An earlier version appeared in *American Fireworks News*, No. 157 (1994).

Measurement of Aerial Shell Velocity

K.L. and B.J. Kosanke

Introduction

In addition to satisfying general curiosity, there are technical questions requiring knowledge of aerial shell velocity. For example, a calculation of how far down range aerial shells will have traveled at various times after having been fired from highly angled mortars requires knowledge of the shell's muzzle velocity and its effective drag coefficient. In particular, the authors (along with Mark Williams) plan to determine the maximum horizontal range of aerial shells which burst after the normal time fuse delay. This study could be conducted empirically by firing different size shells from mortars at various angles. However, such an approach could be prohibitively expensive and time consuming, and it probably would not allow the examination of as many cases as desired. As an alternative, the question could be examined using a computer model of aerial shell ballistics.[1] This would be relatively inexpensive and any combination of shell velocity, shape, and mass; time fuse delay; and mortar angle could be considered. However, without verification using results from actual testing, the modeled results would always be at least a little suspect. Accordingly, the best choice is to conduct a number of field tests to verify the correct performance of the computer model, and then to model the cases of interest. This article is the first in a series, which will describe the down range study introduced above.

To verify the correct performance of the ballistics computer model, it is necessary to know the velocity of aerial shells. In this article two techniques for measuring aerial shell velocities are described. One technique makes the velocity determination within a few feet of the muzzle of the mortar (muzzle velocity). This method is a slight refinement of that used by E. Contestabile.[2] The other method measures velocity by determining the shell's location at points throughout its trajectory. This method is a slight modernization of a method described by T. Shimizu.[3]

Muzzle Velocity Measurements

Velocity measurements can be made by measuring the time taken for a body to travel between two points separated by a known distance. As such, the measurements are the average velocity between the points. However, if the points are close enough together, such that the velocity does not change significantly during the short time interval for the object to move between the two points, the measurement closely approximates the body's instantaneous velocity. Probably the most common method used for this measurement is to setup one or more pair of "trip wires" [a] for the moving object to cross, with a clock started when the first trip wire is broken and then stopped with the breaking of the second trip wire. This is shown schematically in Figure 1. In this case, the average velocity (V) of the object is:

Eq. 1. $V = D / t$

where D is the distance between the trip wires, and t is the time interval.

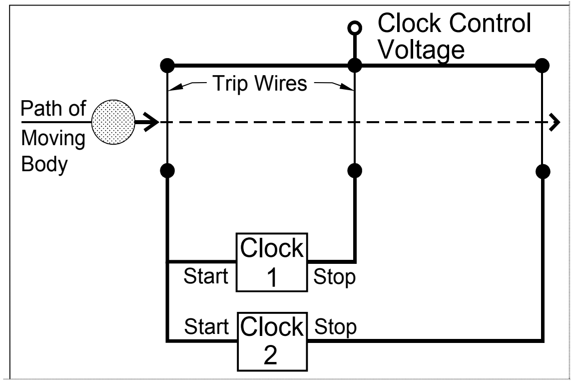

Figure 1. Block drawing of a simple "trip-wire" system for measuring the velocity of a moving body.

In the case of aerial shell muzzle velocity measurements, these trip wires need to be strong enough to withstand the blast of burning gases, yet weak enough not to impede the aerial shell.

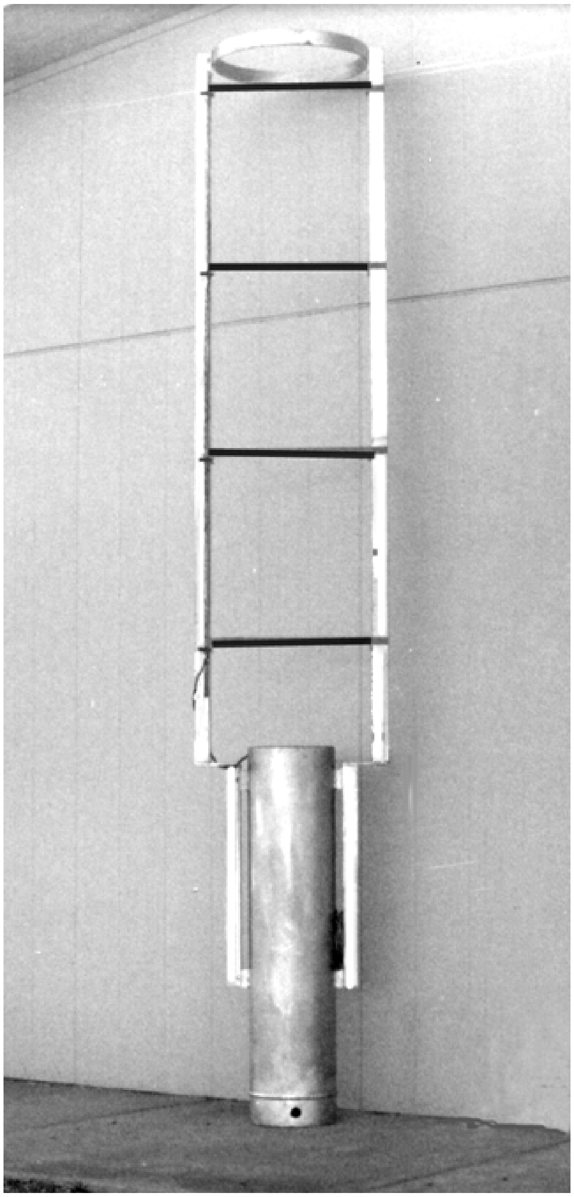

Figure 2. Photograph of a 10-inch test mortar. Colored tape has been used to indicate the location of trip wires.

The authors used 0.019-inch diameter insulated copper wire. The wire is held between electric terminals, which hold the wire strong enough not to come loose as a result of the blast of lift gases preceding the shell, but weak enough for the wire to pull loose without being stretched by the passing shell.

The method used by Contestabile[2] employed grids of wires as trips; however, he reported occasional difficulty with debris propelled ahead of the shell severing the wire grid before the shell arrived. To reduce the likelihood of such problems, care should be taken to limit the presence of material such as the paper lift bag and quick match shell leader, which could constitute such debris. Also the grid can be limited to just a pair of wires, thus offering a minimum target for debris to strike. Contestabile used two grids, placed 1 meter (3.28 feet) apart, with the first grid located 1.7 m above the muzzle of the mortar. In the apparatus used by the authors, the first trip wire was only 1 foot above the mortar and there were three additional wires each at two foot intervals. This allows a total of three velocity measurements. One of the test mortars, with colored tape at the positions normally occupied by the trip wires, is shown in Figure 2. The electronics package, which fires the electric match and then times the breaking of the trip wires, was designed and fabricated by Gary Fadorsen of Pyrotech International, and is shown in Figure 3.

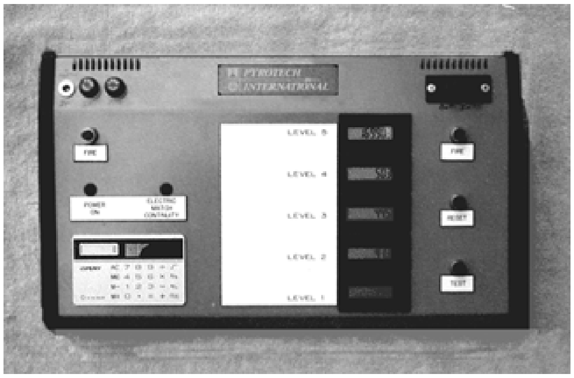

Figure 3. Photograph of the multi-clock electronics package.

As an example of some muzzle velocity measurements, consider the data in Tables 1 and 2. These are the results from a series of measurements of six identical 3-inch cylindrical shells fired from finale mortars (17.5 inches long).

It seems that the individual 2-foot timing method only produces results with a 1 sigma precision of about ± 1 ms. Thus, even though the Pyrotech instrument records times to 0.1 ms, the values reported in Table 1 are given to the nearest ms. It had been hoped that greater precision could be achieved with this method. The timing uncertainty is presumed to be the result of variations in the orientation of the shell upon striking the wire and differences in the amount of yield of the wires before the timing circuits open. The net result is that only the average velocity over the total 6-foot interval is precise enough to be useful. Perhaps with further refinement of the method, the precision can be increased so that 2-foot average velocities can be generated. This would allow an examination of the slowing of shells in the first few feet after leaving the mortar.

Table 1. Raw Data from Measurements of Muzzle Velocity of 3-inch Cylindrical Shells.

Shell No.	Trip Wire Break Times (ms)			
	1	2	3	4
1	59	69	82	89
2	109	121	133	145
3	94	104	(a)	124
4	63	74	84	95
5	94	105	114	124
6	81	92	103	115

(a)This data value was not recorded.

Table 2. Average Velocity Results for 3-inch Cylindrical Shells.

Shell No.	Velocity Measured Between Trip Wires (ft/sec)			
	1 & 2	2 & 3	3 & 4	1 & 4
1	200	150	290	200
2	170	170	170	167
3	200	—	200(a)	200
4	180	200	180	188
5	180	180	200	200
6	180	180	170	176
			Average	188

(a) Measured between trip wires 2 and 4.

All electric matches were fired with a current of about 3 amperes, which is expected to produce a firing time of less than 1 ms.[4] Accordingly, the wide range of times to the breaking of the first trip wire, by shells with similar velocities, is somewhat surprising. This seems to say some interesting things about the dynamics of the combustion of apparently identical lift charges. However, discussion of this subject is better left for another article.

Aerial Shell Trajectory Measurements

If an aerial shell could be tracked throughout its flight, such that its position can be established at a series of known times, using Equation 1, it is again possible to determine its average velocity during each time interval. Note that in the previous method it was the time required to travel a known distance that was measured, and in this method it is the distance traveled during a known time interval that is measured. To see how this might be accomplished, consider the method described by Shimizu.[3] If a time exposed photograph is taken of an aerial shell with an attached star, there will be created a record of the shell's path. If the trajectory of the shell is nearly perpendicular to the location of the camera, the shell's position as seen in the photograph will be an accurate 2-dimensional representation of its path. If the camera's field of view has been calibrated, such as by taking another picture with a series of landmarks, each of which are visible and separated by known distances, the trajectory of the shell can be quantified. The remaining piece of information needed to establish the shell's velocity along its path is the time elapsing as the shell travels along the path. In the method described by Shimizu this was accomplished by taking the time-exposed photograph through a rotating disk with a hole in it. Shimizu's disk was rotated at a rate of 25 revolutions per second. In this way the photograph appears as a series of points, each point indicating where the shell was located at each 1/25 of a second throughout its flight.

In the method used by the authors, the still camera and rotating disk were replaced with a video camera. Video cameras record 60 distinct images (fields) per second and VCR's (at least the more expensive newer ones) play back the individual still images one at a time [b]. Thus it is possible to record and play-back 60 images of the shell's position for each second during its flight. If a transparent plastic film is temporarily taped to the face of the video monitor, the location of a shell at each 1/60 of a second during its flight can be plotted using a fine tipped marking pen [c,d]. Depending on how the camera has been set up and the velocity of the shell at that time, the shell may move only a very little during each 1/60 second. In that case it may be preferred to plot the position of the shell once every 6 or 12 images (i.e., every 0.1 or 0.2 seconds). In this study two cameras were used, one zoomed in to measure the shell's velocity as close as possible to its exit from the mortar, and the other taking a wide angle view encompassing the entire flight path of the shell. The results recorded by the two cameras are illustrated in Figures 4 and 5. In these figures the effect of parallax [d] and round-off errors can be seen as slight inconsistencies in the plotted loca-

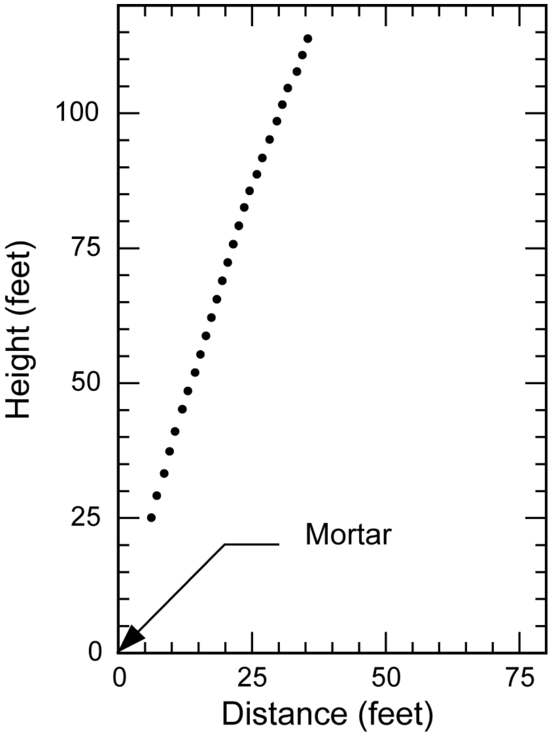

Figure 4. Trajectory of a 4-inch cylindrical aerial shell just after exiting the mortar.

tions of the shell. Such errors tend to cancel out over extended or averaged measurements.

There was one additional modification to the Shimizu method. The externally attached light producing star was replaced with an internal flare, which was mounted to be flush with the exterior of the shell. In this way, the aerodynamics of the shells are not significantly affected by the light source.

To analyze the trajectory data it is necessary to convert it to numerical form. This can be done by removing the plastic film from the video monitor and laying it over graph paper. Alternatively, it is possible to use a plastic film which already has a graph produced on it (such as would be accomplished by making an overhead projection transparency of a piece of graph paper). One way or the other each shell point needs to be converted to an x-y value, and then, using the landmark calibration data, converted to full scale vertical and horizontal distances. At this point, Equation 1 can be used to calculate average velocity between any pair of points along the shell's path. Finally, using the time information (by counting images), the time to apogee and impact can be determined.

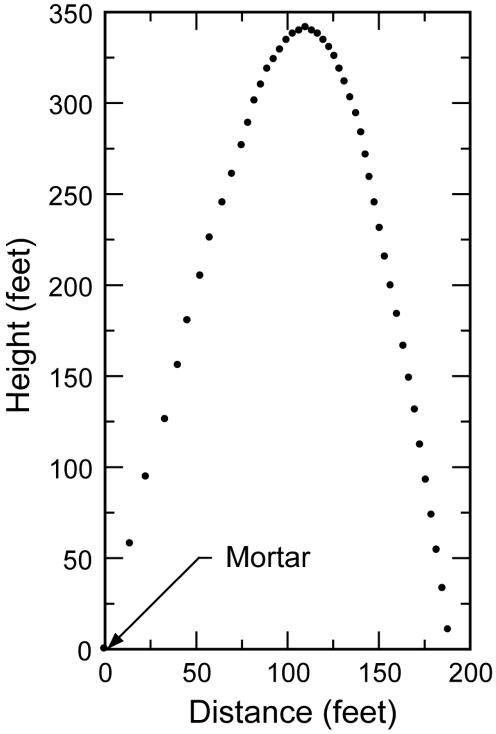

Figure 5. A plot of the entire trajectory of a 4-inch cylindrical aerial shell.

When an aerial shell fires, a large amount of fire projects out of the mortar before the shell exits. This fire makes it impossible to see the aerial shell with its internal flare until a short time after it leaves the mortar. For example, in Figure 4, the first shell trajectory point was recorded about 0.1 second (6 video fields) after fire is first seen in the mortar. At that time the shell has already risen about 25 feet. Using the data of Figure 4, average shell velocities were calculated for each tenth second from 0.2 to 0.5 seconds. The results were: 221, 204, 194, and 187 feet per second, respectively.

In Figure 5, each twelfth point along the shell's trajectory was plotted. This corresponds to one point every 0.2 second along its path. In this case, the shell reached its apogee of 340 feet 4.0 seconds after firing. It fell back to the ground at a point 190 feet down range, 9.2 seconds after firing.

Aerial shells tend to tumble after leaving the mortar. When that tumbling is such that the flare is sometimes blocked from view of the camera by the body of the shell, the light from the flare will intermittently dim or disappear. When this happens, it is possible to measure the rate of that tumbling. In a data set similar to that shown in Figure 5, it was determined that the tumble rate of the shell was 5.3 revolutions per second, and was essentially constant throughout the flight of the shell.

Conclusion

There are other methods, and many variations and refinements that can be used to measure aerial shell velocities. The methods described here are not original and may not be the best for all applications. However, they are the ones most commonly used by the authors and seem to produce adequate results.

Acknowledgments

The authors gratefully acknowledge the assistance of Mark Williams and Scot Anderson for reviewing a draft of this article. In addition, the assistance of Gary Fadorsen, Pyrotech International, in assembling the muzzle velocity timing apparatus is appreciated.

Notes

[a] A trip wire as defined here need not be an actual wire. One possibility considered for aerial shells was to use light beams as the trip wires, such as is often used to measure the muzzle velocity of bullets. However, because of the smoke and fire that exits a mortar well before the aerial shell, this method was discarded as impractical.

[b] The individual images seen on a TV screen are "frames", each of which consist of two 1/60 second "fields" (a and b) through a process called interlacing. In pause mode, VCR's produce an interlaced version of just a single field. Upon advancing to the next still image some VCR's advance two fields. These VCR's are sometimes referred to as a–a machines, and there is 1/30 second elapsing between the still images. Other VCR's (generally the more expensive ones) are so-called a–b machines, which advance only one field at a time and have a time interval of 1/60 second between still images. In measuring shell velocities, it is important to know whether 30 or 60 images are reproduced per second; however, all else described herein is the same.

[c] This should be a pen that will write on "anything", such as Sanford's "Sharpie" permanent marker, which comes in normal and fine tip configurations.

[d] Because of the thickness of the glass on the picture tube of the video monitor, it is necessary to take steps to avoid errors from parallax when marking the screen. This can be done by looking with one eye and attempting to always position one's eye perpendicular to the point on the screen. Note that small errors from parallax will tend to cancel-out in an extended series of measurements. Another problem with the video monitor is the slight curvature of the screen, which makes it difficult to firmly attach the plastic film. Both problems can be eliminated by using a "frame grabber" and dumping the video display to a computer for analysis.

References

1) K.L. and B.J. Kosanke, "Computer Modeling of Aerial Shell Ballistics", *Pyrotechnica XIV*, Austin, TX, 1992.

2) E. Contestabile, R.A. Augsten, and T.R. Craig, "A Study of the Firing Characteristics of High Altitude Display Fireworks", *Proceedings of the 13th International Pyrotechnics Seminar*, Grand Junction, CO, 1988.

3) T. Shimizu, *Fireworks, From a Physical Standpoint, Part 3*, Reprinted by Pyrotechnica Publications, Austin, TX, 1985.

4) K.L. and B.J. Kosanke, "Electric Matches and Squibs", *American Fireworks News*, 150, 1994