AN ACOUSTIC TARGET SCORING AND EVALUATION TECHNOLOGY

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ABSTRACT

This paper addresses research into the application of acoustic-shockwave measurement technology to facilitate the instantaneous scoring of targets (including virtual targets). The scoring data is statistically analyzed and provided in real-time to an operator (or directly to the gunner/gunnery team) for concurrent gunner/weapon system performance evaluation at US Army firing ranges. In particular, this paper discusses the theory of operation, the system components, the usage options, and the value of instant feedback and performance evaluation. When a supersonic projectile travels through the atmosphere, a shock wave is propagated away from the nose of the projectile at the speed of sound. This shock wave propagates normal to the shock front. These shock waves can be detected by an array of sensors that are carefully designed to detect the fast risetimes. The shock wave's sharp risetime allows the accurate calculation of the projectile trajectory geometry. This in turn allows the projectile missed distance, trajectory azimuth and elevation, and projectile velocity to be derived. In addition to solving for the geometrical solution, the first two hundred microseconds of the acoustic pressure profile are examined to extract projectile signature information. This signature information is sufficient to classify the round type.

ABOUT THE AUTHORS

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INTRODUCTION

There is an existing need to facilitate the rapid collection and the subsequent analysis of target scoring data. The leverage of this capability can extend not only in to the gunner-training arena, but also into human factor evaluation of the shooter, whether he is a regular enlisted infantryman or an expert sniper. This instant feedback can further benefit weapon performance evaluation studies, where an arduous data collection and reduction regimen has been the norm.

The systems presented here take advantage of a unique and extremely predictable physical perturbation created by a supersonic projectile as it passes through the atmosphere. The atmospheric medium reacts to the projectile passage as if it were a boat in a fluid; indeed, the same fluid dynamic equations apply. A similar bow wave (shockwave) and stern wave (relaxation wave) are created. This bow wave is a three-dimension cone. However, because of the lower medium density of air, the onset of the bow wave is extremely fast. In addition, the integrity of the shock cone is highly regular. These two factors imply that detection of the time of arrival of the leading edge of the cone will allow the derivation of the trajectory location and orientation.

This is the basis for the methodology employed by the scoring equipment presented herein: times are collected from various sensing elements; a trajectory is derived and optimized; the trajectory is projected onto the target to establish the target hit location; and shot-to-shot variation statistics are calculated. Both hit location data and statistical data are presented on an operator screen within 30 milliseconds of projectile impact.

VALUE IN TRAINING AND HUMAN/WEAPON PERFORMANCE EVALUATION

Review of Non-Acoustic Technology

Originally, targets could only be scored manually. This required the total cessation of fire before a target could be retrieved for evaluation. Another option was to

place a scorer in a trench behind the target. He would then wave “Maggie’s Drawers” if the target was missed. Both of these visual techniques begat errors when a projectile went through an existing bullet hole.

The latest generation, prior to acoustic scoring, included an impact sensor. This scored the target when it shook from the impact of the projectile. This kind of system is still ubiquitous on Government ranges throughout the world. In addition to the “same-hole” problem of the visual targets, it is suffers from other drawbacks. There is no measure of lethality; a grazing shot has the same value as a heart shot. There is no feedback on near miss shots to allow fire correction. There is no identification of cross lane shots. Finally, there is no historical data of the order of the hit points for burst mode performance.

Use on Training Ranges

The acoustic detection technology not only permits the detection of all through-the-target hits, but also can unambiguously register near misses. Most significantly, it allows the actual scoring of the hit point (or miss point) coordinates. Performance of this scoring is obtained with higher reliability and no false hits.

This technology is ideal for tank target ranges where access to targets is limited, yet the large targets must perform around the clock, seven days a week. Tank crews must engage, be scored, and rotate out.

Acoustic scoring systems have been in use for over two years. This type of system can provide accuracies well with the required 120mm for tank ranges.

On individual ranges, where the targets are human silhouettes, there is a requirement to provide the gunner with a graphic feedback so that he can zero his weapon or correct his fire for the various influencing factors. There is also a requirement to statistically score his performance and keep a record of it in order to monitor progress. Again, this type of system is able to provide accuracies with the required 10mm for individual targets.

Use for Weapon Performance Evaluation

Other facilities are motivated by a requirement to evaluate either the weapon performance or the human factor facets of the weapon-gunner interface. In this case, instant feedback of target hit locations aids the principal investigator by providing the data needed to establish lethality, weapon accuracy, and the influence of weapon configuration variations. Real time calculation of weapon performance statistics allows monitoring of tests in progress. In fact, the Commanding General can monitor live tests via an internet connection.

THEORY OF OPERATION

When a supersonic projectile travels through the atmosphere, a shock wave is propagated away from the nose of the projectile at the speed of sound. This shock wave propagates normal to the shock front. The figure below (see Figure 1) shows a Schlierin (air density profile) photograph of an actual projectile. This picture demonstrates the extremely sharp boundary at the shock front generated at the tip of a supersonic projectile. The thickness of this wavefront corresponds to a risetime for wavefront traveling at the speed of sound in air. Shockwaves have a risetime due to viscosity that is predicted[1] to be

$$t_{rise} = \frac{\lambda}{C_S} \frac{P_0}{p_{max}}, \quad (1)$$

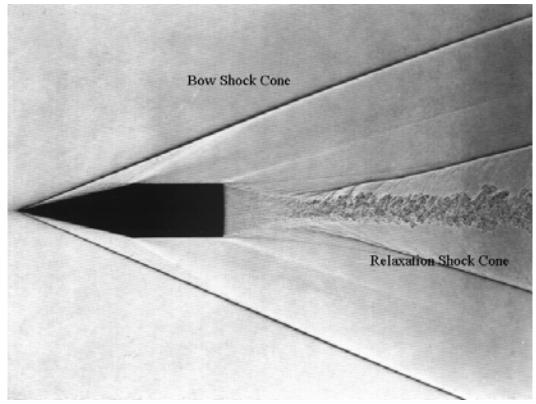

Figure 1. Schlierin Photograph.

where P_0 is ambient pressure, p_{max} is peak shock wave amplitude, and C_S is the speed of sound in air, and λ is the molecular mean free path, $\lambda = 8 \times 10^{-8}$ m. Typical values of p_{max}/P_0 are close to 10^{-3} making the risetime about ¼ of a microsecond.

These shock waves are not only audible but at a distance greater than 100 feet downrange from the weapon, the shock waves created in the vicinity of the bullet are far louder than the blast created at the weapon muzzle. When an extended range microphone (10Hz to 160kHz) is used to record these pressure signals, the signal trace produces the well-known "N" wave. The first peak is associated with the bow shock wave; the second peak is the relaxation shock wave (see Figure 2).

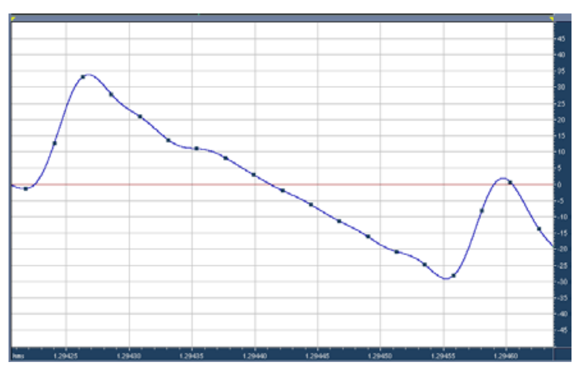

Figure 2. Microphone trace of Pressure Wave Element (Pressure (PSI) vs. Time (μsec)).

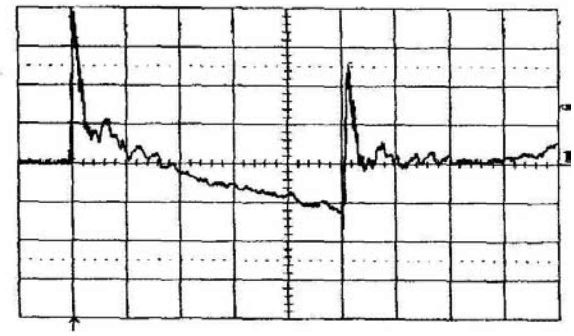

Figure 3. Piezoid Sensor with Low Frequencies Element (Pressure (PSI) vs. Time (μsec))

If a piezoid sensor with a characteristically high frequency sensitivity (500Hz to 1MHz) is used, the fast onset of the signal can be seen in both the bow and relaxation waves. (Refer to Figure 3.)

The shock waves can be detected by an array of sensor elements that are carefully designed to detect the fast risetimes. The fast risetime characteristic of these transducers is critical to the very accurate scoring of the trajectory and its subsequent hitpoint on the target.

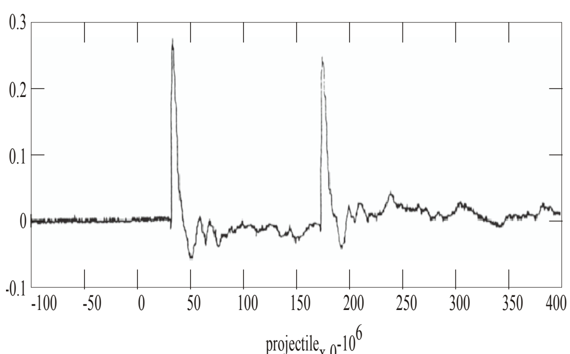

Figure 4. AAI Piezoid Sensor Element (Pressure (PSI) vs. Time (μsec)).

AAI Corporation developed, on Internal Research and Development (IR&D) funds, a high frequency piezoid sensor. This sensor has a low frequency cutoff of 8.8kHz and a high frequency response up to 1 MHz. The low frequency "N" shape is no longer present between the two peaks (see Figure 4). This makes signal processing a little easier. The sensing element is encased in a vibration free housing (see Figure 5). The element itself is the dot in the center and measures 0.1 inch diameter by 0.4 inch in length.

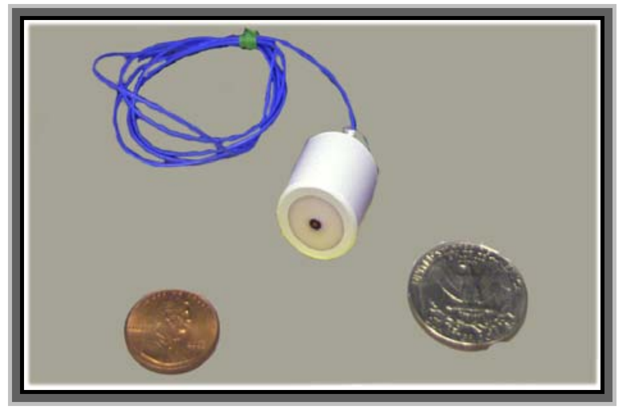

Figure 5. Sensor Element in Housing

SCORING DETECTION COMPONENTS

The algorithms that derive the trajectory and its orientation require 2 or 3 clusters of 3 sensing elements. Figure 6 shows a target scoring bar with 3 clusters (9 sensing elements). Three clusters allow a full three-dimensional trajectory solution to be derived; i.e., the three dimension location as well as azimuth and elevation of the trajectory.

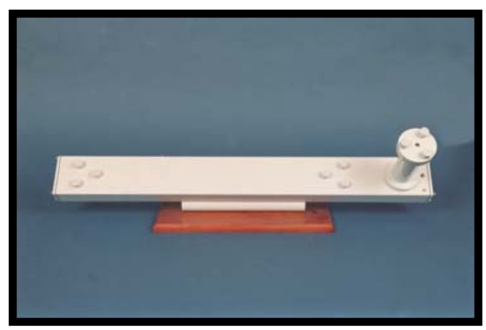

Figure 6. Three Cluster Target Scoring Bar (TDCue™ Model 2F3S) with 9 Sensing Elements.

Figure 7. Two Cluster Target Scoring Bar (TDCue™ Model 2F2S) with 6 Sensing Elements.

However, if trajectory elevation is known to within ±3° elevation, the need for a third cluster is alleviated. The resulting 2 cluster bar is depicted in Figure 7.

The target scoring bar consists of a rectangular tubular extruded hollow bar (cross section is 2 by 4 in.) of various lengths, two end caps, 6 or 9 sensing elements, a temperature sensor (see Figure 8), an all-weather connector, cabling, and a processor board.

The incorporation of a temperature sensor is crucial to maintaining accuracy. This is due to the algorithm's use of the speed of sound in the calculations. The dependence of the sound speed on the temperature can be seen in Equation 2 below[2], where T is temperature in degrees Celsius and C_S is the speed of sound in air

$$C_S = 1087.42\sqrt{1+\frac{T}{273}} \quad [ft/\sec] \qquad (2)$$

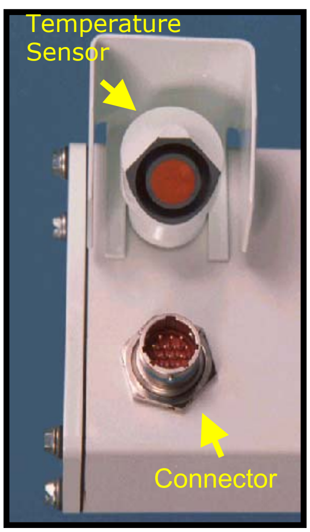

Figure 8. Temperature Sensor and Connector

For the individual target scoring bar, this temperature dependence leads to a small systematic scoring bias error. The most serious challenge to getting correct air temperature is the sun loading of the top surface of the bar. The temperature sensors shown here address this problem.

Notice the speed of sound is independent of the density of air. While this is true there is a very weak dependence on the partial fractions of the air content (the molecule types). This comes into play for high humidity. For a 100% relative humidity at 30°C (86°F), there is a 1.2% increase in velocity.

The speed of sound is instrumental in constructing the normal to the incident shock striking the cluster of the 3 elements. The shock wave strikes each of the sensor elements (see Figure 9). The normal vectors to the plane are then used to derive the trajectory.

The processor board has both a Field Programmable Gate Array (FPGA) and a Digital Signal Processor (DSP). The FPGA collects all the signal data (both times and amplitudes) and passes them onto the DSP. The DSP calculates a solution, optimizes this solution, determines round identification, and sends this data out the connector over RS-232 or RS-422 serial communications (auto-configurable).

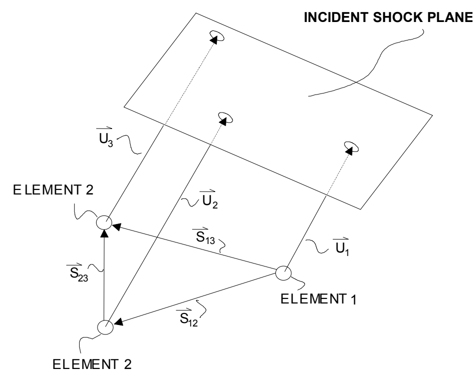

Figure 9. Shock Wave Section striking the 3 Sensing Elements.

USER INTERFACE COMPONENTS

As stated, the target scoring bar scores a result each time a valid hit occurs. The answer is then sent out in standard ASCII over the serial link. Any computer connected to this bar can receive the data from the shot. However, to effectively capitalize on the data, an interface program has been developed that cannot only register hit locations, but also derive statistical data. This data typically includes dispersion information and standard deviations for each shot grouping. It indicates bias offsets from the aim point. This information is presented in real time.

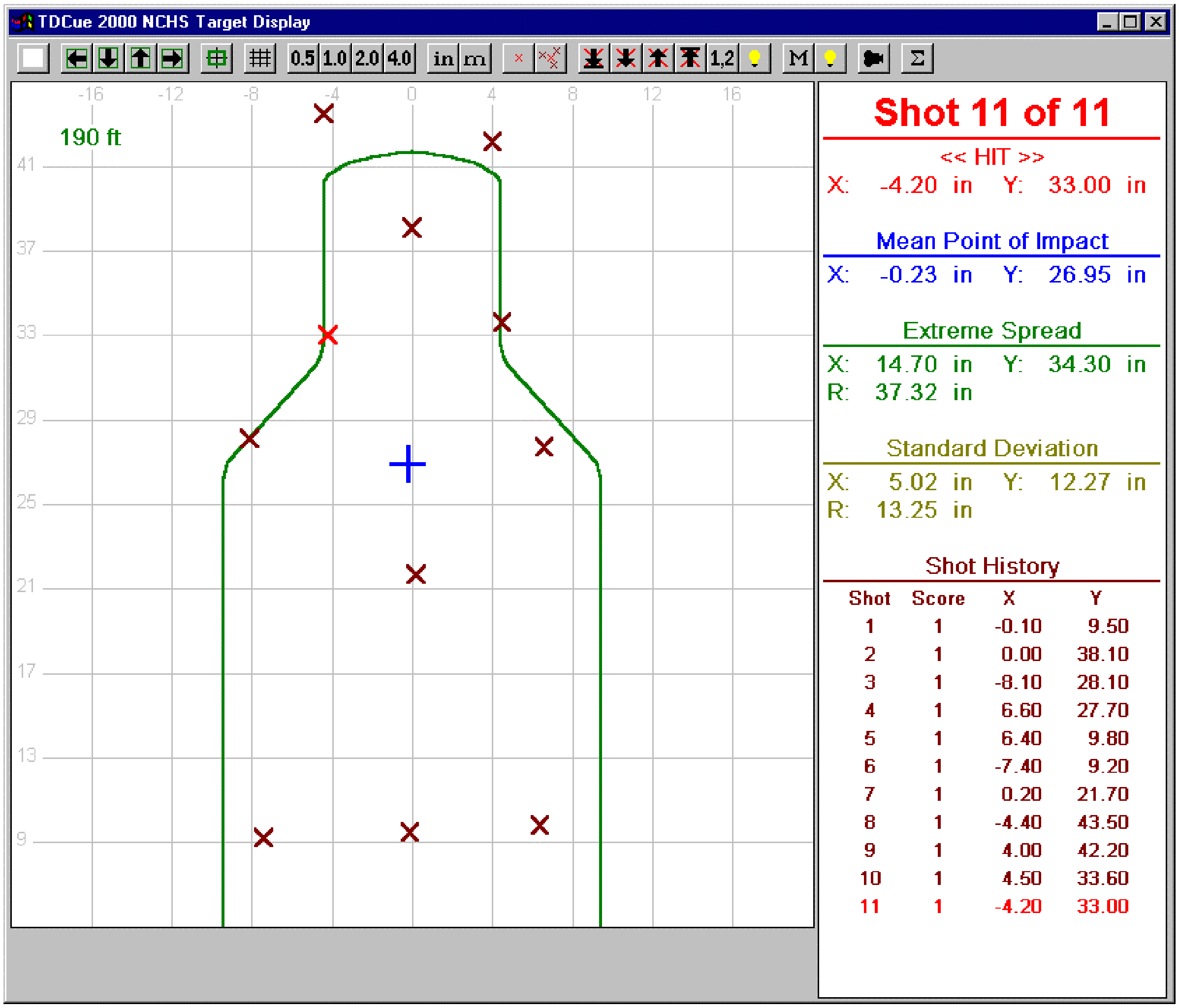

Figure 10. User Interface

The data is presented after each shot to the range officer on the Graphical User Interface (GUI) (see Figure 10). This interface allows the range officer to input all pertinent data regarding the firing session, such as, gunner's name, weapon, bullet type, and purpose of test. As each shot is registered an "X" appears on the target profile in red. This "X" goes to black as the next shot appears. After each shot following the first two, the statistics for the group are recalculated and presented. Off-target shots are indicated with arrows. The number of hits is indicated.

A zoom function facilitates close inspection of the shot grouping. A review function shows the detail of each shot to be scrutinized. Any target (or multiple targets) can be accessed. Meanwhile, all target information from all the range targets equipped with a target scoring bar are recorded and can be accessed in real time or after the session is concluded.

Two system options permit increased flexibility. These are the Firing Point Computer and the Muzzle Blast Detector. The Firing Point Computer is located at the gunner position. It is an all-weather, touch screen computer that produces reduced output to the gunner to provide instant feedback for training purposes. It also provides a login function for the gunner. (See Figure 11.)

Figure 11. Firing Point Computer

While the target scoring bar registers hits and near misses, it does not indicate from which lane the shot originated. Thus, if a gunner from an adjacent lane hits your target, the hit would erroneously be included in

Figure 12. The Muzzle Blast Detector

the shot statistics. The Muzzle Blast Detector eliminates this problem. It is positioned near the gunner to register the associated muzzle blast. (See Figure 12).

USAGE OPTIONS

Because of the system architecture, the communication between the target scoring bars and the host computer can be easily adapted to the range application.

Some test facilities have a single target. In this case, the target scoring bar would be connected directly to the host computer via the RS-422 or RS-232 serial link.

An infantry training range might have 32 lanes with only 3 targets per lane. This type of setup would include the Firing Point Computer and Muzzle Blast Detectors with the 3 bars in each lane connected to its Firing Point Computer. The Firing Point Computer would then communicate via RS-485 multi-drop link to the Tower Computer.

Another configuration occurs at a weapon evaluation facility. This facility might have four lanes with forty targets per lane. The application would look like the diagrammed layout (see Figure 13).

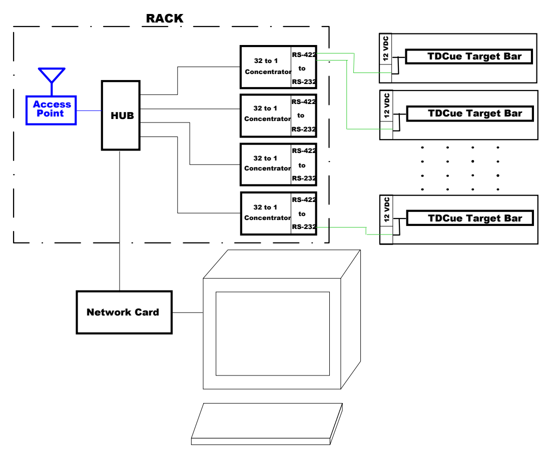

Figure 13. Architecture for Few Lanes and Many Targets per Lane.

Here RS-422 lines are run back to concentrators that convert the serial data to an internet protocol and a single Ethernet connection is fed back to the Tower Computer. The Firing Point Computers are now on a wireless connection with the Tower Computer. With the Ethernet connection, remote researchers can get the test data results in near real time without having to attend the firing sessions, simply by having the GUI on their local computer.

In all applications, the scoring system can be used with or without target lifters. However, it should be noted that because the bar scores on the signal generated by the bullet passing and not on impact characteristics, no physical target is required. This implies the seamless adaptation to virtual targets.

An obvious extension of this technology is sniper detection. Indeed, AAI has developed this technology and is currently under contract to the Army Research Laboratory (ARL) under funding from the USMC Warfighting Laboratory to deliver a system that integrates the sniper detection and location capability with an automatic gun-mounted machine gun on a HMMWV.

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[1] Y. B. Zel'dovich and Y. P. Raizer, *Physics of Shock Waves and High-Temperature Hydrodynamic Phenomena,* (Academic, New York, 1966), Vol. I, Sec. 23.

[2] Dennis A. Bohn, "Environmental Effects on the Speed of Sound," J. Audio Eng. Soc., Vol. **36**, No. 4, pages 223-231, 1988 April.