distance and offset	A measured distance, and the group center measured to .1"	An angle error that grows with range
Air	Temperature, pressure with its type, and altitude	Drop wrong at long range
Latitude and firing direction	A map and a compass	A chart trued firing east is wrong firing west
Twist and bullet length	The barrel, and calipers on the bullet	Wrong spin drift and jump
Turret unit and click value	The scope's specification, checked by test	Every dialed correction wrong

A card trued at long range absorbs that far error, so a wrong sight height then shows up close.[3] Sight height is usually 1.5 to 2 inches on a bolt-action rifle and more on an AR-pattern rifle.[3] Measure yours (see Chapter 4).

Muzzle velocity first

In the supersonic part of the flight, drop depends mostly on muzzle velocity. Short-range drops are poor at revealing it. In one published example, half a MOA of drop error at 200 yards matches about 180 fps of velocity error. At 900 yards the same half MOA matches about 15 fps.[4]

1. Chronograph a string of 10 or more shots of the load as you will shoot it. Prefer a Doppler unit (see Chapter 7). Use the mean. Even a 10-shot mean carries its own error (see Chapter 23).
2. Check whether your chronograph reports true muzzle velocity or velocity at the sensor. An optical unit placed 15 feet downrange reads the velocity at 15 feet. For bullets with a G1 BC of .400 or higher, the bullet loses about 7 to 11 fps over that first 15 feet (less as BC rises).[5] Add that loss back if your chronograph does not correct to the muzzle automatically.
3. Record the powder temperature with the velocity and print it on the card. Muzzle velocity changes with it, so hold the ammunition at that temperature when you shoot (see Chapter 23). On a day you cannot, true the card on observed drops (see "Truing on observed drops" below). If your records give the load a slope, you can correct the velocity with it, within the temperatures those records cover:

```
velocity today = card velocity
                 + slope × (powder temperature today − card temperature)
```

4. Enter the velocity. Do not adjust drag yet.

One view prefers a measured velocity to one worked back from drops, because a wrong velocity also puts the drag at the wrong Mach number.[5] Another view favors calibrating

velocity on observed drops, because chronographs are not always as accurate as hoped.[2] Both views fit one order. Measure velocity well, then true it on drops.

Zero and zero offset

Small zero errors grow with range. A group center .1 inch off at 100 yards puts the impact about 1 inch off at 1,000 yards. An error of .5 inch becomes about 5 inches.[5]

In short, zero this way.[5]

1. Measure the distance to the zero target. If the turrets were dialed off zero for a test (see Chapter 14), set them back first.
2. If your first shots land more than a click or two from the aim mark, click them close.
3. Fire a 5-shot group without moving the aim or the turrets. For long-range work, fire two or three 5-shot groups and use their combined center (see Chapter 17).
4. Measure the distance from the aim mark to the group center to .1 inch.
5. Give that offset to your solver instead of chasing it with clicks.

A click is coarse. A 1/4 MOA click is about .26 inch at 100 yards. A mil, or milliradian, is 3.6 inches at 100 yards. That is about 3.4 MOA, so a 0.1 mil click is about .36 inch. A measured offset is finer than any click.

If you shoot a second load in the same rifle, build a separate chart for it. Fire its zero group with the scope turrets left at your primary load's zero, then enter the new load's measured X and Y offset into its chart. If you use a longer zero for hunting (such as a maximum point blank range zero), note the click adjustment from your primary zero on that card. For a hunting load, also record where the first shot from a cold barrel lands, with the bore clean or fouled to match how you carry the rifle afield, across several separate days.

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Pick your zero session in Varytita and it takes the zero distance from its target and the zero offset from its marked shots.

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Truing on observed drops

Truing makes the chart match where your bullets actually land. Do it in order.

Rule out input errors first. Before you change the drag, check every input in the table above.[5] Then check four that show only at the range: your aim, the parallax setting, cant and the wind. Set the parallax so the reticle stays on the target when you move your head. Level the reticle to a plumb line when you mount the scope, and use a scope level for every shot (see Chapter 7). Cant moves the shot sideways by the drop below the bore line times the sine of the cant, about 1.7 inches per degree for each 100 inches of drop.

Check the turret. In one example, a scope dialed 40 MOA moves the impact only 38.5 MOA, so every dialed solution falls short.[2] Test yours on a tall target at 100 yards. The dialed group lands about 1.05 inches higher for each MOA, so 40 MOA needs about

42 inches above the aim mark. Hang a plumb line down the target, or draw a line checked with a level, and put the aim mark near its bottom.[2]

1. Measure the distance to the target to within a foot at 100 yards, since each yard off is 1 percent.
2. Fire 5 shots at the aim mark.
3. Dial at least the largest correction on your card and fire 5 more at the same aim mark.
4. Dial back and check that the group returns to the zero.
5. Measure the distance between the two group centers along the line and convert it to MOA or mils at that distance.
6. Divide the measured move by the dialed amount to get the tracking factor. Example numbers. Not load data. For the scope above, 38.5 ÷ 40 = 0.9625.
7. Dial each correction divided by the tracking factor.

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Firearms works out the tracking factor from what you dialed and how far the group moved, and Varytita's DOPE card gives the number to dial.

empiricalprecision.com/firearms

Then true. Work through these steps in order.

1. Build the chart with measured inputs, including your latitude and firing direction. Note the ranges where the bullet slows to Mach 1.2 and Mach 0.9. Leaving out the Earth's rotation skews the truing. For example, a .30-caliber bullet fired east at 1,000 yards in North Texas sees nearly 3 inches of vertical Coriolis. A chart trued without it while firing east is then about 6 inches off when you fire west.[6]
2. Shoot a group at a range where the bullet is still above Mach 1.2 and the drop is large. The drop should be at least 20 MOA (about 6 mils).[2] Use 5 to 10 shots so you can locate the group center. If no distance you can shoot reaches 20 MOA, keep the measured velocity and check the chart at your longest distance. Change nothing for a miss the group center's own error can explain (see step 5).
3. Work out the observed drop. Take the chart's elevation for that range. Convert how far the group center printed low or high to MOA or mils at that range. Add it if low, subtract it if high.
4. Change the velocity in your solver until the chart's drop at that range equals the observed drop.
5. Compare the trued velocity with your chronograph average. If the difference falls within the group center's normal wander, it is just shot noise, so keep your chronograph velocity (see the worked example below). If the difference is larger than group wander but within your chronograph's accuracy tolerance (see Chapter 7), confirm it with a second group and adopt the trued velocity. If the difference exceeds what chronograph error could explain, another input is wrong; re-check the table above before changing your chart.

6. If you shoot past the Mach 1.2 range, shoot a group near the Mach 0.9 range. Scale the drag at that Mach number only and leave the supersonic part alone. A single trued BC can fit on a warm day and miss on a cold one.[5]
7. Keep the drag change small. Barrel differences usually fit within a drag factor of 0.95 to 1.05.[5] A factor near or beyond 0.90 or 1.10 means another input is wrong.
8. Log each truing with its range, Mach number, air and result. Keep the log with the rifle and load records (see Chapter 13).

Worked example. Example numbers. Not load data.

Take a 140 gr 6.5 Creedmoor load at 2,700 fps with a G7 BC of .315, on a standard day with a 100-yard zero. At 1,000 yards its chart calls for 31.37 MOA, well over 20 MOA. The bullet arrives at about 1,440 fps, still above Mach 1.2.

Your group at 1,000 yards centers 4 inches below the aim mark. At 1,000 yards 1 MOA is 10.47 inches, so the group is 0.38 MOA low. Add 0.38 MOA to the chart's 31.37 MOA. That total, 31.75 MOA, is the observed drop to true against.

For a quick sense of size, 10 fps moves this load's 1,000-yard drop about 2.83 inches on a chart that stays zeroed at 100 yards. So a 4-inch miss low suggests a velocity about 14 fps slower than the chart assumes (4 ÷ 2.83 × 10). The group center has its own error, about the vertical sigma divided by the square root of the shots (see Chapter 17). Here, 0.35 MOA of rifle dispersion and a 10 fps velocity SD give a vertical sigma of about 4.75 inches at 1,000 yards. A 10-shot center is then good to about 1.5 inches, or about 5 fps. So true on two or more groups before you trust the change.

Evidence · Supported by data
Drop errors in the supersonic band are mostly velocity errors.[4] Doppler-measured drag curves depart from the standards mostly in the transonic band.[2]

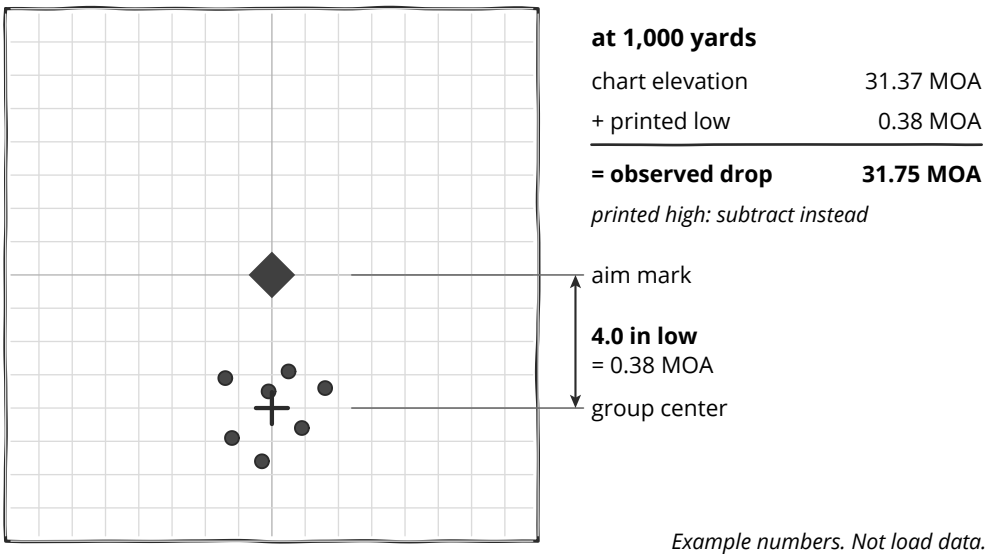


Figure 20-1. Observed drop is the chart's elevation plus how far the group printed low, or minus how far it printed high.

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Varytita trues the chart from an observed drop. Enter the range and the drop, and it solves for the velocity or the drag that explains it.

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Subsonic and rimfire (.22 LR) truing

The supersonic-first truing sequence above assumes the bullet starts well above Mach 1.2. Standard-velocity .22 LR leaves the muzzle near Mach 0.95 (about 1,050 to 1,090 fps) and never flies above Mach 1.2, so you cannot separate velocity from drag using supersonic and transonic ranges.

Rimfire zero geometry also magnifies small setup errors. Most precision .22 LR rifles use a 50-yard zero rather than a 100-yard zero. Halving the zero distance doubles both sight-height and zero-offset sensitivity downrange: a 0.1-inch zero offset at 50 yards becomes a 0.6-inch error at 300 yards—twice the angular error of a 0.1-inch offset at 100 yards.

True a subsonic .22 LR solver in four steps:

1. **Lock down the 50-yard zero and exact sight height.** Confirm turret tracking first, measure bore-to-scope sight height carefully (see Chapter 4), and shoot two or three 5-shot groups at a measured 50 yards to establish a clean zero offset.
2. **Chronograph 10 to 20 shots with a Doppler unit.** Measure the lot's mean muzzle velocity and record the air and ammunition temperature. Because .22 LR velocities change modestly with temperature and lot, keep the chronograph data tied to that lot number (see Chapter 13).
3. **Verify muzzle velocity at 100 to 150 yards.** Fire a 5- to 10-shot group at 100 to 150 yards and check observed drop against the solver. Make small muzzle-velocity adjustments here only if the observed drop exceeds group-center wander and zero/sight-height inputs are verified.
4. **True drag or BC scale at 200 to 300 yards.** Use the **RA4** drag model or a **custom Doppler drag curve (CDM)** for your ammunition rather than a single G1 BC (see Chapter 19). Fire a 10-shot group at 200 to 300 yards and adjust the drag scale or BC until predicted drop matches observed drop across the full rimfire distance span.

Maximum point blank range

Maximum point blank range (MPBR) is the longest span over which you can aim dead on. Over that span the bullet stays within half a vital zone above or below the line of sight.

1. Choose the vital zone's diameter for your target.
2. Make a path table at fine steps, such as every 5 or 10 yards.
3. Change the zero until the highest point of the path, the apex, sits half the vital zone above the line of sight.
4. Find where the path falls to half the vital zone below the line of sight. That distance is the MPBR.

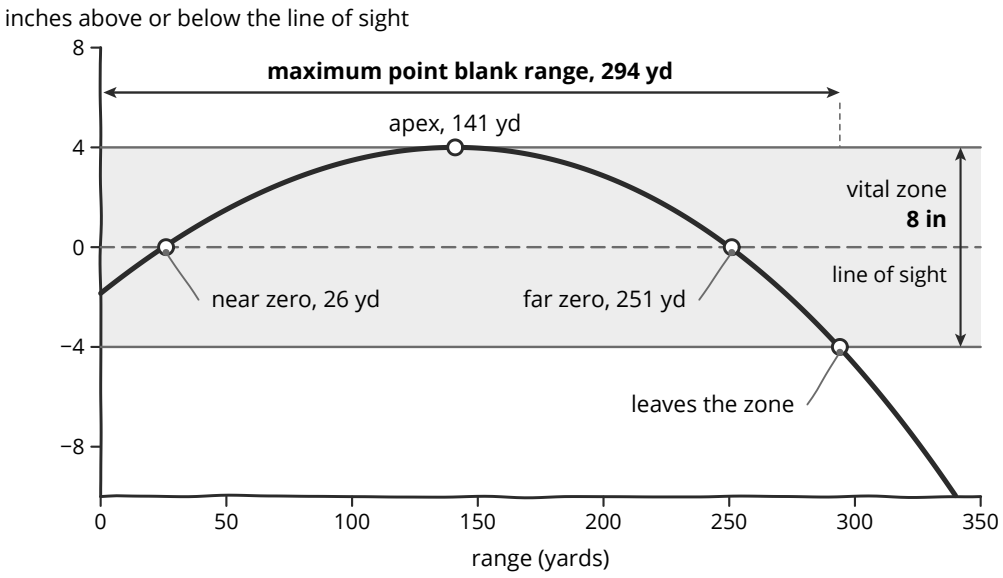
5. Note the two places where the path crosses the line of sight. These are the near zero and the far zero. Zero the rifle at the far zero, or at a shorter range with the computed offset (see "Zeroing at a distance you cannot shoot" below). The near zero is so close to the muzzle that any error in it grows many times over by the far zero.

Inside the MPBR, aim at the center (see Figure 20-2). Beyond it, dial. The size of the vital zone drives the answer more than any other input. The chart holds only with the rifle zeroed for its far zero.

Game class	Typical vital-zone diameter	Half-band (± above/below line of sight)
Varmint and small predator	4 to 6 inches	±2 to ±3 inches
Deer and pronghorn	8 inches	±4 inches
Elk and large big game	10 to 12 inches	±5 to ±6 inches

Worked example. Example numbers. Not load data.

Take a .243 Winchester (6mm-08 class) 95 gr hunting bullet (G1 BC .480) at 3,000 fps with a 1.5-inch sight height and an 8-inch deer vital zone (±4.0 inches). Setting the far zero at 270 yards puts the near zero near 24 yards, places the apex at +4.0 inches near 150 yards, and keeps the path at +3.3 inches at 100 yards, +3.3 inches at 200 yards, and −2.4 inches at 300 yards. The bullet crosses −4.0 inches at about 317 yards, which is the MPBR. Aiming dead center on the vitals keeps the bullet inside the 8-inch zone from the muzzle out to roughly 317 yards without touching a turret—and you can establish that 270-yard zero on a 100-yard range by centering your group 3.3 inches high.



Example numbers. Not load data.

Figure 20-2. Maximum point blank range. The path stays inside a band half a vital zone above and below the line of sight.

EASIER ON EP · VARYTITA · EXTERNAL BALLISTICS

Varytita's MPBR chart finds the zero that keeps the bullet inside your vital zone longest and gives the near zero, the far zero and the MPBR.

empiricalprecision.com/heurisko?tab=varytita

Zeroing at a distance you cannot shoot

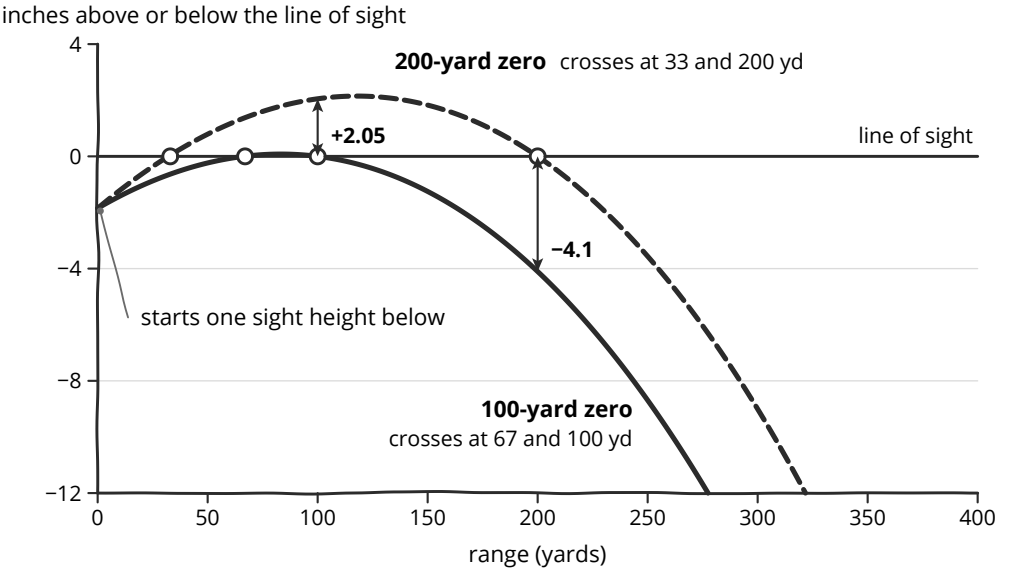
Your range may stop at 100 yards while your chart wants a 200-yard zero or an MPBR far zero. You can zero at the short range by aiming for a computed offset.

A path table for one zero converts to a table for another.

```
New path at dist = old path at dist
                   − (dist ÷ new zero) × old path at new zero

dist       the distance you can shoot
new zero   the zero distance you want
old path   your current path table, inches above (+) or below (−)
           the line of sight
```

Worked example. Example numbers. Not load data. For a 100-yard zero shooting 4.1 inches low at 200 yards, wanting a 200-yard zero on a 100-yard range gives: new path at 100 yards = 0 − (100 ÷ 200) × (−4.1) = +2.05 inches (see Figure 20-3). Center the group about 2.1 inches high—about 2.0 MOA (8 clicks of 1/4 MOA) or 0.57 mil (6 clicks of 0.1 mil).



Example numbers. Not load data.

Figure 20-3. Bullet path against the line of sight for a 100-yard zero and a 200-yard zero.

At the range:

1. Build the chart using measured velocity, BC, air, and sight height—at short range, sight height can shift the offset by over an inch.[7]

2. Read the short-range offset (or compute it above) and print a target with aim and impact marks that far apart at actual size, never "fit to page" (see Figure 20-4); verify scale with a ruler before shooting.
3. Fire a 5-shot group at the aim mark and adjust until group center sits as close to the impact mark as your clicks allow.
4. Measure any residual offset to .1 inch, scale it to the true zero distance (double it for a 200-yard zero shot at 100 yards), enter it as your solver's zero offset, and confirm at the real distance when able.

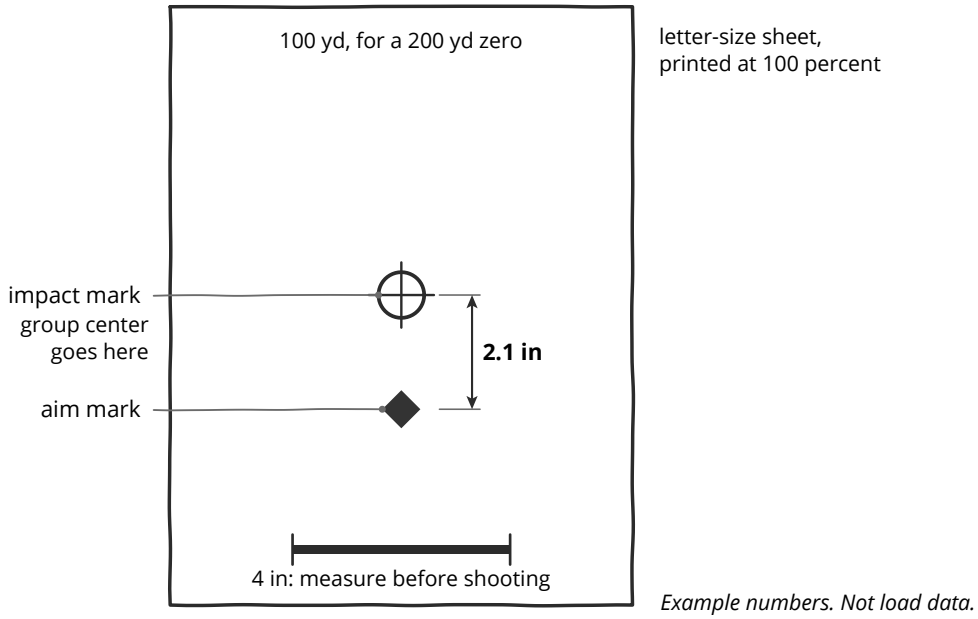


Figure 20-4. A sight-in sheet with an aim mark, an impact mark above it and a check bar.

EASIER ON EP · TARGETS · SIGHT-IN TARGET

The Sight-In Target works out where the group must land at the range you can shoot and prints the aim mark and the impact mark that far apart.

empiricalprecision.com/targets?tab=sight-in

The DOPE card and the field

A DOPE card (see Figure 20-5) should list the air and powder temperature it was built for, with rows at regular or known stage distances showing elevation (in turret units and clicks), wind holds (often built at 10 mph from 3 o'clock and scaled proportionally), and remaining velocity to flag the transonic zone.

Two cautions: with right-hand twist, a card built for a 3 o'clock wind under-holds elevation in a 9 o'clock wind due to aerodynamic jump (see Chapter 19); and because MOA and mil values differ by ~3.4×, dialing the wrong unit causes immediate misses.

Rifle 1, 1:8 right twist zero 100 yd
Load: 140 gr, G7 .315, 2,700 fps
Air: 59 °F, 29.92 inHg station. Powder: 59 °F
Turret: MOA, 1/4 MOA clicks

the air it was built for

range	elev	clicks	wind hold, MOA			vel
yd	MOA	up	5 mph	10 mph	15 mph	fps
100	0.0	0	0.3	0.5	0.8	2,555
200	1.8	7	0.5	1.1	1.6	2,414
300	4.3	17	0.8	1.7	2.5	2,278
400	7.2	29	1.1	2.3	3.4	2,147
500	10.3	41	1.5	2.9	4.4	2,020
600	13.8	55	1.8	3.6	5.4	1,897
700	17.6	70	2.2	4.4	6.5	1,778
800	21.8	87	2.6	5.1	7.7	1,663
900	26.3	105	3.0	6.0	9.0	1,550
1,000	31.4	125	3.4	6.9	10.3	1,441
1,100	36.9	148	3.9	7.9	11.8	1,336
1,200	43.2	173	4.5	8.9	13.4	1,235

below Mach 1.2 (1,340 fps)

Example numbers. Not load data.

Figure 20-5. A DOPE card with range rows, elevation, clicks, wind at several speeds and velocity. Its header names the air it was built for.

Field shots add three factors:

- **Angle.** Multiplying slant range by cos(slope angle) stays within ~0.1–0.2 MIL under 20–25° and 400–500 yards (Chapter 11), but errors grow beyond that—enter look angle directly in a solver for steeper or longer shots.[5]
- **Movers.** Lead (feet) = crossing speed (fps) × TOF. Example numbers. Not load data: a target walking at 3 mph (4.4 fps) at 500 yards with 0.7 s TOF needs ~3 feet of lead.
- **Wind per target.** Compute wind angle along each target's own line of fire.

EASIER ON EP · VARYTITA · EXTERNAL BALLISTICS

Varytita turns the drop chart into a DOPE card to save and print, with a wind column for each speed you list. It also solves each target from its slant range and angle, with lead for a mover and wind for that target's own line of fire.

empiricalprecision.com/heurisko?tab=varytita

Chapter 21

Hit Probability and Error Budgets

Key points

- The goal of load development is hits on a real target at a real distance. The load with the smallest group up close is not always the one that hits farthest.
- Hit chance comes from an error budget. Every uncertainty, in inches at the target, adds to one spread on each axis.
- Past about 500 yards for a typical centerfire rifle, the shooter's wind call usually costs more hits than the rifle or the ammunition.
- Gains from lower velocity SD shrink below about 10 fps for typical long-range targets. The SD worth chasing depends on your distance and target.
- Run the error budget backward to turn a hit goal into limits for mean radius and velocity SD.

Why it matters

Load development ends with one goal. Groups on paper are a means to an end, and the end is hit probability. A Weapon Employment Zone (WEZ) analysis combines the rifle's dispersion, the ammunition's velocity spread and the shooter's own errors in reading wind and range. Its answer is a plain sentence, such as: "With this load, I have an 88 percent probability of hitting a 10-inch plate at 800 yards in a 5 mph wind."

That sentence also shows where effort pays. A handloader can spend a season chasing velocity SD. Hit probability tells you whether that season would buy more hits than practice at reading wind.

How it is done

From groups to hits

1. Start with a composite group of 20 to 30 shots or more. Take its corrected mean radius (MR) in MOA. For a cautious answer, use the upper end of its 90 percent interval (see Chapter 15).
2. Convert the mean radius to a standard deviation on each axis.

```
σ = MR ÷ 1.2533
```

3. If you have separate horizontal and vertical standard deviations for the group, use those instead.
4. Convert to inches at the target distance. One MOA is about 1.047 inches per 100 yards. That is 3.1 inches at 300 yards, 5.2 at 500, 7.3 at 700 and 10.5 at 1,000.

Use the distribution that matches your target's shape (see Chapter 15). A square or rectangular plate uses the normal (single-axis) percentages on width and height separately. A circular plate uses the Rayleigh (radial distance) formula below.

A group shot at 100 yards shows almost none of the velocity SD's effect.[1] So add velocity SD separately at distance. A group shot outdoors already carries some of that day's wind. Adding a full wind error on top errs on the wide side.

List every uncertainty

Use each uncertainty as one standard deviation. The published WEZ wind and range figures are 95 percent bounds, which are two standard deviations.[2] Halve them. Using the ± figure as the standard deviation doubles the error.

Typical values:[3]

Uncertainty	Typical one-sigma values	Notes
Rifle and ammunition	0.17 MOA excellent, 0.33 a good precision rifle, 0.5 a typical hunting rifle	WEZ group sizes of 0.5, 1 and 1.5 MOA,[4] read as 5-shot extreme spreads and divided by 3. Take yours from a composite group
Muzzle velocity SD	5 fps exceptional, 10 good, 15 acceptable, 25 ordinary factory ammunition	Vertical only
Wind call error	0.5 mph with good indicators (high confidence), 1.25 (medium), 2 in a difficult place (low confidence)	WEZ bounds of ±1, ±2.5 and ±4 mph, halved[2]
Range error	1 to 3 yards with a laser rangefinder on a reflective target, 25 to 50 yards by eye	Vertical, and grows with range
BC variation	0.5% meplat-trimmed or pointed (tip-uniformed) match bullets, 1 to 2% factory match, 3% bulk or hunting	Vertical, and small inside 600 yards
Cant	Under 0.5 degree with a level you check, 1 to 2 degrees without one	Horizontal, and grows with range

Then convert each one to inches at the target. For velocity, BC and cant, use your solver. Build the chart again with 10 fps more velocity, 1 percent more BC or 1 degree of cant. Keep the same sight setting, and do not re-zero. Take the difference at each distance. Divide the velocity difference by 10 for inches per fps. Here are the figures for an example 6.5 Creedmoor load (140 gr, G7 .315, 2,700 fps, standard day).[3] Example numbers. Not load data.

One sigma of	At 700 yd	At 1,000 yd
1 MOA of dispersion	7.3"	10.5"
1 mph of crosswind	3.18"	7.19"
10 fps of velocity	1.23"	3.03"
1% of BC	.50"	1.89"
1 degree of cant	2.7"	6.4"

If your solver automatically re-zeroes the rifle at 100 yards when you add 10 fps, it understates how much a faster shot rises downrange, because a faster shot also strikes slightly higher at 100 yards. For this load, a re-zeroed chart shows a 2.83-inch change at 1,000 yards (the right number for truing a zeroed chart in Chapter 20), whereas a shot that is 10 fps faster at a fixed scope setting actually strikes 3.03 inches higher. The difference is the .02-inch rise at 100 yards multiplied by 10 (for 1,000 yards):
2.83 + 10 × .02 = 3.03 inches.

A misread crosswind also moves the shot a little up or down through aerodynamic jump. For this load that is .28 inch per mph at 700 yards and .39 inch at 1,000 (see Chapter 19).[3]

Combine them

Independent errors add by root-sum-square. Combine the horizontal sources and the vertical sources separately.

```
σ total = √(σ1² + σ2² + σ3² + ...)
```

The rule has a consequence. The largest source dominates the total. Shrinking a small source barely changes it.

Turn the spread into a hit chance

For a rectangular plate of width W and height H, with the group centered on it:

```
P(hit) = (share within ±(W ÷ 2) across)
         × (share within ±(H ÷ 2) up and down)

z = (half the plate's width or height) ÷ σ on that axis
```

Read the share for each axis from Table 21-1, or from any normal table. Between rows, use the spreadsheet formula below, or the row with the smaller z for a cautious answer.

Table 21-1. The share of shots within ±z σ of the center, on one axis.

z	Share within ±z σ
0.5	38.3%
1.0	68.3%
1.25	78.9%
1.5	86.6%
1.75	92.0%
2.0	95.4%
2.25	97.6%
2.5	98.8%
3.0	99.7%

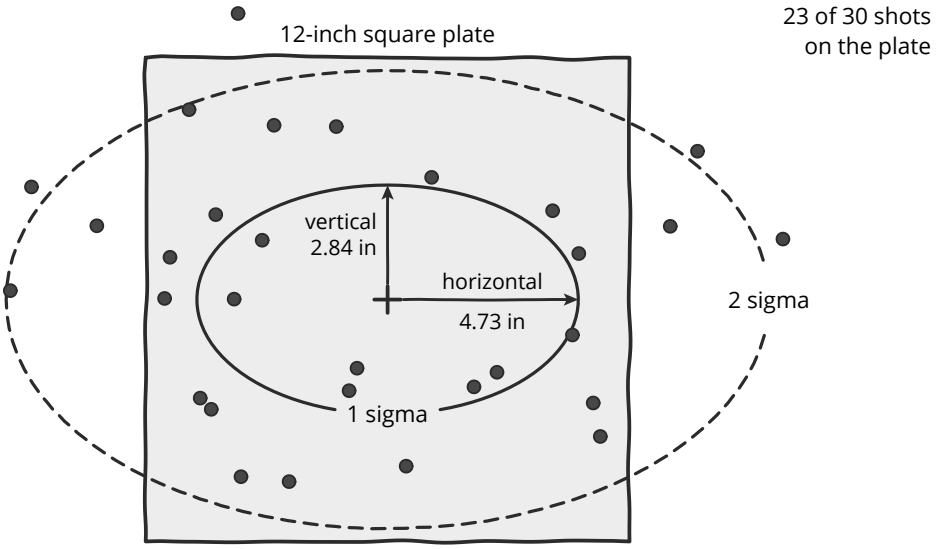
In a spreadsheet, the share for z is 2 × NORM.S.DIST(z, TRUE) − 1, and z for a given share is NORM.S.INV((1 + share) ÷ 2).

For a round plate of radius R, when the group is round with the same sigma on both axes:

```
P(hit) = 1 − exp(−R² ÷ (2 × σ²))
```

If the two sigmas differ, use the larger one for a cautious answer.

Both formulas assume normal errors and a group centered on the target (see Figure 21-1). A zero error or an aim error moves the group off center. That costs more hits than these formulas show.



Simulated shots. Example numbers. Not load data.

Figure 21-1. From a composite group to a hit chance. The group's one-sigma and two-sigma ellipses are laid over a square plate.

Worked example. Example numbers. Not load data.

Take the example 6.5 Creedmoor load and a 12-inch square steel plate at 700 yards. Rifle and ammunition dispersion is 0.35 MOA, one sigma on each axis. That is 2.56 inches at 700 yards (0.35 × 7.3). The velocity SD is 10 fps, which adds 1.23 inches of vertical spread.

The wind call error is 1.25 mph, a typical medium-confidence call.[2] At 700 yards that adds 3.98 inches of horizontal spread (1.25 × 3.18). Range error, BC variation, cant and the aerodynamic jump from the wind call error (see Chapter 19) are left out to keep the example short. Each would lower the hit chance a little.

```
Horizontal σ = √(2.56² + 3.98²) = 4.73 inches
Vertical σ   = √(2.56² + 1.23²) = 2.84 inches

Horizontal: z = 6 ÷ 4.73 = 1.27   share = 0.796
Vertical:   z = 6 ÷ 2.84 = 2.11   share = 0.965

P(hit) = 0.796 × 0.965 = 0.77
```

About 77 shots in 100 hit the plate.

From a hit goal to load limits

Run the same steps backward to set a goal for a load before you test it.

1. Write the target, the distance and the hit chance you want.
2. Split the hit chance between the two axes. The two shares multiply to the hit chance. The wind call usually dominates the horizontal, and the charge barely changes the horizontal spread. So give the vertical a high share, such as 95 percent, and let the horizontal take the rest. For a round plate, work forward with the round formula, trying limits until the hit chance meets the goal.

3. For each axis, find z for its share in Table 21-1. The largest sigma the axis can carry is half the target's size on that axis divided by z.
4. Take out the errors the load cannot change, by root-sum-square. On the horizontal that is the wind call, and cant if you shoot without a level. What is left is the most the rifle and ammunition may add. If the wind call alone uses up the whole allowance, the goal cannot be met at that call. Lower the goal, shoot closer or call the wind better. Work the limits for each candidate bullet, since its drift per mph sets the wind term.
5. Convert that rifle-and-ammunition sigma to MOA and then to a mean radius: MR = 1.2533 × σ.
6. The rifle-and-ammunition sigma counts on the vertical too. Check that it is below the vertical's largest sigma. If so, take it out by root-sum-square. What is left is the velocity allowance. Divide it by the inches per fps at that distance to get the largest velocity SD. If not, the split does not fit. Give the vertical a smaller share, give the horizontal the rest, and repeat steps 3 to 6.

Because these target limits depend on how you split the budget between horizontal and vertical, they are one way to meet the goal, not the only way. Judge a candidate load using the upper ends of its 90 percent confidence intervals (see Chapter 16). Before rejecting a load that misses one limit, calculate its forward hit probability using those upper bounds: tighter dispersion can offset a slightly higher velocity SD (or vice versa) and still meet your hit goal.

Worked example. Example numbers. Not load data.

The same 12-inch plate at 700 yards, with the same medium-confidence wind call of 3.98 inches. The goal is 75 hits in 100.

```
Shares:      horizontal 78.9% (z = 1.25), vertical 95.4% (z = 2.0)
             0.789 × 0.954 = 0.75

Horizontal:  largest σ = 6 ÷ 1.25 = 4.80 inches
             rifle and ammunition = √(4.80² − 3.98²)
                                  = 2.68 inches
             2.68 ÷ 7.3 = 0.37 MOA σ
             MR = 1.2533 × 0.37 = 0.46 MOA

Vertical:    largest σ = 6 ÷ 2.0 = 3.00 inches
             2.68 is under 3.00, so the split fits
             velocity allowance = √(3.00² − 2.68²) = 1.35 inches
             velocity SD = 1.35 ÷ 0.123 = 11 fps
```

The load needs a corrected mean radius of about 0.46 MOA or less and a velocity SD of about 11 fps or less. With a perfect load, the 1.25 mph call alone still holds the hit chance to 87 in 100. A wind call good to 0.5 mph would leave 4.53 inches for the rifle on the horizontal. That is more than the vertical's 3.00, so work the split again with a smaller vertical share before you use it.

Which uncertainty costs the most hits

Change one input at a time and work the hit chance again. Then rank the changes by hits gained or lost. WEZ analysis can serve as this kind of sensitivity test.[2]

Example numbers. Not load data. For the worked example:

Change	Horizontal sigma	Vertical sigma	P(hit)
As worked above	4.73"	2.84"	77%
Velocity SD 10 to 5 fps	4.73"	2.63"	78%
Velocity SD 10 to 15 fps	4.73"	3.16"	75%
Wind call error 1.25 to 0.5 mph	3.01"	2.84"	92%
Wind call error 1.25 to 2 mph	6.86"	2.84"	60%
No wind call error	2.56"	2.84"	95%

Halving the velocity SD adds about 1 point. Moving from a medium-confidence to a high-confidence wind call adds about 15. At 1,000 yards on a 20-inch plate, with 1 percent BC variation added, the pattern holds. Halving velocity SD adds about 2 points there, and a high-confidence wind call adds about 24.

The same numbers give a miss budget. In the worked example, about 20 percent of shots miss out the sides and about 3.5 percent miss high or low. Horizontal misses outnumber vertical ones about six to one, so work on the wind before the ammunition (see Figure 21-2).

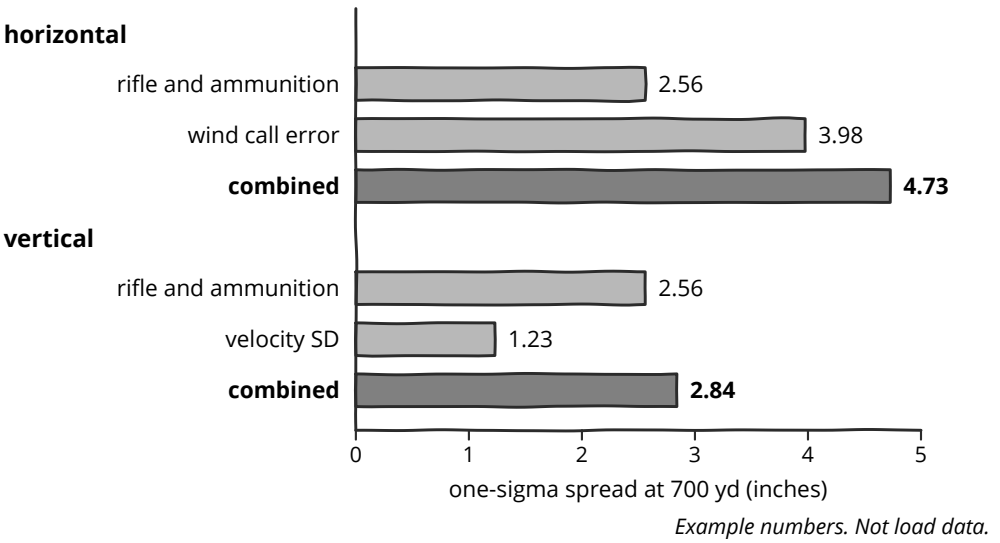


Figure 21-2. The worked example's error budget at 700 yards: inches of one-sigma spread from each source and the combined total on each axis.

Why wind call error usually dominates

For a typical centerfire rifle, past about 500 yards, wind call error usually costs the most hits.[3] In subsonic .22 LR, those distances compress sharply: wind call error dominates by 100 yards, and a 15 fps velocity SD adds roughly 4 to 5 inches of vertical spread by 300 yards. There are three reasons wind dominates.

Drift grows faster than range. Rifle and ammunition spread grows in step with distance. Wind drift grows faster, because the bullet sheds speed. For the example load, drift per 1 mph of crosswind grows from .52 inch at 300 yards to 7.19 inches at 1,000.[3] That is about 14 times the drift over a little more than three times the distance.

Calling the wind is hard. A high-confidence call, with good indicators, is good to about ±1 mph. A call in a difficult place may not get within ±4 mph (see the table above).[2]

A misread costs its full drift. The shot moves by the full drift of the error, whatever the wind's speed.

Gusts add on top. A wind that varies by 3 mph (one sigma) spreads the example load by 9.5 inches at 700 yards. Direction errors cost little near full value and a lot at shallow angles. In a 10 mph wind at 700 yards, a 10-degree error costs the example load .5 inch near full value but 5.1 inches near a 30-degree wind.[3]

Try a simple test. Work your hit chance twice, once with your honest call error and once with none. The difference is your wind-reading skill measured in hits. For most shooters at distance it is larger than anything reloading can add.

> **Evidence · Plausible but unproven**
> In the worked example, wind call error is the largest term at 700 yards: 3.98 inches against 2.56 for the rifle and ammunition. That is a model result, built on measured drift and published estimates of call error.[2] No study has yet measured how call error grows with wind speed.[5]

How much velocity SD is worth chasing

The SD worth chasing depends on your distance and target. To set your own SD target from hit probability:

1. Name the real job: the target's size and the longest distance you shoot it.
2. Use your honest wind call error.
3. Work the hit chance at your measured SD.
4. Work it again with the SD 5 fps lower (see Figure 21-3).
5. Compare that gain with what a better wind call buys at the same distance.
6. Chase SD only when the gain is worth the work to you, or when vertical misses lead the miss budget.

How low to push the SD is a contested question.

Contested: long range needs a single-digit velocity SD

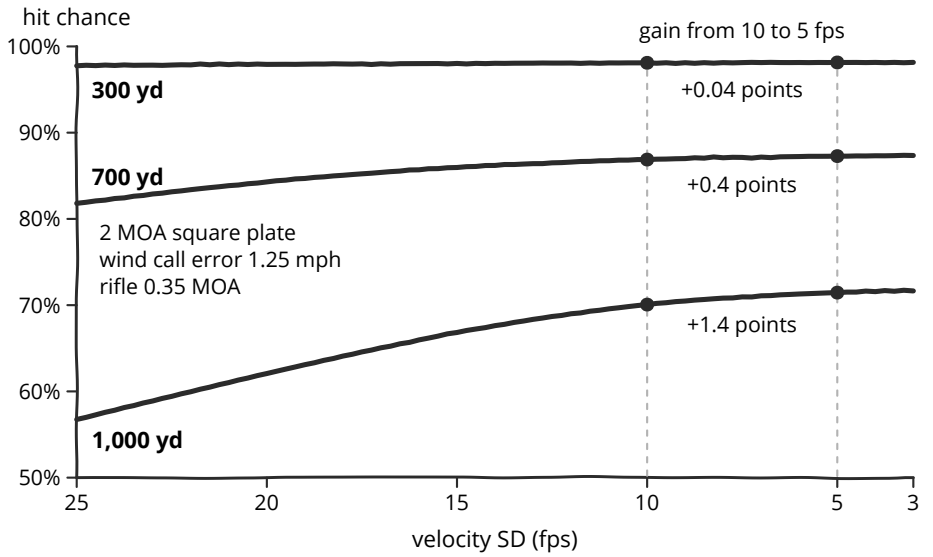
The claim. A velocity SD under 10 fps is the gold standard for long range. It is single digits or nothing.

The physics. Velocity SD moves shots up and down only. It adds by root-sum-square to rifle dispersion and BC variation. Its cost grows with range, but wind error usually grows faster.

The test. Work the hit chance at your distance and target, at your measured SD and at a lower one.

The data. In one modeled long-range scenario with centered groups, cutting SD from 20 to 15 fps gave about 5 more hits in 100. Cutting it from 15 to 10 fps added about 3 more, and cutting it from 10 to 3 fps only about 1 more. The gains were a little larger on the farther of two targets, and they shrank at every step.[6] For a typical centerfire rifle, inside

about 300 yards, a 15 fps SD adds only about .3 inch of vertical. In subsonic .22 LR, by contrast, wind dominates by 100 yards and a 15 fps SD adds roughly 4 to 5 inches of vertical by 300 yards.



Example numbers. Not load data.

Figure 21-3. Hit chance against velocity SD at 300, 700 and 1,000 yards. The curves flatten as SD falls. The plate here is 2 MOA square, so the gains differ from the 12-inch worked example.

The measurement limits the chase too. Instrument error adds to the true SD (see Chapter 7). Ten shots pin an SD only loosely (see Chapter 15). A single-digit SD from a 5-shot string proves little.

The verdict. Plausible but unproven. Lower SD helps, but the gains shrink below about 10 fps when wind error is present.[6] The gains are largest at long range, on small targets, for shooters who call wind well. Inside about 300 yards for a typical centerfire rifle they barely exist. These figures come from a model built on measured drift and dispersion, not from hits counted on targets. A fixed SD target is a habit, not a finding.

Worked example: when single-digit SD protects score (1,000-yard F-Class). Example numbers. Not load data.

F-Class long-range competition is the classic exception where single-digit velocity SD and tight BC consistency genuinely pay off. At 1,000 yards, the circular 10-ring is 1.0 MOA (10.47 inches diameter, radius 5.24 inches) and the X-ring is 0.5 MOA (5.24 inches diameter, radius 2.62 inches). Suppose a bench-rested F-Class rifle shoots 0.25 MOA one-sigma dispersion (2.62 inches at 1,000 yards) and range wind flags compress wind-call error to 0.40 mph (2.88 inches at 7.19 inches per mph), giving a horizontal σ of 3.89 inches. Using

this chapter's 1,000-yard vertical sensitivities (3.03 inches per 10 fps of velocity SD and 1.89 inches per 1 percent of BC SD):

Ammunition consistency	Horizontal σ	Vertical σ	10-ring hits	X-ring hits
15 fps velocity SD, 1.5% BC SD	3.89"	5.96"	44%	14%
15 fps velocity SD, 0.5% BC SD	3.89"	5.33"	48%	15%
7 fps velocity SD, 0.5% BC SD	3.89"	3.50"	64%	22%
5 fps velocity SD, 0.5% BC SD	3.89"	3.17"	67%	24%

Because horizontal and vertical sigmas differ on circular concentric rings, these ring probabilities come from Monte Carlo WEZ simulation (such as Kyvos) rather than the equal-sigma circle shortcut. Once wind flags and a 0.25 MOA rifle shrink the other error terms, vertical spread becomes the bottleneck: cutting velocity SD from 15 fps down to 5 to 7 fps with consistent BC adds roughly 16 to 19 percentage points of 10-ring hits and 7 to 9 points of X-count.

Where effort pays

The same sums rank every step of the process, not only the wind call and velocity SD. Weigh what each step costs against the hits it adds at your distance, and do the cheap steps that pay first.

Count cost in rounds' worth. The components of one loaded round count as 1: the bullet, powder, primer and once-fired brass. A tool counts as the number of rounds its price would buy. Count an hour of your time as 20 rounds' worth, or whatever it is worth to you. A count in rounds keeps its meaning as prices change.

1. List the steps you could add, and what each costs in rounds fired, tools and hours.
2. Write down what each step changes: a velocity error, the velocity SD or the dispersion.
3. Work the hit chance with and without it, at your distance and target (see "Turn the spread into a hit chance" above).
4. Divide each step's cost by the hits it adds. Start with the steps that cost least for each hit.

Worked example. Example numbers. Not load data.

Take the example load at 700 yards on the 12-inch plate, and at 1,000 yards on a 20-inch plate with 1 percent BC variation. Dispersion is 0.35 MOA, velocity SD 10 fps and the wind call 1.25 mph, as above. Costs are in rounds' worth, with an hour counted as 20. The table is sorted by cost for each hit gained at 1,000 yards.

Step	What it changes in this example	Cost, rounds' worth	Hits gained per 100 at 700 yd	Hits gained per 100 at 1,000 yd
Hold the ammunition temperature (Chapter 23)	A 20 fps seasonal velocity error (40 °F at 0.5 fps per °F) cut to 5 fps, with the ammunition held within 10 °F	20, an insulated box	5.5	11
True the drop chart on observed drops (Chapter 20)	Removes a 25 fps error in the chart's velocity, such as an optical chronograph can leave (see Chapter 7)	70: 15 rounds and 3 hours	9.4	19
Choose between bullets and powders by the recommended default (Chapter 16)	Dispersion 1.25 to 1 smaller	440: 118 rounds and 16 hours	6.8	4.1
Weigh every charge instead of throwing (*The Handloading Handbook*)	Velocity SD 11.2 to 10.1 fps, as in *The Handloading Handbook*'s example	95 per 1,000 rounds: about 5 hours	0.3	0.7
One optional case prep task (*The Handloading Handbook*)	Dispersion 5 percent smaller, if the task worked that well	8 to 1,630 over the first 1,000 rounds	1.1	0.7
Prove that one load groups 5 percent smaller than another (Chapter 16)	Nothing on target. It only confirms a gain worth the row above	13,500: 4,510 rounds and 450 hours	None	None
A small-sample ladder, optimal charge weight test or seating sweep (Chapter 17)	Nothing. One to five shots per step measure noise	60 to 120	None	None

For scale, a wind call improved from 1.25 to 0.5 mph adds about 15 hits per 100 at 700 yards and 24 at 1,000 (see "Which uncertainty costs the most hits" above). It costs practice, not tools.

Three things stand out.

- The cheapest steps that fix a velocity error pay most: holding the ammunition temperature and truing the chart.
- Choosing between bullets and powders pays next. Fine changes to the charge or the case do not (see Chapter 16).
- Per-round case prep returns about a hit per 100 at most, even if it works. Proving a small difference costs more than it can ever return, and the small-sample tuning methods return nothing.

Your numbers will differ. Inside about 300 yards for a typical centerfire rifle, velocity errors and velocity SD barely move the shot, so dispersion and the wind are all that count. A measure that throws wider than *The Handloading Handbook*'s example makes weighing pay more. Work the table for your own load, target and distance.

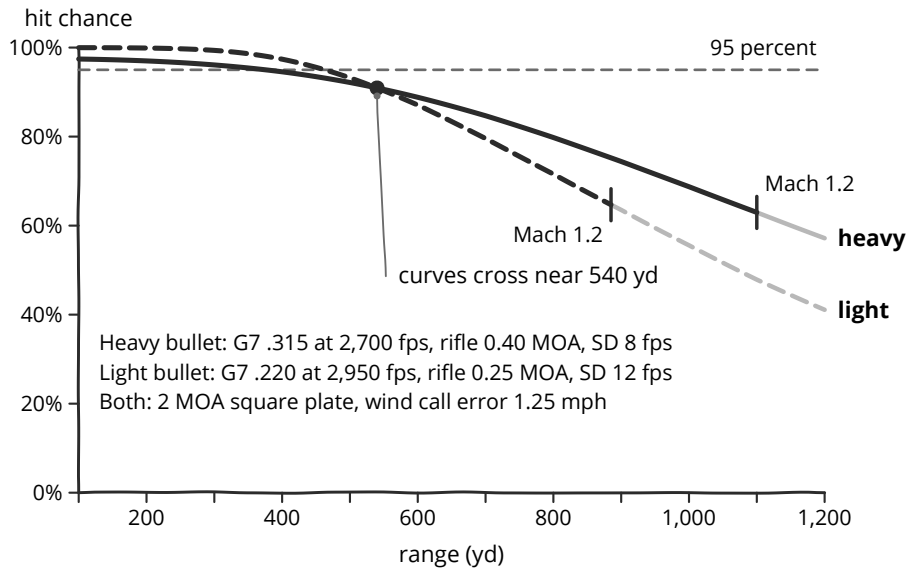
Weapon Employment Zone analysis

WEZ analysis is the full version of this method. It runs a ballistic solver many times. Each run draws every input from its uncertainty, and each simulated shot either hits or misses.[2]

1. Define the target's shape and size. The results depend heavily on them.
2. Set each uncertainty. One published table gives three confidence sets. Crosswind is ±1, ±2.5 or ±4 mph. Range is ±1, ±10 or ±50 meters. Rifle and ammunition precision is a group size of 0.5, 1.0 or 1.5 MOA, not a standard deviation. Velocity SD is 10, 15 or 20 fps.[4] Read each group size as a 5-shot extreme spread. A 5-shot extreme spread averages about 3 standard deviations, so divide the group size by about 3 to use it as one sigma.
3. Fly 1,000 shots at each range. Results then repeat within 1 or 2 percent.[2]
4. Plot the hit percentage against range.
5. Mark the transonic range. Show hit percentages beyond it in gray and read each one as somewhere between that number and zero.[2]
6. Compare systems under the same uncertainty set. Comparison is the main use.

One example compares two bullets in one cartridge. Bullet A is heavy and slower, with a high BC. Bullet B is light and faster, with a lower BC. In a high-confidence set both hit 100 percent out to 800 yards, and beyond that A leads. A stays supersonic to 1,450 yards and B to 1,100. With large range errors, the faster and flatter B might be the better choice.[2] The answer depends on the uncertainties.

The root-sum-square method above gives nearly the same answer as a simulation when the errors are roughly normal and modest in size. A spreadsheet can also run the simulation. Draw each error with a normal random function, such as NORM.INV(RAND(), 0, sigma). Add the errors for each simulated shot, score it as a hit or a miss and count.



Example numbers. Not load data.

Figure 21-4. Hit chance against range for two loads. The curves cross, and each load's transonic range is marked.

EASIER ON EP · KYVOS · DISPERSION SIMULATION

Kyvos runs this error budget for one load from your one-sigma uncertainties and plots the hit chance against range.

empiricalprecision.com/heurisko?tab=kyvos

Most precise up close, or hits farthest

These are different questions. A ranking by group size finds the load with the best average group. Hit chance at distance also depends on BC, velocity SD and how long the bullet stays supersonic. So the smallest 100-yard group can lose at 800 yards. The winner there may group slightly larger but have a higher BC, a tighter velocity SD or more supersonic margin.

To compare loads by hand, work each load's hit chance at each distance. Use its own mean radius and velocity SD, with the same wind call and target for every load. Watch for the distance where the curves cross. Call a winner only where the gap is larger than the uncertainty in your inputs.

EASIER ON EP · MANTEIS · HIT PROBABILITY

Manteis compares the hit chance of several saved sessions at each distance, each from its own group and velocity.

empiricalprecision.com/heurisko?tab=manteis

Chapter 22

Terminal Ballistics and Ethical Hunting Range

Key points

- Reliable bullet expansion depends on impact velocity, not muzzle velocity.
- Cup-and-core, bonded, and monolithic copper bullets have different minimum expansion velocity thresholds.
- Ethical maximum hunting range is the shorter of two limits: your field hit-probability limit (WEZ) and your bullet's minimum expansion velocity distance.
- Measure real field positional dispersion before committing to long-range shots on game.

Why it matters

External ballistics delivers the bullet to the target; terminal ballistics determines what happens when it arrives. Knowing both sets an honest, ethical distance limit in the field.

How it is done

Impact velocity and bullet construction

A hunting bullet does not know how fast it left the muzzle. It only knows how fast it is traveling when it strikes tissue. Aerodynamic drag slows every bullet continuously from the moment it leaves the bore. A typical 140 gr 6.5mm hunting bullet (G7 BC .315) launched at 2,700 fps drops to roughly 2,220 fps at 300 yards, 1,925 fps at 500 yards, and 1,785 fps at 600 yards on a standard day. Example numbers. Not load data.

Every expanding hunting bullet has a minimum reliable expansion velocity. Above that speed, hydraulic pressure inside the nose cavity peels the jacket or petals open, creating a wide wound channel. Below that speed, the bullet fails to open and passes through like a full-metal-jacket projectile, leaving a narrow wound track that risks a slow, unethical loss of game.

Construction sets the velocity window. Always check the bullet maker's published minimum expansion velocity for your exact bullet, because jacket thickness and tip geometry vary even within the same class.

Bullet construction	Typical minimum expansion velocity	Strengths	Trade-offs
Cup-and-core (lead core, copper jacket)	Roughly 1,600 to 1,800 fps	Opens reliably at lower impact speeds and longer distances	Can lose weight or break up on close, high-velocity bone hits
Bonded (lead core bonded to jacket)	Roughly 1,800 to 2,000 fps	High weight retention and deep penetration on heavy bone	Slightly higher expansion floor than soft cup-and-core designs
Monolithic copper (solid copper or alloy)	Roughly 1,800 to 2,200 fps (commonly near 2,000 fps)	Retains nearly 100 percent of its weight; deep, straight penetration; lead-free	Harder metal needs higher impact speed to open reliably; longer for a given weight, which can require a faster twist (see Chapter 18)

A bullet that stays supersonic to 1,200 yards is not a 1,200-yard hunting bullet. Its impact velocity drops below the expansion floor hundreds of yards before it reaches the transonic zone.

> **Safety · See Chapter 2**
> Positively identify your target and what lies beyond it before every shot. Follow all local hunting regulations, including minimum caliber, energy, or non-lead projectile rules. Never take a shot on game at a distance you have not verified from realistic field positions.

Impact energy, sectional density, and penetration

Shooters often check kinetic energy (KE) as a rough guide to downrange power.

```
KE = w × v² ÷ 450,437

KE   kinetic energy in foot-pounds (ft-lbs)
w    bullet weight in grains
v    impact velocity in fps
```

Because velocity is squared, losing speed downrange cuts energy sharply. Using the 140 gr example bullet above, muzzle energy at 2,700 fps is 2,266 ft-lbs. At 300 yards (2,220 fps), energy has fallen to 1,532 ft-lbs. At 500 yards (1,925 fps), it is 1,152 ft-lbs. Example numbers. Not load data.

Kinetic energy alone does not cleanly harvest game. A bullet that hits the heart and lungs and expands properly at 1,000 ft-lbs is far more effective than a 2,500 ft-lbs bullet that clips the edge of the vitals or fails to open. Treat traditional energy rules of thumb (such as 1,000 ft-lbs for deer or 1,500 ft-lbs for elk) as rough sanity checks, not guarantees.

Penetration depends heavily on bullet construction and sectional density (see Chapter 19).

```
Sectional density = w ÷ (7,000 × d²)

w   bullet weight in grains
d   bullet diameter in inches
```

Between two bullets of the same construction, the one with higher sectional density packs more mass behind its frontal area. That extra mass helps it drive straight through hide, muscle, and heavy shoulder bone to reach the vitals. A 140 gr 6.5mm bullet (.264 inch) has a sectional density of 0.287, while a 120 gr bullet of the same diameter drops to 0.246.

Expansion and penetration pull in opposite directions. A bullet that opens very wide creates a larger initial wound channel, which increases drag in tissue and reduces penetration depth. A tough bonded or monolithic bullet opens more conservatively, holds its weight, and penetrates deeper through heavy game, but it requires higher impact velocity to start expanding. Match the bullet to the game's body mass and your expected shot distances.

Setting an ethical maximum hunting range

Your ethical maximum hunting range is the **shorter** of two objective limits:

1. **The terminal limit.** The distance where your bullet's impact velocity falls to its minimum reliable expansion velocity (checked for the temperature and elevation of your hunt).
2. **The hit-probability limit.** The distance where your first-round hit probability on the animal's vital zone drops below your ethical threshold (commonly 90 percent or higher), measured from real field positions and honest wind-calling skill (see Chapter 21).

Do not measure your field dispersion from a concrete shooting bench with a front rest and rear bag. Measure it from the positions you actually use afield: prone over a pack or bipod, sitting off a tripod, or kneeling. Most shooters group roughly two to three times wider from field positions than they do from a shooting bench.

1. Choose the vital-zone size for your game (for example, an 8-inch vital zone for deer-sized game).
2. Measure your field positional dispersion with at least 10 to 20 shots from your actual hunting support. Convert that composite mean radius to a one-sigma angular spread (divide mean radius by 1.2533, see Chapter 21).
3. Enter your trued trajectory, velocity SD, field dispersion, and honest field wind-call error into a Weapon Employment Zone model (see Chapter 21).
4. Find the distance where vital-zone hit probability drops below 90 percent.
5. Find the distance on your drop chart where impact velocity reaches the bullet maker's minimum expansion velocity.
6. Set your ethical maximum range at the shorter of those two distances.

Worked example. Example numbers. Not load data.

Take the 6.5 Creedmoor 140 gr load (G7 BC .315, 2,700 fps muzzle velocity, 12 fps velocity SD) on an 8-inch square vital zone (4 inches from center to each edge). From a pack and bipod in the field, the hunter shoots a one-sigma positional dispersion of 0.50 MOA (roughly 1.5 MOA 5-shot groups). Without wind flags, the hunter's honest wind-call error is 2.0 mph one-sigma. Using the Chapter 19 wind-drift figures and Chapter 21's root-sum-square error budget:

Distance	Impact velocity	Kinetic energy	Horizontal sigma	Vertical sigma	P(hit) on 8" vitals
300 yd	2,220 fps	1,532 ft-lbs	1.88"	1.59"	96%
400 yd	2,070 fps	1,332 ft-lbs	2.84"	2.13"	79%
500 yd	1,925 fps	1,152 ft-lbs	4.03"	2.70"	59%
600 yd	1,785 fps	990 ft-lbs	5.54"	3.31"	41%

Two lessons stand out immediately:

- **With a cup-and-core bullet needing 1,800 fps**, impact velocity holds nearly to 600 yards. Hit probability, however, drops below 90 percent past roughly 340 yards. Field dispersion and wind-call error set the ethical maximum range at about 340 yards, well inside the bullet's terminal limit.

- **With a monolithic copper bullet needing 2,000 fps**, impact velocity falls below the expansion floor near 450 yards. Even if a steadier position and calmer wind kept hit probability above 90 percent to 500 yards, the bullet's expansion velocity would cap the ethical shot at 450 yards.

In both cases, the shorter limit governs. When conditions worsen, such as gusting wind, an awkward rest, or heavy breathing after a climb, shorten your maximum range further.

Evidence · Supported by data
Weapon Employment Zone modeling shows that realistic field dispersion and wind-call uncertainty typically cap ethical vital-zone hit probability well short of a modern hunting cartridge's supersonic or energy limits.[1]

EASIER ON EP · VARYTITA · EXTERNAL BALLISTICS
Varytita reports impact velocity and kinetic energy at every distance for your hunt's air density, and Kyvos computes vital-zone hit probability using your real field dispersion and wind-call uncertainty.
empiricalprecision.com/heurisko?tab=varytita

VI

Part VI

Living With a Precision Rifle

Chapter 23. Barrel Lifecycle, Thermal Management, and Maintenance 154
Chapter 24. Range and Accuracy Troubleshooting 163

Chapter 23

Barrel Lifecycle, Thermal Management, and Maintenance

Key points

- Hold the ammunition at a steady temperature when you fire it, and the velocity you recorded stays true.
- A new lot can change pressure. Your velocity records, not an assumption that it matches, tell you whether it did.
- The throat wears with every shot, so jump and velocity drift over a barrel's life.
- Every change to a component, the rifle or the season reopens a finished load.

Why it matters

A load is not finished when it wins. Seasons change. Powder lots run out. The throat wears a little with every shot. Each change moves velocity, pressure or both. The data you gathered stays true only if you keep checking it.

How it is done

Hold the ammunition temperature

Powders respond to temperature, and each load responds in its own way (see *The Handloading Handbook*). Measuring that response takes more control than a home range gives. A round warms or cools toward the air as soon as it leaves its box, and a warm chamber heats it further. What you can control is the temperature of each round when you fire it. Keep that temperature steady, and your recorded velocity holds true even if you do not know the powder's exact temperature curve.

> **Safety · See Chapter 2**
> Hot ammunition runs at higher pressure. A vehicle in the sun, a pocket and a warm chamber all count toward the hottest your ammunition will see (see *The Handloading Handbook*). Never warm ammunition on purpose.

1. Read the ammunition temperature at every session, with a thermometer in the ammunition box (see Chapter 7). Record it with the session (see Chapters 13 and 14).
2. At the range, keep the ammunition in a closed, insulated box in the shade. Never leave it in the sun, on a dark mat or in a closed vehicle.
3. In the field, carry the rounds in an inside pocket, or in a pack away from the sun. Body heat holds them far steadier than the air around you.
4. Keep the action open until you are ready to fire. Chamber each round only then. In a hold or a cease-fire, unload.
5. If a round sits in a warm chamber before it fires, note it on its shot line before you look at the target (see Chapter 14).

6. Chronograph the load the way you carry it. A hunter's drop chart comes from rounds carried in the pocket, and a competitor's from rounds kept in the shaded box (see Chapter 20).

Evidence · Supported by data
A powder's response to temperature depends on the cartridge, the lot and the rifle, and it is often not a straight line. In one measured powder the slope in the cold was about twice the slope in the heat (see *The Handloading Handbook*).[1]

Watch for heat

Some heat reaches the rounds however careful you are. Your velocity records show it, with no special test.

In a long string. Barrel and chamber heat climb through a long string, and each round that waits in a warm chamber takes up some of it. In any string of 15 shots or more, compare the mean velocity of the last five shots with the first five. Judge the gap against its noise.

```
noise = SD × √(2 ÷ 5)       SD = the string's velocity SD
A rise of more than twice the noise is heat reaching the rounds.
```

Worked example. Example numbers. Not load data.

A 20-shot string has a velocity SD of 10 fps. Its first five shots average 2,701 fps and its last five average 2,719 fps.

```
noise      = 10 × √(2 ÷ 5) = 6.3 fps
twice that = 12.6 fps
rise       = 2,719 − 2,701 = 18 fps
```

The rise is more than twice the noise, so heat is reaching the rounds (see Figure 23-1). Slow the pace, shorten the strings or keep the action open longer between shots. Fire load tests in interleaved 5-round blocks, so no load meets only the hottest barrel (see Chapter 14).

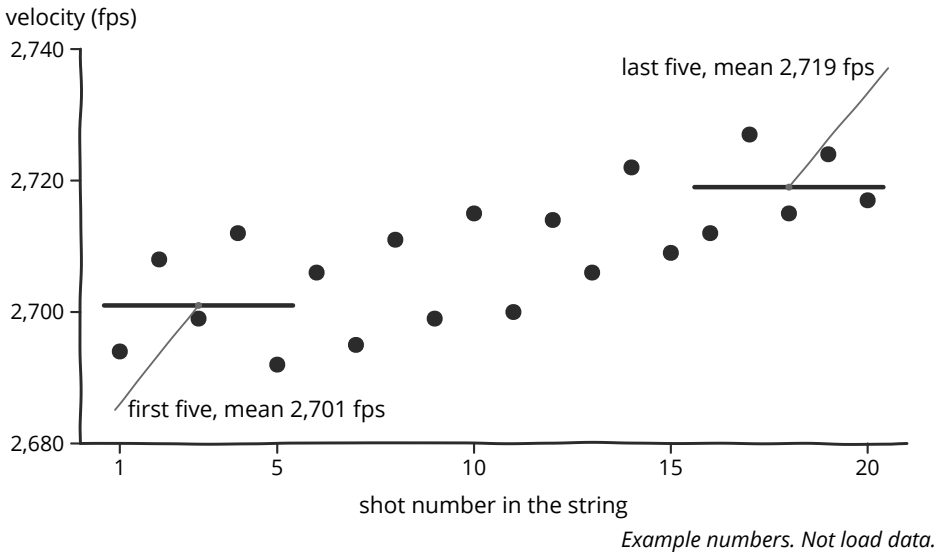


Figure 23-1. Velocity through a 20-shot string. The last five shots average 18 fps faster than the first five, more than twice the noise.

In a timed 20-shot match string. F-Class, High Power, and benchrest matches often require 20 record shots plus sighters inside a fixed clock, where you cannot stop for ten minutes to cool the barrel. Manage heat with three habits: fit a mirage shield (or band) over the barrel so rising heat waves do not bend your sight picture through the scope; open the bolt immediately after each shot so air moves through the chamber while the target is scored; and chamber each fresh round only when you are ready to break the shot, keeping chamber dwell time identical from shot 1 to shot 20.

On a hot day. When the ammunition is warmer than it was at the work-up, fire one round alone first and read its velocity. If it reaches your velocity ceiling, the load is too hot for that day. Stop and reduce the charge (see *The Handloading Handbook*). Any pressure sign means stop now.

On any day far from your records. On a day much hotter or colder than any in your records, compare the session's mean velocity with the record nearest its ammunition temperature. Note the gap in the velocity history (see Chapter 13).

Over a season. The velocity history holds each session's mean velocity and ammunition temperature. Once it spans cold and warm days, it shows how the load responds. Use sessions from one lot, fired after the barrel's first 100 to 200 rounds, so lot changes and a new barrel's speed-up stay out. Group the sessions into cold days and warm days and compare their averages.

```
slope = (warm mean − cold mean) ÷ (warm temperature − cold temperature)
        in fps per °F
```

Worked example. Example numbers. Not load data.

Four cold sessions average 2,712 fps with the ammunition at 34 °F. Four warm sessions average 2,748 fps at 78 °F.

```
slope = (2,748 − 2,712) ÷ (78 − 34) = 36 ÷ 44 = 0.82 fps per °F
```

Day-to-day changes in setup and barrel condition add extra scatter beyond single-session shot noise. Trust a calculated temperature slope only after you have several sessions at both cold and warm temperatures, and apply it only within the temperature span you have measured. Use a measured slope to increase the 1 fps per °F heat margin from *The Handloading Handbook* if needed, never to reduce it.

EASIER ON EP · VARYTITA · EXTERNAL BALLISTICS

Varytita adjusts a velocity measured on another day to today's powder temperature, with the slope you choose, and gives the drop chart for today.

empiricalprecision.com/heurisko?tab=varytita

Ammunition and powder lot changes

Factory ammunition and smokeless powder are both manufactured in lots, and two lots of the same product can differ in velocity, pressure, or dispersion. Your chronograph and target records show whether a new lot matches the old.

Safety · See Chapter 2
A new component lot can change pressure, and a velocity check is your safeguard. In percentage terms, changing the powder charge moves pressure about 3 times as much as velocity, and swapping the primer can move pressure 10 times as much or more.[2] A velocity rise at the same charge is a clear warning of higher pressure. Act on what you measure, and never assume a new lot matches the old.

Factory ammunition lot checks. Before buying a case or taking a new factory lot to a match or hunt:

1. Record the new lot number from the box flap as a new batch in your log (see Chapter 13).
2. Fire 10 check rounds of the new lot over a chronograph at 100 yards (or 50 yards for .22 LR), interleaved with 10 rounds of your old lot if you still have any (or compare against your velocity history at a similar ammunition temperature).
3. Check mean velocity and velocity SD against your old lot using the noise rule below, and check point of impact against your zero. Update your ballistic solver's muzzle velocity and re-confirm zero if the new lot shifted.
4. Confirm precision with a 20- to 30-shot composite (see Chapter 16) before relying on the new lot at distance, especially in .22 LR rimfire where lot-to-lot differences can be large.

Handload powder and component lot checks.

1. When you can, buy enough of one lot for the life of a load.
2. Record the lot number with every load.
3. Do not assume the new lot is different. Do not assume it is the same. Test it.
4. Load new-lot and old-lot rounds at the same charge: your current charge, or one step lower if it sits at or near the published maximum. Load 10 rounds of each lot.
5. Fire new-lot rounds interleaved with old-lot rounds in one session. If the old lot is gone, compare with the velocity in your records at that same charge, for the same rifle and similar conditions.
6. Judge the difference against its noise: $\sqrt{(\text{old SD}^2 \div \text{old shots} + \text{new SD}^2 \div \text{new shots})}$, in fps. A difference under about twice the noise is not shown to be real. A larger one probably is (the barrel-wear example below works the same sum). With 10 shots of each lot and SDs of 9 and 10 fps, the noise is $\sqrt{(8.1 + 10.0)} = 4.25$ fps, and twice the noise is 8.5 fps. Example numbers. Not load data.
7. If the new lot's mean velocity exceeds the old lot's by more than twice the noise from step 6, the velocity rise (and the pressure rise behind it) is real. Reduce the charge and work up again from below. If you tested one step below a near-maximum charge and saw no real velocity rise, step up to your working charge while respecting your velocity ceiling (see *The Handloading Handbook*). If velocity dropped by more than twice the noise, the new lot burns slower. If you adjust the charge upward to restore velocity, never exceed the published maximum charge or your velocity ceiling, whichever comes first.
8. Confirm the new-lot load with 20 to 30 shots before you rely on it at long range.

Barrel wear, velocity drift and the lands

Every shot erodes the throat a little, and the lands move forward (see *The Handloading Handbook*). At a fixed CBTO the jump grows as far as the lands move.

Keep an accurate round count for the barrel. Re-measure the distance to the lands at regular intervals. Use the same tool and the same technique every time (see *The Handloading Handbook*).

Decide in advance how you will handle the moving lands. You can chase them, seating the bullet longer to keep the jump the same. Or you can keep a fixed CBTO and let the jump grow. A load developed in a wide, flat jump band usually tolerates moderate throat erosion without losing precision. If you seat longer to follow the lands, check that the longer round still fits the magazine and feeds reliably.

Worked example. Example numbers. Not load data.

At the rate measured in 6 and 6.5 mm barrels, .004 to .007 inch per 100 rounds (see *The Handloading Handbook*), the lands move .016 to .028 inch over 400 rounds. A load seated .020 inch off the lands at the start could then be .036 to .048 inch off. Overbore cartridges such as 7mm SAUM, 6.5 PRC, and belted magnums erode faster—commonly .010 to .015 inch per 100 rounds—so re-check the lands every 150 to 200 rounds on a barrel burner.

Velocity also drifts over a barrel's life. Many new barrels speed up over their first 100 to 200 rounds. The rise varies from barrel to barrel, and one measured rise was about 80 fps.[3] A load worked up to your velocity ceiling in a new barrel can pass it as the barrel speeds up. Through the first 100 to 200 rounds, check its velocity against the ceiling. If it reaches the ceiling, drop the charge and work up again (see *The Handloading Handbook*).

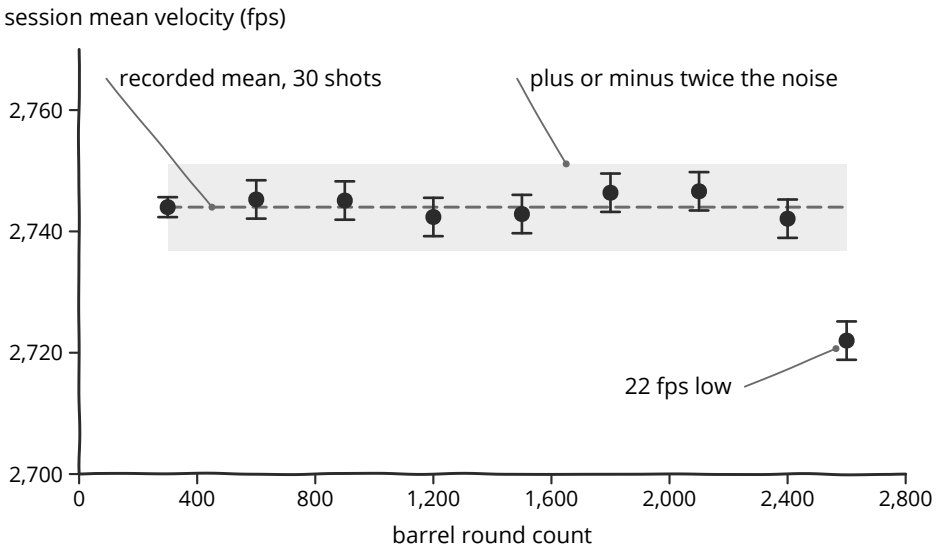
Later, as the throat erodes toward the end of the barrel's accurate life, velocity usually falls.[4] How fast it falls varies too. Track the mean velocity from session to session. Compare each session only with sessions fired at a similar ammunition temperature, and check the change against its noise before you blame wear.

Worked example. Example numbers. Not load data.

Your recorded velocity is 2,744 fps from 30 shots, with the ammunition at 62 °F and an SD of 9 fps. The barrel has now fired 2,600 rounds. Today, with the ammunition held at 60 °F, 10 shots average 2,722 fps with an SD of 10 fps. Is the barrel slowing down?

```
noise = √( (9 ÷ √30)² + (10 ÷ √10)² )
      = √(1.64² + 3.16²) = 3.6 fps
drop  = 2,744 − 2,722 = 22 fps, about 6 times the noise
```

The ammunition was held within 2 °F of the record, so temperature cannot explain a 22 fps drop. The drop is real. Before you blame wear, rule out a new lot and the chronograph setup (see Chapter 24). Had today's ammunition been 25 °F colder, this comparison would say nothing about wear. Compare such a day with a session near its own temperature instead (see Figure 23-2).



Example numbers. Not load data.

Figure 23-2. Session mean velocity against barrel round count, for sessions fired at a similar ammunition temperature. The latest session falls below the band of twice the noise.

EASIER ON EP · ANALYSIS · STATISTICAL TOOLS

Analysis checks a session's average velocity against this rifle's other sessions of the same load, carried to that session's temperature, and names any lot those sessions did not fire.

empiricalprecision.com/analysis

When to re-test

Re-test when one of these changes:

Change	What to do
New lot of factory ammunition	Log the lot number, chronograph 10 check rounds against your previous lot or velocity history, verify zero and solver velocity, and confirm precision with 20 to 30 shots before buying in bulk or shooting a match (see "Ammunition and powder lot changes" above).
New primer, case maker, bullet or powder	Work up again (see *The Handloading Handbook*). Confirm with 20 to 30 shots.
New lot of the same component	Load 10 check rounds at your current charge, or one step lower if it sits at or near the published maximum. Compare their velocity with your records. If the new lot runs faster by more than twice the noise, lower the charge and work up again from below (see "Ammunition and powder lot changes" above). Load in bulk only after the check.
New scope, rings, stock or trigger	Start a new baseline (see Chapters 4 and 14).
New barrel or a changed barrel length	Start over: new lands, new baseline and a new work-up.
Velocity drift beyond noise and temperature	Look for the cause. Re-measure the lands.

Change	What to do
Lands moved out of your jump band	Re-seat and confirm with 20 to 30 shots.
Seating deeper than your worked-up seating, or into the lands	Work up again from the start load at that seating (see *The Handloading Handbook*).
A new season	Re-check your zero and drop chart (see Chapter 20).

Barrel break-in, fire-cracking, and velocity speed-up

A new barrel changes noticeably during its first 100 to 200 rounds. Microscopic reamer marks in the throat smooth down, early thermal fire-cracking begins just ahead of the chamber, and bore friction settles. As this happens, muzzle velocity commonly climbs by 20 to 80 fps over the first 100 to 200 rounds.[3] Wait until the barrel passes this speed-up phase before you finalize a long-range drop chart or draw fine conclusions from load comparisons.

Before firing a new barrel for the first time, run solvent and dry patches through the bore and chamber to remove factory preservative oil and any stray machining debris. Oil left in a chamber increases bolt thrust and can cause erratic early velocities.

> **Safety · See Chapter 2**
> Confirm the rifle is unloaded and the chamber is empty before cleaning. Always wipe oil and solvent out of the bore and chamber before firing, and use chemical cleaners in a well-ventilated area.

Cleaning cadence, carbon rings, and copper fouling

Good cleaning protects precision. Poor cleaning damages barrels faster than shooting does.

1. **Use the right tools.** Use a one-piece coated or polished stainless steel cleaning rod, never a jointed rod whose seams can scrape the rifling. Insert a snug bore guide in the action to align the rod with the bore and keep solvent out of the trigger and bedding. Use brass or nylon jags and brushes sized to your caliber, and push patches from chamber to muzzle whenever the action allows so you do not nick the crown.
2. **Manage carbon and copper separately.** Every shot leaves powder carbon and trace jacket copper. A thin, uniform fouling layer often stabilizes velocity and point of impact. Heavy, uneven copper buildup can constrict the bore, raise pressure, and open groups. Use a carbon solvent for routine maintenance, and use a dedicated copper solvent only when bore inspection, velocity rise, or opening groups show copper is building up.
3. **Control the carbon ring.** Hard carbon accumulates right at the front of the chamber neck (centerfire) or chamber mouth and leade (rimfire), especially in high-round-count centerfire match barrels and rimfire chambers. Left unchecked, a carbon ring pinches the case mouth or engraves the bullet unevenly on firing. That spikes chamber pressure, raises velocity SD, stiffens bolt closing or lift, and opens groups. Inspect the neck-throat junction or rimfire leade with a borescope if you have one, or clean that

area deliberately with a carbon solvent and a properly sized nylon or bronze brush on a regular schedule.

4. **Keep a consistent cadence.** Clean on a repeatable round-count schedule matched to your cartridge and measured results, such as every 150 to 300 rounds for many centerfire precision rifles, or sooner if groups open or velocity climbs. After every cleaning, fire and log your fouling shots before judging zero or group size (see Chapter 14). Rimfire (.22 LR) barrels rely on bullet-lube seasoning and are usually cleaned sparingly, focusing on the breech face, chamber, and carbon ring unless groups degrade.
5. **Semi-automatic / AR-15 maintenance.** Gas-operated precision rifles accumulate fouling in the action as well as the bore. On a regular schedule, disassemble and clean the bolt carrier group, inspect the gas rings for wear (a properly ringed bolt should support the carrier's weight when stood upright on the bolt face), wipe the bolt face and extractor, clean the firing pin channel dry, and swab the chamber locking lugs with a chamber brush and lug swabs so the bolt locks into battery consistently.

Switching .22 LR bullet waxes (3-step seasoning protocol). Different .22 LR makers coat lead bullets with incompatible lubricants (such as oil/wax blends versus beeswax/tallow). Mixing waxes inside the bore degrades groups until the old film clears. Whenever you switch .22 LR brands:

1. **Patch out the old wax.** Push solvent-dampened patches followed by dry patches through the bore and chamber until the patches come out clean, and wipe wax buildup off the breech face and extractor.
2. **Fire 15 to 30 conditioning shots.** Shoot 15 to 30 rounds of the new brand at a fouling aim mark so the bore coats evenly with the new lubricant.
3. **Zero and test only after the bore seasons.** Confirm your 50-yard zero and begin recording test groups (see Chapter 14) only once velocity and impacts settle.

Contested: barrel break-in rituals

The claim. Firing one shot and cleaning to bare metal for 5 to 10 shots, followed by 3-shot strings with cleaning between each, smooths the bore, reduces copper fouling, and extends barrel life.

The physics. Chamber reamers leave fine tool marks across the throat, perpendicular to bullet travel. Firing bullets smooths those marks, and cleaning between shots removes copper so the next bullet contacts steel directly. Hand-lapped match barrels have very few reamer marks to begin with, and hot propellant gas drives throat fire-cracking regardless of how often you clean.

The test. Compare fouling rate, velocity stability, and 30-shot composite mean radius between matched barrels broken in with a shoot-and-clean ritual and barrels simply cleaned before first firing and shot normally.

The data. Controlled large-sample tests are scarce, and barrel makers themselves disagree. Some makers suggest a brief shoot-and-clean sequence for the throat, while others state that cleaning before first firing and shooting normally works just as well.[5] Neither approach stops the normal 100- to 200-round velocity speed-up.[3]

The verdict. Plausible but unproven. Clean a new barrel thoroughly before its first shot to remove oil and debris. Beyond that, an elaborate 50-round clean-after-every-shot ritual has no proven precision or barrel-life payoff. Follow the barrel maker's basic guidance if you choose, or simply shoot the rifle and clean on a steady cadence.

Contested: cleaning to bare metal every session

The claim. Scrubbing every trace of carbon and copper down to bare steel after every range trip keeps a precision rifle at its best.

The physics. Bare steel has different friction than a fouled bore. After stripping to bare metal, muzzle velocity and point of impact often shift for 5 to 20 fouling shots until a steady layer of carbon and copper returns. Frequent heavy brushing or abrasive bore pastes also risk mechanical wear at the throat and crown.

The test. Track cold-bore point of impact, velocity SD, and 20- to 30-shot composite mean radius across sessions cleaned to bare metal every trip versus sessions cleaned on a measured round-count cadence while keeping the carbon ring clear.

The data. Competitive shooters and range logs routinely show a cold-clean velocity dip and point-of-impact shift after bare-metal cleaning, followed by stable velocity and tight groups for hundreds of rounds until heavy carbon or copper buildup degrades performance.

The verdict. Plausible but unproven. Stripping a barrel to bare metal after every short session spends barrel life and ammunition re-fouling the bore with no proven gain on target. Clean on a consistent round-count cadence guided by your target and velocity records, keep the carbon ring clear, and strip copper only when your data call for it.

Chapter 24

Range and Accuracy Troubleshooting

Key points

- Unusual force is a symptom. More force is never the fix. A pressure sign is never noise, and its absence is not proof of safety.
- Change one thing at a time, then measure enough shots to confirm what fixed the problem.
- Check mechanical and optic causes first: loose rings, base, or action screws, parallax error, cant, and turret tracking error masquerade as load problems.
- Small samples mislead, so many range faults are only noise. Judge stringing and far shots against chance.
- Vertical stringing is a velocity problem only when the slow shots are the low ones. At 100 yards it almost never is.

Why it matters

A fault at the range costs ammunition, barrel life, and trust in your data. Worse, shooters often blame a good load for a loose scope ring, a parallax error, a carbon ring in the chamber neck or rimfire leade, or normal small-sample scatter.

Most range problems trace to one mechanical, optical, environmental, or ammunition cause. A fix that changes two things at once teaches you nothing. If the fault comes back, you will not know which change mattered. At the range, some faults are real and others are noise from too few shots. The skill is telling the two apart. One fault is never noise: a pressure sign. For workshop-only reloading faults during sizing, priming, charging, or seating, see *The Handloading Handbook*.

How it is done

Problems at the range

1. Stop at once at a pressure sign or at a shot that sounds or feels wrong. After a wrong shot, unload and check the bore for a stuck bullet before you fire again (see Chapter 2). If a round fails to fire, keep the muzzle downrange for at least 30 seconds before you open the action.[1] Everything else can wait. Pressure signs are unreliable early warnings, and their absence does not prove a load safe (see *The Handloading Handbook*).
2. Look at the target. A flyer may be a hole marked in the wrong place or a shot you pulled.
3. Count your shots. Read every number with its interval.
4. Find the symptom in the table below. Change one thing. Then shoot enough rounds to see whether the change worked (see Chapter 16).
5. Record the conditions, the change and the result.

Symptom	Likely causes	Check	Fix	See
Pressure signs: stiff bolt lift, ejector marks, flattened, cratered or pierced primers	Charge too high for this rifle. Components differ from the published test. Bullet in the lands or seated deeper than tested. Hot ammunition. Carbon ring in the throat. Bolt-action data used in a semi-automatic.	Stop firing. Compare components, charge and velocity with the published data. Inspect the throat for a carbon ring. In a semi-automatic, compare ejector and extractor marks with those at the start load. A primer sign means stop.	Do not fire the rest of the lot. Pull handloaded bullets or quarantine the factory lot. Remove any carbon ring. Work up again from the published start load.	23
A shot sounds or feels weak	A light or missing charge (a squib) can leave the bullet in the bore.	Unload. Look through the bore for a stuck bullet.	Do not fire until the bore is clear. Quarantine the rest of that batch or factory lot.	2
Click, no bang (a misfire)	A primer seated high or upside down. A light firing-pin strike. A contaminated primer.	The primer's dent, and how the primer sat.	Keep the muzzle downrange for at least 30 seconds, then unload. Set the round aside as a reject. Have the rifle checked if the primer is not dented. Check that the bore is clear before you load another round.[2]	2
Loaded round will not chamber, or the bolt closes hard on it	Shoulder not bumped enough (handload). Case too long. Bullet touching the lands. Carbon ring or debris in the chamber. In .22 LR match chambers, mild, uniform engraving resistance is normal, but a sudden increase in closing force points to a carbon ring or thickened cold wax.	Inspect the chamber, throat, and rimfire chamber mouth. Check a handload's base-to-shoulder, length, and CBTO against your records (see *The Handloading Handbook*).	Stop. Do not force the bolt on a live round. Clean the chamber, throat, or rimfire chamber mouth and leade. Set aside rounds that fail to chamber and correct the sizing or seating step in the workshop.	2, 23
Velocity at or over your velocity ceiling, or well above your records at the same temperature	Hot ammunition. A new lot. A new barrel speeding up. Carbon ring pinching the neck or rimfire chamber mouth. A charge or component error.	Ammunition temperature, the lots, the barrel's round count, throat cleanliness, and the batch record.	Stop firing that batch. Clean any carbon ring. For a charge or component error, work up again from the published start load. For a new lot, a new barrel or hot ammunition, drop the charge and work up from below to your velocity ceiling.	23

Symptom	Likely causes	Check	Fix	See
Carbon ring: velocity climbs, SD worsens, or groups open at high round count	Hard carbon buildup at the front of the chamber neck (centerfire) or chamber mouth and leade (rimfire).	Inspect the neck-throat junction or rimfire leade with a borescope, or feel for a tight spot with a sized brush. Check velocity history for an upward creep.	Clean the chamber neck or rimfire chamber mouth and leade deliberately with carbon solvent and a properly sized nylon or bronze brush. Re-check velocity and groups, and tighten your cleaning cadence.	23
Rimfire (.22 LR) sluggish cycling, failure to extract/chamber, or sudden POI shift in cold weather	Cold-weather bullet-wax thickening, or wax and carbon buildup on the breech face, extractor groove, and chamber mouth.	Inspect the breech face, extractor claw, and chamber mouth for waxy paste. Note ammunition temperature and whether the rifle ran cleanly when warm.	Wipe the breech face, bolt face, extractor, and chamber mouth clean with a dry patch or light solvent. Keep ammunition at a steady temperature in an insulated box or inside pocket, or test a lot whose lube stays supple in cold air.	23
Semi-automatic short-stroking or failure to lock back on an empty magazine	Under-gassed cycle, worn gas rings, misaligned or leaking gas block, dry or heavily fouled bolt carrier group, or weak magazine spring.	Check gas-ring seal (bolt should support the carrier upright), inspect around the gas block for carbon leaks, and test with a known-good magazine and full-power factory load.	Clean and lubricate the bolt carrier group, replace worn gas rings, align and secure the gas block, or open an adjustable gas block slightly until lock-back is positive with margin.	23
Semi-automatic violent ejection, bent rims, or torn case heads	Over-gassed cycle, early unlocking, excessive chamber pressure, or rough/dirty chamber walls.	Check ejection pattern and case rims for extractor swipe or bent rims. Chronograph the load and inspect primers and headstamps for pressure signs.	Stop if pressure signs appear. Clean the chamber and locking lugs. Reduce gas flow with an adjustable gas block or heavier buffer, or reduce charge weight if handloading.	2, 23
Semi-automatic erratic velocity, pressure signs, or shortened cartridges after chambering	Bullet setback during aggressive semi-automatic feeding (insufficient neck tension or lack of light crimp).	Measure COAL of a round before and after chambering it from a loaded magazine at full bolt speed.	Do not fire set-back rounds. Switch factory SKUs if a commercial load sets back, or increase neck tension and verify feeding in the workshop (see *The Handloading Handbook*).	2, 23
Semi-automatic POI shifts between bench and sling/bipod positions	Handguard or sling pressure flexing the barrel or contacting the gas block on a non-free-floated rail.	Inspect clearance between the gas block, barrel, and handguard under sling or bipod load. Compare bench-rested zero against slung prone or bipod-loaded groups.	Use a rigid free-float handguard with generous gas-block clearance, verify barrel-nut torque, and keep sling or bipod pressure off the barrel.	4, 8

Symptom	Likely causes	Check	Fix	See
Sudden flyers, wandering zero, or double grouping	Loose scope rings, base screws, or action screws. Damaged optic internals. Barrel contacting the stock.	Check witness marks and torque on action screws, rail, rings, and scope caps. Check free-float clearance along the barrel channel.	Degrease threads if needed, retorque all fasteners to maker specifications, restore barrel clearance, and shoot a new hardware baseline. If zero still wanders, test with a known-good scope.	4, 14
Groups open up or POI shifts with head position	Parallax error.	Place the rifle on bags aimed at the target and move your eye slightly side to side and up and down. If the reticle shifts across the target, parallax is off.	Adjust the side focus or objective ring until the reticle stays locked on the aim mark regardless of eye movement.	5, 20
Horizontal miss grows steadily with distance or dialed elevation	Rifle cant (scope tilted off vertical). Reticle not plumb to the bore.	Check your bubble level and verify the reticle against a plumb line.	Level the reticle to a plumb line when mounting, zero the scope level to match, and check the bubble before breaking every long-range shot.	6, 20
Impacts fall consistently short or tall of dialed elevation across distances	Turret tracking error (actual click value differs from marked click value).	Run a tall-target test at 100 yards along a plumb line and compare measured impact shift against dialed MOA or MIL.	Enter the measured click correction factor in your ballistic solver, or have the scope serviced if tracking is erratic or non-linear.	6, 20
Velocity SD higher than expected	Too few shots. Uneven charges or neck tension. Low case fill with a ball powder. Carbon ring. Chronograph error.	The shot count and the SD's interval. The per-shot log.	Shoot more before you judge. Clean the throat if due. Fix ammunition causes in the workshop (see *The Handloading Handbook*). Prefer a Doppler chronograph.	7, 14, 15, 23
One shot far slower or faster than the rest	Erratic ignition or inconsistent neck tension. A chronograph misread. A blown primer.	Find the shot in the log. Inspect that case.	A blown primer is a pressure sign: stop. Otherwise fix the cause in the workshop or switch factory lots. Keep the reading unless the misread is documented.	15
Vertical stringing	Velocity spread, at long range. Barrel heat. Uneven primer strikes from a weak firing-pin spring. A barrel touching the stock. Position or rest.	Vertical spread against horizontal. Velocity against shot height.	If the slow shots are low and gravity drop explains the offset, work on velocity SD. If not, look at the rifle, the rest and the heat.	4, 14, 15
Horizontal stringing	Wind, bipod or trigger push.	Horizontal spread against vertical. Your wind notes.	Shoot in steadier wind. Check how you load the bipod and press the trigger.	8, 14

Symptom	Likely causes	Check	Fix	See
A flyer	A pulled shot. A hole marked in the wrong place. The normal tail of the group. A loose scope mount.	Look at the hole. Read your shot notes. Check ring and base torque.	Keep it unless you documented the error when it happened.	15
Groups much larger or smaller than last time	Small samples. A change between groups in heat, wind, position or rest.	The shot count. The mean radius interval.	Composite more groups before you decide.	15, 16
Velocity climbs through a string	Barrel and chamber heat. A round left in a hot chamber.	The per-shot log in firing order.	Pace your shots. Do not leave a round in a hot chamber.	14, 23
Point of impact moves between sessions	Temperature. Elevation. Storage humidity.[3] A hardware change.	Where the group prints, its velocity and the air for each session. The scope mounts.	Record the air every session. Treat a hardware change as a new baseline. Hold the ammunition at a steady temperature.	4, 14, 19, 23
Keyholes or oblong holes	Bullet not stable in this twist.[4]	Stability in the coldest, densest air you expect.	Choose a shorter bullet or a faster twist. A hotter load will not fix it.	18
Drops match up close and miss far out	A wrong muzzle velocity, which short ranges hide. An optimistic BC, or a BC in the wrong drag model.[5] Turret tracking error.	That the BC and the drag model match. The measured velocity. Tall-target turret check.	True the velocity first, then the drag.	20

Stringing

Compare the spread up and down with the spread side to side. Vertical much larger than horizontal is vertical stringing. Suspect velocity spread or uneven primer strikes from a weak firing-pin spring. A barrel touching the stock does it too (see Chapter 4). Horizontal much larger than vertical points at wind, the bipod or trigger push.

Judge stringing against chance, not against a fixed ratio. A rule that calls a group strung whenever one axis is 1.5 times the other would call almost half of all round 5-shot groups strung.[6] Use the lines in Table 24-1 instead. A round group is then called strung about 1 time in 20.

1. Find SD horizontal and SD vertical from the group's center, as in the mean radius worked example (see Chapter 15).
2. Divide the larger SD by the smaller.
3. Call the group strung only when the ratio reaches the line for your shots.

For a composite, measure each shot from its own group's center. Then divide each sum of squares by the shots minus the number of groups, not by the shots minus 1.

Table 24-1. When to call a group strung, and when to call velocity linked to height.

Shots	Strung when the larger SD ÷ the smaller SD reaches	Velocity linked to height when the correlation reaches
One 5-shot group	3.10	.88
Two 5-shot groups	2.11	.67
One 10-shot group	2.01	.63
One 20-shot group	1.59	.44
Four 5-shot groups	1.66	.48
Six 5-shot groups	1.51	.40

The ratio lines come from the F-test on two SDs (see Appendix A.8), applied to the two axes. Both columns are two-sided lines at 0.05. Test a load's composite once, not each group in turn. Each extra test is another chance for luck (see Chapter 16).

Worked example. Example numbers. Not load data.

The 10-shot group in Chapter 15 has an SD of .33 inch across and .25 inch up and down. The ratio is .33 ÷ .25 = 1.3, well short of 2.01. That group is not strung.

Next, ask whether velocity is causing the vertical.

1. Take each shot's velocity from the string's average (dv) and its height from the group's center (dh). In a composite, take both from each group's own averages.
2. Work out the correlation between the two. CORREL of the two columns in a spreadsheet gives the same number.

```
correlation = Σ(dv × dh) ÷ √(Σdv² × Σdh²)
```

3. If the correlation is positive and reaches the line in Table 24-1, the slow shots are the low ones. Velocity is moving your vertical, and a lower SD will tighten it. Below the line, a lower SD is not shown to help this group.

Distance matters a great deal here. Take a 140 gr 6.5 Creedmoor load at 2,700 fps. Example numbers. Not load data. There, 10 fps of velocity moves the bullet about .18 inch at 300 yards. At 1,000 yards it moves it about 3 inches.[7] At 100 yards velocity explains almost none of the vertical.[6] Look at the rifle, the rest and the barrel heat first.

Check the drop from gravity, not only the correlation. A positive correlation alone does not mean velocity caused a shot to land low. In a short string, a slow shot can happen to land low purely by chance, producing a high correlation coefficient (r). Always check the physical drop against what gravity actually does.

The change in bullet drop from a velocity change Δv is:

```
drop change = drop(v + Δv) − drop(v)
```

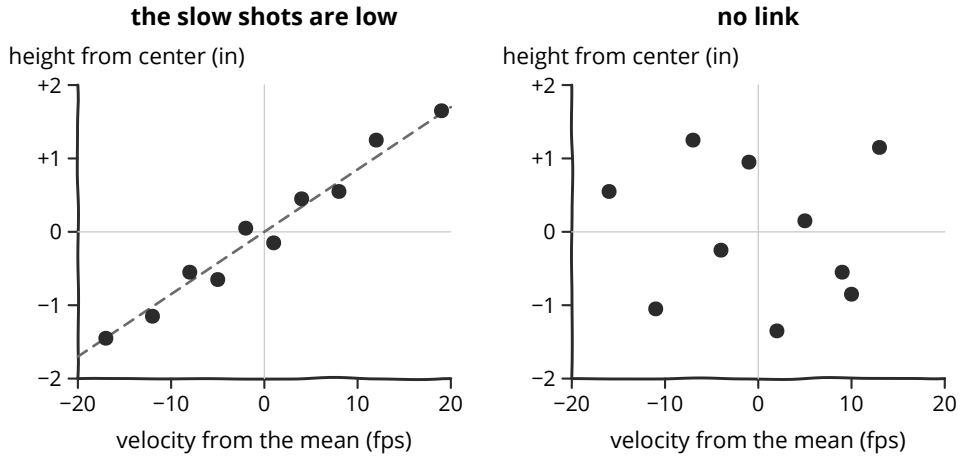
or approximately from time of flight t and total gravity drop from the bore axis y:

```
drop change ≈ −2 × y × (Δv ÷ v)
```

At 100 yards with the example 6.5 Creedmoor load, a shot 20 fps slow has its gravity drop increased by only about .04 inch. If that shot printed .75 inch below the group center, velocity explains only .04 inch of that displacement (about 5 percent). The other .71 inch came from rifle dispersion, aim, cant or rest movement. When the observed vertical displacement is several times larger than the ballistic drop, velocity did not cause the vertical error, even if the correlation happens to be positive.

This is also why real groups almost always remain circular. If velocity variation were a primary driver of vertical dispersion, targets would routinely stretch into vertical ellipses. When your vertical and horizontal spreads are roughly equal (the ratio in Table 24-1 is below the line), velocity variation is not the limiting factor.

From neck tension to the target (for handloaders). You can apply the same correlation formula to test the full chain: neck tension (or seating force) to muzzle velocity, and velocity to target height. If you log seating force at the bench and match each round to its chronograph reading, compute the correlation between seating force and velocity. You will usually find very little correlation across normal neck interference. And because velocity explains very little vertical dispersion inside 300 to 600 yards, neck tension variation rarely reaches the target at all.



Example numbers. Not load data.

Figure 24-2. Velocity against height for two targets. On one the slow shots are the low ones. On the other there is no link.

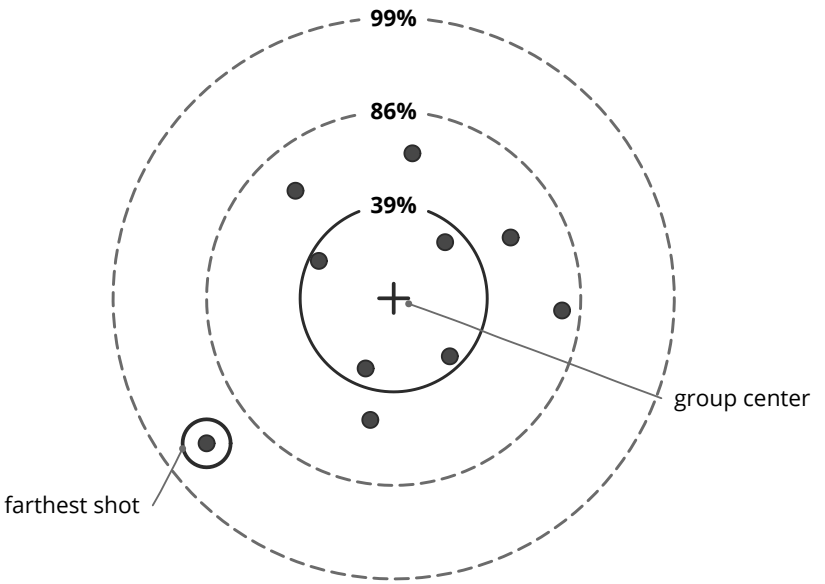
EASIER ON EP · ANALYSIS · STATISTICAL TOOLS

Analysis flags stringing only when it exceeds chance, tests whether slow shots land low, and flies the load to your target distance to show how much vertical spread gravity actually explains. If you record seating forces, Analysis also tests whether seating force correlates with velocity.

empiricalprecision.com/analysis

Flyers

Every committed shot counts (see Chapter 15). A wide shot is often just normal dispersion: about 14 shots in 100 land beyond two standard deviations, so a 30-shot composite holds about four (see Figure 24-3).



Example numbers. Not load data.

Figure 24-3. A 10-shot group with its farthest shot, and the rings that hold 39, 86 and 99 percent of shots.

Judge a suspected flyer against the average radial distance of all *other* shots (excluding the farthest prevents it from inflating the yardstick):

1. Measure each shot's distance from its group center (see Chapter 15), average all except the farthest, and divide the farthest distance by that average.
2. Flag it as a far shot worth investigating only when the ratio exceeds 3.

This threshold holds for 5- to 30-shot groups and composites (testing the single farthest shot once against all others). Even then, ~1 clean target in 20 flags by chance. Investigate causes (such as a loose scope mount), but keep the shot unless you documented the error when fired.

Worked example. Example numbers. Not load data. In Chapter 15's group, shot 9 is farthest at .711 inch; the other nine total 2.888 inches (average .321 inch). The ratio .711 ÷ .321 = 2.2 (< 3) marks shot 9 as normal tail dispersion.

EASIER ON EP · ANALYSIS · STATISTICAL TOOLS

Analysis checks a group or a whole composite for a flyer once, judging each shot from its own group's center against the spread of all the others, and names a shot that stands out.

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Common questions

Question	Short answer	See
Should I choose a MIL or MOA scope?	Either works if reticle and turrets match. MIL (0.1 mrad) simplifies decimal math and dominates practical rifle; MOA (1/4 or 1/8 MOA) gives finer steps for F-Class and benchrest.	3, 5
Should I choose a First Focal Plane (FFP) or Second Focal Plane (SFP) scope?	FFP keeps subtensions true at all magnifications (ideal for PRS and hunting); SFP keeps reticle thickness constant at max power (preferred for F-Class and benchrest).	5
How do I know if my scope turrets track accurately?	Run a 100-yard Tall Target Test along a plumb line: dial a known value (e.g., 10 MIL or 30 MOA), compare actual to dialed shift, and enter any correction factor in your solver.	6, 20
How many shots do I need to evaluate a factory lot or handload?	5–10 shots rule out a bad load; proving a good load takes a 20–30-shot composite; separating two close loads takes 35+ shots per load.	15, 16
My rifle shot a tiny group last week and a big one today. What changed?	Maybe nothing—one of two 5-shot groups from the same load is ≥1.5× larger 30% of the time. Check ring and action torque, then shoot a larger composite.	15, 16, 24
What velocity SD is good enough?	Depends on cartridge, target, range, and wind. Inside 300 yards, a 15 fps SD adds ~0.3" vertical in centerfire but ~4–5" in subsonic .22 LR; 1,000-yard F-Class uses 5–7 fps to protect the 10/X-ring.	15, 21
Why do my drops match at 100 yards and miss at 800 yards?	Short range hides velocity, BC, sight-height, and tracking errors. Verify zero, sight height, and tracking first; true velocity supersonically before adjusting drag near Mach 0.9.	6, 20
Should I use G1 or G7 ballistic coefficients?	Use G7 for sleek boat-tail bullets, G1 for centerfire flat-bases, and RA4 or custom Doppler curves for .22 LR (where G1 diverges downrange). Never mix G1 BCs into G7 settings.	19
Do I need to handload to shoot a precision rifle well?	No. Modern factory match ammunition often meets practical hit-probability goals out of the box. Test by lot with real sample sizes and buy winning lots in bulk.	12, 16, 23
How do I tune a .22 LR rimfire rifle if I cannot handload?	Structured lot testing across match brands/lots (interleaving same-brand lots; patching and seasoning between different waxes) is primary. Track cold-bore shift, clean chamber/carbon ring, and avoid over-cleaning the bore.	12, 14, 16, 23
How do I set my ethical maximum hunting range?	Take the shorter of two limits: where impact velocity drops to the bullet's minimum expansion velocity, or where field-position vital-zone hit probability falls below 90%.	21, 22
When is the cosine rule accurate for uphill or downhill shots?	Within ~0.1–0.2 MIL under 20–25° and 400–500 yards. For steeper angles or longer ranges, enter slant range and look angle directly into a solver.	11, 20
Why is my new barrel speeding up, and when should I finalize my DOPE?	New barrels smooth out and typically gain 20–80 fps over their first 100–200 rounds. Wait for velocity to stabilize before finalizing long-range DOPE.	20, 23
How often should I clean my barrel, and should I clean to bare metal?	Clean on a consistent round-count cadence guided by target and velocity logs, keeping the chamber neck (or rimfire mouth/leade) free of carbon rings. Stripping to bare metal every trip adds no proven benefit and requires re-fouling.	14, 23

Reference

Conversions

Factors marked exact are exact by definition. Other factors are rounded, most to six significant figures, and the worked examples are rounded further (see Appendix A for formulas).

Mass. 1 gr = 0.06479891 g (exact); 1 g = 15.4324 gr; 1 kg = 15,432.4 gr; 1 lb = 7,000 gr (exact); 1 oz = 437.5 gr (exact).

Capacity. 1 cm³ of water at 20 °C weighs about 15.4 gr.

Length. 1 inch = 25.4 mm (exact); 1 mm = 0.0393701 inch; 1 yard = 0.9144 m (exact); 1 m = 1.09361 yards; 1 foot = 0.3048 m (exact); 1 m = 3.28084 feet. So .002 inch is 0.0508 mm.

Pressure. 1 psi = 0.0689476 bar = 0.00689476 MPa; 1 bar = 14.5038 psi; 1 MPa = 10 bar (exact) = 145.038 psi. So 62,000 psi is about 4,275 bar, or 427.5 MPa. Units convert; standards do not. A C.I.P. limit in bar is not a SAAMI limit in psi, and CUP does not convert to psi at all (see *The Handloading Handbook*, Chapter 4).

Air pressure. 1 inHg = 33.8639 hPa (mbar); 1 hPa = 0.0295300 inHg. Standard sea-level pressure is 29.92 inHg, or 1,013.25 hPa.

Velocity. 1 fps = 0.3048 m/s (exact); 1 m/s = 3.28084 fps. So 2,800 fps is 853.4 m/s.

Wind. 1 mph = 0.44704 m/s (exact) = 1.46667 fps; 1 m/s = 2.23694 mph; 1 km/h = 0.621371 mph.

Angles. 1 MOA = 0.290888 mil; 1 mil = 3.43775 MOA. 1 MOA is 1.0472 inches at 100 yards and 2.909 cm at 100 meters; 1 mil is 3.6 inches and 10 cm. Rounding MOA to 1 inch is about 4.5 percent small, almost half an inch per MOA at 1,000 yards.

Temperature and energy. °F = °C × 9/5 + 32; °C = (°F − 32) × 5/9. 1 ft·lbf = 1.35582 J; 1 J = 0.737562 ft·lbf. The standard day in ballistics is 59 °F (15 °C).

Inches per MOA and per mil by distance

Distance (yd)	1 MOA	1 mil	1/4 MOA click	0.1 mil click
50	.52"	1.80"	.13"	.18"
100	1.05"	3.60"	.26"	.36"
200	2.09"	7.20"	.52"	.72"
300	3.14"	10.80"	.79"	1.08"
400	4.19"	14.40"	1.05"	1.44"
500	5.24"	18.00"	1.31"	1.80"
600	6.28"	21.60"	1.57"	2.16"
700	7.33"	25.20"	1.83"	2.52"
800	8.38"	28.80"	2.09"	2.88"
900	9.42"	32.40"	2.36"	3.24"
1,000	10.47"	36.00"	2.62"	3.60"

Appendix A

Statistics, Ballistics, and Evaluation Formulas Reference Sheet

A.1 Mean point of impact and mean radius

Measure each shot from the aim mark, with up and right positive (see Chapter 14).

```
MPI x = (x1 + x2 + ... + xn) ÷ n
MPI y = (y1 + y2 + ... + yn) ÷ n
ri    = √((xi − MPI x)² + (yi − MPI y)²)
MR    = (r1 + r2 + ... + rn) ÷ n
```

The point (MPI x, MPI y) is the group's center. Each ri is one shot's radial distance from that center.

A.2 The small-group correction

A group's center is worked out from its own shots. So the distances measured from that center read small (see Chapter 15). Multiply the measured mean radius by the correction factor:

```
corrected MR = measured MR × √(k ÷ (k − 1))
k = shots in the group
```

Shots per group (k)	Factor	Reads small by
3	1.225	18.4%
5	1.118	10.6%
10	1.054	5.1%

For a composite of several groups, multiply each shot's distance by the factor for its own group's shot count, then average all the corrected radii.

A.3 Rayleigh distribution of radial miss distances

For a round group, where the horizontal and vertical spreads share one standard deviation, σ:

```
MR = σ × √(π ÷ 2) ≈ 1.2533 × σ
Share of shots within z·σ of center = 1 − exp(−z² ÷ 2)
z = how many σ from center
```

Distance from center	Share inside	Share outside
1 σ	39%	61%
2 σ	86%	14%
3 σ	99%	1%

A.4 Velocity mean, SD and ES

```
mean v = (v1 + v2 + ... + vn) ÷ n
SD     = √( Σ(vi − mean v)² ÷ (n − 1) )
ES     = fastest − slowest
```

Divide by n − 1, not n, because the mean comes from the same shots. This is the sample standard deviation, STDEV.S in spreadsheets.

A chronograph's own noise adds to the true SD by root-sum-square (see Chapter 7):

```
true SD = √(measured SD² − instrument SD²)
```

Heat in a long string shows as a rise from the first five shots to the last five (see Chapter 23):

```
noise = SD × √(2 ÷ 5)
rise  = mean of the last five − mean of the first five
```

A rise of more than twice the noise is heat reaching the rounds.

A.5 Confidence intervals and degrees of freedom

The chi-square distribution gives the confidence interval for standard deviation. For a 90 percent confidence interval with n − 1 degrees of freedom:

```
Lower = SD × √( (n − 1) ÷ χ²(0.95) )
Upper = SD × √( (n − 1) ÷ χ²(0.05) )
```

Here $\chi^2(0.95)$ is the chi-square value with 95 percent of the distribution below it, and $\chi^2(0.05)$ is the value with 5 percent below it. In a spreadsheet, $\chi^2(0.95)$ is CHISQ.INV(0.95, n − 1).

Shots	Degrees of freedom	$\chi^2(0.05)$	$\chi^2(0.95)$	90% interval, times measured SD
5	4	0.711	9.488	0.65 to 2.37
10	9	3.325	16.919	0.73 to 1.65
20	19	10.117	30.144	0.79 to 1.37
30	29	17.708	42.557	0.83 to 1.28

Degrees of freedom for groups on paper. Each shot gives two degrees of freedom, one for x and one for y. Each group center uses up two. With each radius measured from its own group's center:

```
σ estimate = √( Σ ri² ÷ (2 × (n − g)) )
df = 2 × (n − g)        n = total shots, g = groups
```

One 5-shot group has 2 × (5 − 1) = 8 degrees of freedom. Six 5-shot groups (30 shots) have 2 × (30 − 6) = 48.

Mean radius uses each shot slightly less efficiently than this direct σ estimate, so for mean radius multiply df by 0.915. That factor, π ÷ (4 × (4 − π)), reflects the relative efficiency of mean radius for round normal scatter and comes from the mean and variance of the Rayleigh distribution (see A.3). One 5-shot group then has 7.3 degrees of freedom (giving a 90 percent interval of 0.71 to 1.77 times the corrected mean radius, see A.2), and six 5-shot groups have 43.9 degrees of freedom (0.85 to 1.22 times). Use the formulas above with that df in place of n − 1. Spreadsheets round a fractional df down, which moves the interval slightly. The tables give the exact values.

Other confidence levels. For confidence c, the lower bound uses χ^2 at (1 + c) ÷ 2 and the upper bound uses χ^2 at (1 − c) ÷ 2. A 95 percent interval uses $\chi^2(0.975)$ and $\chi^2(0.025)$. It is the interval to use when you compare two loads.

Velocity SD from	Degrees of freedom	95% interval, times measured SD
5 shots	4	0.60 to 2.87
10 shots	9	0.69 to 1.83
20 shots	19	0.76 to 1.46
30 shots	29	0.80 to 1.34

For mean radius, the interval depends on how the shots were grouped. Multiply the corrected mean radius by these.

Mean radius from	Degrees of freedom	90% interval	95% interval
One 5-shot group	7.3	0.71 to 1.77	0.67 to 1.99
Two 5-shot groups	14.6	0.77 to 1.45	0.74 to 1.56
Three 5-shot groups	22.0	0.81 to 1.34	0.77 to 1.42
Four 5-shot groups	29.3	0.83 to 1.28	0.80 to 1.34
Six 5-shot groups	43.9	0.85 to 1.22	0.83 to 1.26
Ten 5-shot groups	73.2	0.88 to 1.16	0.86 to 1.19
Five 3-shot groups	18.3	0.79 to 1.38	0.76 to 1.47
Ten 3-shot groups	36.6	0.84 to 1.24	0.81 to 1.30

A.6 Comparing two loads' mean radii: F-test

Compare two loads' mean radii with an F-test on the square of their ratio (see Chapter 16):

```
F    = (MR_B ÷ MR_A)²
df_A = 2 × (n_A − g_A) × 0.915
df_B = 2 × (n_B − g_B) × 0.915

B    = the load with the larger mean radius
MR   = mean radius, corrected for small groups
n, g = shots and groups
```

In a spreadsheet, 2 × F.DIST.RT(F, df_B, df_A) gives the two-sided p-value. Spreadsheets round the degrees of freedom down, which changes p very little.

Shot distances from a group's center are neither normal nor independent of each other. A t-test on the radii, such as Welch's, calls identical loads different 7 to 11 times in 100 at the 0.05 line when the shots are fired in groups. This F-test stays near 5 in 100 in every layout.

Mean-radius ratio needed for a two-sided p below 0.05 (equal shots per load, 5-shot groups):

Shots per load	10	20	30	50	100
Larger ÷ smaller mean radius	1.70	1.45	1.35	1.26	1.18

A.7 Sequential testing and family-wise boundaries

Each look at the data after a block is one more chance of a false alarm. Five looks at a plain 0.05 threshold call two identical loads different about 14 times in 100.[1] O'Brien-Fleming thresholds hold the overall false-alarm rate at 0.05 across equally spaced planned looks.[2]

O'Brien-Fleming two-sided p-value thresholds (overall 5 percent):

Planned looks	Look 1	Look 2	Look 3	Look 4	Look 5	Look 6
2	0.0051	0.048				
3	0.00051	0.014	0.045			
4	No cut	0.0042	0.019	0.042		
5	No cut	0.0012	0.0084	0.022	0.041	
6	No cut	0.00037	0.0036	0.011	0.024	0.040

No cut means the threshold is below 0.0001. So few shots almost never clear it. Skip the math at that look. The thresholds are rounded down, which errs on the strict side. With more than two loads, divide each look's threshold by the number of pairs as well (see Table 16-6).

More than two loads. When you test several loads at once, divide the threshold α by the number of pairs:

```
Pairs = loads × (loads − 1) ÷ 2
Adjusted α = α ÷ Pairs
```

Count the pairs from the loads you started with, even after some are cut (see Chapter 16).

A.8 Comparing velocity SDs: F-test

Compare two velocity SDs with an F-test on their variances:

```
F    = s_B² ÷ s_A²
df_B = n_B − 1,  df_A = n_A − 1

B = the load with the larger SD
n = shots
s = velocity SD
```

F.TEST(range1, range2) gives the two-sided p-value. A 1.5 to 1 difference takes about 50 shots per load to detect with 80 percent power (see Chapter 16).

SD ratio needed for a two-sided p below 0.05, equal shots per load:

Shots per load	10	20	30	50	100
Larger ÷ smaller SD	2.01	1.59	1.45	1.33	1.22

For stringing, the same test compares the two axes of a group or composite, B being the wider axis, each with n − g degrees of freedom (see Table 24-1). For a composite, use 2 × F.DIST.RT(F, df_B, df_A).

A.9 External ballistics and hit probability

Stability (see Chapter 18)

```
Sg              = 30 × m ÷ (t² × d³ × l × (1 + l²))
Velocity factor = (v ÷ 2,800)^(1/3)
Air factor      = ((T + 460) ÷ 519) × (29.92 ÷ Pst)
Sg corrected    = Sg × velocity factor × air factor

m    bullet weight (gr)       d    bullet diameter (in)
l    length in calibers       t    twist in calibers per turn
v    muzzle velocity (fps)    T    air temperature (°F)
Pst  station pressure (inHg)
```

Below 1,120 fps, hold the velocity factor at its 1,120 fps value. Read Sg against Table 18-1. For a tipped bullet, use the metal length in the (1 + l²) term.

Spin and spin drift (see Chapters 18 and 19)

```
Spin rate (rpm)     = muzzle velocity (fps) × 720
                      ÷ twist (inches per turn)
Spin drift (inches) = 1.25 × (Sg + 1.2) × TOF^1.83
TOF                 = time of flight (s)
```

Wind (see Chapter 19)

```
Crosswind       = wind speed × sin(wind angle)
Deflection (ft) = W × (TOF − dist ÷ v0)
```

```
wind angle  the angle between the wind and the line of fire
W           crosswind speed (fps) = crosswind (mph) × 1.46667
TOF         time of flight (s)
dist        distance to the target (ft)
v0          muzzle velocity (fps)
```

A zero at another distance (see Chapter 20)

```
New path at dist = old path at dist
                 − (dist ÷ new zero) × old path at new zero
```

Cant (see Chapter 20)

```
Sideways shift ≈ drop below the bore line × sin(cant)
```

Hit probability (see Chapter 21)

```
σ         = MR ÷ 1.2533
σ total   = √(σ1² + σ2² + σ3² + ...)
z         = (half the plate's width or height) ÷ σ
P(hit)    = (share within ±z across) × (share within ±z up and down)
P(circle) = 1 − exp(−R² ÷ (2 × σ²))
```

Each axis has its own σ and z. Read the shares from Table 21-1, or in a spreadsheet as 2 × NORM.S.DIST(z, TRUE) − 1. The circle formula is for a round plate of radius R and a round group.

From a hit goal to load limits (see Chapter 21)

```
largest σ         = (half the plate's width or height) ÷ z
rifle σ           = √(horizontal largest σ² − wind call σ²)
MR limit          = 1.2533 × rifle σ
velocity SD limit = √(vertical largest σ² − rifle σ²)
                    ÷ inches per fps
```

Work in inches at the target, and convert rifle σ to MOA for the MR limit. If rifle σ is larger than the vertical's largest σ, give the vertical a smaller share and work again.

Appendix B

Firearm and Range Safety Card

With every firearm

1. Treat every firearm as if it is loaded. Check the chamber yourself whenever you pick up or hand off a rifle.
2. Keep the muzzle pointed in a safe direction at all times.
3. Keep your finger off the trigger and outside the trigger guard until your sights are on the target and you have decided to fire.
4. Know your target, your backstop, and what lies beyond both.

At the range and in the field

5. Wear eye and ear protection whenever you are on an active firing line. Use double hearing protection near muzzle brakes.
6. Use a chamber flag whenever the rifle is cased, uncased, or on a cold firing line.
7. Confirm the rifle is clear of bore obstructions and that any suppressor is properly aligned and tight before firing.
8. Shoot only known-good ammunition that matches the cartridge stamped on the barrel. For handloads, fire only loads that have completed a safe work-up (see *The Handloading Handbook*).
9. Stop immediately at any pressure sign: stiff bolt lift, new or heavy ejector marks, or flattened, cratered, or pierced primers.
10. Keep ammunition out of direct sun and out of a hot chamber. Do not leave a live round sitting in a hot chamber while waiting to fire.
11. If a shot sounds or feels wrong, stop. Unload the rifle and inspect the bore for a stuck bullet before firing again. If a round fails to fire, keep the muzzle downrange for at least 30 seconds before opening the action.
12. Wash your hands and face after shooting or handling fired brass and targets. Do not eat, drink, or smoke until you have washed.

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Glossary

Aerodynamic jump. A small shift of the shot up or down, caused by a crosswind acting on the spinning bullet. *p. 119*

Arm. One setup in a test, such as one way of preparing cases or one seating depth, fired against another. *p. 106*

Ballistic solver. A program that works out a bullet's trajectory from your inputs. It gives the elevation, the wind per mph, the velocity and the time of flight at each distance. *p. 127*

Barrel tuner. An adjustable weight on the muzzle, moved in small steps to change how the barrel vibrates. Whether it helps by a useful, repeatable amount is still open. *p. 107*

Baseline. The rifle's measured performance in one fixed hardware state. Loads are compared only within one baseline. *pp. 15 and 78*

Batch. One factory ammunition lot number, or handloaded rounds built together from one lot of each component, with an ID such as Lot 41928 or B3-2. *p. 70*

BC. Ballistic coefficient. An index that compares a bullet's drag with the drag of a standard reference projectile. A higher BC means less velocity loss and less wind drift. A BC means nothing without its drag model. *p. 119*

Block. A run of rounds of one load fired in a row, such as 5 or 10. A pass fires one block of every load. *p. 78*

Button rifling. Rifling formed by pulling or pushing a hard carbide button through the bore, displacing metal to form the grooves without cutting steel away. Because cold-forming leaves internal stress in the steel, the barrel is stress-relieved afterward. *p. 20*

Cant. A tilt of the rifle and scope to one side. It moves the shot sideways by the drop below the bore line times the sine of the cant, so it grows with range. A scope level on every shot keeps it small. *pp. 34 and 129*

Carbon ring. Hard carbon buildup at the front of the chamber neck (centerfire) or chamber mouth and leade (rimfire). Left unchecked, it pinches the case mouth or engraves the bullet unevenly on firing, raising pressure, stiffening bolt closing or lift, and degrading velocity SD and group size. *p. 160*

Chi-square distribution. The distribution used to turn a sample SD into a confidence interval. *p. 88*

Click value. How far one click of a scope turret moves the aim. A 1/4 MOA click is about .26 inch at 100 yards, and a 0.1 mil click about .36 inch. Take it from the scope's specification and verify it with a Tall Target Test. *Chapters 3, 6, and 20*

Cold-bore shift. A repeatable difference between the point of impact of the first shot fired from a cold, fouled barrel and the center of subsequent shots in a string. *p. 55*

Composite group. Several groups of one load overlaid on their own centers and analyzed as one sample. *p. 89*

Confidence interval. A range calculated from your sample so that, over many repeated tests, a stated percentage of such intervals (such as 90 or 95 percent) contain the true value. It narrows as you fire more shots. *p. 84*

Contour. The outside shape of a barrel along its length: its diameters and taper. Also called the profile. *p. 15*

Coriolis effect. Drift caused by the Earth turning under the bullet in flight. It depends on latitude and the direction of fire. *p. 126*

Crown. The finished edge of the bore at the muzzle, the last steel the bullet touches. *p. 15*

Cut rifling. Rifling cut one groove at a time by a hook cutter drawn through the bore many times. *p. 20*

Degrees of freedom. The number of independent pieces of information left after estimating a mean or a center. *p. 88*

Density altitude. The altitude in the standard atmosphere that has the same air density as the air you are in. Higher temperature, lower pressure and higher elevation all raise it. *p. 123*

DOPE card. Data on previous engagements. A card that turns a trajectory into the numbers you dial or hold. *p. 127*

Doppler chronograph. A chronograph that tracks the bullet by radar. In one test, two Doppler units agreed within about 1 to 5 fps. *pp. 38 and 83*

Drag coefficient. How much drag a shape makes at a given Mach number. It is not a constant. *p. 119*

Drop chart. A table from a ballistic solver that gives the elevation, the wind per mph, the velocity and the time of flight at each distance. It belongs to one rifle and one load, and the DOPE card is printed from it. *p. 136*

Dummy round. A round with no primer and no powder, marked so it can never mix with live rounds. It is used to find the magazine length and to set up seating. *p. 24*

ES. Extreme spread. The center-to-center distance between the two shots farthest apart, or the gap between the fastest and slowest velocities. It grows with the number of shots, so never compare ES across different shot counts. *p. 84*

F-test. A test that compares two spreads, such as two mean radii or two velocity SDs, through the ratio of their squares. *p. 95*

First focal plane (FFP). A riflescope design in which the reticle sits ahead of the magnification erector lens, so the reticle scales with the target image and subtensions remain true at every magnification setting. *p. 29*

Fixed sample. A way to rank several loads: prepare and fire 30 to 35 rounds of every load in interleaved blocks, then decide. It is simple and fair, but it costs the most rounds. *p. 94*

Fluting. Lengthwise grooves milled into the outside of a barrel to save weight. *p. 16*

Flyer. A shot far from the rest of its group. Often the normal tail of the group. Keep it unless the error was documented when it happened. *p. 86*

Form factor. A bullet's drag divided by the drag of the standard projectile at the same Mach number. *p. 121*

Fouler. A shot fired to condition a clean bore. It gets its own line in the log but is kept out of the data. *p. 82*

Free recoil. Shooting without gripping or pulling the rifle into the shoulder, letting the rifle track straight back in its bags (common in Benchrest and F-Open); also the calculated recoil energy of an unrestrained rifle. *p. 44*

G1 and G7. The two standard drag models a BC is quoted against. G1 fits flat-base bullets and G7 fits long boat-tail bullets. *p. 119*

Hammer forging. Forming a barrel by beating a blank down onto a mandrel that carries the reverse of the rifling. *p. 20*

Hit probability. The share of shots expected to hit a target of a given size at a given distance. It combines dispersion, velocity SD and the shooter's uncertainties. *p. 137*

Instrument error. A chronograph's own scatter. It adds to the true velocity SD. *p. 38*

Interleaving. Rotating loads block by block so heat, fatigue and weather fall on each load alike. *p. 78*

IPHY. Inches per hundred yards (1.000 inch at 100 yards), sometimes called Shooter's MOA, as distinct from True MOA (1.0472 inches at 100 yards). *p. 11*

Ladder test. Firing one shot, or a short string, at each of a series of rising charges to look for a node. With so few shots, random scatter makes flat spots in most ladders. A ladder is still the right way to work up for pressure and velocity. *p. 107*

Lag time. The time drag costs a bullet compared with flight in a vacuum. Wind drift follows it. *p. 119*

Lands. The raised ribs of the rifling. The bullet's jump is measured to them. *p. 15*

Law of Large Numbers. As shots add up, the sample average approaches the true average. *p. 2*

Line of sight. The straight line from the scope to the aim point. The bullet leaves the muzzle below it, rises through it and falls back through it at the zero distance. *p. 23*

Look. One test of the data partway through a comparison, such as after each block. Each look is one more chance for luck, so planned looks use thresholds stricter than 0.05. *p. 94*

Mach number. Speed as a multiple of the speed of sound, which is about 1,116 fps in standard air. Mach 1.2 is about 1,340 fps. *p. 119*

Magazine length. The longest round your magazine feeds and cycles every time, found with dummy rounds. It caps COAL for every round fed from the magazine. A round loaded by hand, one at a time, is not bound by it. *p. 15*

Mean radius (MR). The average distance of every shot from the group's center, the MPI. Unlike ES, it uses every shot. *p. 84*

Mil. Milliradian, an angle unit used on turrets and reticles. One mil is 3.6 inches at 100 yards, about 3.4 MOA. *pp. 11 and 129*

Miller twist rule. A formula that gives the stability factor, Sg, from the bullet's weight, length and diameter and the barrel's twist. *p. 115*

Mirage. Shimmering optical distortion caused by light refracting through layers of air at different temperatures, useful as a downrange wind indicator and capable of shifting apparent target position. *p. 59*

MOA. Minute of angle. One True MOA is about 1.047 inches at 100 yards. *pp. 11 and 84*

MPBR. Maximum point blank range. The longest span over which you can aim dead on while the bullet stays within half a vital zone above or below the line of sight. *p. 132*

MPI. Mean point of impact. The average of all x values and of all y values of a group's shots. It is the group's center. *p. 84*

Muzzle pressure. The gas pressure behind the bullet as it leaves the muzzle. It rises as the barrel gets shorter. *p. 18*

Natural point of aim (NPOA). The point where the rifle settles naturally on target without muscular tension once the shooter relaxes into position and reaches natural respiratory pause. *p. 43*

Node. A claimed span of charges where velocity or point of impact barely changes with charge. Nodes found with one shot per step disappeared in larger samples. *p. 107*

Normal distribution. The bell curve. Shot positions on each axis are usually modeled with it. *p. 85*

Optimal charge weight. A method that fires 3-shot groups at a series of charges and picks the middle of three neighboring charges whose groups center on the same point. A 3-shot group's center wanders by more than the effect sought. *p. 107*

p-value. The chance of a gap at least as large as the one measured if the loads were really the same. It is not the chance that one load is better. *p. 95*

Parallax. Apparent movement of the reticle across the target when the shooter shifts eye position, caused by the target image not focusing on the same optical plane as the reticle. *p. 29*

Pass. One round of blocks in which every load fires one block. The starting load rotates from pass to pass. *p. 81*

Rayleigh distribution. The distribution of shot distances from a round group's center. About 39, 86 and 99 percent of shots fall within 1, 2 and 3 times the per-axis standard deviation (σ). *p. 86*

Root-sum-square. How independent errors combine: square each one, add the squares and take the square root. The largest source dominates the total. *p. 139*

Rounds' worth. A way of expressing cost in units of loaded rounds. The components of one loaded round (bullet, powder, primer and once-fired brass) equal 1 round's worth. A tool is valued by how many rounds its price would buy, and an hour of your time is counted as 20 rounds' worth. *p. 145*

SD. Standard deviation. How far a typical value sits from the average. You measure it for velocity and for each axis of a group. There is no universal SD target. Set yours from hit probability at your distance. *p. 84*

Second focal plane (SFP). A riflescope design in which the reticle sits behind the magnification erector lens, keeping apparent reticle thickness constant across power settings while subtensions hold true only at one calibrated magnification. *p. 29*

Sectional density. Bullet weight divided by the square of its diameter, in pounds per square inch. *p. 121*

Sequential tournament. A way to rank several loads: test after every block, cut a load as soon as its p-value against the leader falls below that look's threshold, and keep shooting the rest. It saves the most rounds when one load is much worse, but each look needs a stricter threshold. *p. 94*

Session. One range trip with one rifle, with its own ID, plan, ammunition lots, and conditions. For handloaders, a loading session is one sitting of work in the workshop that starts a new batch. *p. 70*

Sg. Gyroscopic stability factor. It compares the bullet's spin with the air's push to turn it over. Below 1.0 the bullet tumbles. An Sg of 1.5 or more gives full BC with a margin. *p. 113*

Sight height. The distance from the center of the bore to the center of the scope. *p. 15*

Sighter. A shot fired to check the aim offset before the test shots. It is logged but kept out of the data. *p. 82*

Small-group correction. The factor √(k ÷ (k − 1)) that removes the small-group bias in mean radius. Groups of 3, 5 and 10 shots read about 18, 11 and 5 percent small without it. *p. 87*

Spin drift. Drift toward the side of the rifling twist: right for a right-hand twist, left for a left-hand twist. It does not depend on the wind and grows faster than distance does. *p. 119*

Station pressure. The air pressure where you stand, as a barometer there reads it. It is not the sea-level pressure in weather reports. *p. 123*

Statistical power. The chance a test detects a real difference of a given size. *p. 95*

Stringing. A group that is longer on one axis than chance explains. *p. 163*

Tall Target Test. A mechanical verification procedure in which you dial a large elevation adjustment along a plumb line at 100 yards and compare actual bullet impact shift to the dialed value to measure turret tracking factor and reticle cant. *p. 34*

Temperature sensitivity. The change in velocity per degree of powder temperature. Concern starts near 0.5 fps per °F. *p. 154*

Time of flight. The time a bullet takes to reach the target. Drop charts list it at each distance, and lag time and spin drift are worked out from it. *p. 120*

TOP Gun Principle. An empirical rule of thumb linking a rifle's expected mechanical precision to the ratio of muzzle kinetic energy to rifle weight—heavier rifles shooting milder cartridges tend to group tighter. *p. 27*

Tracking factor. How far a scope moves the impact divided by how far it was dialed, measured on a tall target. Dial each correction divided by it. *pp. 34 and 130*

Transonic. The speed band from about Mach 1.2 down to about Mach 0.8, where drag changes fastest and predictions are least reliable. *p. 120*

Truing. Adjusting the chart's velocity, and then its drag near Mach 0.9, until the predicted drops match the drops you observe. *p. 127*

Twist rate. The length of barrel in which the rifling makes one full turn, written 1:8 for one turn in 8 inches. A smaller number means a faster twist and more spin. *p. 20*

Two-phase screening. A way to rank several loads: screen every load with a small sample, such as 10 shots, and cut only a load whose p-value against the leader falls below the screening level. Then fire 25 more of each survivor and decide on the pooled shots. It saves rounds but can cut a good load. *p. 94*

Vital zone. The circle on a target that a shot must land inside, given by its diameter. Its size drives the MPBR more than any other input. *p. 127*

WEZ. Weapon Employment Zone analysis. It combines the rifle's dispersion, the ammunition's velocity spread and the shooter's errors in reading wind and range into a hit probability. *p. 137*

Wind call. Your estimate of the wind's speed and direction for a shot, which sets the hold or dial for drift. Its error is given in mph. Past about 500 yards it usually costs more hits than the rifle or the ammunition. *p. 137*

Yaw. The angle between the bullet's axis and the direction it is flying. A bullet can leave the muzzle with some, and a marginal twist lets it persist. *pp. 18 and 113*

Zero and zero distance. The zero is the sight setting that brings the bullet's path back onto the line of sight at one distance, the zero distance, such as 100 yards. A zero error is an angle, so it grows with range: .1 inch at 100 yards is about 1 inch at 1,000. *p. 127*

Zero offset. How far the zero group's center sits from the aim mark, measured to .1 inch and given to the solver. *p. 127*

Index