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A Review of the Literature on Use of Tracer Observation as an Antiaircraft Firing Technique

by

Robert J. Foskett, E.W. Frederickson, and Robert D. Baldwin

HumRRO Division No. 5 (Air Defense)

September 1968

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FOREWORD

This report presents the results of a literature and personal opinion survey concerning the effectiveness of tracer observation as a technique for adjusting antiaircraft firing.

The study was conducted during FY 1967-68 at the request of Joint Task Force Two (JTF-2) of the Joint Chiefs of Staff of the Department of Defense. The survey was done in support of JTF-2 planning for the firing phase of Test 3.1/3.5, an evaluation of the effectiveness of various ground-based air defense weapons (which, due to the disestablishment of JTF-2, will not be conducted).

The study was conducted by HumRRO Division No. 5 (Air Defense), Fort Bliss, Texas, under Dr. Robert D. Baldwin, Director of Research. In addition to the authors, several other HumRRO staff members made significant contributions to the results of this study: LTC W.E. Burrell (Ret.) reviewed the training methods and manuals used for teaching tracer observation; Dr. R.E. Wienke analyzed and wrote a preliminary draft of a portion of the section on human factors requirements; Dr. A.L. Kubala reviewed the man-machine dynamics literature and wrote draft materials for the discussion of that factor.

HumRRO research for the Department of the Army is conducted under Contract DA 44-188-ARO-2 and Army Project 2J024701A712 01, Training, Motivation, Leadership Research.

Meredith P. Crawford
Director
Human Resources Research Office

Military Problem

In recent years there has been an increased emphasis on low-altitude penetration and attack by tactical and strategic aircraft. This emphasis has created a corollary need to examine the defensive capabilities of forward area air defense systems, most of which are visually sighted weapons.

All of the direct-fire forward area weapons (light antiaircraft gun systems and infantry-type weapons) employ tracer ammunition as a primary or auxiliary technique for adjusting fires. Although tracer observation has been used as an air defense fire control technique for years, highly divergent opinions exist among military commanders concerning its effectiveness.

Research Objective

At the request of Joint Task Force Two (JTF-2) of the Joint Chiefs of Staff a review of relevant military and research literature was made to (a) identify alternative techniques of using tracers for air defense fire control purposes, (b) determine the human, physical, and environmental factors that influence the effectiveness of tracer observation, and (c) examine training methods and devices that have previously been used for teaching tracer fire control techniques.

Method

Two approaches were used to obtain the desired information:

(1) Knowledgeable scientists and engineers, and officers and enlisted men with either World War II or recent firing experience, were informally interviewed.

(2) Military reports and journal articles and human factors research results were reviewed to identify factors that may affect the ability of gunners to utilize tracer feedback information.

Results and Discussion

The results of the informal interviews tended to confirm the existence of divergent opinions concerning the effectiveness of tracer observation as a technique for adjusting fires in air defense engagements. Although tracer observation does provide useful information concerning lateral miss distance for stationary (or very low-speed) targets, the principal use of tracers in air defense seems to be limited to establishing the initial aim point of the weapon. Subsequent adjustment of fire seems to occur on a trial-and-error basis.

Discussions with physical scientists and engineers indicated that firing tests have been oriented primarily at evaluating the visibility and burning rates of various chemical compositions of the tracer element. Although simulated tactical firing has been done in test situations, no test seems to have been done to evaluate the relative hit frequencies of tracer vs. non-tracer firing weapons. Apparently there also have been no controlled tests to compare the effectiveness of different tracer firing rates—that is, the number of tracers fired per unit time.

An examination of relevant psychological research showed a number of human factors problems that may adversely affect human use of tracer feedback information:

(1) Limitations on depth perception result in inaccurate judgments of the location of the tracer in space.

(2) Visual illusions of tracer stream curvature occur that may cause systematic biases in localizing aiming errors.

(3) The rate of firing tracers may exceed the ability of observers to process the information.

(4) The visual feedback is delayed in time and requires the gunner to remember the amount of aim point offset (e.g., lead or lag) that existed when a burst of tracers was fired at the moving target.

(5) The machine dynamics incorporated in the design of forward area weapons appear to be incompatible with the angular velocities and accelerations that characterize an aircraft's movement toward and away from the weapon. If the ground-based weapon is inherently unable to continuously track the center-of-mass of the target, little use can be made of tracer observation to determine the desired offset of the aim point.

(6) A review of previous training methods suggests that substantial individual differences exist among gunners in utilizing tracer feedback information. There is a lack of specific guidance in the training literature concerning the relationship between the type of visual cues that are presented to gunners during firing and the necessary corrective actions that are required. Proficiency in developing accurate firing based on tracer observation procedures apparently accrues on a trial-and-error basis, rather than in response to a planned sequence of learning experiences. The need for training commands to depend upon trial-and-error learning and "experience" for proficiency development is an understandable result of an absence of knowledge concerning the cause-and-effect relationships between the visual feedback information and the necessary corrective actions.

Conclusions

The divergent opinions concerning the use of tracer feedback that exist today also were prevalent during the 1920s and 1940s. Although tracer ammunition has been used for a considerable period of time, there seems to be a total lack of objective test data concerning its utility as an aid for adjusting an aim point.

When the basic psychological requirements associated with tracer reading are examined, it is not surprising to find that practical firing experiences have shown relatively small hit proportions when tracers are used as a fire control aid. Considering (a) the time delays that occur between firing and tracer sensing, (b) the rate of information processing required, (c) the need for the gunner to remember past leads or lags, and (d) the frequent incompatibility of weapon and target dynamics, it might well be that the average hit frequency of tracers is no different from that of non-tracer firings.

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A Review of the Literature on Use of Tracer Observation as an Antiaircraft Firing Technique

Chapter 1

INTRODUCTION

MILITARY PROBLEM

Joint Task Force Two (JTF-2) of the Joint Chiefs of Staff has a general mission to evaluate (a) the effectiveness of the techniques and tactics used by aircraft of different nations for penetrating forward area air defenses, and (b) the effectiveness of various types of radar and visually sighted air defense weapons.

A number of the visually sighted air defense weapons of potential interest to JTF-2 employ tracer observation as a primary or secondary technique for adjusting fire. These direct-fire weapons include the following systems:

(1) The M2, .50-caliber machinegun.
(2) The M55 Quad .50-caliber system.
(3) The M42, 40-mm self-propelled, light antiaircraft system.
(4) The M139 20-mm Vehicle Rapid Fire Weapon System (VRFWS).
(5) The Vulcan 20-mm "Gatling gun."

Although tracer observation has been used as a technique of fire control with air defense weapons for a considerable period of time, highly divergent opinions existed among military commanders concerning its effectiveness. At the request of JTF-2, a study was conducted by the Human Resources Research Office to evaluate current information concerning the effectiveness of tracer observation as a fire control technique for ground-based air defense weapons.

RESEARCH OBJECTIVES AND METHOD

A survey was made of existing military test reports, human factors research literature, and training materials concerning use of tracers. In addition, informal interviews were conducted with scientific, engineering, and military personnel who had personal experience in the development, testing, or use of tracer ammunition for fire control purposes.

Objectives. The survey had the following objectives:

(1) To identify the techniques of using tracers for fire control purposes.
(2) To determine the psychological, physical, and environmental factors that may affect the utility of tracer observation as an antiaircraft fire control technique.
(3) To examine the training programs and devices that have been used for teaching tracer fire control procedures.

Method. The literature survey included (a) an analysis of military documents dating back to the 1920s and (b) a review of relevant psychological research in the areas of visual perception, man-machine dynamics, and information processing. Interviews were conducted with personnel experienced as research psychologists or ballistics engineers, and with officers and enlisted men having either World War II or recent experience in using tracer ammunition.

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ORGANIZATION OF THIS REPORT

The results of the surveys are described in four sections. Chapter 2 presents (a) a description of the use of tracers for determining aiming errors, (b) a discussion of several ammunition and environmental factors that affect tracer usage, and (c) the results of early published military tests of tracer firings.

Chapter 3 presents analyses of the human factors that influence the accuracy of using tracer feedback for fire control. The human factors section includes analyses of the effect of man-machine dynamics, visual illusions, and information processing rates and time delays.

Chapter 4 presents the results of informal interviews with experienced engineers and gunners, and briefly summarizes the training procedures that have been used. (A more complete discussion of training programs and devices is contained in Appendix A.)

Chapter 5 concludes the main portion of the report and presents a summary discussion of the results and their implications.

Chapter 2

THE HISTORY AND CHARACTERISTICS OF TRACER AMMUNITION

HISTORY OF TRACER USE WITH AIR DEFENSE WEAPONS

The basic purpose of tracer observation is to provide information to the gunner concerning where the gun is firing. The information indicates whether the projectiles have been fired at the correct line and lead angles.

The line (or elevation) angle determines the vertical-miss distance of the projectile at the time it intersects the vertical plane in which the target is moving. If the projectile's position in the target's vertical plane is coincident with the target's position in that plane, then that projectile is called a "line shot." If the projectile intersects the target's vertical plane either above or below the position of the target, that projectile is called an "off-line" shot.

Once the correct line of the weapon has been established, it is necessary to move the barrel of the weapon in the horizontal plane to obtain the correct lead angle. Lead is the displacement of the aim point of the weapon ahead of the moving target. The amount of lead required to obtain intersection of the projectiles with the horizontal plane of the target is determined by (a) the time-of-flight of the projectile, (b) the speed of the target, and (c) the slant range from the gun to the target. Unless the target is flying a circular orbit around the weapon, the correct lead continuously changes as the target moves on a crossing (tangential) course with respect to the position of the weapon.

Traditionally, tracer observation has been used in conjunction with some sort of sighting system. In a 1937 publication discussing various methods of controlling machinegun fire, it was concluded that nearly all the methods required tracers to be used as an aid to fire control (1). By 1943, the belief was that the principal advantage of using sights occurred at the time of opening fire (2). The sights were used to give the firer a means of establishing an initial lead and then tracer information could subsequently be used to adjust the lead.

Near the end of World War II and during the years that followed, there was an increased use of computing sights on smaller automatic antiaircraft weapons. Computing sights such as the M38 sight presently used on the M42, 40-mm weapon system require crewmen to estimate the target course line and target speed. Other types of computing sights, such as U.S. Navy Mk-14 sights, require the gunner to estimate only the target range.

After the initial settings, both of these sight systems require the use of tracer observation as a basis for correcting the aim point during firing. The question of the accuracy of the information acquired from tracer observation apparently was not addressed directly during the development and the use of the tracers.

CONSTRUCTION AND CHARACTERISTICS OF TRACER AMMUNITION

Two types of small-arms tracer bullets are manufactured—those made from ball ammunition, and those made from armor-piercing ammunition. The ball tracers have the rear half of the lead core replaced by the ignitor and tracer composition. The armor-piercing tracers have a portion of the steel core replaced by tracer and ignitor composition (3).

The tracer element consists of a burning substance in the cavity, usually at the rear of the bullet, which produces a "plume" of incandescent particles that trail behind the bullet when it is fired. Some tracer bullets are designed to burn with a dim trace until they reach a certain distance from the weapon, at which time they burn brightly. This design feature is included in order to reduce the possibility of disclosing the gunner's position, as the "plume" affords visual detection of the tracer round from all angles of observation. Average ignition points and burnout ranges for various types of tracer ammunition are shown in Table 1.

Table 1

Range to Bright Trace and Burnout Ranges

Type of Ammunition	Average Range to Bright Trace	Approximate Burnout Range
5.56-mm, M196	35-60 meters	800 meters
7.62-mm, M62	45-70 meters	850 meters
.50-cal.	50-200 yards	
40-mm	0 yards	3,500-5,500 yards

TRACER BRIGHTNESS

The brightness of a tracer or tracer stream is affected by the chemical composition of the tracer element, and the size of the plume. Attempts have been made at the U.S. Army's Frankford Arsenal to establish the size of the plume. In interviews, Arsenal personnel estimated that the plume associated with small-caliber tracers has a maximum diameter of ten calibers and a length of about four bullets.

The brightness of the tracer element also has been of some concern in the development of tracers. An attempt to quantitatively measure the tracer brightness was made by Frankford Arsenal in 1965 in connection with the development of the Special Purpose Individual Weapon (SPIW) system (4). Instrumentation was developed to dynamically measure the light output of tracers under daylight conditions as a function of the range from the weapon. Figure 1 (4) shows the

Candle Power/Range NATO Tracers

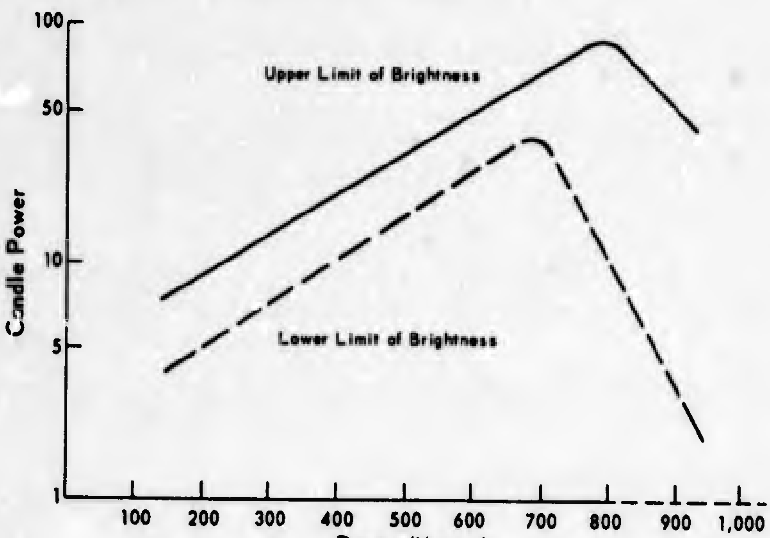

Figure 1

upper and lower limits of NATO tracer ammunition brightness as a function of range. Discussion with the Arsenal personnel showed that NATO tracer specifications did not quantitatively establish the desired brightness level for tracer ammunition.

It was suggested by the Arsenal engineers that further experimentation needs to be done to establish the required brightness values for a given detection probability and known background brightness. One of the problems that arises in designing a tracer that could be used during bright daylight conditions is to keep it from blinding the firer when the same tracer is used for night firing.

Environmental factors often affect the visibility of the tracer plume. U.S. Army Field Manual 44-2 (5) states that, "when the sky becomes hazy so as to reflect sunlight into the observer's eyes, the observer cannot clearly distinguish the tracer in the equally bright sky." Variable density goggles have been used to improve the visibility of tracers when the sky is hazy (5).

The visibility of the tracer stream is also influenced by the rate of fire of the weapon. For example, some high rate of fire weapons, such as the .50-caliber and 7.62-mm machineguns, normally fire tracers mixed in a 1:4 ratio with ball ammunition. Larger and lower rate of fire caliber weapons use a high explosive shell with every round containing a tracer element.

AMMUNITION DIFFERENCES

Differences in ammunition exist in that various types of tracers have different times of flight. Table 2 presents times of flight for three types of ammunition. Various kinds of ball ammunition also have different times of flight and even different trajectories. The differences in the construction of the rounds and the fact that the tracer projectile loses mass as the tracer element burns, cause the trajectories of tracer and ball ammunition to be slightly different. Ammunition engineers have labored long and arduously to match these trajectories, but it appears there will still be enough difference at some ranges to result in misses by the ball rounds when the tracer rounds appear to be on target.

Table 2

Ammunition Times of Flight

Type of Ammunition	Range (meters)	Time of Flight (seconds)
5.56-mm, M193	500	.76
	1,000	2.47
7.62-mm, M80	500	.77
	1,000	2.16
.50-cal. API-T-M-8	500	.57
	1,000	1.31
	1,500	2.29

A 1964 report by the U.S. Army Test and Evaluation Command stated that M14 rifles, zeroed using M62 tracer cartridges at a range of 500 and 600 meters, produced hits three to four feet below the point of aim when M80 ball ammunition was used (6).

Firing Table (FT) 7.62-A-2 states that the data for ball ammunition, M59, also apply to tracer ammunition, M62, to the burnout range (approximately 900 meters), and that beyond the burnout range the tracer round falls off faster than the ball round (7).

OPERATIONAL EVALUATION OF TRACERS

During the 40-year history of tracer ammunition, very little field research has been conducted that would objectively establish the effectiveness of using tracers for adjusting antiaircraft fire. A few documented tests were conducted in a 15-year period prior to World War II because the U.S. Army was concerned with the increasing use of airplanes in military roles, and was trying to find better ways to defend itself against this threat to the field army.

In the late 1920s, several field tests were conducted at Aberdeen Proving Grounds (8, 9, 10). The tests were primarily concerned with evaluation of new antiaircraft equipment then under development, including fire directors, sound locators, height finders, and searchlights. The guns that were used varied from 3-inch to 37-mm weapons and .30- and .50-caliber machineguns. The primary purpose of the tests was to compare the firing results for various fire control systems and sighting devices with the results obtained when tracers were used to control firing.

The hit percentages for the .30- and .50-caliber machineguns when using tracer-controlled fire are shown in Table 3. The targets used were sleeves towed at low speeds (in relation to the speeds of present aircraft). Hit data were also recorded for the firing results when various types of mounts, sights, and fire directors were used.

Table 3

Tracer Firing Results, Aberdeen Proving Grounds

Year	Caliber	Number of Tracer Rounds Fired	Target Characteristics			% Hits
			Average Slant Range (yards)	Average Altitude (feet)	Average Speed (miles per hour)	
1926	.30	45,214	896	a	81	1.29
(8)	.50	15,507	1,445	a	81	.49
1927	.30 (Tripod Mounted)	8,700	736	360	66	2.195
(9)	.30 (Pedestal Mounted)	8,935	913	321	72	1.791
	.50	10,309	1,128	622	67	1.445
1929	.30	26,198	1,552	563	75	.43
(10)	.50	9,342	1,163	554	77	.65

[a]Altitude not specified.

The data for fire-direction devices showed hit percentages of about the same magnitude as that reported for tracer-controlled firing. As a result of these tests, interest seems to have been generated in the use of small arms in air defense, particularly in the use of the machineguns.

By the mid-1930s, central tracer-control equipment was used to adjust antiaircraft firing. This equipment consisted of optical directors, data computers, and stereoscopic height finders which determined the correct lead that should be used by the weapon. The gunner on the weapon merely kept his sights on the target, tracking its center of mass, and the proper sight deflection was controlled by the central fire-control equipment. A visual observer, or "spotter," observed the tracer firing and inserted corrections into the central control equipment. This method of fire control had become standard for antiaircraft automatic weapons batteries just before World War II (11).

During 1941, firing records were kept by the Coast Artillery School during the training of student officers. Tracer control was used for the .30- and .50-caliber machineguns and for the 37-mm antiaircraft guns. Nearly a half million rounds of ammunition were fired at towed sleeve targets during this training period. The percentage of hits obtained is shown in Table 4 (12).

Table 4

Tracer Firing Results, Coast Artillery School[a]

Type of Weapon	Approximate Number of Rounds Fired	% Hits
.30-cal.	400,000	.7
.50-cal.	8,000	.6
37-mm	3,500	.2

[a]Reference 12.

The hit percentages reported by the Coast Artillery School for 1941 are generally lower than those reported for the Aberdeen tests, probably because of differences in the training level of the gunners used. The Aberdeen results were from research tests and probably reflect the performance of relatively experienced gunners, whereas the Coast Artillery School results are averaged over the firing accomplished during training by inexperienced personnel.

The next known field test was conducted during 1963-1965 by the U.S. Army Combat Developments Command Experimentation Command (13). The general purpose of the test was to obtain data on survivability of Army aircraft when engaged by various types of visually sighted weapons that could be expected to be found in the forward combat area. Drones, towed banners, and reduced-scale and full-size helicopter shapes were used as targets. The weapons that were used to engage the aerial targets all do (or can) use tracers as the means of fire control. These weapons were the M14 rifle, .30- and .50-caliber machine-guns, and the twin 40-mm antiaircraft guns. Both hit and kill probability data were obtained.

The results of this firing test are classified, so they will not be reported here. The study is cited to indicate that some firing results of recent field tests are available; however, a comparison of tracer and ball ammunition was not attempted.

Chapter 3

HUMAN FACTORS CONSIDERATIONS

MAN-MACHINE SYSTEMS ANALYSIS

The most common method of using air defense weapons requires that they continuously track the moving target. Tracking requires correct and efficient operation of the weapon controls (a psychomotor skill) and the visual tracking of the target (a perceptual skill). Coordination of these two skills is necessary for success in keeping the gun pointed in the right place. As the target's dynamic characteristics—the rate of position change and acceleration—become more complex, such as when the target maneuvers for weapon delivery or takes evasive action, the task of the man-machine tracking system becomes quite difficult and sometimes impossible.

Tracer feedback information is used to increase the accuracy of target tracking in several weapon systems. The type of tracking required in the current air defense situation is termed pursuit tracking. The gunner's visual display has two moving elements, the desired system output (the target's position) and the actual system output (the projectile's position). The task of the gunner is to eliminate the difference between the desired output and the actual output.

Most air defense tracking situations are characterized by continuous changes in the velocity and angular acceleration of the target with reference to the weapon. The variations in angular velocities and angular accelerations for a 400-knot target that has a minimum crossing range of 200 meters are given in Figure 2. The angular velocity is at a minimum at extreme ranges and reaches a maximum at 0°, which is the point of minimum range. The angular acceleration is also at a low value of extreme ranges, but reaches a maximum value at 30° before crossover and drops to 0°/sec² at crossover. After crossover there is a negative angular acceleration that reaches a maximum value at 30° beyond crossover and then returns to a low value of negative acceleration at the

Angular Velocity and Angular Acceleration of 400-Knot Aircraft at a 200-Meter Crossing Slant Range

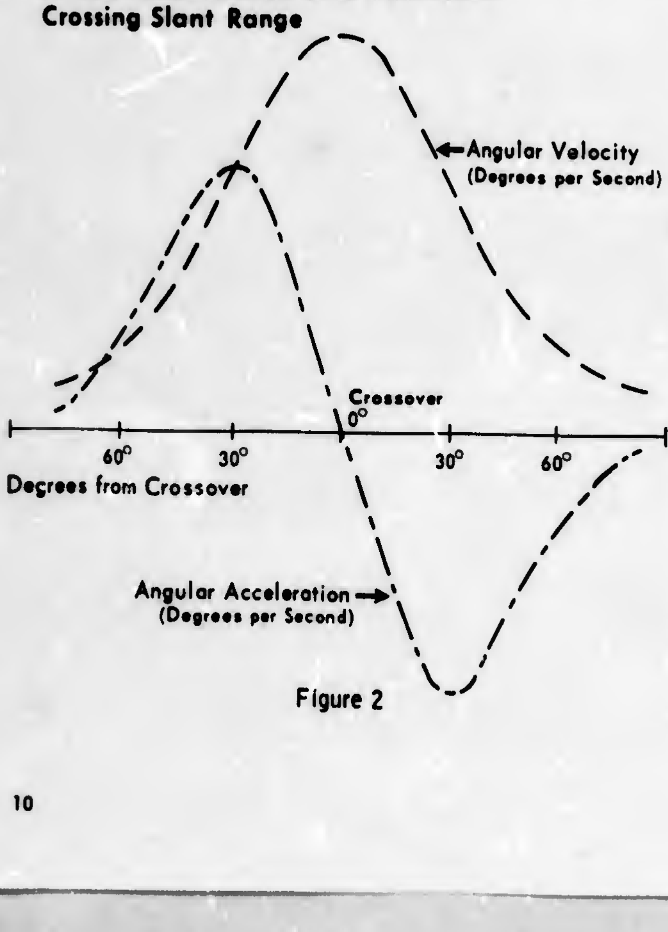

Figure 2

extreme outgoing range. From this example, it can be concluded that even a simple target movement presents a complex pursuit tracking task.

Tracking targets that have angular acceleration is much more difficult than tracking constant-rate targets, according to the research literature on tracking behavior (14). If the target has angular acceleration, the accuracy with which it can be tracked depends, to a considerable extent, on the machine dynamics of the tracking system.

A complete examination of the tracer feedback problem could not be made without consideration of the dynamics of the man-machine system. Ely, Bowen, and Orlansky (15) suggest that tracking performance, such as that required in the air defense situation, can be described in the terms of servo-theory. Figure 3 presents a schematic representation of this type of analogy. The schematic shows (a) a display, which would essentially be the sight picture of the weapon; (b) a human operator, who would detect errors present in the display, process the error information, and make control changes; (c) a machine element—the weapon—with its dynamic characteristics.

Man-Machine Schematic in Servo Theory Terms

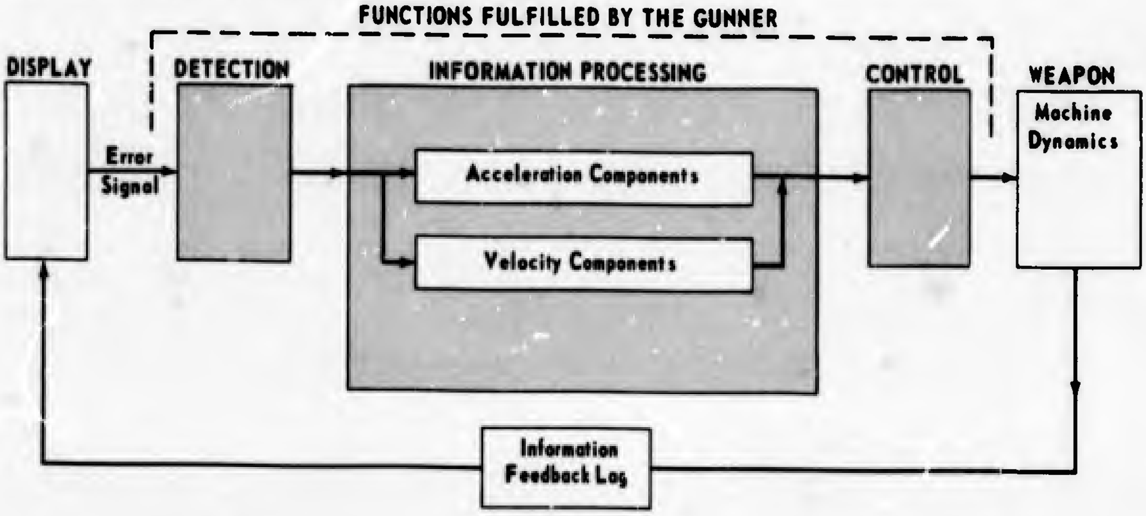

Figure 3

According to Briggs[1], the sources of error in a simple system are found both in the display section and in the machine dynamics aspect. Between these two sections of the system there is at least one control section. In most weapon systems, tracking difficulty is primarily a function of the characteristics of the control system that result in display changes. Of particular importance are the number of integrations and lags that exist between the control input and the system output. In Figure 3, the gunner's output becomes the input to the weapon control system. The gunner and the weapon system work together in sharing the task load.

The amplitude and frequency of the control manipulations required of the gunner are a function of the order of the control system of the weapon and the dynamic characteristics of the target that he must track. The dynamic characteristics of a target aircraft have already been discussed briefly (see Figure 2). Control systems are ordered on the basis of the relationship of the required inputs and the resulting outputs of the overall system.

[1]Personal communication with C.E. Briggs, 1967.

The simplest order of machine control is referred to as a "zero order" or "position" control. Among air defense weapons, this type of control is exemplified by a man tracking an aircraft with a rifle. If the gunner observes an error in his aim point, he can correct it in a single positioning movement. In laboratory studies this type of control has proved to be the best suited to human capabilities—probably because both the magnitude and the direction of error are directly observed, and the corrective movement is directly proportional to the size of the observed aiming error.

A first-order control system is usually referred to as a "rate" or "velocity" control. The controls of the M55 and M42 weapon systems are examples of rate control systems. With this type of system, the gunner adjusts the aim point by controlling the rate of traverse and elevation of the gun mount. If an error in aim point is observed—for example, if the weapon is lagging the target—the gunner must increase the rate of traverse to match the rate of the target. Two control movements are required, one to catch the target and one to reduce the rate to stay on the target. Also, the amount of control movement is not directly proportional to the amount of the observed error as is the case with a zero-order control. Rate control systems have proved to be nearly ideal in laboratory studies for tracking targets of constant or nearly constant velocity. However, they have been demonstrated to be poor in tracking targets that have angular acceleration or deceleration.

An "aided" system is one that combines two orders of tracking. A "rate-aided" system is one that combines a positioning control with a rate control. If a rate-aided system were employed on a weapon, a control adjustment for a lag would not only increase the rate of traverse, but would also automatically position the tube of the weapon. Hence, the aiming error and the rate of traverse would be corrected simultaneously. This system, like the zero-order control, has the advantage of requiring only one control movement, instead of two as in the pure rate control system. Again, however, this type of control is most useful with a constant velocity target.

A second-order system is referred to as an "acceleration" system. With an acceleration system, a control movement would cause the weapon mechanism to accelerate at a constant rate, whereas neutralizing the control would allow the weapon to traverse at the rate at which it was moving at the time it was neutralized. Assuming that the gunner observes that he is lagging the target, he would move his control to cause the weapon mount to accelerate toward the target. As he approached the target, he would return the control to the neutral position, allowing the weapon to approach the proper aim point at a constant velocity greater than that of the target. As the proper aim point is reached, the gunner would move the control to decelerate the weapon to the target velocity, and finally, neutralize the mechanism when the target velocity was achieved by the weapon system. Four control movements would be required to null the error with a second-order system: accelerate, neutralize, decelerate, and neutralize. This type of control is best suited to tracking targets that display a constant rate of acceleration and/or deceleration.

Higher-order control systems could be described, but weapons usually have the lower-order type of controls. As the order of control increases, so does the number of control movements required to null an error in the display. As the number of required control movements increases, the difficulty of the task for the human operator also increases.

The situation depicted in Figure 2 has large variable angular accelerations in addition to the constantly changing angular velocities. A device to successfully track such a target would require at least a fourth-order, and possibly higher-order control system. An increase in the minimum crossing range from 200 meters to 800 meters would decrease the angular accelerations to a maximum of 2.5°/sec^2, which would be essentially equal to 0°/sec^2. In this new case, a lower-order system could be used.

These considerations indicate that an aircraft flying at 400 knots would have to be at least 800 meters away if the target is to be tracked accurately by a low-order system. A study of relevance was conducted by Eckles et al. (16), using aircraft flying at a constant speed of 100 miles per hour. It was found that tracking improved significantly as a function of increased crossing range, with the 1,000-meter course significantly better than the 500-meter course, which was, in turn, significantly better than the 100-meter course.

The concept and importance of the order of the system have been developed to some length to show that tracers can have no beneficial effect on firing if the weapons system dynamics are inadequate to allow successful tracking of the target. For example, a third-order system tracking a 400-knot target with a crossing range of 200 meters presents a nearly impossible tracking task due to machine limitations, and therefore the addition of tracers to aid in determining aiming errors could have little or no effect on the accuracy of tracking. Thus, any test of the utility of tracers should employ target and machine dynamics that are compatible, if valid results concerning the effect of tracers, per se, are to be obtained.

PERCEPTUAL ANALYSIS

Tracer ammunition is used to aid the gunner in assessing aiming error, by providing miss-distance information. The task of tracer reading is not as simple as it was originally conceived when aerial-target speed was very slow. With the addition of tracers, the gunner had to process two types of information: (a) the target position information, and (b) the delayed tracer-target relationship information.

The basic problems associated with obtaining, assessing, and using the information required to perform the air defense gunner's job successfully are addressed in detail in the following sections. As the specific problems are introduced, relevant information from the human factors literature is presented.

TRACER READING

Tracer reading is the process of correctly determining the position of the tracer round in relation to the target. The accuracy with which the gunner is able to locate tracers in space relative to target aircraft is a function of the amount of information that is available to him. In trying to obtain adequate information, three problem areas interfere with the gunner's tracer reading.

Depth Perception Cues

The two groups of information cues available for determining tracer-target relationships are binocular and monocular depth perception cues. The primary binocular cue is retinal disparity, which is the basis for stereoscopic vision. The requirement for stereoscopic vision in tracer observation was explicitly stated in 1943 by Grossman (17). Briefly, stereoscopic vision is believed to result from the slight differences in the positions of the projected image of the object on the retina of the two eyes.

The Geometry of Binocular Depth Perception

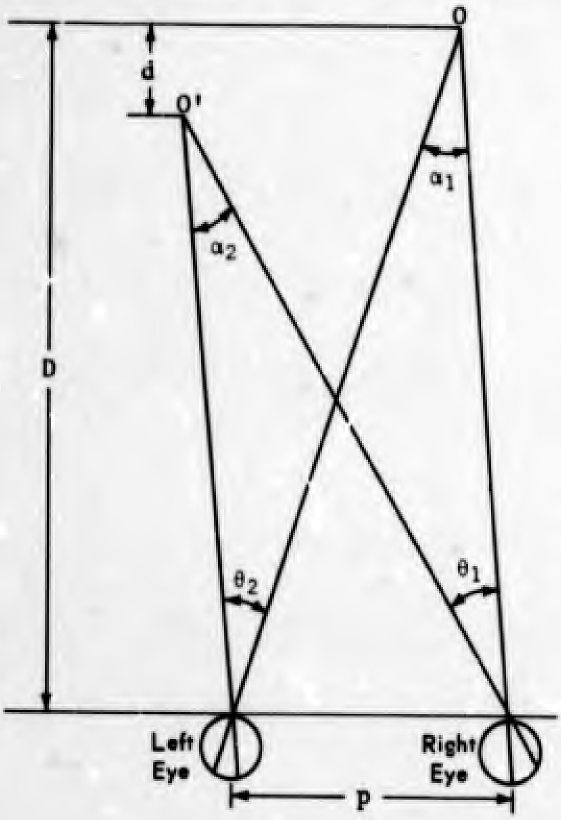

Figure 4

This disparity is also the basis for the process that permits the maximum precision in the perception of the differences in depth of two objects. The geometric factors and relationships that underlie this concept are shown in Figure 4.

In this illustration, p represents the distance between the two eyes and O is the object being fixated in the visual field (an aircraft). O' represents another nearer object in the visual field (a tracer round). D is the distance to the fixated object O and is measured along the perpendicular to the line joining the two eyes, and d is the linear distance between the two objects along this perpendicular. The visual angle formed by the lines of sight between the two objects is θ_2 for the left eye and θ_1 for the right eye. The apex angle α_2 is the angle formed by the intersection of the lines of sight from the two eyes to O', and α_1 is a similar angle for the lines of sight to O.

Note that $\theta_2-\theta_1$ is a difference in visual angles subtended in the two eyes by the lines of sight to the two objects. Thus (ideally), $\theta_2-\theta_1$ is a measure of the retinal separation of the two object images in angular measure. The geometry in Figure 4 implies

$$\theta_2-\theta_1 = \alpha_1-\alpha_2. \quad (1)$$

The angles α_1 and α_2 can be determined by Taylor series expansions. Suitable approximations can be given for the angles when D is substantially larger than p or d and when O' is close to the perpendicular to p on which O lies. These conditions are satisfied for a great majority of cases. The approximations to α_1 and α_2 under these conditions are,

$$\alpha_1 = \frac{p}{D} \quad (2)$$

and

$$\alpha_2 = \frac{p}{D \pm d}, \quad (3)$$

where α_1 and α_2 are in radians. Call

$$\alpha_2-\alpha_1 = \theta_1-\theta_2 = \eta \quad (4)$$

and substitute the values of α_1 and α_2 from (2) and (3) in (4) to obtain the approximation

$$\eta = \frac{pd}{D^2}. \quad (5)$$

In equation (5), the denominator is actually $D(D \pm d)$ which, for d small relative to D, is approximated by D^2.

The critical step is the determination of the value of η, the angle difference between the objects. The threshold linear instance d_τ can be determined using special depth perception apparatus (18). The distances p and D can be physically measured, but when D becomes large, direct measurement is impractical. Graham (18) defines the limiting range, D_{lim} of stereoscopic vision as that range at which one object can just be discriminated as closer than a second object located at infinity.

Suppose that α_1 is the apex angle of the object at infinity, for example, $\alpha_1 = 0$. Suppose further that we take the least discriminable difference, η, as 30 seconds of arc (a large value). Then, by equation (4), $\alpha_2 = 30$ seconds of arc. To convert to radians, this value of α_2 must be divided by 206,265 so that $\alpha_2 = 30/206,265$ radians. Assume an average value of p to be 0.072 yard (65 millimeters). Solve equation (2) for D and substitute these two values of α_2 and p to obtain $D_{lim} = (0.072)(206,265)/30 = 495$ yards.

However, Graham points out that past research has shown that the angular separation of the two stimuli and the size of the stimuli are critical variables. As the two stimuli are separated and as the stimuli become smaller, η becomes larger.

Depth perception ability has been discussed in several military publications concerning tracer reading (2, 11, 19, 20). One article stated that there was an absence of stereoscopic vision at ranges exceeding 300 yards (2). Another author concluded that an observer cannot be sure that the tracer is within 250 yards of the range of a target located at 500 yards (20).

Experimental evidence reported by Ogle in Davson (21) indicated that the limit for stereoscopic vision was about 635 yards, which was equivalent to a threshold angular difference of 24 seconds of arc between the two stimulus objects.

Prior to and during World War II, U.S. Army ordnance engineers tried to build range cues into the tracer round by making tracers that burned out at 800 yards or changed color at a given range. Another type of tracer gave off puffs of smoke at timed intervals. The report made the following conclusion: "None of these experiments were of material assistance. The first two did tend to mark range-points on the trajectory, but no one knew the range to the target exactly or quickly enough to be able to use the information successfully." (11)

The evidence, therefore, indicates that unaided stereoscopic vision cannot effectively be used in determining the relationship of the tracer to the target at distances beyond about 500 yards.

One of the primary monocular cues is interposition, so called because an object physically closer will cut off part of or be seen against another object farther away. This cue has been applied to tracer observation and is referred to as "superimposition" in Army field manuals (5, 19, 22). A tracer that leads the target too much will appear to be eclipsed by the target, and a tracer that lags the target will appear to be silhouetted against the target. To read tracers using these cues, the gunner must first get line shots, or shots that appear to intersect the line of sight from gun to target. The superimposition cues resulting from line shots then can be interpreted as to whether or not the lead is correct (19, 22, 23).

Time and distance limits exist for sensing tracer superimposition cues. For a target 16 yards long travelling 400 miles per hour, the time for observing whether the round is ahead or astern of the target is only about 8/100 second (23). Because of the short duration of the tracer-target positional relationship, the task becomes quite difficult.

A second limitation, viewing distance, was described in a U.S. Army Air Defense School manuscript:

> "A tracer picture may be very clear when the target is near the observer, but as range increases, the sharpness of the picture diminishes. At long ranges the picture becomes almost entirely obscured. Thus, tracer observation for lead information (observer at the gun) is limited to ranges of about 1,500 yards.

There is no limit for reading line information as long as the target and tracer are distinguishable." (23)

Tracer Illusions

The second problem associated with the reading of tracers results from illusions that occur concerning the apparent trajectory of the tracers in relation to the target.

"If the tracer stream were laterally straight in appearance, the limitations of depth perception would have little effect on the problem, it being necessary only to pass the line of the tracers through the target. Unfortunately, however, the tracer stream presents a definitely curved appearance, both in the lateral and in the vertical plane." (3)

The vertical curve (see Figure 5) of the tracer stream is a real curve and not an illusion. It is due to the actual gravitational drop of the projectile below the line of the bore.

The lateral curve of the tracer stream is both real and fictitious. The real element (see Figure 6) of the curve is produced by the traverse of the gun during firing. By firing several tracer rounds successively in a constantly changing azimuth, the observer can see this real element of a curve in the sky, formed by the individual tracers at varying ranges and azimuths. This curve can be clearly seen even when firing and traversing a gun without a target.

The fictitious element of lateral curve (see Figure 7) is produced by a combination of (a) the motion of the target and (b) the target being watched by the gunner and used as a reference point. If the gunner focuses his attention on the tracers, the target appears stationary and its lateral motion is incorrectly perceived as lateral motion of the individual tracers in a rearward direction.

This optical illusion can be observed even when a single tracer is fired from a stationary gun, provided that the moving target and tracer are visible together. Tracers fired from a slow-firing gun exhibit a lateral curve, attributable entirely to the optical illusion, whereas the tracer stream from a machine-gun invariably produces a lateral curve both from the horizontal movement of the gun and the optical illusion when a moving target is used. When firing at targets on crossing courses, the vertical and lateral curves combine to give a very sharp curve. On an incoming, diving course, the only visible curve is the vertical curve caused by the influence of gravity on the bullet.

Another aspect of the illusion is called the tracer hump (see Figure 7), which occurs at the point of maximum apparent curvature. At a certain instant the gunner's eye tricks him into thinking the target has stopped in the sky while the tracer appears to float by the target (23). This illusion is somewhat analogous to the one that is commonly experienced by a railroad traveler. When sitting in one train car, it is very difficult for a passenger to tell whether his own train is backing up or whether an adjacent train is moving forward; the visual cues allow either interpretation.

The tracer hump can be very misleading when seen by the tracer observer, especially if he tries to use it to establish correct lead. For this reason, all articles on the techniques involved in tracer observation emphasized the importance to the gunner of "localizing his vision" to the target area (5, 19, 22, 23). The term means that the gunner focuses his eyes on the target aircraft rather than looking at the entire tracer stream. If the gunner can localize his vision, he sees only the tracers in the immediate vicinity of the target and would not be as easily misled by the tracer hump.

Vertical Drop of the Round Due to Gravity

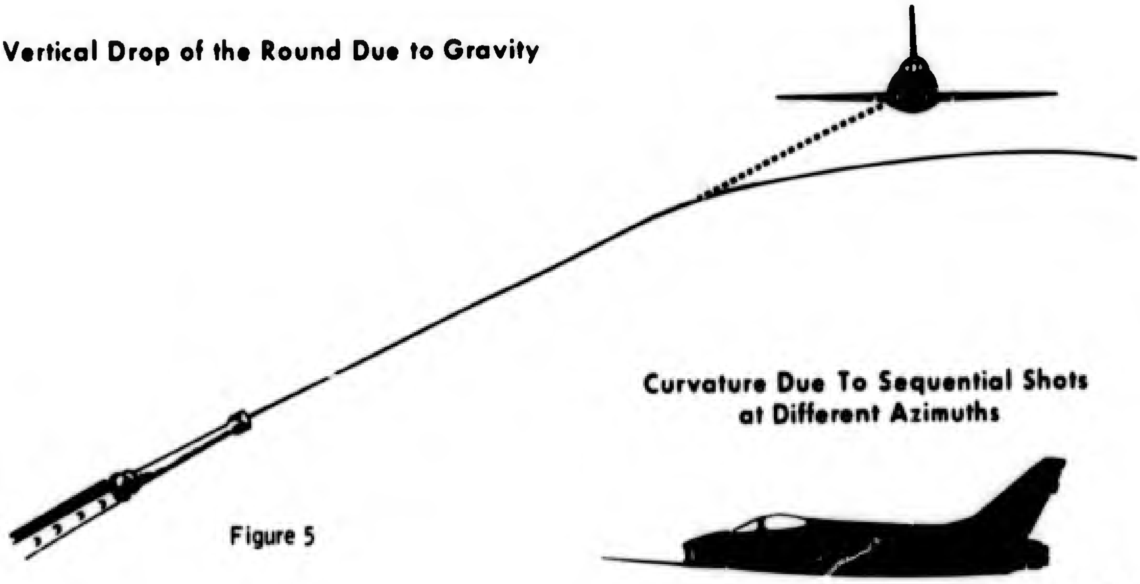

Figure 5

Curvature Due To Sequential Shots at Different Azimuths

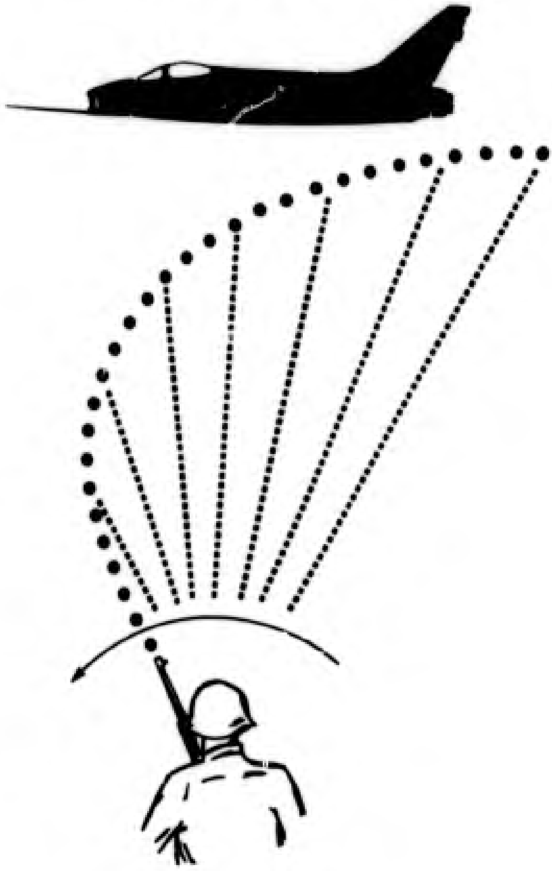

Figure 6

Tracer Hump

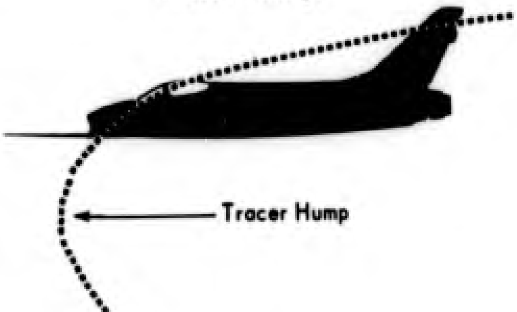

Figure 7

The use of the tracer hump in establishing lead has been rejected because the hump appears to move forward of the aircraft as a function of the increase in aircraft velocity (23). Rejection for that reason is difficult to understand, for the correct lead should also be increased as the velocity of the aircraft increases; therefore, it would appear that the distance of the hump in front of the aircraft could provide relative lead information. The lead information could not be absolute, however, because range is also a critical factor.

In the 1930s it was discovered that, although the gunner apparently could not use the tracer hump to any advantage, an observer located at a certain distance from the gun in the direction toward which the target is moving (downcourse), could detect firing errors based on the position of tracer hump in relation to the target (24). This is also known as tangential observation. The required downcourse observer distance was given by the formula:

$$b = \frac{V \times Dm}{450 \text{ meters per second}}$$

b = downcourse distance from weapon (in meters)
V = target speed (in meters per second)
Dm = slant range to midpoint of target course (in meters)
450 = a constant factor (19)

From the downcourse position, the observer has a different view of the tracer than does the firer. In this position, the observer can sense whether the shots are leading or lagging by the relative position of the tracer hump, appearing either ahead or astern of the target. This judgment of proper lead can be made on non-line shots as well as line shots. The downcourse observer can then inform the gunner as to the necessary fire corrections. It was believed that a group of human "spotters," using tangential observation, could adjust the fire by remote control better than could the firer himself (25).

However, problems do exist with this method, as indicated by this question: "The idea is theoretically sound, but how can an observer be kept at the correct location when the target is an aeroplane moving at high speed?" (11) The use of tangential observation is still advocated in current training manuals (19).

INFORMATION PROCESSING

Feedback Time Lag

After a gunner has fired one or more rounds, he does not know, at least for a short time period, how correctly he has previously aimed his weapon. The target continuously changes position in relation to the gun, but the gunner must wait until a given round reaches the vicinity of the target before he has information that will allow him to adjust his fire. The tracer observer, then, has to use stale information. "In view of the fact that the target will be in the effective field of fire for only a few seconds, this delay is critical." (5)

As an example of these situations, assume the following conditions: The maximum range of a weapon is 1,000 meters. An aircraft approaches on straight course with a minimum crossing range of 500 meters. In this situation, machinegunners using .50-caliber ammunition would have time delays varying between a maximum of 1.3 seconds for a maximum firing range to a minimum of .57 second for the minimum crossing range. The feedback delay may result in further confusion because several additional tracer rounds may have been fired at changing aim points during the time of flight of the initial round fired.

When the time of flight equals one second, and a gun fires two rounds per second, three rounds will have been fired by the time the first round appears in the vicinity of the target (23). In addition, not only may one's own tracers confuse the observer, but also tracers from other guns may make the problem more difficult. General Sunderland (24), who was greatly involved with antiaircraft firing in the 1930s, wrote, "I cannot believe that a gunner can identify with any degree of certainty the tracers from his gun when other guns in the immediate vicinity are firing at the same target."

The effect of the time of flight of the tracer round results not only in a delay of information, but also in a shorter period of effective fire and a reduction of the number of possible hits. During a firing engagement, a preliminary period of adjustment is needed to get line shots. This time period is approximately proportional to the projectile time of flight. Once line shots have been obtained, another period of experimentation is needed by the gunner to get the correct lead. However, the correct lead is seldom held with permanence. The lead used varies around the correct lead and the amount of the total firing time during which the correct lead is used is approximately inversely proportional to the time of flight of the projectile (26).

Stale Information

As a result of the feedback delay, the gunner must use short-term prediction to effectively use the stale information that is provided. Bilodeau (27) has pointed out that prediction is an important aspect of a pursuit tracking task. For example, when a gunner who is tracking a target observes a tracer round in the vicinity of the target, his weapon is pointing in a different direction than when that tracer round was fired. To use the aiming error information which that specific tracer provides, he must remember the relationship between his weapon and the target at the time that round was fired. He must also remember what control movements he has made since then and predict where the tracer rounds should have gone. Then he must predict the aim point at which future rounds must be fired in order to hit the target. If the observer could perform these skills perfectly, the use of tracers would hardly be a difficult task for him. Conklin (28) also concluded that any variable that reduces the accuracy of short-term prediction adversely affects tracking.

The time delay of the visual feedback varies as the firing range changes. This means that the aiming error information becomes stale at different rates during an engagement. There is no known experiment in which variable, nonlinear visual feedback has been examined. However, the work of Warrick (29), of Smith and Smith (30), and of Smith (31) clearly indicates that even linear delay in visual feedback reduces the accuracy of the tracking task. Warrick found that feedback delays of as little as 40 milliseconds degraded performance. Smith and Smith, and Smith found that delays in the order of 500 milliseconds make motor skills very difficult to perform.

Information Load

Another critical problem lies in the information processing requirement of the weapon system. Although it is not believed that the basic problem of tracer feedback can be successfully understood in terms of information theory, there seems little doubt that the error signals can and probably should be examined in information theory terms.

One important factor in the information theory approach is that tracers are discrete elements—separated in time and in space. Thus, the information provided is intermittent. Although it cannot be stated just what portion of the tracer stream is actually important, the most critical information is obviously conveyed from the vertical plane of the target. Any given projectile can lead, lag, be above or below, or be on target. Ignoring miss distance, there are about 2.3 bits of information provided by each tracer. If there is one tracer per second, as there would be with a one-in-ten mix, then the information rate would be 2.3 bits per second. If there were two tracers per second, then the information rate would be 4.6 bits per second. If the firing rate increased to 10 tracers per second, the sequential relationships of adjacent tracers would probably become important and information redundancy will be introduced. The redundancy would be a function of rates of horizontal and vertical traverse (slew rates) of the weapon, and so it is very difficult to establish the functional relationship.

If a machinegun were fixed in space, then—within ballistic accuracy—all the projectiles would strike the same point. Thus, 10 tracers would provide no more information than a single tracer. Under this set of conditions the information rate would be the same as that provided by a single tracer: 2.3 bits per second. However, if an extremely fast target were being tracked, then it would be possible that through the tracking errors introduced, each round could provide information essentially independent of the preceding round in relation to its strike on or near the target. The information rate would then be 23 bits per second.

Both of these values are theoretical limits and it is unlikely that either will be approached in the air defense situation, although the lower limit might be approached when tracers are fired at stationary ground targets. Should the upper limit be approached, then the information would be presented at too fast a rate for adequate processing by a human sensor. Morgan and Lund (32) state that man's channel capacity lies between 2 and 25 bits per second. The higher information presentation rates will result in the loss of some information and in some situations degrade performance.

On the one hand, Ely et al. (15) state that the general effect of intermittently presented data is to degrade tracking performance. Battig, Voss, and Brogden (33) found that performance was improved by increasing the frequency of presentation of information up to 16 presentations per second. They also found that performance was degraded in an approximately linear fashion as a function of the percent of decrease of time that the operator was allowed to view the display.

It is somewhat difficult to interpret just what this means with respect to tracer observation, since tracers are intermittent only at certain specified points, such as in the plane of the target. However, it is probable that better performance can be expected at moderate to high tracer mix ratios, particularly when the target is traveling at a high angular rate.

Chapter 4

A REVIEW OF PERSONAL OPINIONS AND TRAINING PROGRAMS

INTERVIEWS OF AIR DEFENSE PERSONNEL

As part of this study, informal interviews were conducted with officers having World War II gunnery experience, and with enlisted men who currently are participating in tests conducted by the services of various types of antiaircraft weapons. The purpose of these informal interviews was to obtain opinions of experienced personnel concerning (a) the usefulness of tracer observation for determining aiming error and (b) other uses that tracers may have.

The interviews were centered about several issues concerning tracer use: (a) determining initial aiming error, (b) self-destruct features, (c) gunner's confidence, (d) pilot reactions, and (e) military service differences. The discussion of each of these issues is essentially a summary of the interview responses.

(1) Initial Aiming Errors. The original purpose of tracers was to provide information as to where the gun was firing. This information then could be used to adjust the pointing of the weapon if some error was indicated. Gunners who were interviewed expressed various views on this point. Marine gunners, trained for recent tests of a Hispano-Suiza gun, felt that tracers could be used in directing fire, and indicated that it was quite evident where the rounds were going (implying that it was quite easy to read the tracers).[1]

Two highly experienced Army gunners said that they and their gun crews attempted to use tracers only to get a "ball park" estimate of firing accuracy.[2] Other Army gunners with less experience appeared to believe that tracer feedback information could definitely be used to adjust fire.

German air defense officers assigned to the German Air Force Air Defense School, Fort Bliss, Texas, were of the opinion that tracers could be used to adjust fire, at least under World War II conditions of slow-speed aircraft. In the German system, the man who observed tracers stood just behind the gunner and gave the gunner corrections as he "read" the tracers. Here, the observer visually followed the tracer and not the target.

(2) Self-Destruct Features. Tracers also have been used for a purpose completely aside from fire control. Frequently AA weapons were fired above terrain occupied by friendly troops. In these cases, it was highly desirable to have a self-destruct projectile to protect the troops from falling rounds. Fuzes for smaller-caliber projectiles have proved to be unreliable in the past, so tracer burn has been used to initiate the self-destruction of the rounds.[3]

(3) Gunner Attitude. Because tracers have a long history, and they do permit the gunner to see that he is really doing something, the majority of the

[1] U.S.M.C. gunners assigned to Hispano-Suiza tests at Twentynine Palms, California.
[2] U.S. Army Air Defense Board gunners.
[3] Frankford Arsenal engineers.

personnel interviewed indicated that they would always want some tracers in their ammunition mix. If tracers were eliminated from AA ammunition, it is possible that a major re-education would be needed to convince the gunners that they were actually doing something when they fired their weapons.[1]

(4) Pilot Fear Factor. It was pointed out by several gunners that tracers may distract or frighten pilots. It was believed that tracer fire could cause a plane to fail in its mission, even when no damage was inflicted on the aircraft by the weapon. The credibility of this is difficult to determine, as informal reports from combat pilots differ. A few pilots have said that they would prefer to fly against tracers because they can then see where not to fly. Others reported a fear response to seeing tracers being fired at them which resulted in their altering their entire course.

The possiblity that tracers might result in pilot distraction led, between 1942 and 1944 (3), to the development of a variation of the M1 tracer called a "headlight tracer." This tracer presented a frontal visibility three times as bright as the original M1 tracer. Initial combat reports indicated that a psychological effect upon enemy pilots was evident. The Tenth Air Force, in December 1944, stated: "Preliminary reports indicated that they (caliber .50 headlight tracer cartridges) . . . make adjustment of fire easier. Enemy pilots seem to be less aggressive and show a tendency to break off combat at a longer range than with standard ammunition. . . ."

As a result, it became the standard-caliber .50 headlight tracer M21. Only after the war did the Air Force establish that enemy pilots had not been as easily frightened by this ammunition as was first reported, which led to the discontinuance of the M21 tracer.

(5) Surface Gunnery. A number of the guns used for air defense also have a ground support role, or at least have been employed in this manner. When used in this role, it is reported that tracers are useful.[2] The opinion was expressed that it is much easier to determine where rounds are hitting when reading the tracers against a contrasting terrain background than against the sky or clouds.

(6) Service Differences. The interviews conducted during this study also were concerned with differences or agreements among the United States military services concerning the usefulness of tracer ammunition. As gunners from different services were questioned, it became apparent that each service approached the air defense problem with different weapon emphasis. The Marine Corps currently has no gun systems that are specifically used for air defense (USMC primarily uses missile systems); however, they are testing a Hispano-Suiza air defense gun system.

At the present time the Navy does not normally use tracers except, possibly, in amphibious operations. The ship gun installations are all radar controlled and do not require inputs derived from tracer reading. One specific difference between the air defense situation in the Army and Navy was emphasized. At sea, naval ships are normally separated at such a distance that an enemy aircraft attacking one ship will most probably be out of range of all guns except the larger radar-controlled guns of the other ships. Aircraft attacking a given ship will almost always approach with a head-on aspect to that ship. Therefore, shipboard gunners would rarely fire at crossing targets with small-caliber weapons. The shipboard gunner fires from a moving platform and must compensate for the roll of the sea, adding complexity to the task.

[1]Personal communication with Dr. Katchmar of the U.S. Army Human Engineering Laboratories.
[2]Frankford Arsenal engineers.

(7) Tracer Mix. A review of the literature and discussions with contemporary experts did not provide a definite answer on how tracer-to-ball ammunition mixes have been determined. The tracer mix and the weapon's rate of fire determine the tracer rate. Tests of firing accuracy as a function of tracer rate have not been conducted.[1] Initially, when a combination of high explosive and armor piercing rounds was fired, two or three of each type followed by a tracer round for observation was a typical mix (one in five). The Germans in World War II apparently used much the same variation in ammunition mixture, but used a mix with only one round of each type (one in three). During this time, the U.S. Navy apparently allowed their ship's gunnery officers to draw any mix of ammunition they felt was appropriate.[2]

The literature reviewed and interviews with gunners indicated that a number of reasons have determined firing tracer mixes. In brief these were as follows:

(a) Weapon rate of fire. Weapons with a high rate of fire will produce a higher tracer rate for a given mix. Therefore, high rate-of-fire weapons typically use a lower tracer mix.

(b) Muzzle velocity. The number of rounds in the vicinity of the target is determined by muzzle velocity as well as firing rate. Therefore, weapons with higher muzzle velocity typically use higher tracer-to-ball mixes.

(c) Number of weapons involved. Most gunners interviewed believed that lower tracer-to-ball mixes should be used with multiple weapons to reduce the confusion resulting from the many tracers in the vicinity of the target.

(d) Self-destruct features. Explosive rounds often use tracer burn-out to provide a self-destruct feature. This is especially important when firing over friendly troops.

(e) Deterrent value. It was believed during World War II that the sighting of tracer ammunition caused attacking pilots to break off their attacks earlier than otherwise.

SUMMARY OF TRAINING PROCEDURES

One discussion of the ability of air defense gunners to use tracer information concluded that a "good" gunner has a "feel" for correct tracer sensing (1). Apparently it requires a great deal of firing experience for a gunner to develop this "feeling." Whenever successful task performance reflects behavior that is primarily a result of unknown cause/effect relationships (such as between the use of tracer feedback information and firing accuracy), that behavior might better be referred to as an "art" rather than a "skill."

It was stated by one author that ". . . a good machinegunner is one who has been trained to let his eyes deceive him, for the correctly placed tracer never seems to actually hit the target." (1) Another article reported that gunnery skills can be acquired only in a ". . . school of fire where many rounds of ammunition are fired and many guns are worn out in affording an opportunity for students . . . to learn to spot and to learn to make corrections as a result of such spotting." (24) Using such an approach to training essentially leaves it up to the individual gunner to develop the "feeling" necessary to read and use tracer ammunition.

[1] Frankford Arsenal engineers.

[2] Interviews with U.S. Navy personnel assigned to White Sands Missile Range, New Mexico.

Antiaircraft fire has not been the only area in which a need has been found for people to learn to use tracer observation. The summary of a report concerning the use of 20-mm tracers, fired from aircraft mounted cannons, reported that ". . . all pilots were unanimous in stating that there is a need to learn how to use tracer ammunition. At first there is the very natural tendency to watch the tracers. Pilots must be conditioned on what to expect tracer ammunition to 'look like' and how to use it properly." (34)

In various training programs, emphasis has been placed on the gunner knowing how to interpret what he does see. Training men to do this has been quite difficult and it may indeed be beyond present training technology. Appendix A contains a discussion of current U.S. Army and British Army practices. Included are descriptions of several simulation devices that were used during World War II, in addition to a simulator currently under development for the National Aeronautics and Space Agency (NASA).

Chapter 5

DISCUSSIONS AND IMPLICATIONS

This review of the uses of tracer ammunition in air defense has shown a surprising lack of data that bear on questions concerning the effectiveness of tracer feedback information. In the research and development literature there was no indication that any controlled tests have been conducted to evaluate the usefulness of either tracers vs. non-tracers, or alternative mixes of the two types of ammunition, although testing has been done at U.S. arsenals concerning the physical properties of tracers.

Even though a few tests of hit expectancies for tracers have been conducted over a span of more than 20 years, no tests have been made that compared non-tracer hit frequencies with tracer hit frequencies. This lack of controlled test data also is reflected in the variation in tracers-to-ball ammunition mixes that have been used by the military services at different times.

Apart from documenting the absence of definitive test results, it is believed that the major contribution of this survey exists in the appraisal of various human factors considerations, particularly the discussion of man-machine dynamics. As described in Chapter 3, most air defense engagements involve a requirement for a ground weapon to track and fire upon an aircraft that is continuously varying its angular velocity and acceleration with regard to the ground weapon. For the ground weapon to continuously maintain an accurate track of the aircraft, the weapon's machine dynamics must be of an order (complexity) that will permit a corresponding matching of the weapon's angular velocities and rates to those of the target.

If the weapon cannot continuously and accurately track the target's dynamics, no systematic method of correcting the lead and line aiming errors will increase hit expectancies beyond those hits that would occur as a result of chance coincidence of the weapon's aim point and a target's position in space. Indeed, there is reason to suspect that the hit frequencies that have been obtained in previous tests involving tracer fire control and continuous tracking would be no greater than would occur if either (a) a "barrage-fire" technique were used in which a fixed and static aim point were established ahead of the aircraft, or (b) only non-tracer ammunition were used in conjunction with a continuous tracking and firing procedure.

The results of this survey indicate a need for controlled firing tests designed to evaluate the effectiveness of tracer fire control for various combinations of aircraft dynamics, weapon dynamics, and tracer firing frequency. As an initial step, tests are needed in which the dynamic tracking capabilities of the target and the weapon are compatible.

This type of compatibility is needed to obtain baseline data concerning how effectively man can react to the visual feedback provided by tracer observation in itself. These baseline data would be needed to evaluate subsequent tests involving incompatibility in the target and weapon dynamics, since hit frequencies obtained in the latter tests would be a function of errors due to (a) dynamic incompatibility and (b) the gunner's response to the visual feedback.

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Appendix A

TRAINING PRACTICES AND SIMULATORS

U. S. Training Practices

A review was made of Department of the Army publications to determine the information that is currently published as doctrine for the use of tracers in adjusting antiaircraft fire. The information regarding doctrine forms the basis from which training Programs of Instructions (POI) are prepared. Included in this review were Field Manuals, Army Subject Schedules, Army Training Programs, Army Training Tests, and training films.

The most complete discussion of the use of tracer ammunition is contained in Field Manual 44-62, Air Defense Artillery Automatic Weapons Gunnery (19), in which it is pointed out that tracers will provide the necessary information to make adjustments during engagement to achieve hits on the target. Three basic principles are stressed:

(1) Localize vision to immediate area of the target.

(2) Determine whether the tracer is superimposed on the target or vice versa.

(3) Read the tracer only when it passes from the nose to the tail of the target.

Two illusions that interfere with proper reading of tracers are pointed out:

(1) The illusion of curvature.

(2) The tracer hump.

These illusions are explained, and the trainees are told that by concentrating their vision in the target area and not watching the tracer from the gun barrel out, these illusions will not be distracting. The ability with which gunners can do this is unknown. It is probable that the tracer illusion cannot be entirely ignored unless the area of visual focus is narrowed considerably.

The superimposition principle is stressed because stereoscopic vision does not function at the distances usually fired in the air defense situation. The observers are told that they must first obtain line shots before adjustments can be made in lead. Superimposition cues are used to determine the correctness of both line and lead. The point is also made that this tracer sensing should not be made in the first instance, but only after the tracer has been completely read, that is, followed from the target nose to target tail.

After the observers are told how to obtain the information from tracer reading, they next learn the meaning of, and what to do with, the information that is available from tracer reading.

A practical observation of tracer rounds is presented in Training Film 44-1858, "The Computing Sight M19 Series (M19A1) and (M38) - Nomenclature and Operation" (35). The film depicts a situation in which application of the information obtained from tracer reading is required. Emphasis, however, is primarily on operation of the sight, rather than reading of the tracers.

U.S. Army Air Defense Artillery Battalions, Army Training Program 44-15 (36) contains a basic program for training all air defense units using tracers as

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a means of fire control. The instruction involving the use of tracers occurs during the unit training phase and consists of the following breakdown of training time:

(1)	Use of sights and tracer observation	8 hours
(2)	Firing at aerial targets	12 hours
(3)	Antimechanized firing	8 hours
(4)	Air Defense gunnery and fire control	9 hours
		37 hours

The ammunition allowance that is to be used for this training is also specified in ATP 44-15, as follows:

(1) .50-caliber:
- (a) Advanced individual training — 56 rounds per individual.
- (b) Advanced unit training — 1,000 rounds per flexible gun.
- (c) Service practice and test — 2,000 rounds per flexible gun.
- (d) Advanced unit training (M55) — 2,666 rounds per M55.
- (e) Service practice and test (M55) — 5,334 rounds per M55.

(2) 40-mm:
- (a) Advanced individual training — 11 rounds per individual.
- (b) Antimechanized firing — 20 rounds per M42.
- (c) Training test — 400 rounds per M42.
- (d) Service practice — 800 rounds per M42.

(3) Crew. Crews firing the above ammunition:
- (a) Flexible .50-caliber gun — 2
- (b) M55 — 4
- (c) M42 — 5

Specific training methods and procedures which are to be used are determined by the individual instructor who has available for his use all of the material that has been mentioned. Additional guidance is provided for the instructor in Army Subject Schedule 44-6 (37), which indicates that all instruction in tracer observation should be given in the classroom except for that practice accompanying firing.

British Army Practices

Another current training program briefly reviewed was the one given by the British on the 40-mm gun (38). The British Army reportedly no longer uses tracer observation as a means of adjusting antiaircraft fire, but does use tracer observation during training. Tracers are used during training in order for the gunners to observe the results of their firing, and to get a general idea of how they are aiming.

The training program consists of 12 weeks during which a gunner fires two days of single shots at towed aerial targets so he can observe each round. He then fires three days at moving aerial targets with increasing speeds, and finally one day at ground targets.

After a gunner is assigned to a unit, a regular program of testing requires him to maintain certain performance levels. Constant training is conducted with live firing. In addition to feedback from tracer observations during firing practice, the gunner sees the results of his performance on gun camera film. Each antiaircraft unit uses a 16-mm gun camera, the film from which is developed and ready for viewing 30 minutes after firing (2).

An interesting point was brought out with reference to the British use of tracers in a document reporting the activities of the U.S. Army Ordnance Department during World War II (39):

"The most urgent requests for improved .50-caliber ammunition from 1940 onward came from the Air Force. But the Antiaircraft Command was also concerned, particularly after the Lend-Lease Act made British problems and experience in antiaircraft defense a strong consideration. British faith in tracer ammunition fortified the belief of the American Antiaircraft Command in the usefulness of tracers to guide machinegun fire."

As pointed out above, the British Army long ago gave up the use of tracer ammunition as a means of fire control; the U.S. Army still uses tracers

Training Devices

There are no tracer simulators used currently for training purposes, but a great many gunnery trainers were developed during World War II, a few of which included a simulation of tracer fire (40). This section describes only those training devices that simulated tracer fire.

3-A-2 Dual Projector Trainer and 3-C-25 Trace Projector Trainer. The 3-A-2 Dual Projector Trainer was developed early in World War II to teach all phases of aerial free gunnery, such as (a) recognition, (b) range estimation, (c) deflection, (d) tracking, and (e) ammunition conservation. This same training device was subsequently adopted to ground-to-air gunnery; the 40-mm version was known as the 3-D-14k Dual Projector Trainer, and the Navy had a 20-mm version known as the BuOrd Gunnery Trainer Mk III (41, 42).

The device consisted of two synchronized 16-mm projectors located behind an actual gun or a simulated gun mount (Figure A-1 and Figure A-2). One projector carried a film of attacking aircraft and the sound of the bomber at which the student was firing. The other projector carried a film with the sound of the gun and either a dot or a ring sight to show the correct point of aim during the time the target was in range. If the student fired before the plane was in range, a loud bell would ring. A mock gun resembling an aircraft machinegun was set up to swing in azimuth and elevation. When fired, it could project a spot of light on the screen to give the students points of aim.

Sketch of 3-A-2 Dual Projector Trainer

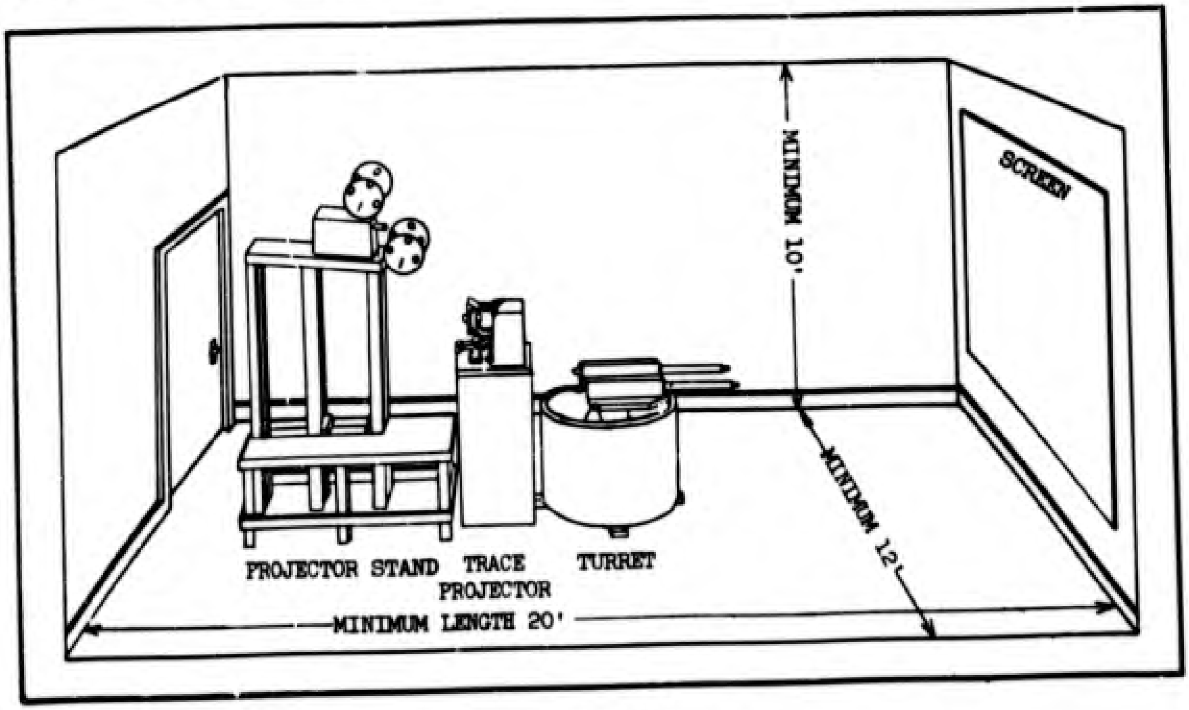
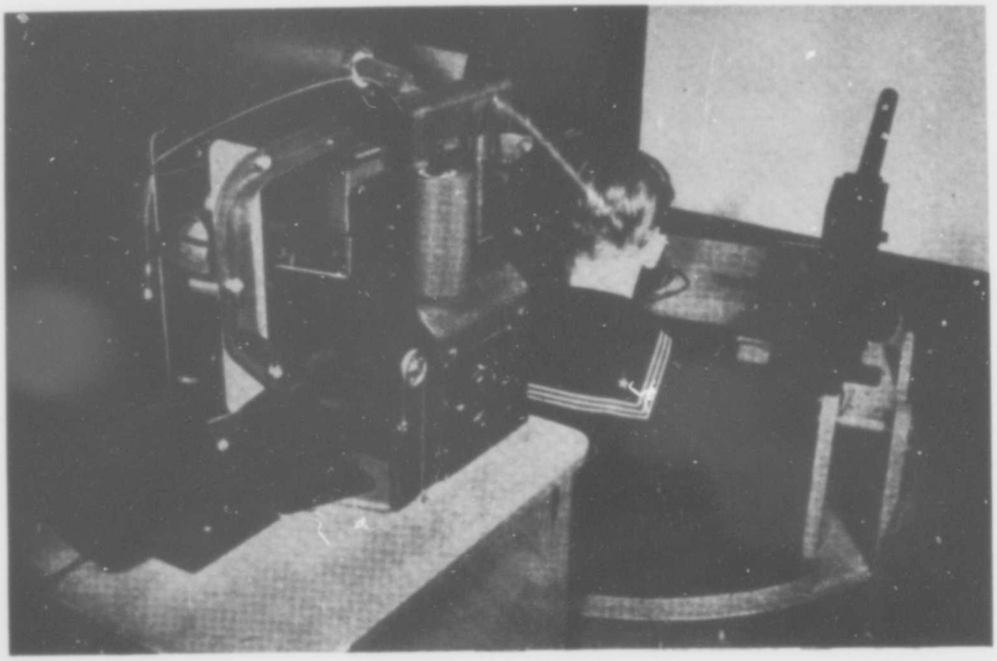


Figure A-1



Trace can be used by the gunner to determine the line of apparent motion of his target and therefore the direction of lead, but cannot be used to indicate the correct amount of lead. The tracer stream may appear to be passing through the target when the bullets are missing by hundreds of feet because of the optical illusion caused by lack of depth perception at long distances. Although these facts are well known, demonstrating them to the gunnery student so convincingly that he will not misuse trace in combat is a difficult problem for the instructor.

The Trace Projector Trainer is used to simulate tracer fire in connection with the 3-A-2 Dual Projector Trainer. The device is supplied with a Mk. 3 Training Turret which is mounted in front of the 3-A-2 screen, and the student aims and fires exactly as he does with any other 3-A-2 turret setup. Only the Mk. 3 Training Turret can be used with this device.

TRACE PROJECTOR TRAINER

WEIGHT (with turret)	OPERATION
Shipping: 750 lbs. Net: 400 lbs.	Power required: 110 volts, 25 amps., including turret.
SIZE (with turret)	Space required: Install with 3-A-2 Trainer and Mk. 3 turret. (Mk. 3 will be supplied with Trace Trainer automatically.)
Boxed: 8' x 4' x 4'. Device: 6' x 4' x 6'.	Operating personnel: 1 (same as 3-A-2 operator). Student capacity: 1.

DEVICE 3-C25

SOURCE: Taken from Reference 41.

Figure A-2

Four modes of operation were possible with the 3-A-2:

(1) "Observe": The correct point of aim was shown on the screen all during the attack.

(2) "Familiarize": The correct point of aim was shown only when the student fired the gun.

(3) "Teach-Test": The student only saw the correct point of aim when the instructor pushed a button, but he could see his point of aim.

(4) "Super-Teach-Test": The student saw neither the correct nor his own point of aim until the instructor pushed a button.

An infrared scoring device was used with the trainer to record "rounds fired" and "hits made." An additional device known as the 3-C-25 tracer projector trainer was developed for use with the 3-A-2 trainer to give a simulation of tracer fire. A trace was projected on the screen each time a "tracer" was fired. The percentage of tracers could be selected by a knob giving 12½%, 25%, and 50% of the rounds fired as tracers. The spots of light representing the tracers remained stationary on the screen until the time for burnout had elapsed. The burnout time could be selected by a switch to give 600, 1,200, and 1,800 yards of trace.

The trace projector was mounted between the 3-A-2 and the gun (see Figure A-1). It contained four rolls of paper mounted so that the paper unrolled in the up, down, left, and right directions at a speed that was controlled by the burnout setting. Behind the paper was a projection lamp, lenses, and a needle mounted so that it would punch a hole in the four moving sheets of paper each time a tracer round was fired. The needle was linked to the gun so that the light passing through the needle hole gave a spot of light at the point on the screen toward which the gun was pointing. As the sheets of paper slowly moved the needle hole became smaller, causing the spot of light on the screen to diminish in size.

Another device, called the "Initial Trace Unit," was mounted on the gun and gave a flash of light that appeared to move from the muzzle of the gun to the tracer spot on the screen.

No information has been found that suggests how realistically the tracers were simulated. The 3-A-2 trainer and various versions of it, namely the 3-D-14k (40-mm) and Mark III (20-mm), appear to have been widely used. The 40-mm version was still in use by National Guard units in the mid-1950s. A paper prepared by the Applied Psychology Panel concerning various synthetic gunnery trainers states that, "The Mark III Trainer is probably the most valuable of the synthetic antiaircraft gunnery trainers in the final phases of gunnery indoctrination." **(43)**

Mark I Machinegun Trainer. A gunnery trainer giving a three-dimensional presentation also was produced during World War II. It was designed to give drill in tracer control of machinegun fire. It was designated the Mark I Machinegun Trainer and is described below:[1]

> "The gunner operated a dummy .50-caliber antiaircraft machinegun [see Figure A-3] which was capable of firing two simulated shots per second at moving airplanes, projected on a large screen. Every third shot was a tracer bullet, reproduced in flight by means of polarized spots of light also projected on the screen.
>
> "Through these special projection devices, and with the aid of polarizing glasses worn by the gunner, both airplanes and tracers were made to appear in three-dimensional space with all possible realism. The sound of the airplanes and the sound and kick of the gun were reproduced. The total rounds fired and hits scored were counted automatically. As in actual practice, the difficulty of hitting the target increased with range.

[1]Personal communication from E. Barry Nann, Assistant to Vice President, Research, Polaroid Corporation, 11 April 1967.

Mark I Machinegun Trainer

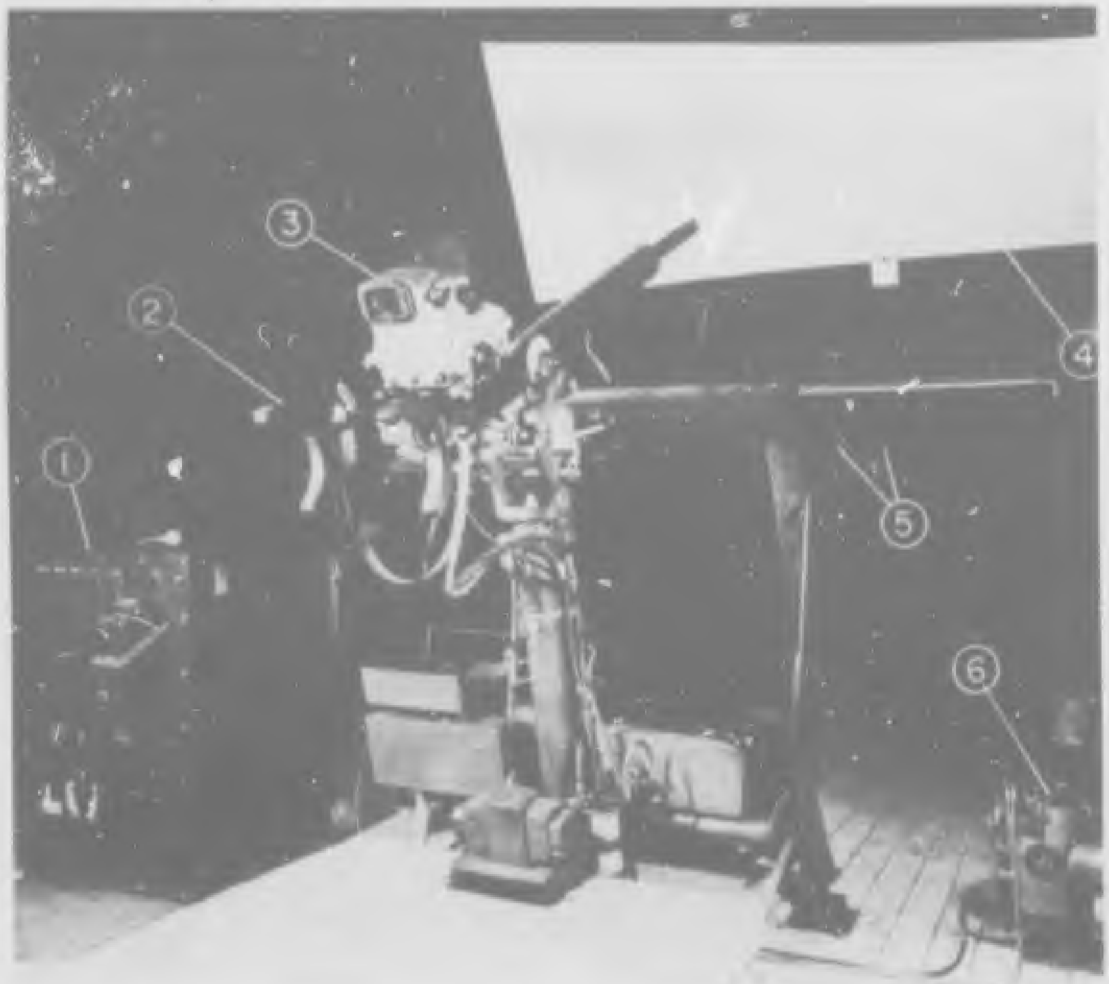


Figure A-3

"The trajectory of the tracer bullets was simulated by a bank of 16 individual tracer projector units [see Figure A-4], each projecting two spots of light, simultaneously, through two separate lenses. The two spots correspond to a right-eye and a left-eye view of an actual tracer bullet in flight, visible for $2\frac{1}{2}$ seconds and apparently travelling a distance of 4,200 feet. The 16 projections are timed to give a tracer image every $\frac{1}{4}$ second, and are mechanically aimed by the position of the gun at the moment of firing and immediately released to give a straight trajectory. The size of the spots of light varied from large to small to simulate an actual tracer bullet going off into space.

"The targets were projected, in three-dimensions, by means of a 35-mm motion picture projector [see Figure A-5]. The target film had, in addition to the standard sound track, recorder marks on the inter-frame spaces which were offered to the recorder mechanism which recorded a hit at any instant during a given target flight if the gun aim is correct. The ballistics of the gun and the target's range, course, and speed were all taken into account."

During World War II this trainer was evaluated along with other training devices. It was found that the tracer illusion of the Mark I differed significantly from the visual effect of real tracers (43). The tracer illusion suffered from the following:

(1) Tracers did not appear to pass behind the target for shots taken with too much lead.

(2) Real tracers are brightest near the muzzle of the weapon, but this was not so with the Mark I.

Mark I Tracer Projector Bank

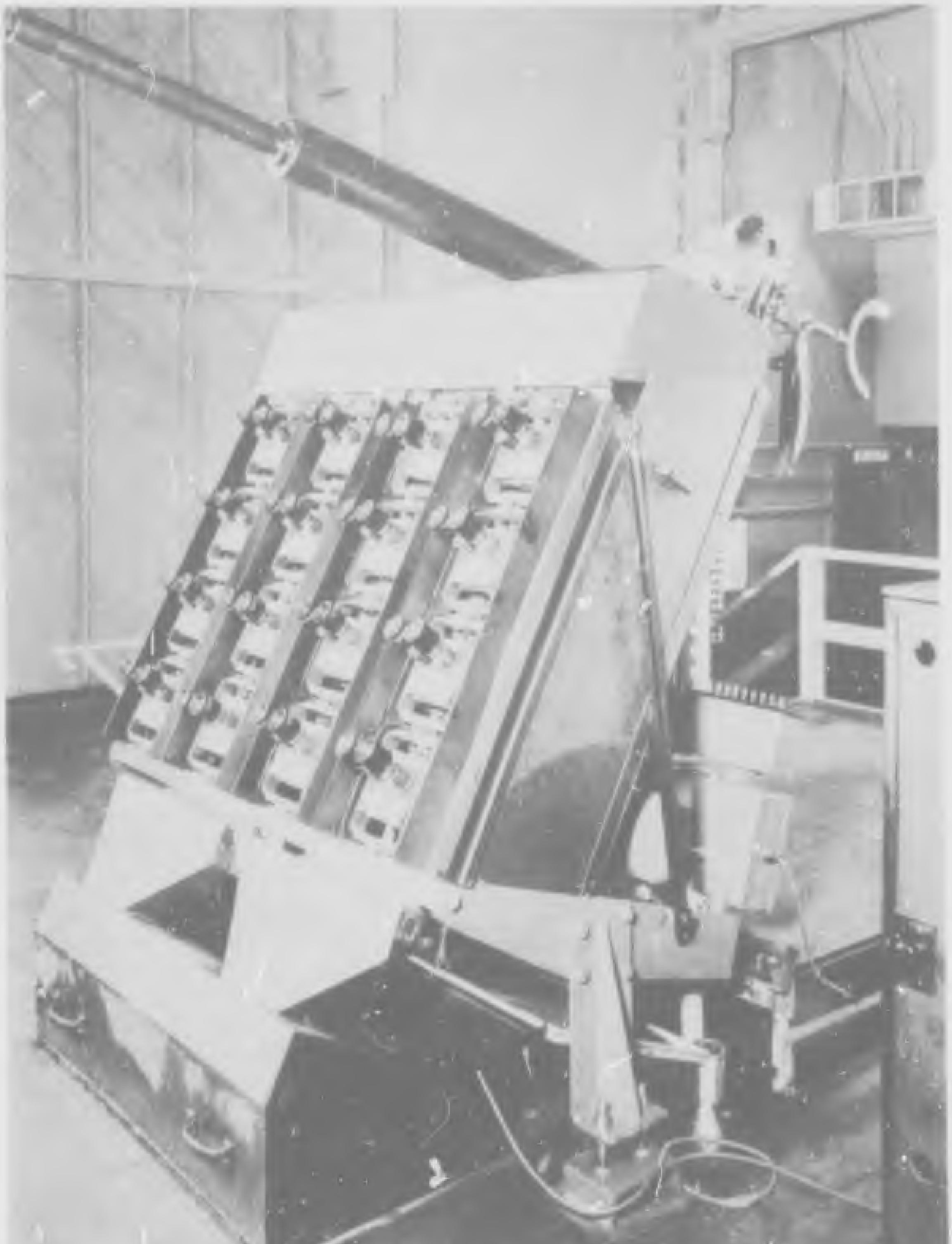


Figure A-4

Mark I Projector

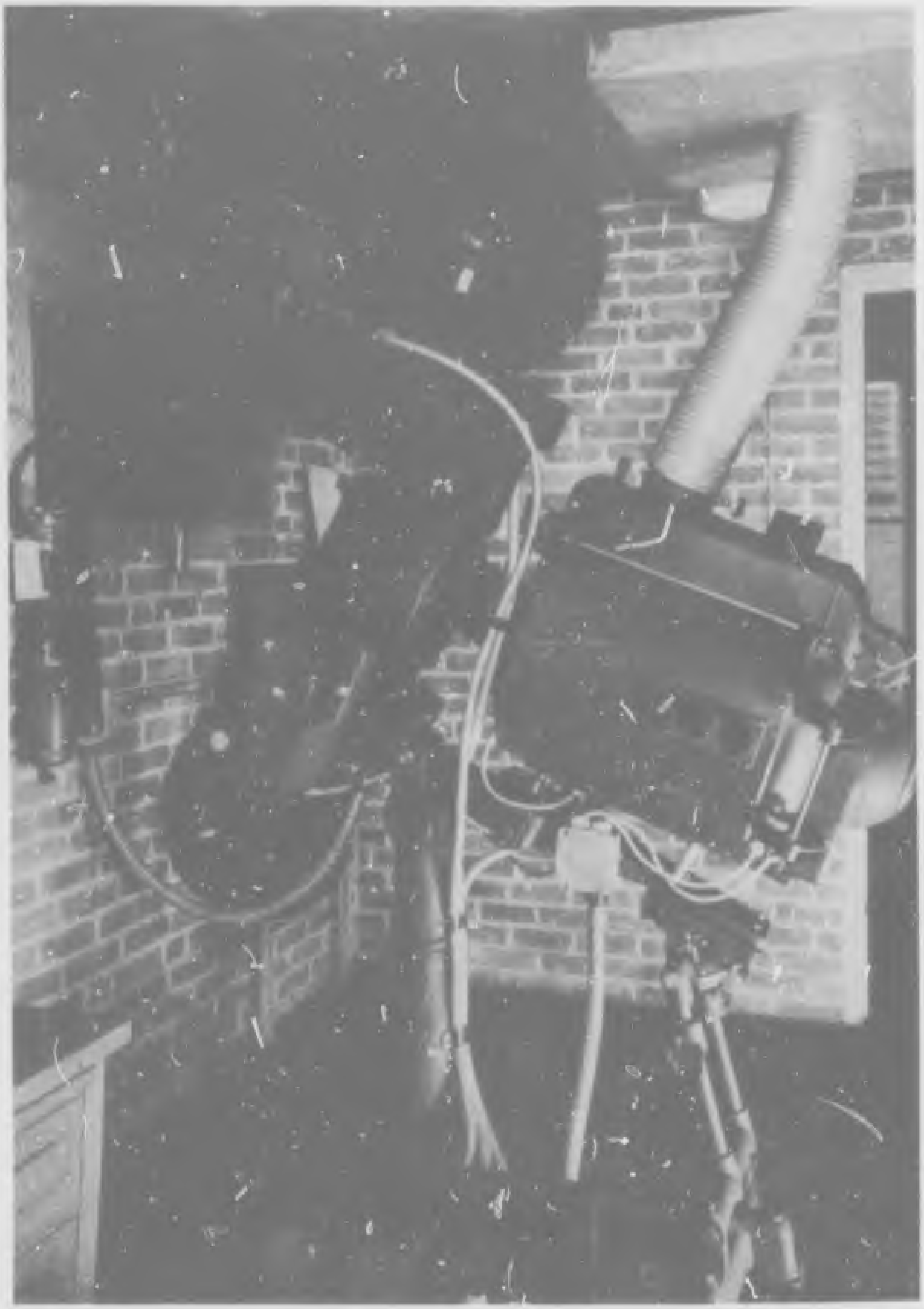


Figure A-5

It was believed that the gunner's performance was low beyond the third training session, and that the trainer would probably be best used in later stages of tracer indoctrination.

AA Machinegun Trainer, M9. A third synthetic gunnery trainer employing tracer simulation was developed during World War II. It was known as the AA Machinegun Trainer, M9 (44). The M9 trainer consisted of three main groups of parts:

(1) Gun and Associated Mechanism. The gun looked like a water-cooled, .50-caliber machinegun on a pedestal mount set 50 feet from a moving target range (see Figure A-6). It fired plastic pellets with electrically controlled bursts of compressed air. The pellets were fired on a 1:30 scale range so that their times of flight simulated those of the .50-caliber bullet. The pellets glowed when illuminated by ultraviolet light so that they simulated tracer ammunition. A compressor provided the pneumatic force for the plastic pellets. An ultraviolet lamp illuminated fluorescent pellets to simulate night firing conditions.

(2) Sound Equipment. Both the sound and recoil of the .50-caliber gun were simulated. A phonograph record provided the sound by means of two large loudspeakers. Both battle sounds and machinegun sounds are reproduced.

(3) Target Assembly. The targets consisted of three miniature metal targets, each supported on a still wire with an attached towline (see Figure A-7). A straight course, a diving course, and a climbing course were simulated. Paper targets were also provided to check the students' aiming accuracy.

About 1,000 of these trainers were to have been made during 1943, but no information has been found to indicate how valid they were as a training device.

Articles have been found that describe other types of tracer simulators, but these were to have been used with the fire director systems used during World War II and could not apply to any equipment in use today. The devices were crude and the literature indicates that their use was limited.

Sketch of M-9 Compressed Air Machinegun Trainer

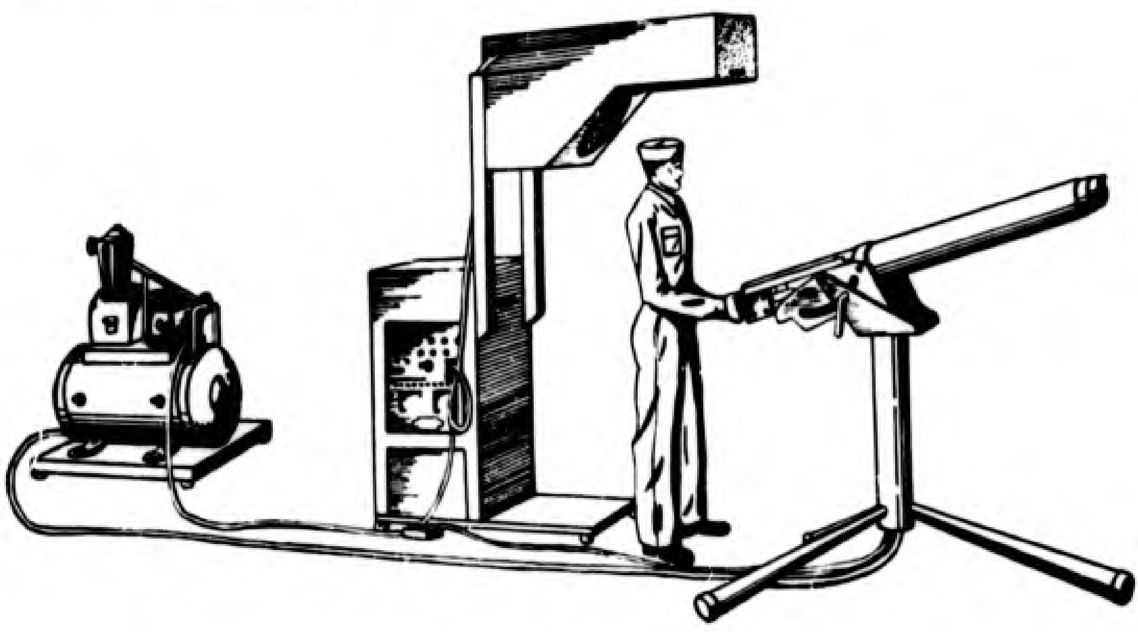


Figure A-6

Target System for AA Machinegun Trainer, M9

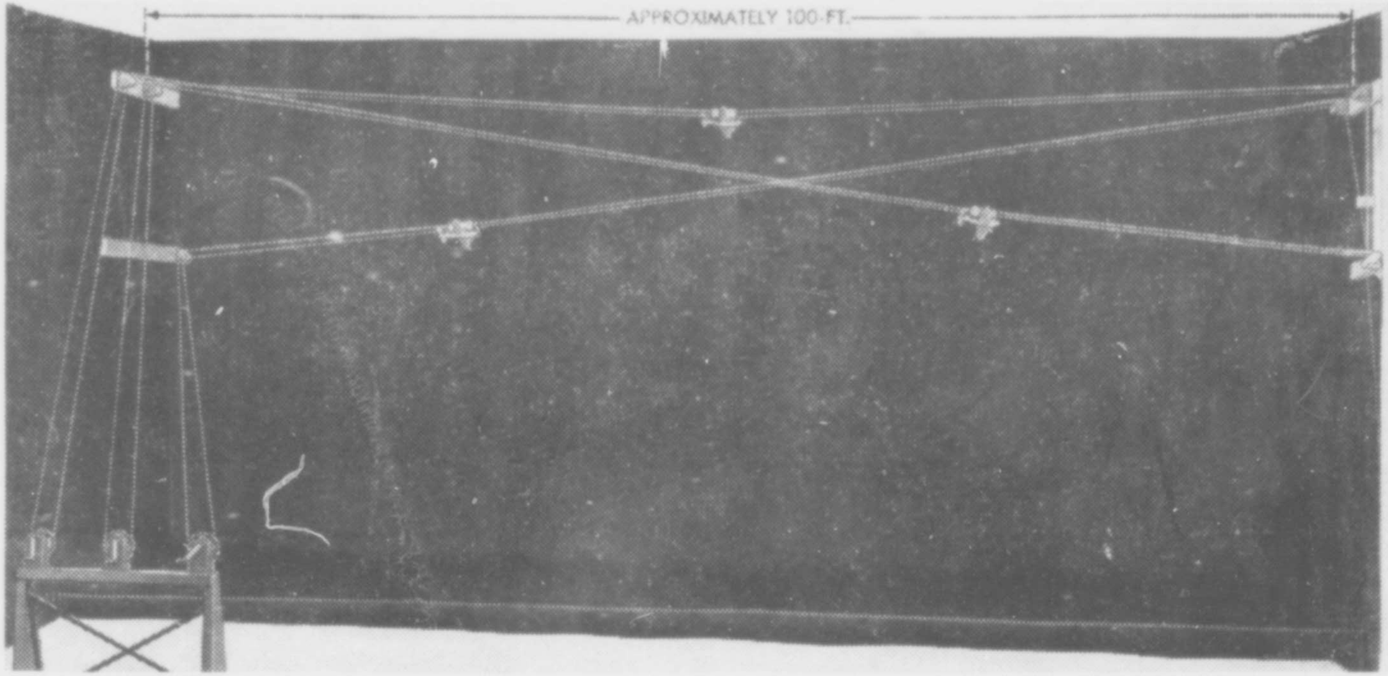


Figure A-7

NASA 2 Computed Visual Display. A modern-day device that has a tracer fire simulation capability was developed by the General Electric Electronics Laboratory for the NASA Apollo program. The system was originally developed to be used in experiments simulating spacecraft docking maneuvers.

Basically, the system uses a digital computer to generate the information needed for pictorial representation of a three-dimensional space to be presented on a color television tube. The visual display may contain terrain, buildings, or moving vehicles, and provides an animation that is unique in that several observers may independently move about.

A computer program stored on paper tape contains information about the locations of the various points, lines, surfaces, and colors of the scene that is to be represented. This information is read into the computer memory.

The view seen on the television screen is a view of the computed space as seen from a particular point in the space. This viewpoint may be moved around by means of a joystick or other type of control so that the screen appears as if it were a porthole in a vehicle moving about in a simulated world. The system has the capability for three simultaneous and independent color displays.

One of the computer programs that is presently available simulates tracer fire from a moveable weapon mounted on a moving aircraft. One display monitor is controlled by the "pilot's" joystick and speed controls so that the terrain and target appear to be moving on the screen as if an aircraft were actually moving over them.

A second monitor shows the "gunner's" view. The gunner has a joystick that controls the orientation of his weapon with respect to the aircraft so that the view on his monitor combines his motion with the aircraft's motion. The gunner also has a trigger that allows tracers to be simulated on his display. Small yellow dots appear in the center of his display when the trigger is pressed. If the rounds theoretically pass into the pilot's field of view, then they will also appear on his monitor. The tracer rounds produce a red flash when they strike the ground. The program as presently written assigns to each simulated round a constant velocity, and does not provide for velocity reduction due to the drag caused by air resistance; however, the drop of the round due to gravity is represented.

The target appears as a small red box moving over the terrain in a preprogrammed, irregular path. The pilot maneuvers his controls so that the target appears on the screen as if the aircraft were flying by. The gunner attempts to orient the target in the center of his display, and as he presses the trigger tracer rounds appear to move toward the target. The computer compares the location of each round to the location of the target and gives a hit indication when a round strikes the target. The hit indication is in the form of a red pyramid that appears to stand on its point over the target, simulating an explosion or smoke column. The height of the pyramid is proportional to the number of hits.

NASA 2 was primarily built to simulate spacecraft docking maneuvers, but programs may be written to allow simulation of an enormous variety of situations. A program could easily be written to simulate tracer rounds being fired at an aircraft by a weapon on the ground. One monitor could show the gunner's view and another could show the view from the aircraft. The third display could be used for a second weapon or for a downcourse observer. The tracers could be given the ballistics of a particular weapon system so such things as the rate of fire, dispersion, tracer burnout, and times of flight could be realistically simulated.

Almost any kind of target could be simulated, including multiple targets. Future improvements to the system will probably give better resolution, a wider field of view, and more picture realism, which could provide a much more realistic and flexible tracer fire simulation than has been built in the past.

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13. ABSTRACT

A survey was performed concerning the effectiveness of observing the trajectories of tracer ammunition as a method of adjusting antiaircraft firing. The survey included (a) a review of military reports and journal articles dating from the 1920s, (b) an analysis of relevant psychological research, particularly in the areas of visual perception, information processing, and man-machine dynamics, and (c) informal interviews of military personnel, scientists, and engineers. It was learned the current highly divergent opinions concerning effectiveness of tracer feedback were also held prior to and during World War II. The documents reviewed failed to show any testing in which tracer and non-tracer techniques of firing were compared for hit frequencies or any other comparative measure of effectiveness.

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14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Antiaircraft Firing						
Man-Machine Dynamics						
Tracer Ammunition						
Visual Perception						