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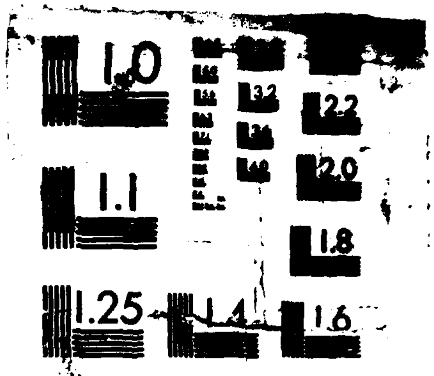

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TECHNICAL REPORT BRL-TR-2771

PROJECTILE FOLLOWER SYSTEM

AD-A182 362

T. ROBERT BECHTOL

DECEMBER 1986

US ARMY BALLISTIC RESEARCH LABORATORY
ABERDEEN PROVING GROUND, MARYLAND

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An analysis is made of the photographic problems related to obtaining both high resolution and high framing rate motion pictures of high velocity tank gun projectiles in flight. Current and postulated solutions are examined in light of current and projected ammunition performance. Basic performance requirements for a projectile follower system are presented.

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ACKNOWLEDGEMENTS

Mr. C. David Brown, Instrumentation Development Division, CSTA, was assigned the principal engineering responsibilities for getting a Projectile Follower System designed, built, and fielded. His engineering analyses and the contractual effort he has managed are noteworthy contributions to the program.

Mr. John D. Dickens, while on assignment from the Australian Army Engineering Development Establishment to the Instrumentation Development Division, CSTA (5/85 to 12/85) and then to Interior Ballistic Division (1/86 to 7/86), as a Special Projects Officer, contributed heavily to initial considerations for a projectile follower, with much of his work being incorporated into the system.

Mr. Dickens and Mr. Brown will report separately on the engineering aspects of the Projectile Follower System development, which are extensive.

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INTRODUCTION

The purpose of this note is to set forth the discussions and analyses leading up to the decision to develop and install a projectile follower system (PFS) on an Aberdeen Proving Ground range, and to describe some of the problems related to the specific aspects of the high-speed photography involved.

The PFS consists of a servo driven mirror (Figure 1) whose angular sweep rate is synchronized with the speed of a projectile such that the image of the projectile as viewed through the mirror appears stationary to a camera. This will enable slow motion photography of Mach III projectiles, without any appreciable blur over critical positions of its trajectory, e.g., at muzzle exit.

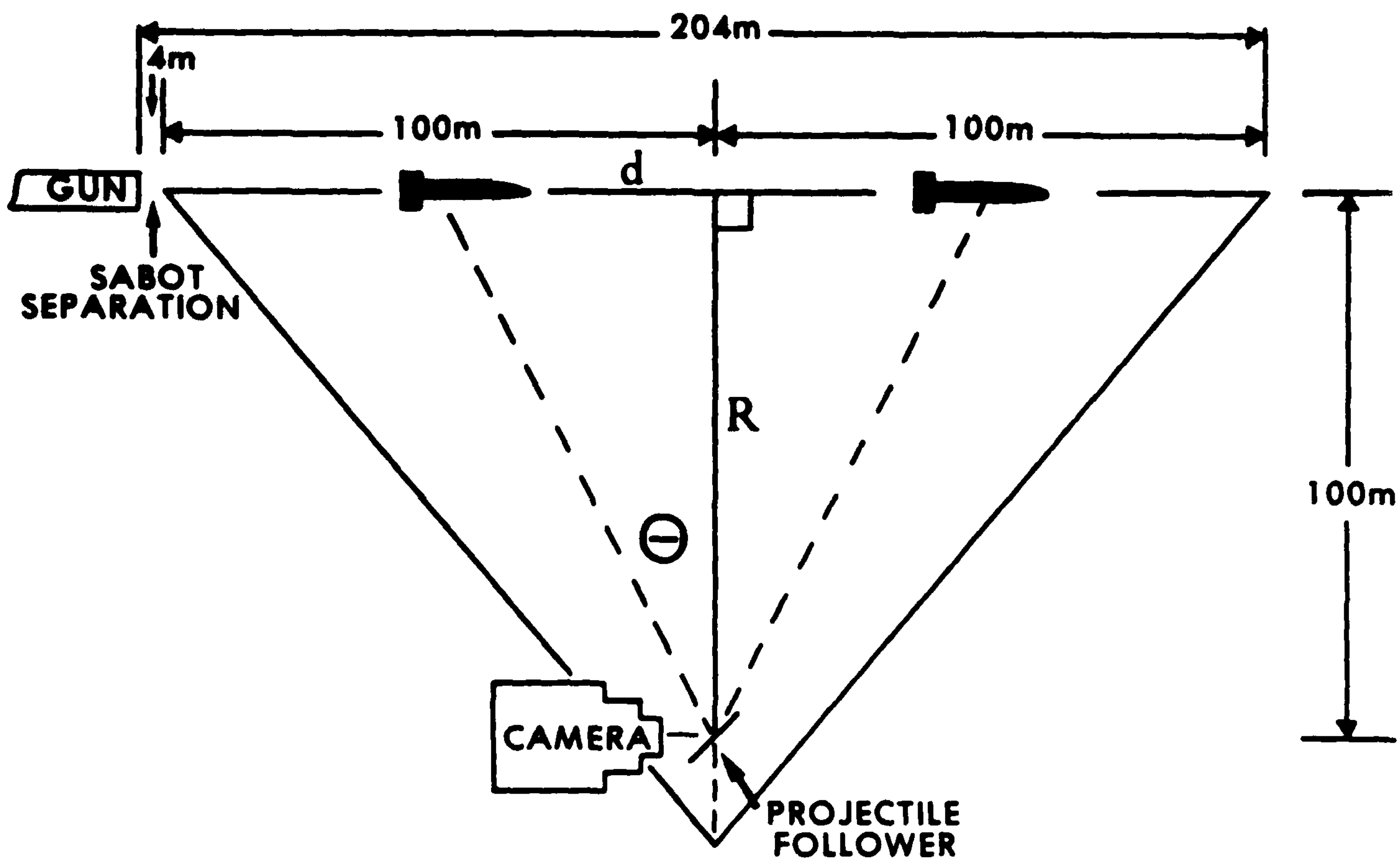


Figure 1. Projectile Follower

The projectile follower system consists of the projectile follower and associated driving electronics in addition to ancillary cameras, computers, timing systems (strain patches and sky screens for example), illuminating beam projector, calibration, and whatever else is necessary for an integrated system in the field.

The projectile follower is based on a well-known concept which has been implemented at times by others; e.g. L.E. Davidson at APG in 1962 (reference 1). Interestingly, his idea for using a cam to represent the changing angular velocity of a tracked missile is conceptually the same as the presently proposed use of computer "downloaded" trajectories for control of the scanning mirror.

BACKGROUND

Historically, events in ballistic technology occur in brief periods of time and are accompanied by violent releases of energy. Thus the task of obtaining data with which to describe these events numerically has been a challenge to weapon systems engineers since the dawn of the technology. Of the many data acquisition media available to researchers photography has been a workhorse. Ballistics photography has contributed effectively to both ballistics science and, as a technology in its own right, to much new and innovative photographic instrumentation. This in turn has produced spin-offs of great benefit to the general public. The projectile follower is just such a highly innovative technique for extending the capabilities of high speed photography.

The purpose, or application, of the projectile follower is several-fold:

1) There exists an urgent need for continuous motion picture photography of new high velocity tank gun projectiles in order to obtain data which describe the dynamic motions of the projectiles during the early post- launch phase of the trajectory, e.g. the first 200 meters:

a) High resolution photographs are required in order to observe and measure effects which occur to the projectile during flight - yawing motion for example, but not limited to that.

b) A later, future, application will be to study the dynamic motion of projectiles at any place along the trajectory.

2) High resolution photographs are required at the time of sabot separation in order to observe what happens to the projectile and petals of the sabot at that time, and to observe and to measure effects on the projectile, e.g. induced motion and possibly damage to the projectile and fins. For certain phenomena a framing rate of 500 pictures per second is adequate, with coverage of a long portion of the trajectory of up to 200 meters. Other phenomena which occur at sabot separation require much higher framing rates, using rotating prism cameras, with subsequent loss of resolution and picture quality but still superior in definition to a "fixed" camera. From this need a requirement for simultaneous high speed and very high speed camera coverage is inferred.

3) There exists a certain amount of interest in obtaining high frame rate photographs of a tank gun projectile as it approaches and contacts a target. This is not an immediate need but represents a readily achievable extension based only on a modification of the basic timing and, since there is a great deal more time during which to accelerate the mirror, should be relatively easy to do. The immediate and specific need is for coverage of the initial part of the trajectory.

The basic problem in obtaining good motion picture photography of high velocity projectiles can be readily seen by examining the motion induced blur in the picture. For example, a half meter long projectile moving with a velocity of 1.5 to 2 meters per millisecond moves 150 to 200 millimeters in 0.1 millisecond, which happens to be an ordinarily brief exposure time for photography in natural light. But even for that brief exposure time the blur is

$$\frac{(150mm\ to\ 200mm)\ [distance\ travelled]}{500mm\ [pojectile\ length]} * 100\% = 30to40percent \qquad 1$$

which is totally unacceptable. Even a tenth of that, corresponding to an exposure time of 10 microseconds, is not very good and falls outside the realm of ordinary photography. Adequately intense illumination for motion picture photography of high velocity objects over long path lengths with a single camera has not been practically possible; however, well recognized techniques have existed for producing high quality single frame photographs. These have been used to good advantage.

A solution to the problem lies in a technique which allows the optic axis of the camera to point directly at the high velocity object during the entire time of observation - or over the total length of flight path of interest. In order to do this one must take into account several controlling parameters and trade-offs. Basically one must harmonize the camera focal length, the frame size, the framing rate, the image linear-rate, the image size, exposure time and aperture setting, with the projectile velocity, size, length of flight path to be covered, and the illumination level and direction of lighting.

A great deal of success in employing this technique has been realized by personnel at the Royal Armaments Research and Development Establishment (RARDE), Fort Halstead, England during the recent past (references 2, 3). Called a "Flight Follower" there, the instrumentation they have developed has been used for several years and has been routinely producing excellent pictures. The capabilities of that system are limited and have matured. As will be shown later, the acquisition of that design would not satisfy the data requirement here.

Dr. Edward M. Schmidt, BRL, reported in 1972 (reference 4) having derived the mathematical expression describing the function of a device conceptually the same as the projectile follower. Resources could not be provided at that time to implement his proposal.

In 1962 L. E. Davidson, D&PS, Aberdeen Proving Ground, designed and built a camera mount utilizing programmed mirror rotation for missile tracking (reference 1). That system was electro-mechanical and used a suitably shaped cam driving a push rod which in turn actuated the scanning mirror. An operator override provided for tracking corrections. Tracking rates of 0 to 15 degree per second were possible. The system was adequate for photographing man-guided missiles. Further development was not pursued.

A new design is now being pursued which takes advantage of new computer technology, new materials, and new shaft angle encoders, in order to produce a system which is adequate for present needs and which has significant growth potential.

OPERATIONAL PARAMETERS

For discussion purposes and initial calculations the following conditions were established:

Projectile velocity realm	1,500 to 2,000 meters/second
Projectile size: length	0.4 meter and longer
Projectile size: diameter	20 mm and larger
Trajectory coverage	100 to 200 meters of flight path
Projectile deceleration	Approx. 90 to 120 m/s^2
Framing rate: Framing camera	500 frames per second
Framing rate: Prism camera	up to 10,000 frames per second
Image to frame size ration	1:3 or better
Gun caliber	120 mm, 105 mm, and larger

At the point of the program for which the projectile follower is required the gun will be the 120 mm smooth bore and the ammunition will be the M866 and the M829. Subsequently heavier projectiles will bring the muzzle velocity downward, but in general the muzzle velocity of developmental projectiles can be expected to rise. For the purpose of tentative design considerations the following "Straw Man" was suggested:

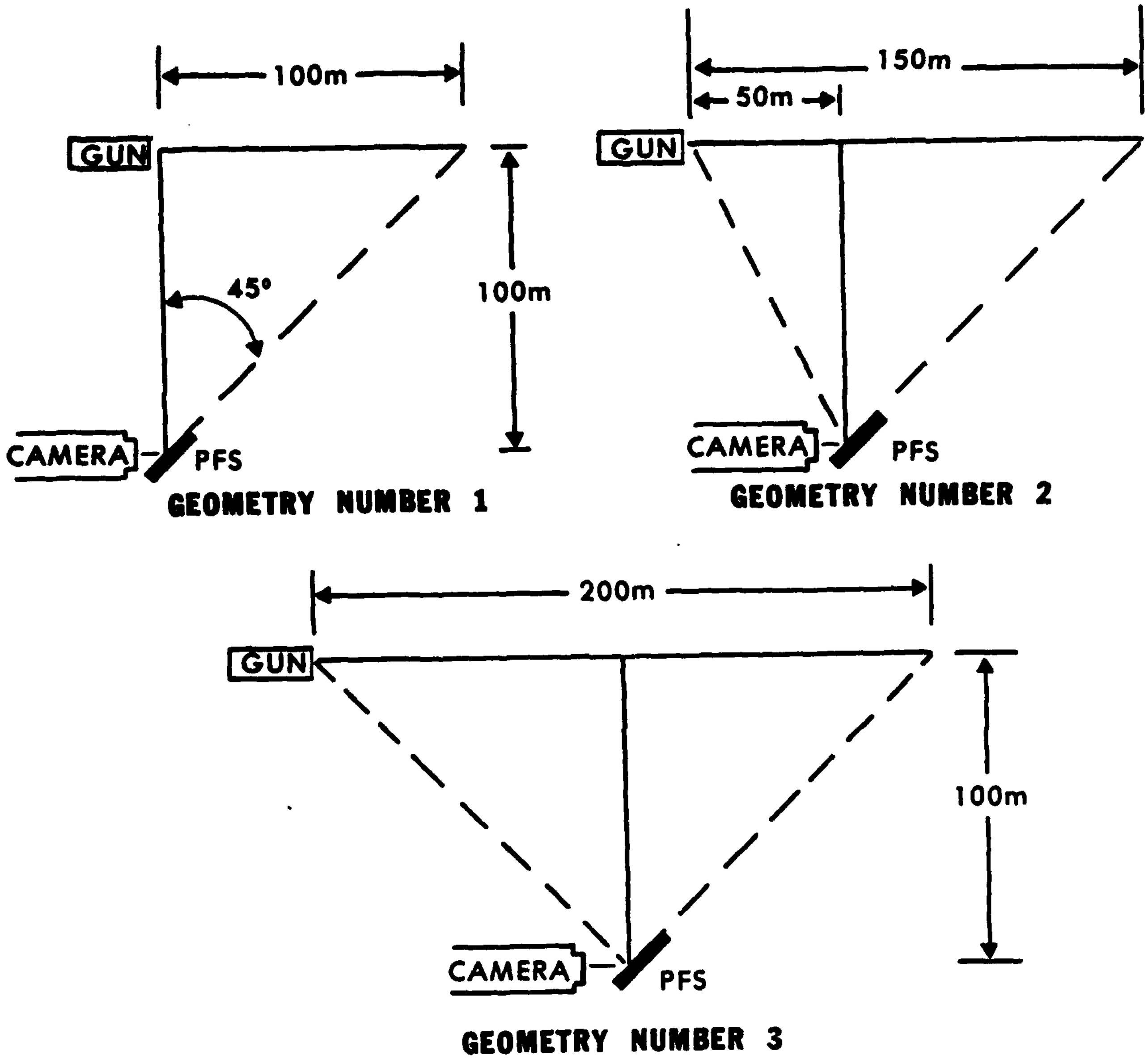


Figure 2. Geometries for Potential Projectile Follower Installation

Gun bore		**120mm**
Projectile:		
	Diameter	**24mm**
	Length	**0.5 meter**
	Velocity	**1,670 m/s**
	Deceleration	**Approx. 90 to 120 m/s^2**
	Coverage	**Approx. 200 meters**
Geometry:		
	Zero point	**Plane of the muzzle**
	Firing line	**Horizontal**
	Sweep plane	**Horizontal**
	Sabot separation	**About 4 meters in front of gun**
	Sabot sep. tm.	**+2 milliseconds**
	Point of perpendicularity	**104 meters from muzzle**
	Total covered	**204 meters**
	Timing pulse	**-4 ms ± 0.1 millisecond**
	Firing pulse	**-14 ms ± 0.5 millisecond**
	Offset	**100 meters**

Figure 2 shows several geometries for potential projectile follower installation, with geometry #3 chosen for initial calculations and design considerations.

The timing pulse would be derived from "hoop" strain patches on the gun tube and, as had been the case for other researchers in the U.K., has been adequate for the necessary synchronizing. The firing pulse, although providing longer lead time, is less reliable. BRL experience shows that by raising the firing voltage to about 75 volts that the uncertainty may be reduced considerably, from about ± 2 ms to about ± 0.5 ms. Further discussion follows.

DISCUSSION

In order for the projectile to be in the field of view of the camera throughout the 200 meters of desired coverage it is necessary for the optic axis to sweep at an angular rate corresponding exactly to the angular rate of the projectile as viewed from the camera. The problem is complicated by the fact that, although the linear rate of the projectile is fairly constant, the angular rate is changing constantly, first increasing to the point of perpendicularity and then decreasing thereafter, the maximum rate being

$$\omega = \frac{V_o}{R} \qquad (2)$$

where,

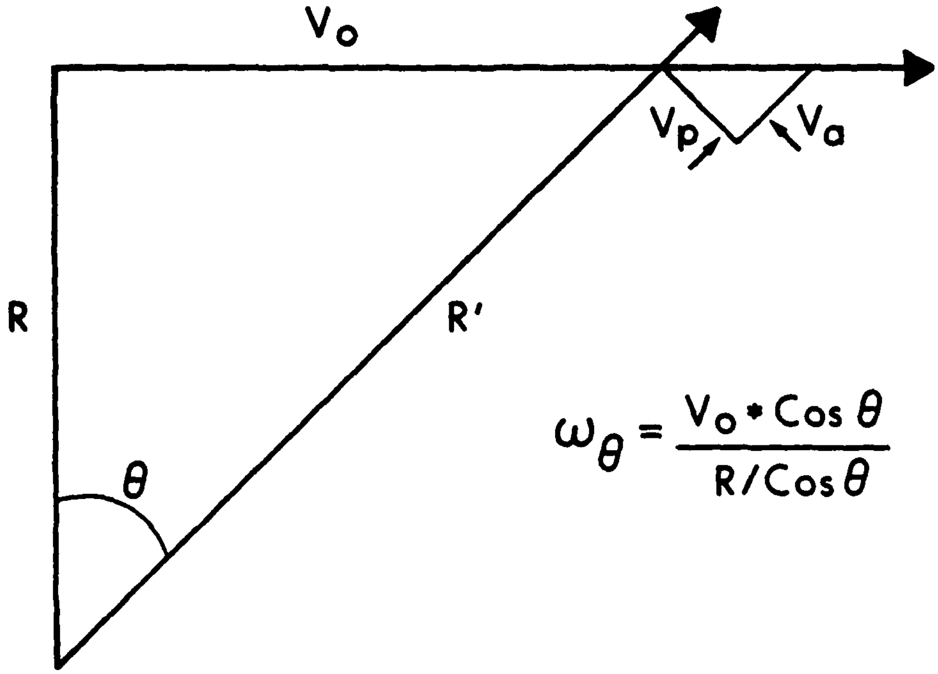


Figure 3. Extended Field of View

ω = radians per second,
V_o = projectile velocity, and
R = distance normal to line of flight.

assuming Vo to be constant.

For any other point on the 200-meter flight path, the angular rate, ω_{oa}, of the optic axis is

$$\omega_{oa} = \frac{V_o \cos\theta}{R/\cos\theta} = \frac{V_o}{R}\cos^2\theta \qquad 3$$

where θ is the angle between the optic axis and a line perpendicular to the line of fire, the angular rate of the PFS mirror being just half this, or

$$\omega_m = [\frac{V_o}{R} * \cos^2\theta] / 2. \qquad 4$$

When we include the projectile deceleration we have

$$\omega_m = [\frac{V_o - at}{R} * \cos^2\theta] / 2. \qquad 5$$

At any time, the angle θ is

$$atn\ \frac{d}{R}, \qquad 6$$

where d is the projectile position relative to cross over (see figure 1). That is

$$d = (V_o * t - a * t^2 / 2) - 100, \qquad 7$$

making d negative prior to cross over. Replacing d in equation 6 gives

$$\theta = atn\ \frac{[(V_o * t - a * t^2 / 2) - 100]}{R}. \qquad 8$$

Replacing θ in equation 5,

$$\omega_m = \frac{(V_o - at)}{R} * \cos^2[\ atn\ \frac{(V_o t - at^2 / 2) - 100}{R}\ ] / 2. \qquad 9$$

Electronically, the PFS must follow the above curve precisely in order for the image of the projectile to remain centered in the camera field of view.

TIMING

For discussion purposes we have assumed the following:

Muzzle velocity	1,670 meters per second
Trajectory coverage	200 meters
First sighting	Muzzle position plus 4 meters

The firing pulse for tank gun ammunition occurs about 13 milliseconds prior to the round emerging from the muzzle of the gun; however, there is an uncertainity in this time of as much as several milliseconds. This uncertainity won't do for initiating the PFS. As shown previously, time synchronization must be good to 0.1 ms in order to "capture" the projectile in the field of view of the camera and keep it there over the entire period of the event (0.1 second). Experience has shown that a "hoop" strain patch placed on the exterior of the barrel at a position just forward of the initiation of rifling will produce a pulse which occurs about 4 milliseconds prior to emergence, and is very repeatable. For the British at RARDE this pulse has been adequate for initiating their Flight Follower. A strain patch at the muzzle could be used to signal emergence of the round and serve as a "zero" point. Two patches spaced about 0.5 meter apart along the barrel could be used as a representation of the muzzle velocity as an input to the PFS.

As a check on the PFS and for diagnostics sky screens would be placed in front of the gun in order to get position vs. time data, particularly for rounds which "go awry".

ADVANTAGES OF THE PROJECTILE FOLLOWER SYSTEM

BLUR REDUCTION

If the synchronization between the PF sweep rate and the actual angular rate of the projectile were perfect the blur in the direction of motion would be zero. If the perfect match is not achieved then relative motion will occur thus introducing two detrimental effects. Assume there is a 1% error in the predicted muzzle velocity, i.e.,

$$V = 1{,}670 \pm 16.7 \textit{ meters per second}$$

First, during the total flight time of interest, i.e. 0.1 second, the projectile will travel a distance of approximately 167 ± 1.67 meters, neglecting deceleration for the moment. The magnitude of this error is enough to allow the projectile to drift out of the field of view of the camera, for which the design objective was stated as 2 meters at a distance of 100 meters (Figure 3).

Secondly, the blur for a 1% error in velocity with a typical exposure time of 1 ms (millisecond) amounts to

$$B = \pm\ 1.67\ m/s * .001\ sec \qquad 10$$

$$B = \pm\ .0167\ meters \qquad 11$$

$$B = \frac{.5\ m \pm 0.0167\ m}{.5\ m}\ X\ 100 = 3.6\% \qquad 12$$

This amount of blur is unacceptable for good metrical photography. Of interest, a 1% mismatch in velocity produces about the same amount of blur as 1% of the blur for a still camera using the same exposure time; i.e.

$$B = 1{,}670\ m/s * 0.001\ sec \qquad 13$$

$$B = \pm\ 1.67\ meters \qquad 14$$

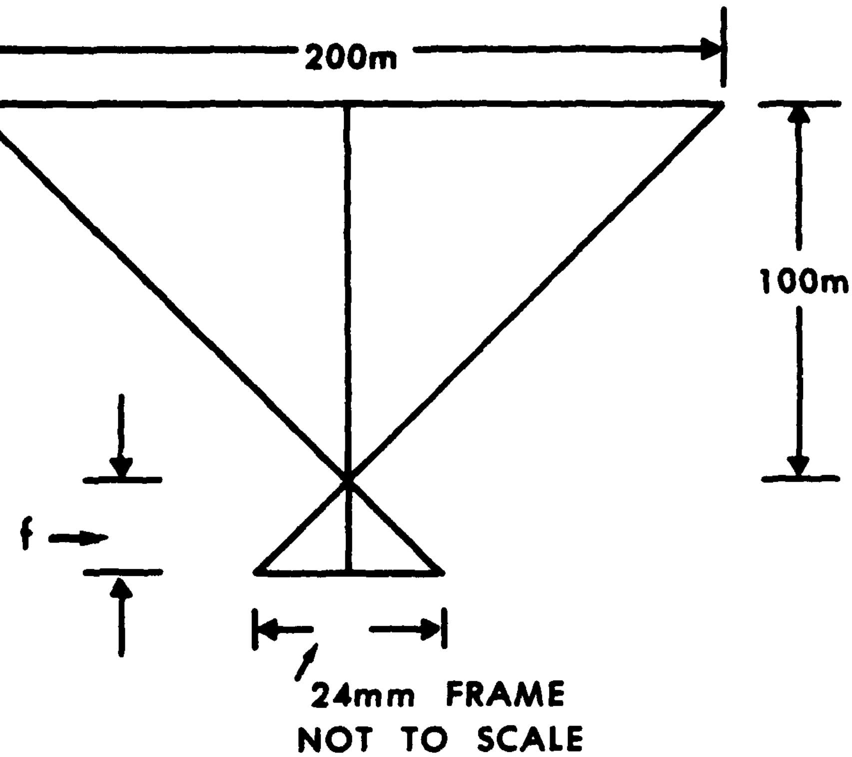
$$percent\ blur = \frac{.5m \pm 1.67m}{.5m}\ X\ 100\% = 4.34\% \qquad 15$$

The indication from the above is that the angular velocity mismatch between projectile and projectile follower should not exceed 0.1% for good photography. Correspondingly, for good still photography the exposure would have to be reduced by 10^{-3}, or for this example to 1 microsecond. For other reasons, as well, the latter is impractical.

FIELD OF VIEW

In order for a single camera to cover 200 meters of the flight path of a high velocity projectile the camera must be off the line of fire a sufficient distance so that the projectile can be "seen" with conventional fast optics (Figure 4).

For this geometry the image size of a 24mm diameter by 500mm long projectile would be



$$f = \frac{200 \times 1000}{24 \times 100}$$

$$= 12\text{mm}$$

Figure 4. Field Geometry

$$\frac{L}{12} = \frac{.5}{100}, \ L = 0.06mm \quad 16$$

$$\frac{D}{12} = \frac{.024}{100}, \ D = 0.003mm \quad 17$$

Image size to frame size ratio $\frac{.06}{24} = 400$

which is much too small for any practical purpose. For a fixed frame size increasing the focal length reduces the size of the field of view. For a fixed focal length increasing the stand-off distance decreases the size of the image. In concept the Projectile Follower allows for the choice of the offset and focal length in order to optimize the image size for the particular application.

LARGE IMAGE SIZE

The design objective for the Projectile Follower called for an image to frame size ration of 1:3. In any camera system this produces a large image of the object which, other things being equal, results in a great deal of useful information about the object. This is a principal advantage of the PFS and, coupled with blur reduction capability, is the chief reason for developing the projectile follower.

INCREASED EXPOSURE TIME, OR HIGHER FRAMING RATES

For any motion picture camera the exposure time for any particular frame cannot exceed about half of the reciprocal of the framing rate. For a rate of 500 frames per second this amounts to about 1 ms; but, the exposure time can be much briefer, which is often the case. Since the relative motion between the image and the film is very low when using the PFS the longest possible exposure time may be used. Being able to use longer exposure times allows for photography under poorer lighting conditions or it reduces the requirement for artificial illumination and large lenses (large apertures). Conversely, since the object is in the field of view of the camera for the entire period of the event very high framing rates may be used where high sampling rates are required over the entire period of the event (Figures 5 and 6).

The PFS in situ calibration would be accomplished as follows. Retro-reflectors, or tape, would be placed along the line of fire as follows:

1. at the plane of the muzzle of the gun

2. at 1 meter intervals in front of the gun for a distance of 10 meters

3. at 10 meter intervals from 0 to 200 meters

A CW laser would be set up as shown in figure 5 so that it is projected through the PFS mirror to the line of fire. As the PFS mirror scans the line of fire the laser sweeps successively over the retro-reflectors and the return pulse from each, which is received by the photo detector, is a precise indication of when the optic axis was pointed at that spot on the line of fire. These pulses along with the timing pulses, the stored trajectory positions, and the PFS mirror positions are recorded against a common time base and compared. Synchronization to the retro pulses of 50 microseconds should result in excellent projectile tracking.

CONCLUSION

The urgency of the need for better metrical photography for application to tank gun ammunition development has necessitated a re-examination of a scanning technique which would allow continuous motion picture photography of tank gun projectiles over long sections of their trajectories. The re-examination, including analytical as well as examination of the related work of others, revealed great promise for the development of this technique; hence, on December 4th, 1984 the BRL requested and funded CSTA to acquire such a system and to install it on a range for the benefit of the BRL research programs. That work has been initiated and is to be reported separately.

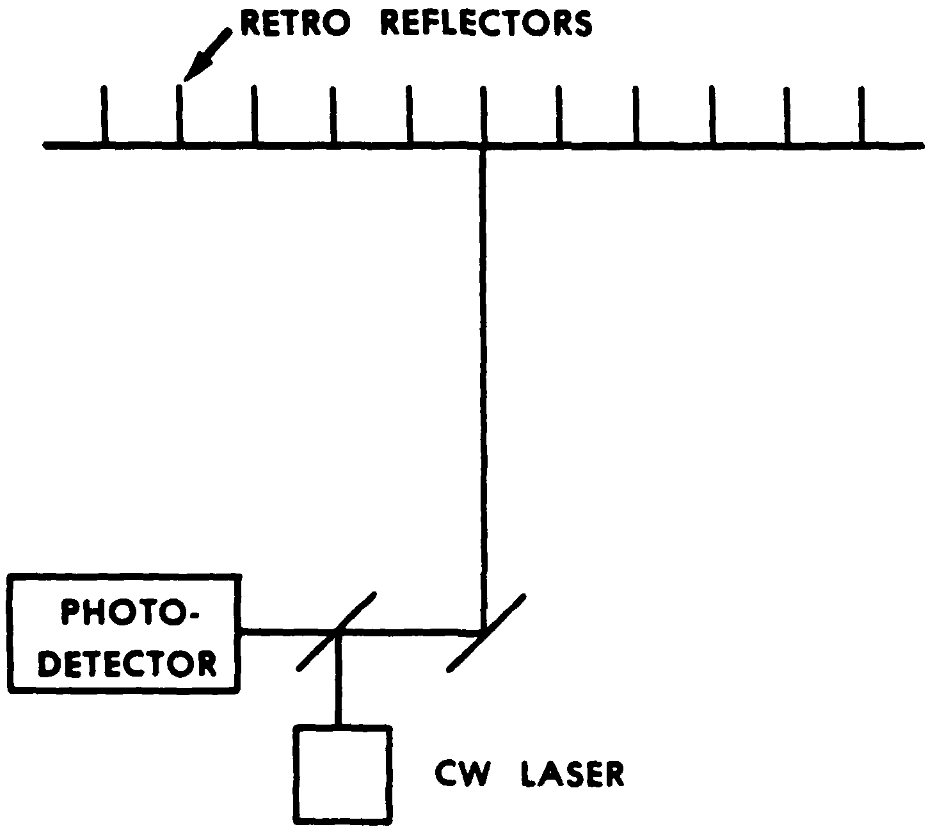


Figure 5. Calibration

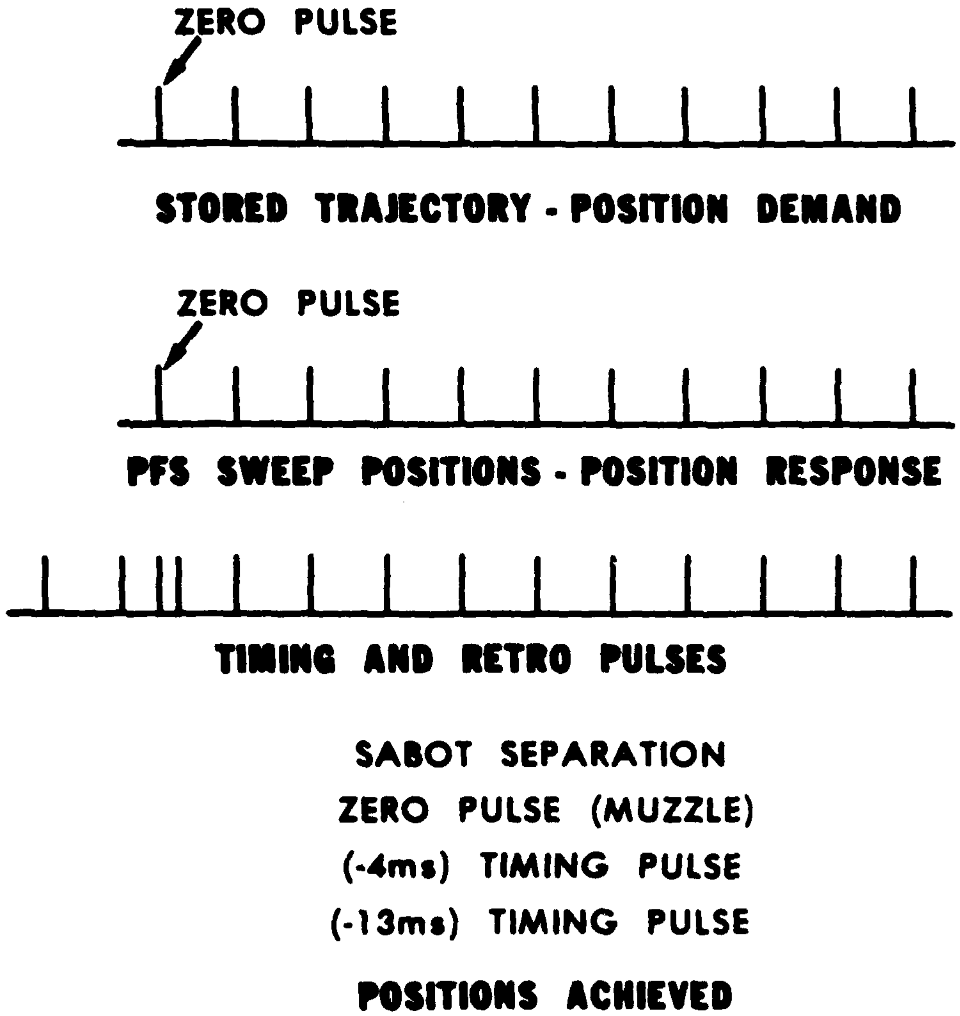


Figure 6. Timing Comparison

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