Sonic Range Finder Based on Gunshot Acoustics

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ABSTRACT

A homemade sonic range finding system is arranged to measure the distance from a rifle to a target that is 35-55 meters away. With a microphone at the gun's location and a corner reflector at the target, the abrupt sound of the gunshot itself serves as the signal whose time of flight is measured. The system's performance is compared to that of a commercial laser range finder, which measures the time delay for an optical reflection. Both methods yield accurate results. For the homemade system, however, corrections must be made for the supersonic propagation of the bullet's shock wave toward the target. These corrections provide insights into the acoustics of gunshots.

Keywords: sonic, laser, range finder

While sonic range finders (motion detectors) have found many applications in table-top physics laboratory exercises, they cannot be used to measure distances beyond several meters (Cline & Risely, 1988). A better choice for measuring long distances in outdoor experiments is a laser range finder. The chosen model, a Nikon ProStaff 550, can measure distances from 10 to 500 meters based on the time of flight of infrared photons issued by a pulsed laser diode (Amann et al., 2001). A diffusely reflecting object, e.g., a piece of white paper, is able to reflect the photons back to the range finder with sufficient intensity to be measured. For the shortest measureable distance of 10 m, the round-trip time of flight of a photon is 67 ns, which can be accurately measured with digital circuitry.

Table-top sonic range finders have difficulty measuring large distances because the inverse square law reduces the intensity reaching the target. The reflected signal can be enhanced by placing a corner reflector (inside corner of a box) at the target (Morse, 1990). Such a corner acts as a retroreflector, directing the reflected waves back along the incident direction. Modern road signs contain microscopic arrays of such corner reflectors in order to reflect light from a car's headlights back to the driver (Greene & Filko, 2010). The use of a single large corner reflector enabled us to measure the acoustic reflection of the sharp sound of a fired rifle. Based on ray optics, the time of flight for sound (or light) to move through a corner reflector is the same as for a flat reflector located at the apex of the corner (Nicholson, 2007). Hence the corner's apex is the correct reference point for echo-based distance measurements.

The purpose of this study was to implement a 50-meter-scale sonic ranging system and compare its accuracy to that of a commercial laser range finder. Both techniques may be of interest to physics educators and students: the sonic system for its wave propagation subtleties, and the laser device for its versatility.

METHODS

When handling a rifle, firearm safety is of utmost importance. Both authors had been certified in hunter safety, eye and ear protection was worn, and a large safety zone (on private property) was maintained around the target.

Figure 1 (Left) shows the arrangement of the outdoor sonic range finder. A 22-caliber long rifle was mounted on a table and aimed nearly directly at a corner reflector assembled from three 0.6-m-square pieces of 12-mm-thick, foil-coated, rigid Styrofoam insulation. A Shure model 430 omnidirectional microphone was located in the same horizontal plane as the rifle, slightly behind and to the side of the muzzle. An insulating shell of foam rubber shielded the microphone from stray noise and table vibrations. The distance d from the microphone to the reflector's apex was measured using a tautly stretched metal tape and set at 35, 45, or 55 m. With the dimensions shown, the angle between the reflection axis and the bullet path was less than 2^{o}. Signals from the microphone were recorded with a Tektronix TDS 3012 digital oscilloscope with single-shot triggering. Figure 1 (Right) is a photograph of the shooting range, with the corner reflector in the distance.

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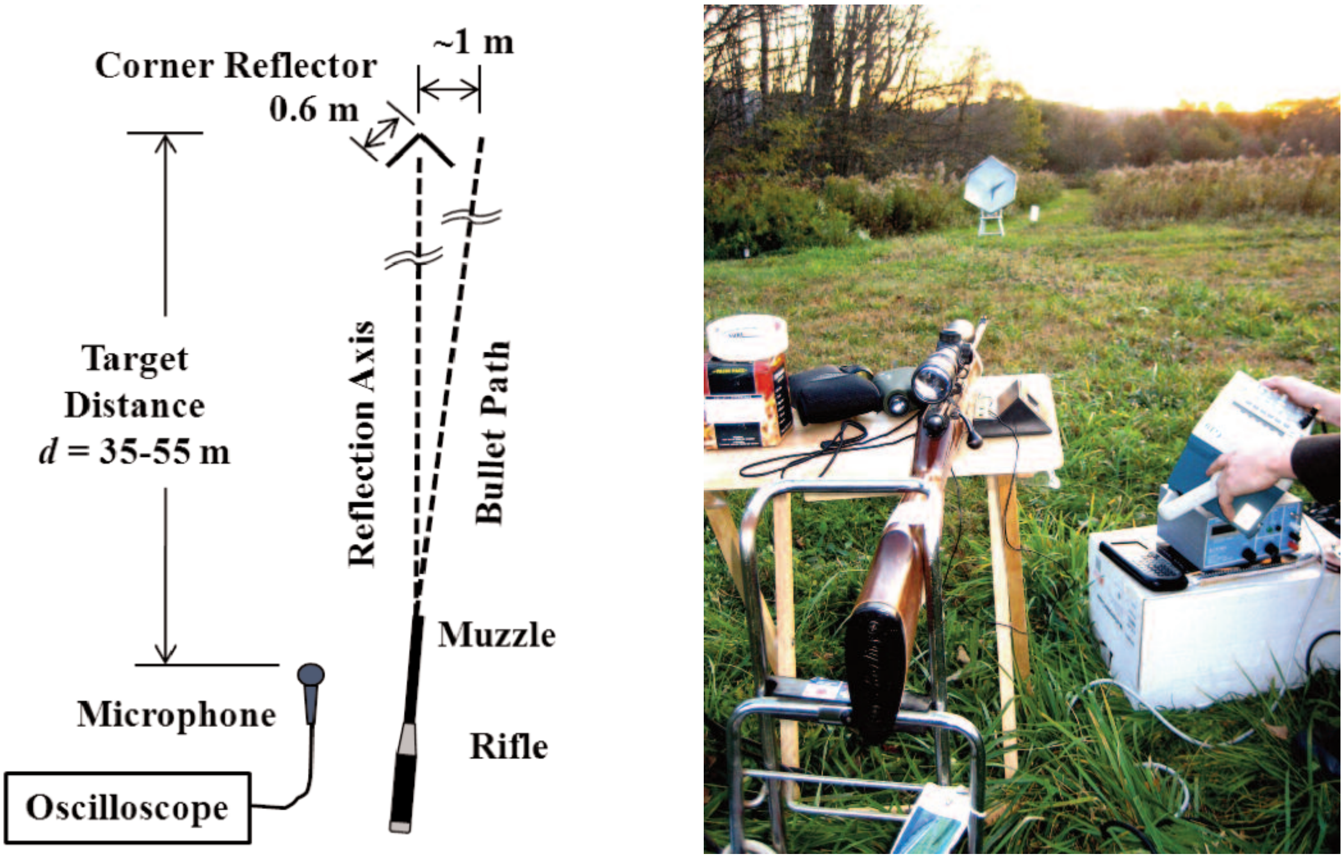

Figure 1. A homemade range finder for target shooting. Left - The sharp sound of the gunshot traveled to the corner reflector then back to the microphone. An oscilloscope recorded both the original and reflected microphone signals. The angle between the reflection axis and bullet path – exaggerated in this figure – was less than 2°. Right - Photograph of the shooting range. A 22-caliber rifle was aimed near the right edge of a distant corner reflector. The microphone (not shown) was placed to the left of the gun. Straddling the gun are a digital thermometer and laser range finder.

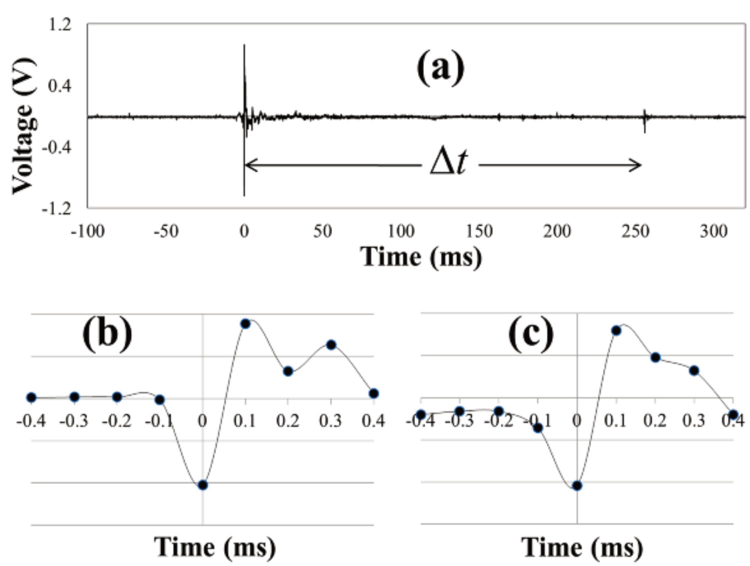

Figure 2. (a) Oscilloscope waveform captured from the microphone for the 45-m shot. The original signal returns as a reflection after an echo time Δt. (b) The original signal is shown with an amplified time scale. Each dot is a datum from the oscilloscope's memory. (c) The reflected signal is shown for comparison, with its vertical amplitude enlarged.

Figure 2a is a plot of voltage as a function of time obtained by downloading the microphone signal captured by the oscilloscope (for $d = 45$ m). Compared to the large initial gunshot signal, the reflected sound is coniderably attenuated but still discernable. In Figures 2b and 2c, the original and reflected signals are displayed, respectively, with amplified scales. That the two signals are very similar in shape is evidence of their common origin.

Each signal spans approximately 0.1 ms from trough to peak. This time scale, which depends on the bullet's size (Sadler, *et al*., 1998), is a characteristic signature of a ballistic shock front having reached the microphone, as opposed to the longer-time-scale oscillations from the residual muzzle blast of ejected gases. Recordings by Maher (2006, 2007), with a microphone near the path of a supersonic bullet, clearly show a single oscillation with a sub-millisecond period (the shock front) followed by a few cycles of muzzle blast oscillations spanning several milliseconds. The former, with its delta-function sharpness, is easily identified against background noise (Figure 2).

The oscilloscope, set at a time base of 40 ms per division, recorded data points every 0.1 ms. The largest amplitude data point in the original signal and the largest amplitude point (of the same polarity) in the reflected signal were identified. The time between these two points is the echo time Δt.

Analysis. A crude attempt to transform the echo time Δt into the target distance d is

$$d_{\text{uncorrected}} = \frac{v_s \Delta t}{2}\ , \tag{1}$$

where v_S is the speed of sound in air at temperature T (in degrees Celsius), given by the empirical relationship

$$v_s \approx \left(331 + 0.6T\right) \text{m/s}\quad .$$

The factor of two in the denominator of Equation 1 takes into account the round trip that the sound must traverse to form an echo. All data were collected at temperatures ranging from 9°C to 12°C ($v_S \approx 337$ m/s).

A more careful analysis of the sonic data must take into account two subtleties, which are illustrated in Figure 3.

Time-zero correction. In the experiment, the rifle's muzzle is located in front of the microphone by a distance of $L = 30$ cm, and it is also displaced laterally by the same 30 cm. Upon the rifle's firing, the wavefront issued from the muzzle undergoes aperture diffraction, allowing some of the acoustic energy to travel in the 45° backward direction toward the microphone (at the speed of sound). Time zero for the oscilloscope measurements occurs when this wavefront crosses the

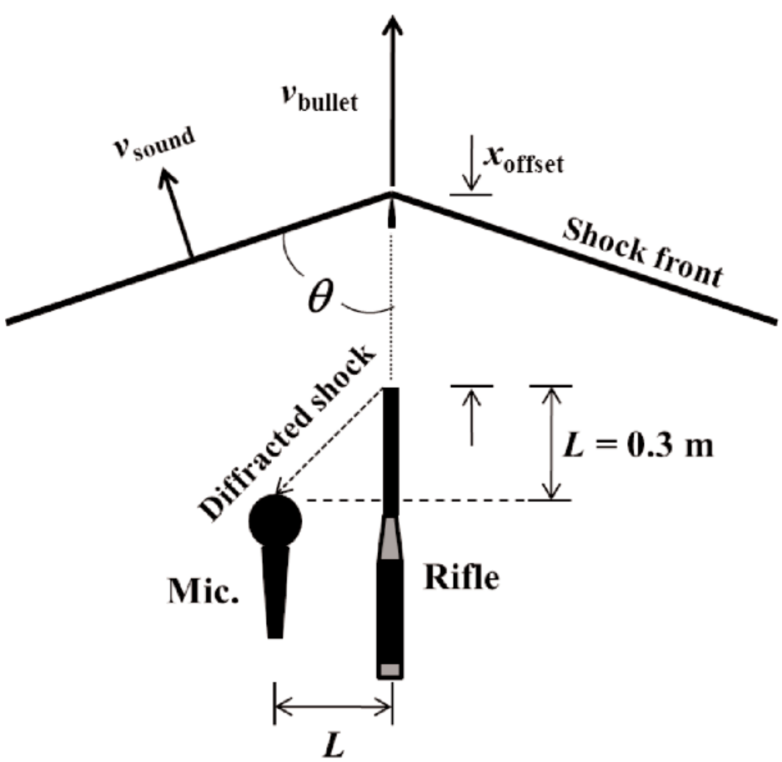

Figure 3. The supersonic bullet creates a shock cone of half-angle θ. The apex of the cone propagates forward at the speed of the bullet. Normal to the wavefront, propagation occurs at the speed of sound. At the moment the shock front reaches the microphone (by diffraction), the bullet has advanced a distance x_{offset}.

microphone. At this moment, the forward-directed wave has propagated from the muzzle toward the target by a distance x_{offset}, which affects how the echo time is interpreted.

Supersonic correction. The 22-caliber bullet leaves the muzzle at a speed of 384 m/s, which exceeds the speed of sound in air (Mach number $M = v_{bullet}/v_S = 1.14$). As long as the bullet remains supersonic, the shock's apex advances towards the target at the bullet's speed rather than the speed of sound (Settles, 2006). The half angle θ of the shock cone is $\sin^{-1}(1/M)$. When the bullet is issued from the muzzle $\theta = 61^{o}$, and this angle approaches 90^{o} as the bullet slows. When the bullet becomes subsonic, the acoustic front becomes a plane wave and travels ahead of the bullet at the speed of sound.

To apply supersonic corrections requires knowledge of the bullet's velocity as a function of distance traveled. Commercial external ballistics software (Sierra, 2007), which accounts for the bullet type, barometric pressure, temperature, humidity, and altitude, was used to obtain this velocity information, which is plotted in Figure 4. The bullet type was a known for the experiment, the temperature was measured using a digital thermometer, and the other environmental pa-

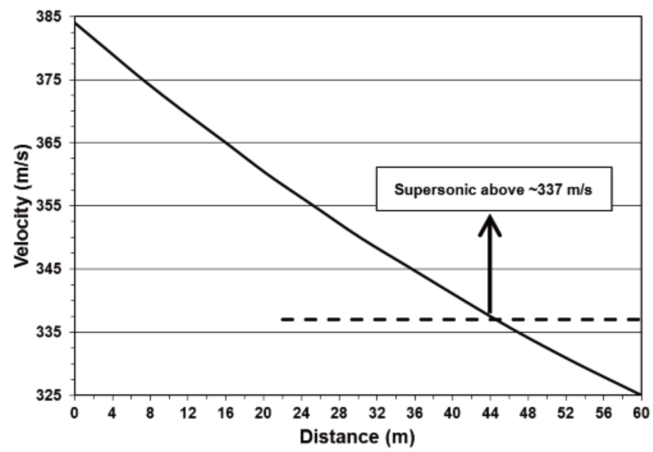

Figure 4. Velocity values for a Federal 22-caliber bullet (36-grain, model 745) at various downrange distances, obtained from commercial ballistics software. The bullet is supersonic out to a range of 44 m.

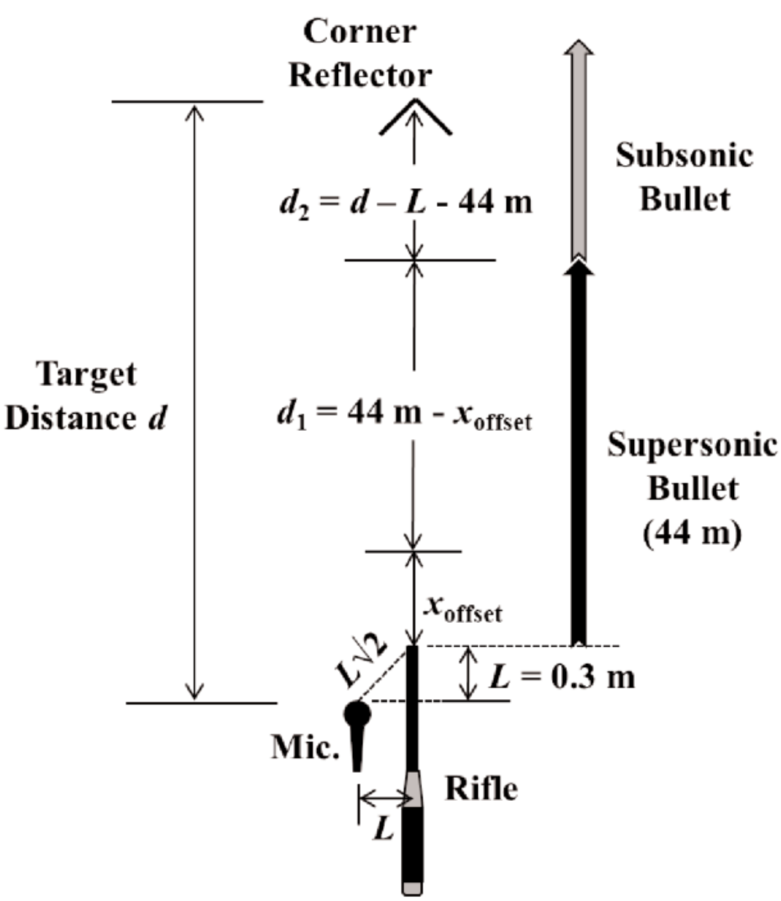

Figure 5. Accounting of the distances needed to correct the sonic data.

rameters were retrieved online. The software is based on the Siacci/Mayevski G1 drag model, which dates back to the 1880's and remains the standard for small-arms ballistics calculations (Ingalls, 1886; Klimi, 2009). The bullet is supersonic out to a range of 44 m, with an elapsed time that can be obtained from the Figure 4 data. Distance and time are used to compute the bullet's average speed during the supersonic phase of its motion to the target.

The three chosen target distances, d = 35, 45, and 55 m, straddle the supersonic/subsonic boundary. For the 35-m case, the bullet remains supersonic well beyond the target. For the 45-m case, the bullet's subsonic transition occurs essentially at the target. And for the 55-m case, the bullet's path to the target is part supersonic and part subsonic.

Figure 5 shows the various distances that determine the echo time Δt recorded at the microphone (for the 45- and 55-m cases). The shock wave has advanced a distance x_{offset} beyond the muzzle at the moment the oscilloscope is triggered (time zero). Through the distance d_1, the shock wave advances at the bullet's supersonic speed. For distance d_2, the bullet is subsonic, so the wavefront travels at the speed of sound, as it does when returning through distance d to the microphone.

The sonic data were processed using the following relations.

$$x_{\text{offset}} = \left(\frac{L\sqrt{2}}{v_s}\right) \cdot v_{\text{muzzle}} = 0.48\,\text{m} \quad \text{(time-zero correction)},$$

and

$$\Delta t = \frac{d_1}{\bar{v}_{\text{supersonic}}} + \frac{d_2 + d}{v_s} \tag{2}$$

where v_{muzzle} is the bullet's initial velocity upon emerging from the rifle muzzle, v_s is the speed of sound in air, $\bar{v}_{\text{supersonic}}$ is the bullet's average supersonic speed, and distances d_1, d_2, and L are defined in Figure 5. The target distance was computed from the measured echo time Δt by solving Equation 2 for distance d.

RESULTS AND DISCUSSION

Table 1 contains the measured echo times and the target distances obtained from all three methods: tape measure, homemade sonic range finder, and laser range finder. The sonic ranges are reported without corrections (from Equation 1) and with corrections (from Equation 2). The first row is the sonic echo time, and the last row is the percent difference between the corrected sonic range and the laser range.

It is evident that the time-zero and supersonic corrections are necessary to render the sonic data consistent with the laser and tape measure values. Compared with the tape measure numbers, the sonic data are discrepant by only 0.3 m, 0.7 m, and 0 m for the short, medium, and long ranges, respectively. The laser range finder reports numbers to the nearest 0.5 m for distances less than 100 m (and +/- 1 m for larger distances). In this 50-m-scale experiment, therefore, the laser data are subject to readout errors of approximately 1%. The sonic data has implicit uncertainty mainly due to imprecision in the bullet velocity data, which are obtained from simulation software. Assuming a 1% random error in any individual distance datum, the discrepancy between any two distance methods would be $\sqrt{2}\,(1\%) = 1.4\%$, consistent with the last column in Table 1, which compares the sonic and laser data.

For physics experiments involving distances too great for a standard sonic motion detector, a digital oscilloscope, microphone, and corner reflector can be fashioned into a sonic range finder with accuracy better than 2%. A loud, sharp sound is necessary to produce a detectable echo. The crack of a 22-caliber rifle provides an ideal acoustic signal. Interpretation of the echo time is complicated by the supersonic propagation of the bullet, which introduces the bullet velocity into the analysis. Shock waves in general and gunshot acoustics in particular are interesting topics for introductory physics students to consider. A suggested follow-up experiment would be to orient the rifle transverse to the reflection axis, so that the acoustic signal travels to the target at a single speed, v_s. Using blank cartridges (explosion but no bullet) would also eliminate the need for supersonic corrections. However, with no bullet carrying a shock front towards the target, the reflected muzzle blast may be harder to discern from background noise because of inverse-square-law attenuation. While audio recordings of gunshots may appeal to the curiosity of a physicist, they can also assist law enforcement officials in obtaining forensic evidence about the type of ammunition used (Maher, 2010).

Table 1: Comparison of rifle range data obtained by three different methods: tape measure, sonic range finder, and laser range finder.

Range	Short	Medium	Long
Echo Time Δt (s)	0.1900	0.2555	0.3194
Target Distance d (m)			
Tape Measure	35.0	45.0	55.0
Sonic Range Finder (Uncorrected)	33.6	43.1	53.8
Sonic Range Finder (Corrected)	34.7	44.3	55.0
Laser Range Finder	35.0	45.0	54.5
Sonic - Laser Difference	-0.9%	-1.6%	0.9%

The homemade sonic range finder constructed for this study was pursued more as a proof of concept than as a practical tool. A related, much simpler outdoor experiment can be conducted in a school setting. The experimenter stands approximately 50 meters in front of a large reflecting surface (e.g., side of building) and knocks together a pair of wood blocks at a steady rate, so that each new sound coincides with the previous echo. The target distance and frequency of sound pulses can be used to compute the speed of sound in air.

For quick and accurate distance measurements, a commercial laser range finder requires no special reflector or user skills (akin to a point-and-shoot camera). It is ideal for large-scale physics experiments, such as the one just described, in which a tape measure might be impractical. Modern optics and electronics allow for easy determination of distances using the time of flight of photons.

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