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# NAVAL POSTGRADUATE SCHOOL

## Monterey, California





# THESIS

AN ANALYSIS OF OPTIMAL TRACKING RATE FILTERS
IN SUPPORT
OF THE SUPPLEMENTAL FIRE CONTROL TEST

BY

George Edward Newman

March 1978

Thesis Advisor: S. H. Parry



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# An Analysis of Optimal Tracking Rate Filters
# in Support
# of the Supplemental Fire Control Test

by


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Submitted in partial fulfillment of the
requirements for the degree of

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## ABSTRACT

Evaluation of tank fire control systems is the subject of much emphasis at the present time. Test data collected during a fire control test conducted by the United States Army Material Systems Analysis Activity is examined using several different analysis procedures. The objective of the analysis is to determine the optimal time to employ in the tracking rate filter of a tank fire control lead prediction algorithm. An additional objective is to quantify individual components of target error and to investigate the character of these errors as a function of varying tracking rate filter times.

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# I. INTRODUCTION

Currently much emphasis is being placed on the development of advanced tank fire control systems. Tanks incorporating these advanced systems are expected to constitute a significant part of the Allied force opposing the formidable Soviet threat present in Eastern Europe.

This thesis presents an analysis of data collected during a tank fire control test conducted by the United States Army Material Systems Analysis Activity (AMSAA) in September 1977. The specific area of analysis involves the investigation of the optimal time to employ in the tracking rate filter used in a tank fire control lead prediciton algorithm. The analysis also had the objective of identifying individual components of tank gunnery error. An investigation was made of the relationship between these errors and the value assigned to the tracking rate filter utilized in the fire control system.

Section II of this thesis motivates the need to pursue the development of advanced tank fire control systems and provides a historical development of improvements which have been made in fire control technology. An overview of recent experimentation which has been conducted to investigate the dynamics associated with engaging moving targets is included.

The test purpose and test scenario is described in sufficient detail in Section III to provide the reader with an understanding of how and why the test was accomplished. A knowledge of the test scenario allows the reader to evaluate the analyses, and the analyses results, in light of the restrictions imposed by the scenario.

The test data obtained from AMSAA was the raw instrumentation data as it was recorded during the conduct of the test. Before any analysis could be performed on the data it had to be expressed in standard units of measure. A description of the data reduction process is included in Section IV.

Initially four analysis procedures were used to investigate the test data. Procedures 1 and 2 dealt with analyses whose objectives were to establish a relationship between mean azimuth tracking error and varying tracking filter intervals. These intervals were called "delta time". Procedures 3 and 4 investigated the relationship between the mean azimuth tracking rate error and delta time.

The final phase of the thesis analysis used two models to describe total target azimuth error as a function of delta time. Through the use of these models an optimal delta time for the tracking rate filter was identified. Additionally, valuable insights were gained relative to the characteristics of individual components of total target azimuth error.

# II. BACKGROUND

## A. HISTORICAL DEVELOPMENT

The events of the 1967 Arab-Israeli War once again served to remind the nations of the world who maintain standing armies that mobile armored warfare can be, and often is the element within the combined arms team which can most effectively bring about success on the battlefield. Not since the early campaigns of World War II in which the German panzer divisions introduced Blitzkrieg, or lightning war, had the effectiveness of tank warfare been as devastatingly emphasized.

Although the basic tactics of armored warfare as advanced by Liddell Hart, Heinz Guderian, and Erwin Rommel have changed little since inception, the same is not true of the fighting machines employed in the armored conflict. The modern battle tank bears little resemblance to its forerunners of World War II. Dramatic technological advances have been made in areas such as metallurgy which has vastly enhanced the effectiveness of armor plating. Development of more reliable and durable vehicle power plants and suspension systems give the modern tank mobility and durability characteristics which would have been difficult to envision three decades ago. Similar improvements have occurred in the areas of fire power and fire control. Clearly all of these advancements serve to leave the modern tank with little in common with its forerunners except perhaps for the manner in which one goes about evaluating tank effectiveness. It has been said that of all battlefield targets which the tank is expected to engage, the most difficult consists of hostile tanks. As a consequence, the ability to "kill" enemy tanks has become the criterion of the tactical effectiveness of tanks. The adoption of this criterion implies that tanks which are effective against enemy tanks are at least as effective against targets other than tanks. While this may not be universally true, in general the ability to destroy other tanks is a satisfactory baseline measure of tank effectiveness [1].

Unlike tanks of the past, tanks on the modern battlefield must be able to successfully engage and kill moving enemy tanks in order to ensure their own survival. Although the ability to successfully neutralize moving enemy targets has always been a highly desirable capability to possess, its utter necessity is of relatively recent vintage. Technological breakthroughs in the area of turret stabilization now permit the modern tank to fire its main gun at the same time that it closes with its target. In order to survive, the tank being engaged must be able to neutralize its moving adversary.

The key to the delivery of effective neutralizing fire against a moving target is a fire control system which effectively assists the tank crew in the employment of the vehicle's armament. It would be difficult to locate an experienced tank gunner who would not concede that one of the more difficult aspects of tank gunnery is the precise estimation of range to the target. To assist the gunner in range determination, the United States Army began installing optical range finders on its tanks soon after the close of World War II [1]. Following the installation of these devices no dramatic new advances were made in the area of range determination until the recent advent of the laser range finder. The laser range finder's ability to very accurately determine range to target with little or no degradation by ambient light or weather conditions makes it an ideal component of any state-of-the-art fire control system. Range information is produced by the laser range finder in the form of electrical impulses. These impulses become meaningful to the tank gunner only after they have been properly interpreted by another element of the fire control system, the electronic ballistics computer. Although the electronic ballistics computer serves the same basic function as the mechanical computer which it replaced, its role in the fire control system has been greatly expanded because of the order of magnitude increase in computing capability which it possesses over its predecessor. With input data from ancillary fire control system components, the electronic ballistics computer can compute target range, vehicle cant, crosswind, air temperature, powder temperature, air pressure, and tube wear parameters. Those parameters are in turn used by the computer to determine corrections in main gun azimuth and elevation to compensate for the effects of gravity, drift, parallax, gun jump, tube droop, and crosswind on the trajectory of the projectile. Included in the azimuth corrections is the lead required to hit a target which is moving [2].

## B. RECENT EXPERIMENTATION

Within the past several years there has been a high priority among members of the armor community and material developers to determine the relationship, if any, between combat vehicle survival on the battlefield and vehicular mobility and agility. Mobility as used within the present context refers to the ability of a vehicle to reduce its exposure time to a hostile force by moving at a high speed. Agility is defined as the ability of a vehicle to perform evasive maneuvers. It should be clear that any increased survivability which a combat vehicle gains because of its inherent mobility or agility results from the fact that these characteristics have lessened the effectiveness of the fire being delivered by the hostile combat vehicle. Alternatively expressed, the difficulty encountered by the hostile vehicle in hitting its intended target may be increased because the effectiveness of its fire control system has in part been neutralized. Having thus hypothesized the foregoing implicit, albeit subtle relationship between degradation of fire control system effectiveness and survivability, it seems desirable to attempt to gain definitive information regarding their correlation.

Experiments conducted in the Federal Republic of Germany and analysis of data collected at the United States Armor Center have indicated that high mobility/agility may increase combat vehicle survival on the battlefield. Specifically the

German experiment indicated that there was a high survivability payoff when vehicular lateral accelerations of approximately 0.7g were attained. Two field tests recently conducted in the United States gathered gunner tracking performance and hit probability data against maneuvering targets. These tests were the S-Tank Agility/Survivability (STAGS) Test and the Anti-Tank Missile Test (ATMT). Because of test conditions and other constraining factors, neither of these tests generated vehicular lateral accelerations above 0.4g; therefore, the data from these tests could not be used to substantiate earlier findings concerning vehicle survivability relative to lateral accelerations in the 0.7g range [3].

The most recent effort to gather field test data regarding high mobility/agility vehicular characteristics and their corresponding correlation to survivability has been undertaken as a partial objective of the Armored Combat Vehicle Technology (ACVT) program. In order to accomplish this objective, the United States Army Combat Developments Experimentation Command (CDEC) was given a directive to conduct a High Mobility/Agility field experiment beginning in November 1977. The experiment was named the High Mobility/Agility, Phase IIA, Extended (HIMAG IIA EXTENDED) and was conducted at the CDEC field test site at Fort Hunter Liggett, CA. The HIMAG IIA test utilized a wheeled target vehicle which performed evasive manuevers (designated sinusoidal wave patterns which generated lateral accelerations up to 0.7g) on an airfield located at the field test site. During the maneuvers the target vehicle was tracked by TOW and M60A1 gunners who were positioned at specified ranges and offsets relative to the vehicle maneuver path. Analysis of the gunner tracking data relative to the apparent motion of the test vehicle was intended to provide information regarding the relationship between vehicular mobility/agility and vehicle survivability. As indicated earlier, the testing was conducted to provide data from which a relationship (if any) between degradation of fire control effectiveness and target vehicle mobility/agility can be established.

In September 1977, the United States Army Material Systems Analysis Activity concluded a test at Aberdeen Proving Ground (APG), MD, whose objectives were very similar to those set forth for the HIMAG IIA test. The testing at APG differed from that planned in the HIMAG IIA test in that the APG test was conducted in a highly instrumented laboratory environment and therefore could not be classified as a true field test. The analysis conducted in this thesis utilizes a portion of the data collected in the APG test. A description of that test is presented in a subsequent section of this thesis.

## III. TEST DESCRIPTION

As discussed in Section II, the dynamics of the modern battlefield place a high premium on the modern tank's ability to successfully engage hostile moving targets. Future fielding of vehicles which possess increased mobility/agility characteristics will make the task of hitting these highly maneuverable targets more difficult and will therefore intensify the need for more effective fire control systems. The testing completed by AMSAA at APG in September 1977 represents an important link in the development chain necessary to field a fire control system which will meet future challenges.

### A. PURPOSE

The APG test was entitled "Supplemental Fire Control Test, M60A3" and its purpose was to examine the implementation of the fire control lead prediction algorithm, and to assess the system's capability to cope with moving targets traveling at varying speeds and directions of motion. An algorithm is, by definition, a rule for solving a certain type of problem. The problem to be solved in this instance is that of aiding, to the maximum extent possible, a tank gunner in hitting hostile targets which are moving as previously described. In the absence of a fire control system which incorporates a lead prediction algorithm, the tank gunner is required to mentally compute the lead necessary to hit the moving target and having computed this lead, he must manually move the turret controls causing the lead to be included in the firing azimuth. Using this method, the training, experience, and aptitude of the individual tank gunner are key elements in whether or not he is successful in hitting the moving target.

The APG tests were conducted using an M60A1E3 fire control system. This fire control system assists the tank gunner by automatically computing the lead required to hit a moving target and by automatically moving the turret, thereby incorporating the computed lead into the firing azimuth. The lead computation is made by the fire control ballistics computer according to the lead prediction algorithm. A typical moving target firing sequence for a tank equipped with an M60A1E3 fire control system would be the following. The tank gunner places the center of the sight reticle pattern on the center of mass of the moving target and tracks in this manner for a specified amount of time. After the gunner has maintained his track of the target vehicle for the minimum amount of time he engages a lead lock fire control switch which initiates the ballistic computer computation of the lead. Having computed the lead, the fire control system automatically inserts the lead by causing the tank turret to rotate by an angular amount which corresponds to the calculated lead. At the same time that the turret is being rotated, the sight reticle pattern is moved by the amount of lead in the direction opposite to that in which the turret is rotated. Movement of the sight reticle pattern allows the gunner to continue to track the target vehicle center of mass even though in actuality the target vehicle is being led. The advantages offered by a fire control system which incorporates an automatic lead option can be summarized as follows. First, the gunner is no longer required to compute the necessary target lead mentally. In essence, the human error involved in lead calculation is eliminated. Second, the fire control system automatically moves the turret in azimuth by an amount corresponding to the computed lead. Since the gunner is relieved of the responsibility of manually moving the turret controls, he is more able to concentrate on tracking the maneuvering target vehicle. Finally, the movement of the sight reticle pattern allows the gunner to continue to track the center of mass of the target vehicle versus having to maintain the sight reticle pattern at a constant distance (actually at a constant angle which corresponds to the calculated lead) in front of the target vehicle.

Based on the foregoing discussion, it seems clear that a fire control system which automatically computes and inserts target lead in moving target situations is a very desirable option to pursue. Given that premise, the next logical question to be answered is the following. What are the critical elements of fire control lead prediction algorithm which when optimized, yield the best solution to the problem? Although there may be alternative solutions to this question, the analysis performed in this thesis deals with an investigation of the optimal characteristics of the tracking rate filter.

A description of the function performed by the tracking rate filter is helpful in illustrating the vital part it plays in the lead prediction algorithm. The lead prediction algorithm relies on the fact that when the gunner is tracking the moving target through the fire control sight, the traverse rate of the turret corresponds to the angular rate of change of the target as viewed from the firing platform (the tank). When the correct distance to the target is known (as determined by the laser range finder) and is coupled with other factors such as projectile type, powder temperature and tube wear, the ballistics computer can utilize this data to compute the projectile time of flight (TOF) from the gun to the target. The TOF multiplied by the mean angular traverse rate of the tank turret equates to the angular lead required to hit the moving target. From the relationship,

Lead = TOF x Mean Angular Rate of Turret

it is clear that the correct specification of the angular rate is essential to a correct lead computation.

By definition, rate represents change per unit of time. The question arising in the foregoing problem centers around choosing the "unit of time" which will be optimal in terms of minimizing the error of the lead prediction algorithm. The "unit of time" as specified in this context will be referred to in the remainder of this thesis as "delta time". The problem can be illustrated by using examples which represent extreme cases. Assume that the angular turret rate was computed based on the mean traverse rate of the turret over a delta time of 10 seconds. Suppose that the target vehicle was not moving for the first 5 seconds of the delta time period, yet moved at a mean rate of 3 mils per second thereafter. The mean angular rate of movement in this example is 1.5 mils per second; however, this is not representative of the movement of the target in the critical period just before firing takes place. A similar extreme case can be visualized at the opposite end of the spectrum whereby the mean angular rate is computed based on a delta time period which is too small to be realistically representative of the true angular rate. It seems apparent that the optimal delta time parameter lies somewhere between large delta time values (10.0 seconds will be considered large) and those approaching zero as a limit. The purpose of this thesis is to present an analysis of the APG test data with an objective of isolating the range wherein optimal delta time values occur.

## B. TEST PROCEDURE

The APG fire control test under consideration was composed of two phases, a steady-state phase and a transient phase. Each phase involved simulated firings by a stationary M60A1 tank fitted with a M60A1E3 turret, at a simulated target which was moving in a horizontal plane. Because of the non-firing aspect of the test, it was accomplished in a building at APG especially equipped for the conduct of fire control testing. The terminology "steady-state" refers to the motion pattern which the simulated target described. The test was designed so that the evaluation of the fire control lead prediction algorithm would be based on the data collected during the steady-state test phase; whereas, other types of analyses would be accomplished using the transient test data. Because the subject of this thesis involves an analysis pertaining to the fire control lead prediction algorithm, a full test description will be presented for the steady-state test phase only.

Throughout the test, the simulated target was a laser-generated spot of light which was projected onto a large rectangular screen positioned 31.5 meters in front of the center of mass of the tank test vehicle. The motion of the simulated target was controlled by projecting the output of the laser onto a mirror which in turn reflected the energy onto the target screen. The mirror used in the projection process was mounted on a drive mechanism so that the mirror motion could be controlled by a programmable mini-computer. The desired target motion was accomplished by programming the mini-computer with an appropriate function describing the motion. In the steady-state test phase the mini-computer was programmed with a sine function resulting in a sinusoid profile being projected on the projection screen. As viewed through the tank fire control sight, the back and forth motion of the projected laser spot represented the apparent motion which would be presented by a target vehicle moving at a constant speed around a circular path. Simulation of varying target ranges and speeds was accomplished by varying the range and rate of the mirror angular movement. The steady-state test phase was conducted by running a sequence of tracking runs (simulated firings) at simulated ranges of 500 meters and 1500 meters. Simulated target speeds were 50 kilometers per hour (kph) at the 500 meter range and were 25 kph, 35.4 kph and 50 kph for the 1500 meter range. These range and speed combinations correspond to target vehicle maneuvers which would generate lateral accelerations of 0.175g, 0.35g and 0.7g respectively. An illustration of the target simulation apparatus and setup is depicted in Figure 1.

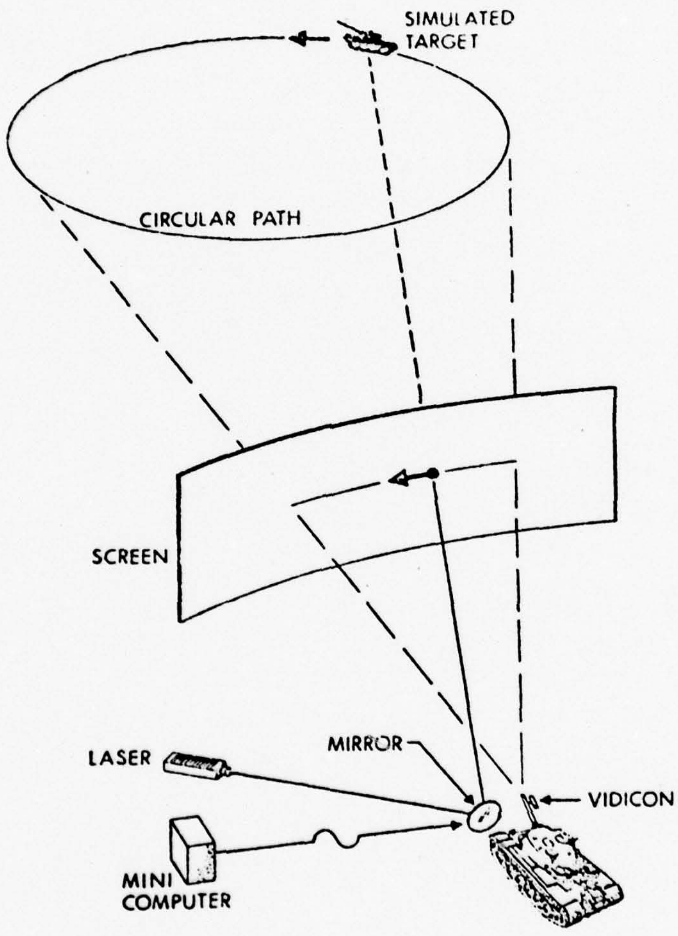



Figure 1

The M60A1 tank was emplaced with cant blocks under the right track which resulted in a 90.2 mil (5.07 degrees) cant. The purpose of the intentional cant was to cause the target to have an apparent motion in elevation, as well as in azimuth, even though the simulated target was being projected in a horizontal plane across the projection screen. Instrumentation on the test vehicle included a gated television (TV) camera which recorded the view through the main gun fire control sight and also a gated TV camera mounted on the gun tube which was canted to correspond to the boresight of the main gun. Each gated TV camera was connected to a videotape recorder. Utilization of the gated TV instrumentation in conjunction with a target simulated by a high energy light source made it possible to continuously record the position of the fire control sight and the position of the gun tube relative to the position of target throughout the test tracking runs. Data recorded in this manner were readily convertible to angular deviations and therefore became a fundamental portion of the data base for each of the test tracking runs.

During the testing, the test system was operated by either of two tank gunners from the United States Army Armor Center, Fort Knox, Kentucky. The training and proficiency of these individuals was considered by the sponsoring agency at the Armor Center to be representative of typical tank gunners found throughout the Army. Each gunner was allowed to gain familiarity with the test equipment and the test scenario prior to being utilized in a tracking run (being recorded) for record.

Within each recorded tracking run there were approximately 11 simulated firings. The gunners were instructed to track the simulated target during the entire duration of a given tracking run. The test system was set-up so that the test director could initiate a simulated firing sequence by activating a ready light located in the gunner's sight. When the gunner observed the illumination of the ready light he initiated the following firing sequence. Tracking of the simulated target was maintained by the gunner by his slewing of the turret and gun (and correspondingly the fire control sight) at the appropriate rate in azimuth and elevation. When the gunner made the judgement that his tracking motions matched the motions of the target he activated the fire control lead lock enable switch. Activation of the lead lock enable switch initiated the computation of required lead and its subsequent automatic insertion into the firing azimuth. After the lead insertion and simultaneous movement of the sight reticle pattern, the gunner reacquired target tracking. The firing sequence culminated in the gunner's activation of the firing mechanism. Throughout the firing sequence, test instrumentation recorded critical data relative to the command to fire, the activation of the lead lock enable switch and the gunner's initiation of a trigger pull. The commands to fire given to the gunner were given at various position locations of the target on its sinusoid path so that a full spectrum of its apparent motion would be represented in the recorded tracking run data.

## IV. DATA REDUCTION METHODOLOGY

### A. INTRODUCTION

This section contains a detailed discussion of the data reduction methodology. It is provided for those readers not familiar with the character of the Supplemental Fire Control Test data. Those persons not in this category may skip this section without loss of continuity.

### B. RAW DATA TRANSFORMATION

A characteristic of many highly instrumented testing programs is that the data collected during the conduct of the testing is very seldom useful for analysis purposes in its raw form. Most often, before any analysis can be conducted the raw test data must be converted into units which are meaningful in terms of the subject under investigation. The foregoing is applicable to the fire control test data which is analyzed in this thesis.

The APG test consisted of a series of separate tracking runs. Each individual test tracking run was characterized by a designated run number, target range, target speed and gunner identification. Approximately 32 runs were conducted during the steady-state testing phase. Each tracking run was roughly 4 minutes in duration. The analysis performed in this thesis used data from seven tracking runs. The remainder of the tracking runs were not analyzed because the time available did not permit both the development of analysis methodology and analysis of all the test data. In light of the time constraint, primary emphasis was placed on the development of analysis methodology. All of the runs selected for analysis (runs 136 through 142) were conducted at a simulated range of 1500 meters and with a simulated target speed of 50 kph. This range and speed combination corresponded to maximum target vehicle lateral accelerations of 0.7 g. As noted previously, there is much interest in obtaining data relative to gunner performance against targets capable of generating high lateral accelerations. The selected target range and speed combination was chosen on the basis of the foregoing consideration. Although only one range and speed was investigated in this thesis the analysis methodology employed is equally applicable to tracking runs conducted at different simulated speeds and distances.

Throughout each test tracking run, data from the test instrumentation was collected and recorded on magnetic tape at an average rate of 106.55 samples per second. The composition of an individual magnetic tape data frame, or logical record, included the following elements of information: time the logical record was created; tracking/firing sequence event code; mirror drive position location; and azimuth/elevation position location relative to the simulated target. Other types of data were also included in the logical record; however, that data was not used in the present analysis and therefore will not be discussed.

The general approach taken with regard to the data transformation was to write a Fortran computer program which would transfer selected portions of the raw data onto a blank magnetic tape while simultaneously accomplishing desired transformations on the raw data during the transcription process. The magnetic tape created as a result of this procedure contained the test data expressed in a meaningful form for analysis purposes. Subsequent paragraphs will include a description of the character of the raw data and of the transformations which were performed during the tape transcription process.

As previously stated, logical records were created at an average rate of 106.55 records per second. The time component on each logical record was recorded in units of hours, minutes and seconds to the nearest hundredth. Because of the manner in which the logical records were generated and recorded, occasional adjacent pairs of records had identical recorded times. The hours and minutes portion of the time data was converted to units of seconds during the data reduction/transcription process.

Each logical record included an event code which corresponded to one of four specific phases within the tracking/firing sequence. Event code 2032 specified that the gunner was in the normal tracking mode. Code 2033 reflected that the test director had given the gunner a command to initiate a firing sequence. The gunner's engagement of the fire control lead lock switch was signified by event code 2035. The actual firing event corresponding to the gunner's trigger pull was designated by event code 2038. Each of these event codes was transcribed to the analysis tape without alteration.

The position-location of the simulated target was recorded in raw data form from instrumentation connected to the mirror drive pedestal. The back and forth movement pattern of the mirror drive resulted in raw data which ranged from -48 to -4048. The units of the raw data had no physical significance as initially recorded; however, after being transformed, the data was expressed as an angular measure with a range of 0 to $2\pi$ radians. During the conduct of the testing, it was noted that there was a slight amount of mechanical slack within the mirror drive pedestal which resulted in a minor deviation between the actual location of the mirror drive and the location which was being recorded by the test instrumentation. Personnel at APG in charge of the test instrumentation were able to quantify and record this deviation thereby allowing the necessary correction of the mirror drive data to be accomplished during the data transformation process. A plot of the transformed mirror drive position data is shown in Appendix A, Figure 2.

The last elements of the test data contained in the logical record which required transformation were the gun tube raw azimuth and elevation data. Gated TV video cameras were used to record the gun tube position data in units of "counts". Prior to the beginning of each tracking sequence, a calibration of the gated TV instrumentation was performed to obtain the proper alignment between the TV instrumentation and the boresight of the tank gun tube. The data resulting from the calibration was recorded on the magnetic tape record. This calibration data was utilized to reexpress the azimuth and elevation "count" data as centimeter displacement relative to the target. It was noted earlier that the M60A1 tank was intentionally canted 90.2 mils in the counterclockwise direction relative to the target. In order to establish a common coordinate system between the gun tube TV camera instrumentation and the target, a transformation was used to rotate the camera coordinate system 90.2 mils clockwise. The final step was to convert the azimuth and elevation data expressed in centimeters to an angular expression which would facilitate the planned analysis of the data. Since the distance between the target and the gun components was known and remained constant throughout the testing, the desired transformation to mils was accomplished by dividing the centimeter deviation data by the known distance to obtain radians. The radian measure was subsequently converted to mils.

C. DATA TRANSCRIPTION AND SMOOTHING

As a consequence of the high sampling rate at which the test data was collected and recorded, approximately 25,500 logical records of raw data were created for each individual tracking run. Because of the enormous amount of data which was generated during the series of tracking runs, it was not considered practical to analyze each individual logical record of data. Analysis of the data had to proceed under the constraint imposed by computer core storage capacity, yet could not be reduced in volume to the point that significant information was lost. The amount that the data could be condensed without significant information loss was largely subjective and therefore did not lend itself to a unique solution.

Two separate data tapes were created using the computer program previously described. Each of the tapes contained data pertaining to tracking runs 136 through 142 but they differed in the amount of data which each contained. The initial tape (tape I) created from the raw data tape contained gun azimuth and elevation tracking data and mirror drive position data, along with corresponding time data. Logical records pertaining to times when the lead enable switch was engaged and those corresponding to simulated firings were not transcribed. Thus, only logical records which pertained to normal tracking were transformed and copied to the new tape. The volume of the raw data was reduced by processing and transcribing every 22nd logical record of the tracking data. Since the raw data was recorded at 106.55 logical records per second, transcribing every 22nd record reduced the data to a sequence occurring approximately 4.84 times per second. The rationale for choosing each 22nd record was to obtain tracking data points at approximately 0.2 second intervals. A 0.2 second interval between logical records was chosen because previous fire control testing at APG, similar to that being investigated in this thesis, had employed a data base collected at 0.2 second intervals. Subsequent analysis of the data collected at this rate had been practical in terms of the amount of computer core storage required and also had provided a satisfactory record of the dynamics of the tracking process.

A preliminary analysis of the test data included plotting gun tube azimuth and elevation data versus time for each tracking run. The plots obtained for tracking run number 136 are representative of those obtained for other tracking runs. These plots are shown in Appendix A (Figures 3 and 4). The data transcribed on the initial data tape was also printed so that the character of the data could be examined for each logical record. As will be explained in detail in the section concerning Data Analysis Methodology to follow, the relationship between varying filter delta time intervals and mean gun tube azimuth error rates was analyzed. Based on the analysis of the data contained on tape 1, it was concluded that a subsequent tape (tape 2) should be produced from the raw data tape. The decision to create a second tape for analysis purposes was motivated by the need to obtain greater resolution for the optimal time span for the tracking rate filter than the 0.2 second interval would permit. Additionally, empirical evaluation of the azimuth and elevation data revealed erratic fluctuations in adjacent logical records which suggested the need to perform a smoothing process on the raw data to eliminate the observed aberrations.

Appropriate changes were made in the data reduction program so that the gun tube azimuth and elevation data on every third logical record was processed by a data smoothing routine. Processing each third logical record of the raw data tape resulted in a data recording density which averaged 35.52 logical records for each second of tracking time. In order to further reduce the number of logical records recorded per second, only each second logical record of the smoothed data was transformed and subsequently transcribed to magnetic tape 2 for analysis. The transcription of each second record of the smooth data sequence resulted in a recording rate which averaged 17.75 logical records per second. As previously noted, the time between adjacent logical records was not constant and for this reason the time interval between subsequent logical records on the transcribed tape was either 0.05 seconds or 0.06 seconds. Tape 2 included mirror drive position data, and event code data in addition to time, and gun tube azimuth/elevation data. The entire tracking, command to fire, lead insert, and firing sequence was included in the data transcribed to the second analysis tape, whereas tape 1 included only logical records pertaining to perids when the gunner was in the normal tracking phase.

The smoothing routine utilized in the data reduction program to smooth the gun tube azimuth and elevation tracking data used the technique of taking running medians of three until convergence. The method was developed by John W. Tukey. The Fortran coding of the smoothing algorithm was taken from a text entitled "Interactive Data Analysis" by Donald R. McNeil [4].

# V. DATA ANALYSIS METHODOLOGY

The purpose of this section is to describe the analysis which was conducted regarding the optimal "delta time" to use in a tank fire control tracking rate filter. Several different analysis approaches were utilized in this thesis. Each approach will be described and will be followed by the conclusions which were drawn from the analysis.

## A. AZIMUTH TRACKING ERROR

Tape I was used as the data base for the analysis of gunner mean azimuth tracking errors as a function of delta time. The procedure employed was to investigate how the gunner azimuth tracking error changed as the delta time (averaging time) was increased from zero to a maximum of approximately 10.25 seconds. The reader will recall that because of the way the time data was initially recorded there was not a constant time interval between each logical record of data. The time between the logical records used in this analysis was either 0.20 seconds or 0.21 seconds. The delta time steps used in the averaging process were at either of these time intervals. For the sake of clarity the following discussion will consider that the time between successive logical records was a constant 0.20 seconds.

Two different procedures were used to calculate mean gunner azimuth tracking error. The first procedure (procedure 1) employed was to start at the beginning of the tape containing the test data and calculate the mean gunner azimuth tracking error by grouping the logical records into N-tuples where N was increased from 1 to 50 in increments of 1. Considering data records in groups of N-tuples corresponded to a delta time averaging interval of (N-1)(0.20 seconds), depending on the assigned value of N. As an example when N equalled 1, the tracking error from all logical records was taken individually and a mean was taken of the entire group. This corresponded to a zero delta time. When N equalled 2, the mean error was computed for each adjacent logical record pair and the mean of all the pairs was taken as the tracking error for a delta time corresponding to 0.2 seconds. The effect of this averaging procedure was to "leap frog" through the data by grouping logical records 1 and 2 as a pair, 3 and 4 as the second pair until finally K-1 and K constituted the final pair. An analogous "leap frog" effect occurred when the logical records were grouped as 3-tuples on through 50-tuples. Logic in the Fortran analysis program detected time breaks in the normal tracking data caused by simulated firings and skipped these areas in the averaging computations. A general description of the Fortran program used to accomplish the foregoing is located at Appendix B, flowcharts 1 and 2.

The second method (procedure 2) employed to compute mean azimuth tracking error was to calculate the error for increasing delta time intervals starting with the last logical record prior to a simulated firing sequence, proceeding backward in time. The rationale for using this scheme was based on the idea that the gunner's tracking performance was most likely best (had minimum error) prior to a simulating firing. By investigating mean tracking errors in the critical time just prior to firing it was hoped that some relationship between mean gunner error and delta time could be established which was not detectable by the first procedure employed. Delta time was increased in increments of 0.2 seconds by including 1 additional logical record in the averaging process each time the computation was repeated. Mean errors were calculated for each tracking segment prior to a firing sequence and then these means were combined to form an overall mean for the entire block of data. Flowchart 4 gives a description of this procedure.

At this point it is appropriate to recall that the analysis being conducted involved searching for an optimal delta time to assign to the tracking rate filter in a tank fire control lead prediction algorithm. Lead prediction as used in the context of this thesis involves the problem of determining the angular amount by which to augment the gun firing azimuth in order to compensate for the lateral motion of a moving target. The point to be made is that the solution of the lead prediction algorithm provides a correction to azimuth, not elevation. Because of this consideration the analysis conducted in this thesis is keyed on searching for an optimal delta time which will minimize azimuth firing error. Errors occurring in elevation are not considered in the analysis.

A scatterplot of delta time versus azimuth error in mils for analysis procedure 1 and 2 is shown in Figures 5 and 6 respectively. The mean tracking error in each of these scatterplots decreases as delta time increases. During the tracking sequence the gunner's failure to perfectly track the target in azimuth results in positive azimuth tracking errors when he overleads the target and negative errors when he underleads. With increasing delta time these positive and negative errors tend to cancel themselves resulting in a mean tracking error which approaches zero. Comparison of the mean azimuth tracking errors of the two procedures for delta time values between zero and approximately 1 second shows that the mean errors are less for procedure 2. In procedure 2 the errors were computed starting just prior to the firing sequence moving backward in time. This suggests that the gunner was tracking the target with less average error in azimuth just before the firing sequence than at other times in the tracking sequence. Each gunner who participated in the test was told prior to the initiation of testing that he should track the target as conscientiously during non-firing tracking sequences as during the firing sequences. Even though each gunner was given these instructions, the lower mean errors just prior to a firing tend to reveal the human inclination to perform most effectively during those times he perceives to be most important.

The conclusion to be drawn from the foregoing analysis is simply that increasing delta time periods increase the chances that the gunner's positive and negative azimuth tracking errors will cancel themselves, thus resulting in a mean tracking error tending to zero. This result seems to argue that perhaps only large delta times should be considered for use in the fire control lead prediction algorithm. This consideration will be addressed again in the analyses to follow.

## B. AZIMUTH TRACKING RATE ERROR

Analysis of the mean azimuth tracking rate error as a function of delta time was accomplished in a manner very similar to that described for the mean azimuth tracking error. Again, tape I was used as the data base for the analysis. Analysis procedure I and 2 were modified so that mean azimuth tracking rate errors were calculated where mean azimuth error had been previously computed. The modified versions of procedures I and 2 will be referred to as procedures 3 and 4 respectively.

As was the case for its counterpart, procedure 3 grouped the logical records of data into N-tupes where N was iterated from I to 50 in I unit increments. Azimuth tracking rate error was computed between adjacent logical records by subtracting the error for the i'th record from the (i'th + I) record error and by dividing this result by the time between the two records. Delta time intervals were increased according to the expression (N)(0.20 seconds). As an example when N equalled I the error rate calculation was:

$$\frac{\frac{2-1}{\Delta} + \frac{3-2}{\Delta} + \ . \ . \ . \ + \frac{K-(K-1)}{\Delta}}{K-1}$$

where K = total number of logical records in data base

$\Delta$ = time between adjacent logical records.

For a delta time interval of 0.40 seconds, which would be the case when N equalled 2, the computation was:

$$\frac{\dfrac{\frac{2-1}{\Delta}+\frac{3-2}{\Delta}}{2}+\dfrac{\frac{4-3}{\Delta}+\frac{5-4}{\Delta}}{2}+\ldots+\dfrac{\frac{(K-1)-(K-2)}{\Delta}+\frac{(K)-(K-1)}{\Delta}}{2}}{\frac{(K+1)}{2}-1}$$

The general scheme shown above was repeated for delta time calculations through N equals 50. Whenever the program logic detected a time break in the tracking sequence this interval was skipped and the rate calculations were continued for the logical records following the break. A description of the procedure 3 error rate computation is given in flowchart 3.

As in analysis procedure 2, procedure 4 located the last logical record prior to a simulated firing sequence and began error calculations starting at that point proceeding backward in time. As before, the size of the N-tuple in a given interation of the analysis procedure governed the length of the delta time period. In general the delta time period was (N) (0.20 seconds) for any given N. The value of N was incremented in steps of 1 from an initial value of 1 to a maximum value of 50. The rationale for beginning error rate computations just prior to a simulated firing sequence was the same as outlined in the discussion of analysis procedure 2. Procedure 4 is described in flowchart 5.

The results of the mean azimuth error rate computations for procedure 3 and 4 are shown in Figures 7 and 8 respectively. The plots clearly indicate that the error rate decreases as the interval of delta time increases. This result is similar to that which was obtained in the case of the mean azimuth error. The explanation for the decreasing trend again lies in the fact that as delta time becomes greater, the positive and negative tracking rates begin to cancel themselves resulting in a mean tracking rate error which approaches zero. It is interesting to compare the slopes of the mean error rate scatterplots (Figures 7 and 8) with the slopes of the mean error scatterplots (Figures 5 and 6). The slopes of the error rate plots are greater than those for the mean error plots. The difference in the steepness of these slopes can be explained as follows. Positive and negative azimuth tracking errors are the result of tracking first in front of the target and then behind the target. In order to generate positive and negative azimuth tracking error rates it is not necessary to track back and forth across the target. Positive (negative) error rates can be caused by nonconstant movement of the turret even though throughout the period that the errors are generated the gun tube is always leading (lagging) the target. Based on the foregoing it seems reasonable to expect a higher rate of error cancellation of mean azimuth error rates, as compared to those of mean azimuth errors, for a given interval of time.

The magnitude of the mean azimuth tracking rate errors are smaller for procedure 4 than for procedure 3. This supports the earlier observation that the gunner tended to track the target with less error just prior to a firing sequence than during those times when a firing was not eminent.

The results of analysis procedures 3 and 4 did not reveal any significant information regarding the optimal value for a delta time that had not been observed in analysis procedures 1 and 2. All four of the analyses demonstrated that mean error could be reduced by increasing the length of the delta time interval.

## C. TOTAL TARGET AZIMUTH ERROR (MODEL I)

The data base used for the analysis discussed in this section employed the data recorded on tape 2. This was the second tape which was transcribed from the magnetic tape containing the raw test data. The time interval between the logical records on tape 2 was either 0.05 seconds or 0.06 seconds. The data contained on tape 2 represented each of the four phases of each tracking run. This is contrasted to tape 1 which contained only data pertaining to periods when the gunner was in the normal tracking sequence.

The method of analysis described in this section was the initial attempt to quantity azimuth error as function of turret rate, gunner error, target rate and delta time. This was done in the following manner.

The first step in the analysis process was to establish a common coordinate system in which to express the turret and target positions. This step was necessary in order to be able to define relationships between target motion and turret motion which would permit computation of total target azimuth error as functions of these motions.

Among the elements of data contained in each logical record of tape 2 was the mirror drive position expressed in radians. The range of the mirror drive position data was 0 to $2\pi$ radians. The mirror drive position data represented the position of the target (the laser spot) as it moved back and forth across the target screen. Since the target motion was sinusoidal, taking the sine of the mirror drive data resulted in transforming the position of the target to a scale ranging from -1 to +1. The radius of the projection path across the target screen was computed to be 60.323 centimeters therefore by multiplying the converted mirror drive position data by this value the target motion could be expressed in centimeters with a range of -60.323 to +60.323. In order to have a coordinate system with zero as an origin, the scale was shifted in a positive direction by adding 60.323 to each coordinate value. The result was a coordinate system which reflected the target motion on a scale ranging from 0 to 120.646 centimeters. The corresponding range of this coordinate system expressed in mils was 0 to 38.163 mils.

The azimuth tracking data recorded as an element on each logical record indicated the deviation of the gun sight from the target in mils. The sign convention employed when this data was initially collected was to assign a negative value to the deviation when the sight was to the right of the target and to assign a positive value when the sight was to the left of the target. With the knowledge of the target location and with the known deviation between the gun sight and the target it was possible to locate the position of the sight in the target coordinate system. Expressed in symbols the relationship was as follows:

$$X = Y - Z$$

where

X = coordinate of the gun sight

Y = coordinate of the target

Z = deviation in azimuth between the gun sight and the target

Having achieved the goal of creating a coordinate system common to both the sight and the target the next step in the analysis was to derive an expression for target azimuth error which would be a function of the gun and target parameters, as well as delta time.

For the sake of clarity it is appropriate to point out that the gun sight rate computed in this analysis is equitable to the turret rate. The only time when these quantities would not be identical would be for a moment of time directly following the gunner's activation of the lead lock enable switch. That period of time is not pertinent to this analysis therefore gun sight rate and turret rate should be considered to be synonymous.

In this analysis the model used to compute the total target azimuth error was:

$$E(\Delta t) = G(\Delta t)TOF - B - (F)TOF$$

$$= (G(\Delta t) - F)TOF - B$$

where $E(\Delta t)$ = Total target azimuth error (mils)

$G(\Delta t)$ = Mean turret rate delta time before lead insertion (mils/sec)

TOF = Projectile time of flight (sec)

B = Gunner error in azimuth at firing (mils)

F = Mean target rate during the TOF (mils/sec)

$\Delta t$ = Denotes that the parameter is a function of delta time (sec)

The azimuth error computed using the model above will be positive when the target miss occurs to the right of the target and will be negative when the miss occurs to the left of the target. The first and last terms in the equation will cancel themselves when the mean turret rate before lead insertion equals the mean target rate during the projectile time of flight. When these two rates are identical the lead computed by the fire control prediction algorithm will equal the true lead required to hit the target. The gunner azimuth error at the time of lead insertion was used in the model as a substitute for the gunner azimuth error at the time of trigger pull. The actual gunner azimuth error at the time of firing could not be computed from the data which was transcribed on analysis tape 2. After lead insertion the gun tube azimuth no longer coincided with the sight azimuth thus the position of the sight relative to the target could not be determined. All of the computations performed in this thesis used the gunner azimuth error at lead insertion as a surrogate for the actual gunner azimuth error at the time of firing. In this analysis although it was not possible to determine how closely the gunner azimuth error at lead insertion approximated the gunner azimuth error at firing, it seems logical that any error caused by this approximation is not large. Tank gunners are taught in their gunnery instruction to obtain an estimate of the target movement rate prior to lead insertion by tracking the target center of mass. After lead insertion has been accomplished the gunner resumes tracking of the target center of mass until firing has occurred. Since the gunner is theoretically tracking the target center of mass at both lead insertion and at firing, the error at these two distinct times should be highly positively correlated.

The projectile time of flight used in this analysis was 1.0699 seconds. This parameter value was obtained from AMSAA and it represents the expected length of time required for a projectile to travel a distance of 1500 m.

Flowcharts of the Fortran program used to accomplish the computations described in this section are located in Appendix B, flowcharts 8 through 15. The actual azimuth error computation is accomplished in the subroutine described in flowchart 12.

A scatterplot of the total target azimuth error versus delta time is shown in Figures 9 and 10. Figure 9 shows the mean azimuth error over a delta time interval ranging from 0.06 seconds to 5.59 seconds. The delta time interval was expanded from its lower value to its upper value by including one additional logical record in the error calculation each time the computational loop was repeated. This resulted in an incremental delta time step of either 0.05 seconds or 0.06 seconds. The maximum delta time value of 5.59 seconds represented the inclusion of 100 logical records in the azimuth error computation. The plot shown in Figure 10 reflects the azimuth error result when a maximum number of 33 logical records were used in the computation. Limiting the maximum number of logical records (used in the computation) to 33 had the effect of magnifying the detail of the scatterplot for all data points occurring in the delta time interval from 0.06 seconds to 1.81 seconds.

Figure 9 shows that the computed azimuth error is a minimum at a delta time equal to approximately 0.68 seconds, but increases for all delta times which are greater than 0.68 seconds. The point where the minimum error occurs is shown in greater detail in Figure 10. From this figure the delta time corresponding to minimum target azimuth error can be determined to be equal to approximately 0.70 seconds.

In order to gain a clearer insight concerning why the azimuth error minimum occurred at 0.70 seconds a comparison was made of the mean deviation between the turret rate before lead insertion (as a function of delta time) and the target rate during the projectile time of flight. It can be seen from the target azimuth error equation that azimuth error is sensitive to differences between these two rates. Figures 11 and 12 show the results of the rate comparison. Both of these figures show that the minimum deviation between the turret rate and target rate occurred at a delta time interval near 0.70 seconds. Comparison of Figure 11 with Figure 9 shows that the two plots are essentially identical with the exception that minimum ordinate of Figure 11 is slightly less than that of Figure 9. This difference is caused by the inclusion of the gunner azimuth error at lead insertion in the target error computation whereas this error was not included in the rate comparison.

The results of this analysis demonstrated that azimuth error is highly sensitive to the error which results because the turret rate before lead insertion is not equal to the actual target rate after firing. In contrast to the error identified above, the error resulting from the gunner's failure to have the sight reticle on the target in azimuth at the time of firing was not great. This suggests that the magnitude of the target azimuth error is very dependent upon the effectiveness of the fire control lead prediction algorithm.

After the analysis described above had been accomplished, a critical appraisal of the target azimuth error model was made for the purpose of identifying improvements which could be made in the model structure. Keeping in mind that the primary purpose of the entire analysis was to investigate the principal dynamics of azimuth error as a function of delta time, it was considered desirable to redefine the model in terms more descriptive of the real world. The redefinition of the model and the subsequent analysis on the elucidated model are described in the next section.

D. TOTAL TARGET AZIMUTH ERROR (MODEL 2)

This analysis was similar in many respects to the analysis described in the preceding section. The analysis was conducted on the data recorded in tape 2 and made use of the procedures required to construct a target coordinate system based on the mirror drive position data.

The model used to compute total target azimuth error as a function of delta time, target rate, turret rate and gunner error was a summation of three sources of azimuth error. The first source of error was that error caused by an incorrect lead computation resulting because the turret rate was not equal to the target rate in a variable delta time interval prior to lead insertion. The difference between these two rates multiplied by the time of flight of the projectile is equal to the error due to incorrect lead. This first error is called lead prediction error. The second source of error identified in the model is the error created as a result of the gunner's failure to place the sight reticle on the target center of mass in azimuth at the time of firing. This error will be referred to as gunner azimuth error. The third and final source of azimuth error included in the model is that error caused by a target rate after firing which is different from that computed during a given delta time interval prior to the gunner's insertion of lead. The difference between these two target azimuth rates multiplied by the projectile time of flight will be called the target induced error. The target induced error reflects the error caused by evasive movement of the target after firing which was not predicted based on the target's movement in a delta time interval prior to lead insertion. As an example, it would be logical to expect that target induced error would be high for target vehicles possessing high mobility/agility. The model composed of the errors just described can be expressed as follows:

$$E(\Delta t) = A(\Delta t) + B + C(\Delta t)$$

$$= (D(\Delta t) - G(\Delta t))TOF + B + (F - D(\Delta t))TOF$$

$$= (F - G(\Delta t))TOF + B$$

where

$E(\Delta t)$ = Total target azimuth error (mils)

$A(\Delta t)$ = Lead prediction error (mils)

$B$ = Gunner error in azimuth at firing (mils)

$C(\Delta t)$ = Target induced error (mils)

$D(\Delta t)$ = Mean target rate delta time before lead insertion (mils/sec)

$G(\Delta t)$ = Mean turret rate delta time before lead insertion (mils/sec)

TOF = Projectile time of flight (sec)

$F$ = Mean target rate during the TOF (mils/sec)

$\Delta t$ = Denotes that the parameter is a function of delta time (sec)

The target azimuth error expressed by this model will be positive if the target miss occurs to the left of the target and will be positive for misses to the right of the target.

From an examination of the model above it can be seen that the product $D(\Delta t)$TOF occurs twice and that it cancels itself. After the cancellation of these terms the resulting model is identical to the model used in the previous analysis of the total target azimuth error. The value of expressing the model as it is done in this analysis is to permit the total target azimuth error to be segmented into three distinct sources of error. By quantifying the azimuth error in terms of its unique sources it was hoped that insights could be gained concerning which of these three sources contributed most significantly to the total error.

General flowcharts of the Fortran program used to implement the azimuth error model are located in Appendix B, flowcharts 8 through 15.

The results of the analysis described in this section will be presented by using scatterplots that display total target azimuth error sources as a function of increasing delta time. Because the analysis objective was to gain insights regarding the relationship between the target azimuth error and delta time, emphasis was placed on the general trend of the target error as delta time increased rather than on the magnitude of the error.

The scatterplot of target induced error versus increasing delta time is shown in Figures 13 and 14. These two figures were created from the same data; however, the plot shown in Figure 14 reflects a delta time period which is approximately one-third of that shown in Figure 13. Figure 13 shows a general positive trend in the target induced error beginning at a delta time of approximately 1.0 seconds. This positive trend results because as delta time is increased the mean traverse rate of the turret becomes increasingly less representative of the target rate after firing. As was observed in tracking rate analyses (Section VB), the mean azimuth tracking rate tends to converge to zero with increasing delta time. Figure 14 shows that the target induced error global minimum occurs at a delta time equal to approximately 0.93 seconds. This indicates that for the data used in this analysis the target induced error can be minimized by selecting a delta time of 0.93 seconds. Because the azimuth error model includes two other error sources in addition to target induced error, it cannot be concluded that a delta time of this duration minimizes total azimuth target error.

A scatterplot of the mean deviation between the turret rate and the target rate prior to lead insertion is shown in Figure 15. The deviation in the rate is plotted versus increasing delta time. The deviation multiplied by the projectile time of flight (a constant) represents the source of error earlier identified as lead prediction error. The decreasing trend of this plot reflects an inverse relationship between increasing delta time and the rate deviation. As the delta time interval is increased the instantaneous tracking errors made by the gunner tend to cancel themselves with the result that the average turret rate becomes an increasingly better approximation to the actual target rate.

The two sources of target azimuth error discussed above represent opposite error trends as delta time is increased. The lead prediction error decreases with larger delta time whereas the target induced error increases. The results of the summation of these two sources of error are shown in Figures 16 and 17. This scatterplot shows that the target induced error clearly dominates the lead prediction error. As shown in Figure 17 the global minimum of the sum of these errors occurs at the delta time equal to approximately 0.70 seconds.

The third source of target error not considered in Figures 16 and 17 is the gunner azimuth error at firing. This error is independent of delta time. For the reasons explained previously, gunner error at lead insertion was used as a substitute for the actual gunner error at firing. When the three components of the target azimuth error model are summed and plotted versus delta time, the results are as shown in Figures 18 and 19. By comparing these figures with those shown in 16 and 17 it is apparent that gunner azimuth error at firing (as modeled by the gunner error at lead insertion) is not a major contributor to the total target azimuth error. The plots shown in Figures 18 and 19 are identical to those shown in Figures 9 and 10 thus verifying that the models used in analysis method 1 and method 2 were identical except for the manner in which they were expressed. Both models show that a delta time corresponding to approximately 0.70 seconds results in the minimum total target azimuth error.

Of the three sources of error included in this target error model, the error term which contributes most to the total target azimuth error is the target induced error. The scatterplot shown in Figure 20 represents the mean azimuth error minus the target induced error. Comparison of this figure with Figure 18 shows that the target induced error clearly dominates the other factors in the model. Without the target induced error in the model the total target azimuth error is drastically reduced. Considering the dominance of the target induced error over the other error sources, it is apparent that total target azimuth error can most effectively be minimized by reducing the target induced error.

## VI. CONCLUSIONS

In this thesis several analysis techniques were developed for the purpose of analyzing the tank fire control test data. The analysis objective was to investigate the optimal time (delta time) to assign to the tracking rate filter employed in a tank fire control lead prediction algorithm. An additional objective was to gain insights concerning the dynamics of target error. This involved the identification of sources of target error and the investigation of the relationship between these sources and delta time.

The relationship between azimuth tracking error and delta time was analyzed in Section VA. Both analysis procedures 1 and 2 demonstrated that the gunner mean azimuth tracking error decreased as delta time was increased. The gunner mean azimuth tracking error was shown to be smaller just prior to firing sequence than at other times in the tracking sequence. This suggested that the gunner was motivated to track the target more conscientiously during those times just before a firing sequence than at those times when firing was not imminent.

Analysis procedures 3 and 4 in Section VB investigated gunner mean azimuth tracking rate error as a function of delta time. The results showed that the mean azimuth tracking rate error decreased as a function of increasing delta time.

The results obtained from analysis procedures 1 through 4 demonstrated that the mean azimuth tracking error and mean azimuth tracking rate error could be minimized by assigning large values to the tracking rate filter. The insights gained serve to motivate the subsequent analyses which were conducted but did not provide any findings that isolated a unique value to assign to the tracking rate filter.

Based on the initial analysis it became apparent that subsequent analyses should include the portions of the test data pertaining to the firing sequences as well as the data representing the non-firing sequences. In addition it was concluded that it would not be possible to arrive at any meaningful findings relative to an optimal delta time value unless the interval of time between adjacent data records was reduced by including more records per unit time in the analysis. Based on these findings a second analysis tape was transcribed from the raw test data which included the additional data that was not included in the initial analysis.

Model I described in Section VC was formulated to quantify total target azimuth error as a function of delta time. The results of this analysis procedure showed that minimum target error occurred at a delta time equal to 0.70 seconds. It was determined that error produced by the gunner's failure to have the sight reticle on the center of mass in azimuth was small in comparison to the error caused by movement of the target after firing that was not predicted by the lead prediction algorithm prior to firing.

Analysis Model 2 quantified total target azimuth error as the sum of three individual sources of error. The three sources were lead prediction error, gunner azimuth error, and target induced error. The lead prediction error and the target induced error were investigated individually to determine their characteristics as a function of delta time.

The results of the analysis employing Model 2 revealed an inverse relationship between the lead prediction error and increasing delta time. Target induced error was shown to increase as delta time became greater. The gunner azimuth error was not a major component of azimuth error when compared to the lead prediction error and the target induced error. The target induced error component dominated the other two components in terms of magnitude and therefore was the major contributor to the total target azimuth error. Both Models 1 and 2 demonstrated that total target azimuth error was minimized at a delta time equal to approximately 0.70 seconds.

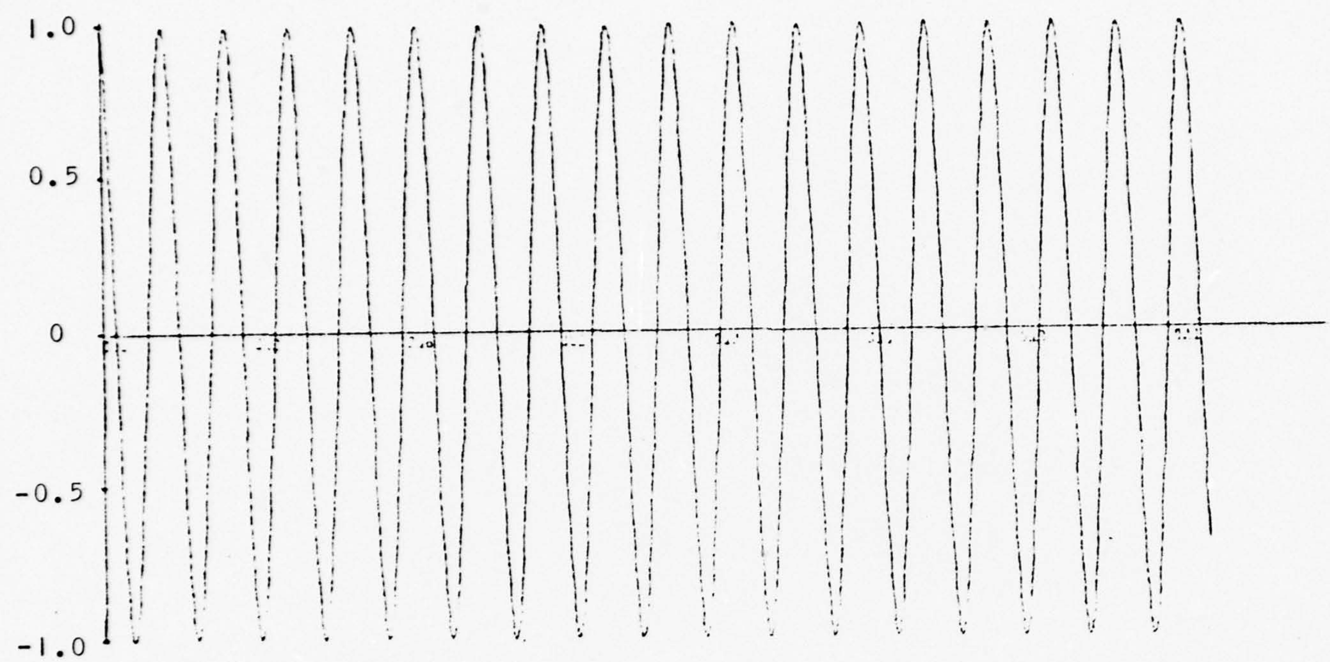
The value of the analysis procedures described in this thesis does not lie entirely in the determination that the minimum total target azimuth error occurred at a delta time of 0.70 seconds. This finding is no doubt dependent on the character of the test scenario and therefore would be expected to change somewhat if other scenarios were used. The importance of the analysis is that it lends insights concerning which components of the total target azimuth error are most dominate and how components vary as a function of delta time.

# APPENDIX A. FIGURES

The figures depicted in this Appendix show plots of the raw test data and results of the analyses conducted in the thesis.

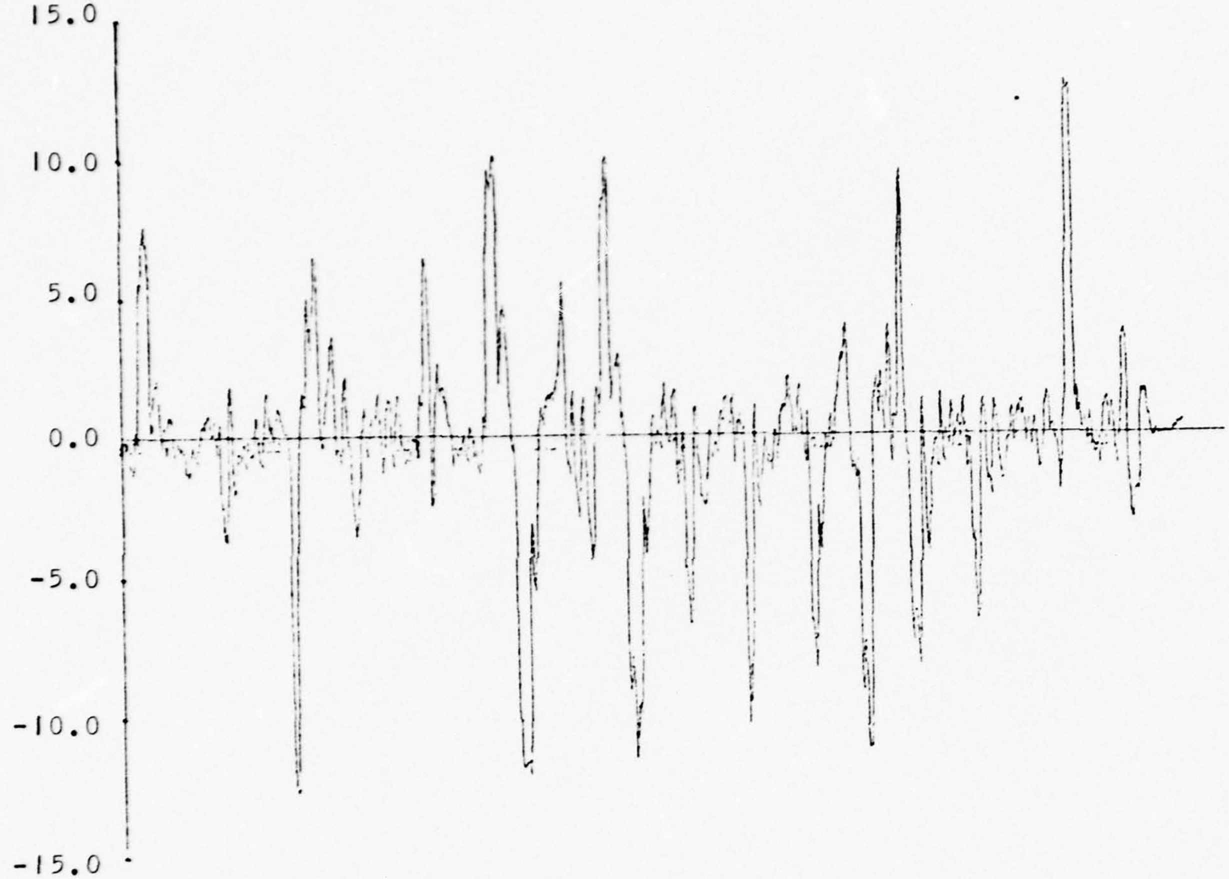
Figures 2 through 4 are plots of the raw test data. Figures 5 through 8 show the results of analysis procedures 1 through 4 respectively.

The results obtained from the analysis employing Model 1 are shown in Figures 9 through 12. Figures 13 through 20 depict the results of the analysis in which Model 2 was utilized.




X-SCALE=3.00E+01 UNITS INCH.
Y-SCALE=5.00E-01 UNITS INCH.
MIRROR DRIVE(SINE) VS TIME(SECS)

Figure 2




X-SCALE=3.00E+01 UNITS INCH.
Y-SCALE=5.00E+00 UNITS INCH.
AZIMUTH ERROR(MILS) VS TIME(SECS)

Figure 3

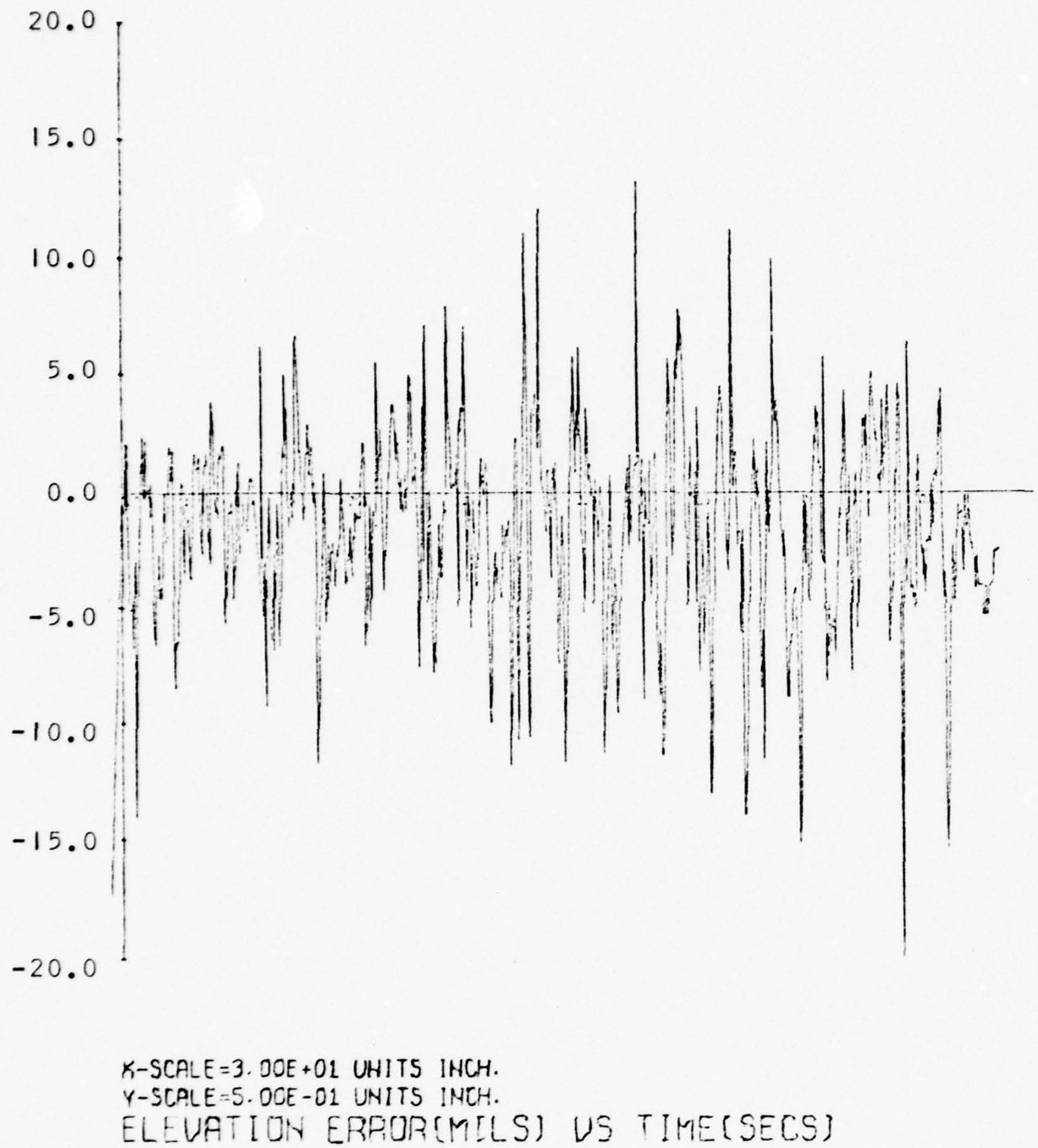
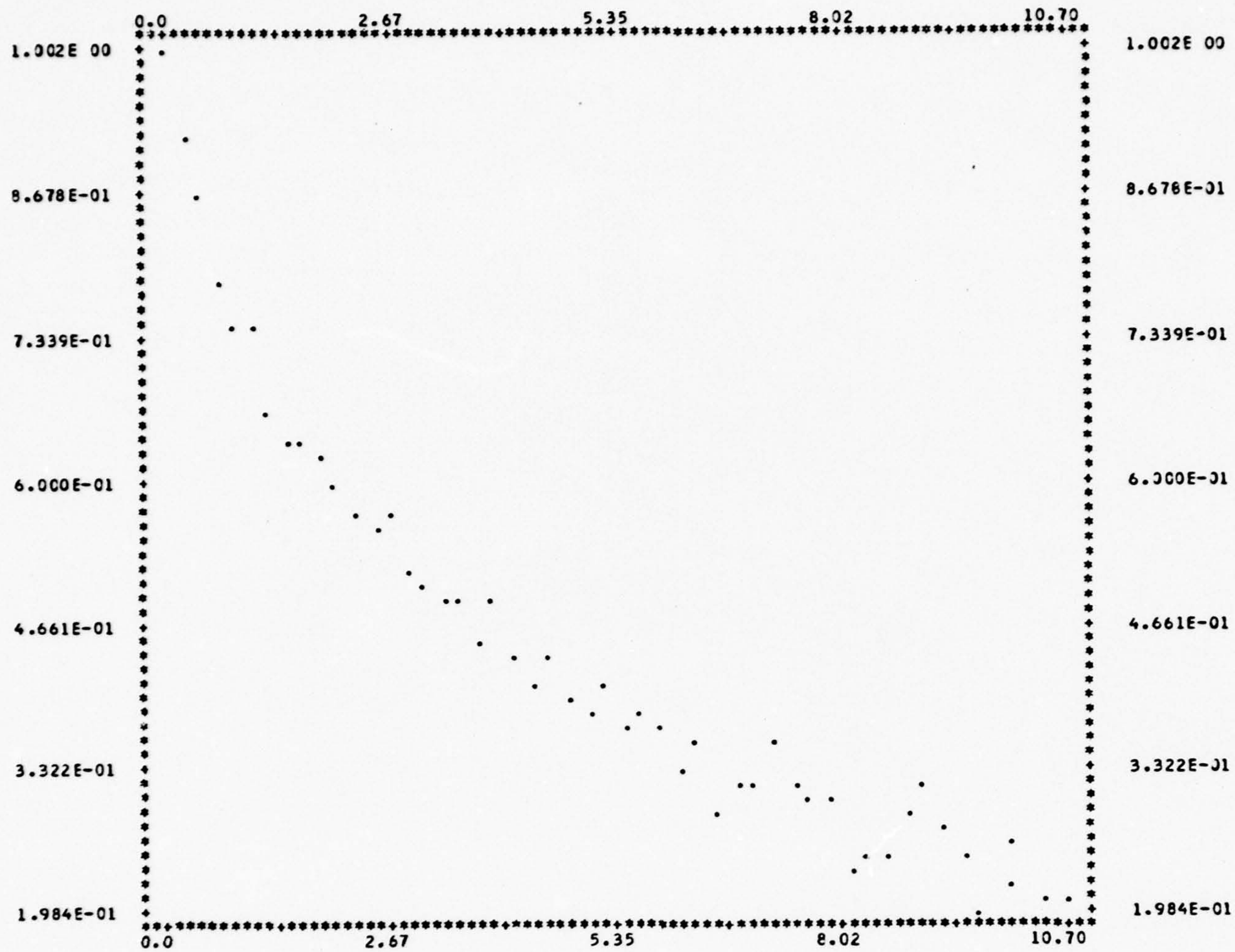

20.0
15.0
10.0
5.0
0.0
-5.0
-10.0
-15.0
-20.0
X-SCALE=3.00E+01 UNITS INCH.
Y-SCALE=5.00E-01 UNITS INCH.
ELEVATION ERROR(MILS) VS TIME(SECS)

Figure 4

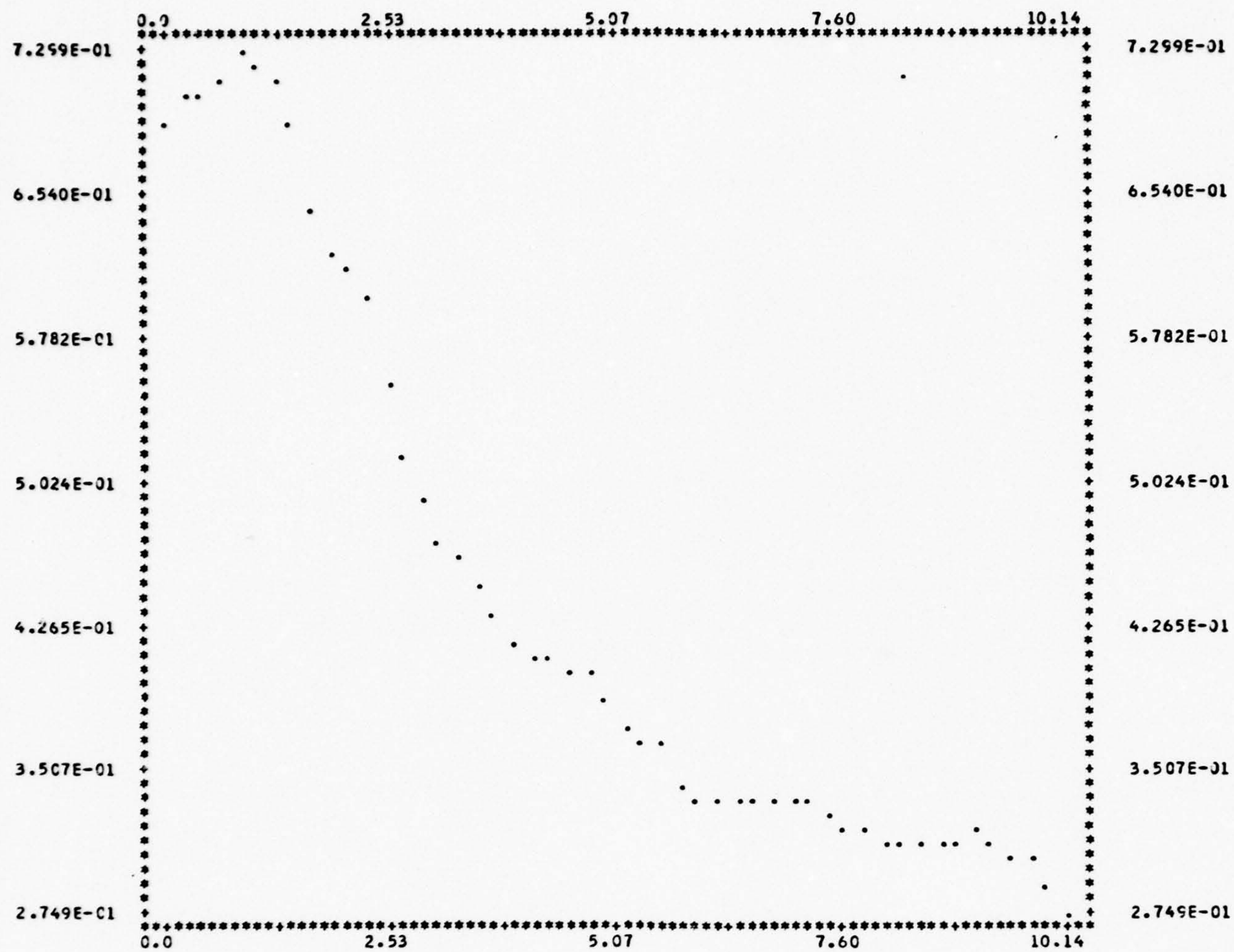



X-SCALE: "*"= 0.134E 00 UNITS

Y-SCALE: "*"= 0.134E-01 UNITS

PLOT OF DELTA TIME(SECS) VS MEAN AZIMUTH TRACKING ERROR(MILS)
(FORWARD IN TIME FROM BEGINNING OF TRACKING SEQUENCE)

Figure 5

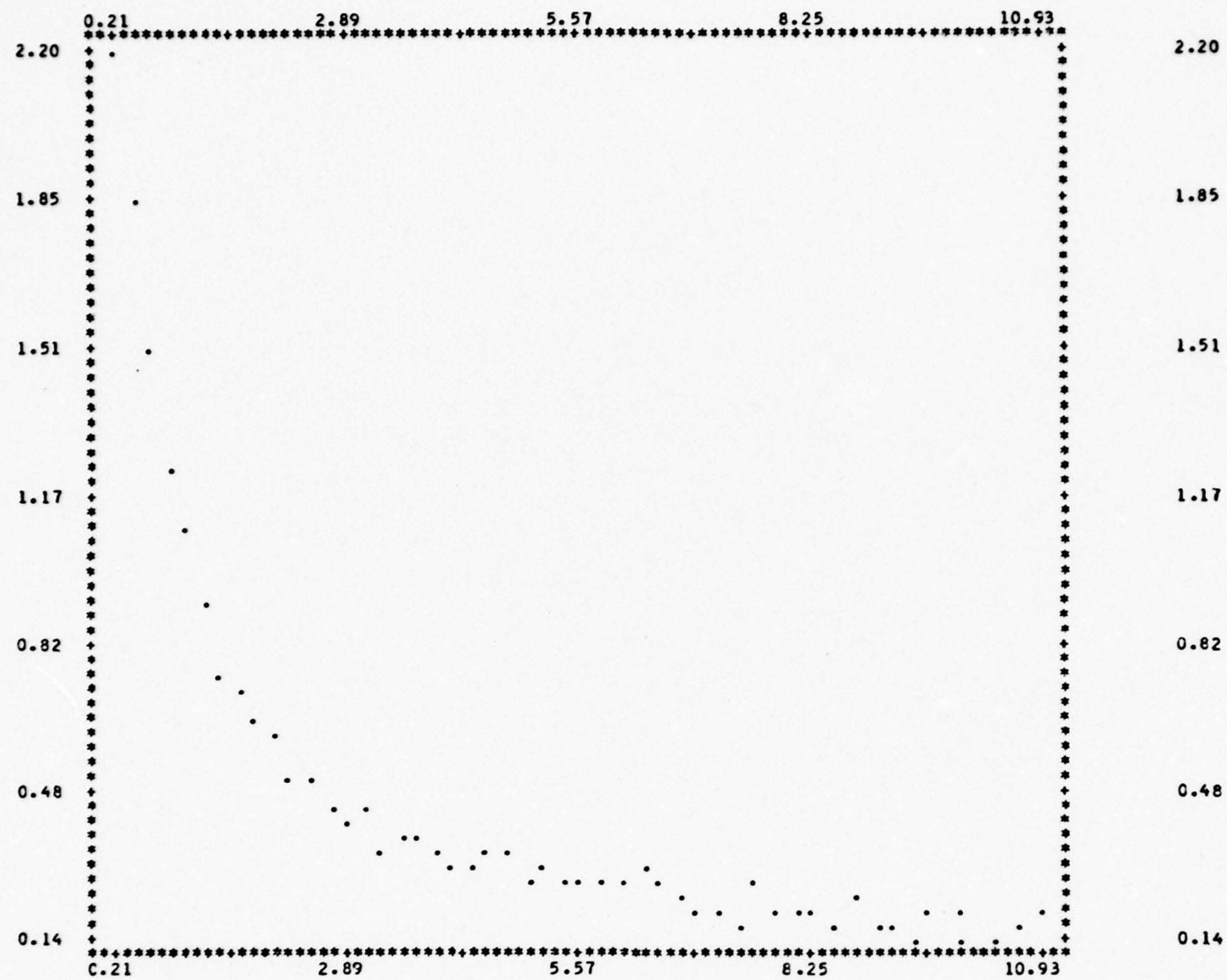



X-SCALE: "*"= 0.127E 00 UNITS

Y-SCALE: "*"= 0.758E-02 UNITS

PLOT OF DELTA TIME(SECS) VS MEAN AZIMUTH TRACKING ERROR(MILS)
(BACKWARD IN TIME FROM LEAD INSERTION)

Figure 6

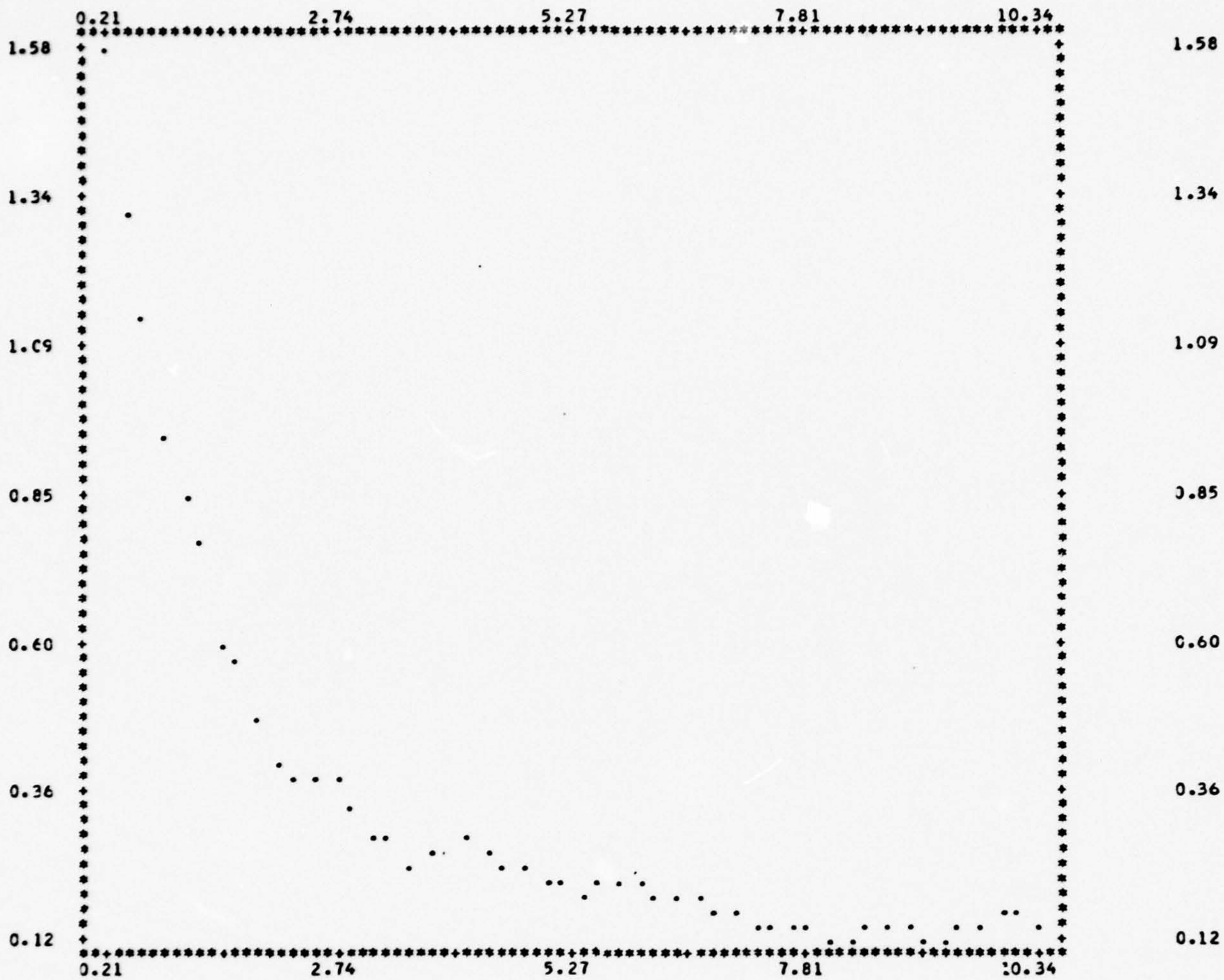



X-SCALE: "*"= 0.134E 00 UNITS

Y-SCALE: "*"= 0.344E-01 UNITS

PLOT OF DELTA TIME(SECS) VS MEAN AZIMUTH TRACKING RATE ERROR(MILS/SEC)
(FORWARD IN TIME FROM BEGINNING OF TRACKING SEQUENCE)

Figure 7

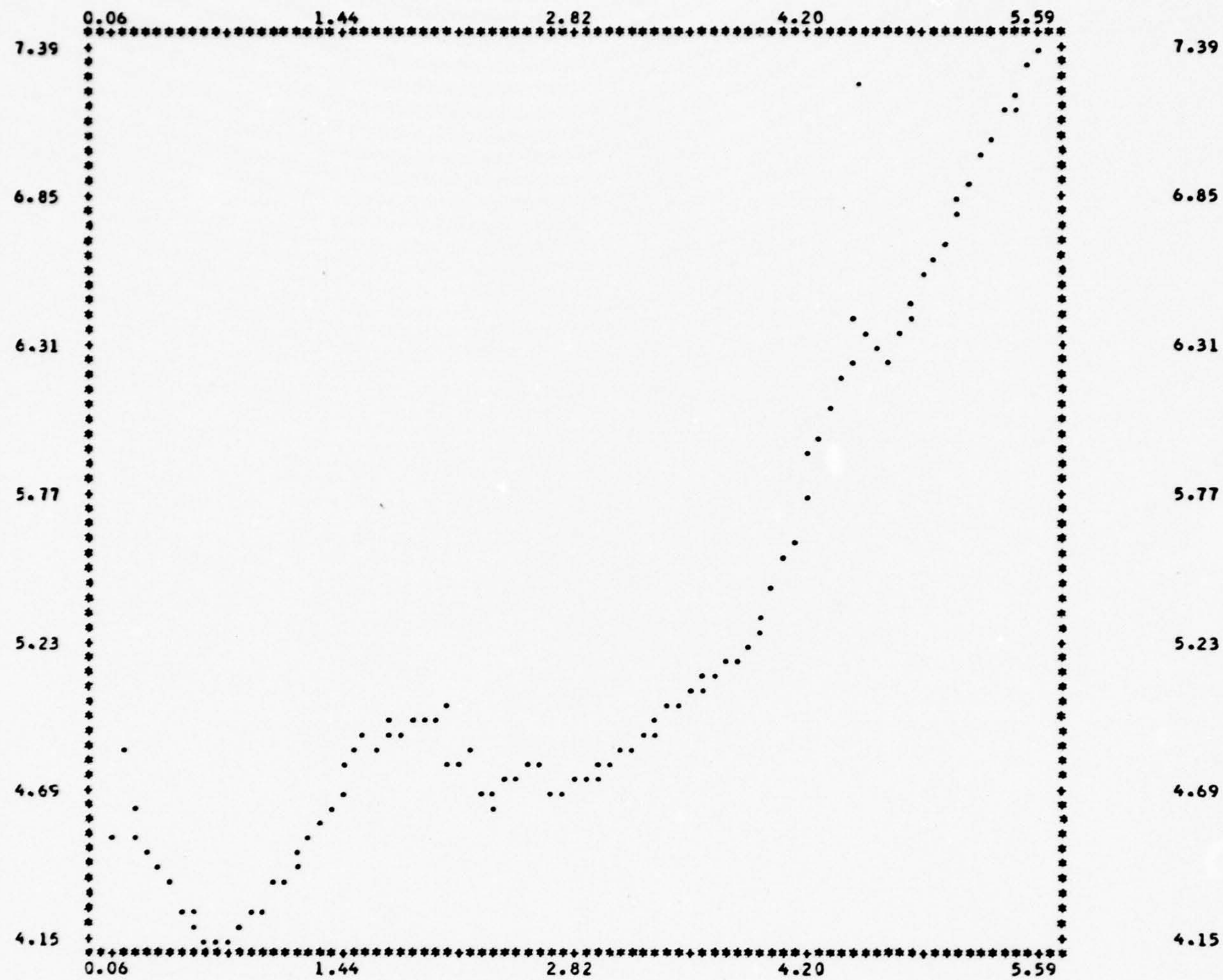



X-SCALE: "*"= 0.127E 00 UNITS

Y-SCALE: "*"= 0.245E-01 UNITS

PLOT OF DELTA TIME(SECS) VS MEAN AZIMUTH TRACKING RATE ERROR(MILS/SEC)
(BACKWARD IN TIME FROM LEAD INSERTION)

Figure 8

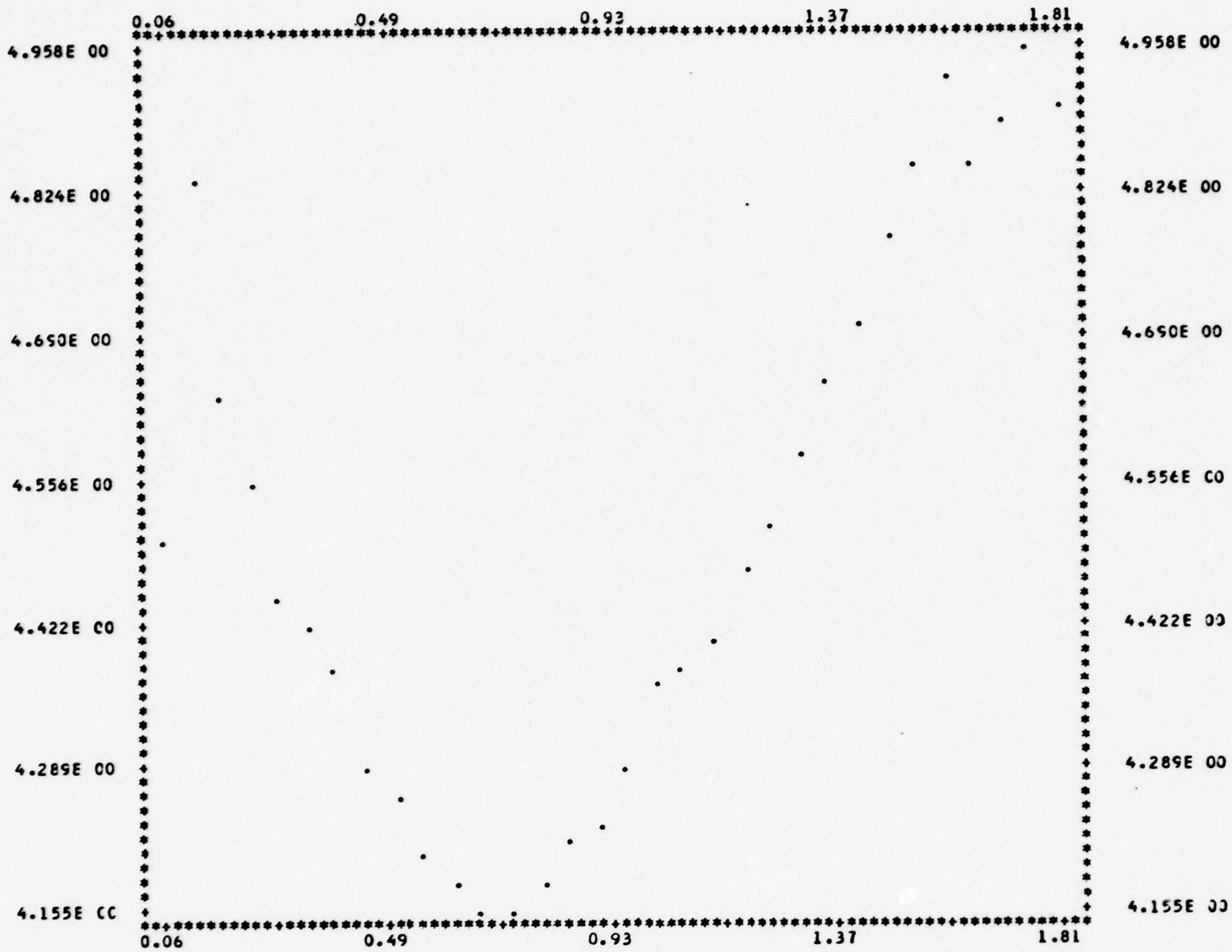



X-SCALE: "*"= 0.691E-01 UNITS

Y-SCALE: "*"= 0.539E-01 UNITS

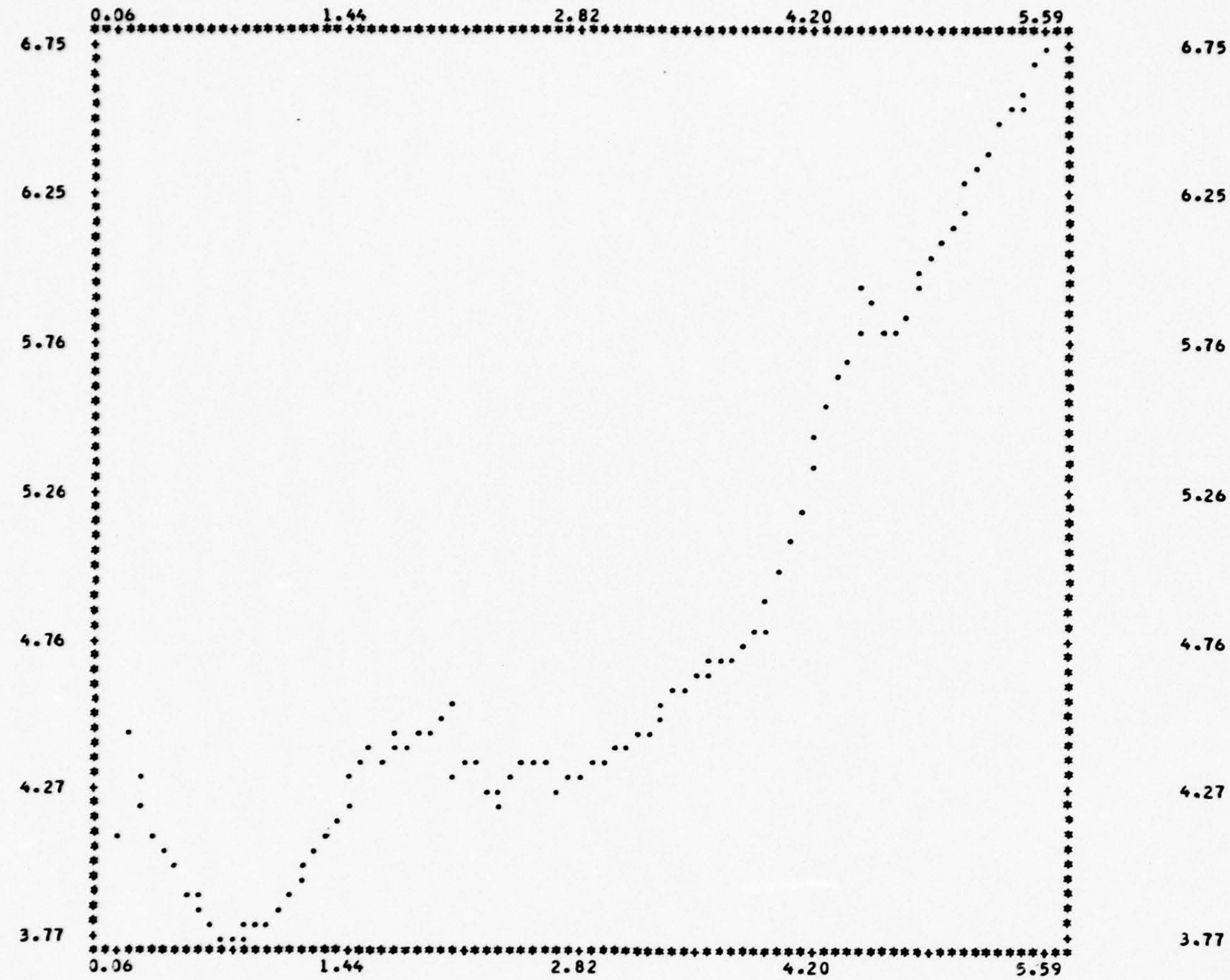
PLOT OF DELTA TIME(SECS) VS TOTAL TARGET AZIMUTH ERROR(MILS)

Figure 9




X-SCALE: "*"= 0.218E-01 UNITS
Y-SCALE: "*"= 0.134E-01 UNITS
PLOT OF DELTA TIME(SECS) VS TOTAL TARGET AZIMUTH ERROR(MILS)

Figure 10

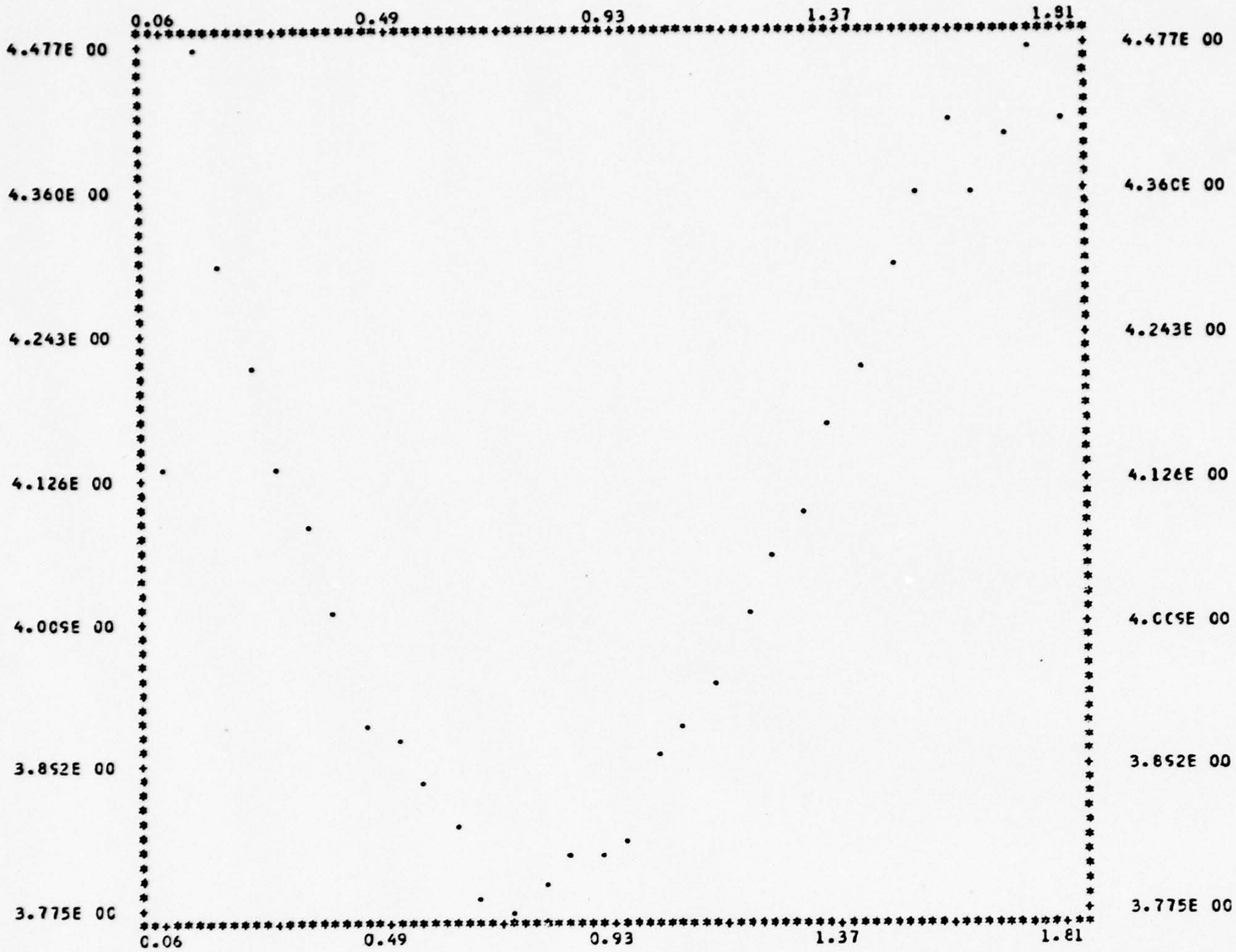



X-SCALE: "*"= 0.691E-01 UNITS

Y-SCALE: "*"= 0.495E-01 UNITS

PLOT OF DELTA TIME(SECS) VS MEAN DEVIATION BETWEEN TURRET AZIMUTH RATE(MILS/SEC) AND TARGET AZIMUTH RATE(MILS/SEC)
(TURRET RATE BEFORE LEAD INSERTION;TARGET RATE DURING PROJECTILE TIME OF FLIGHT)

Figure 11

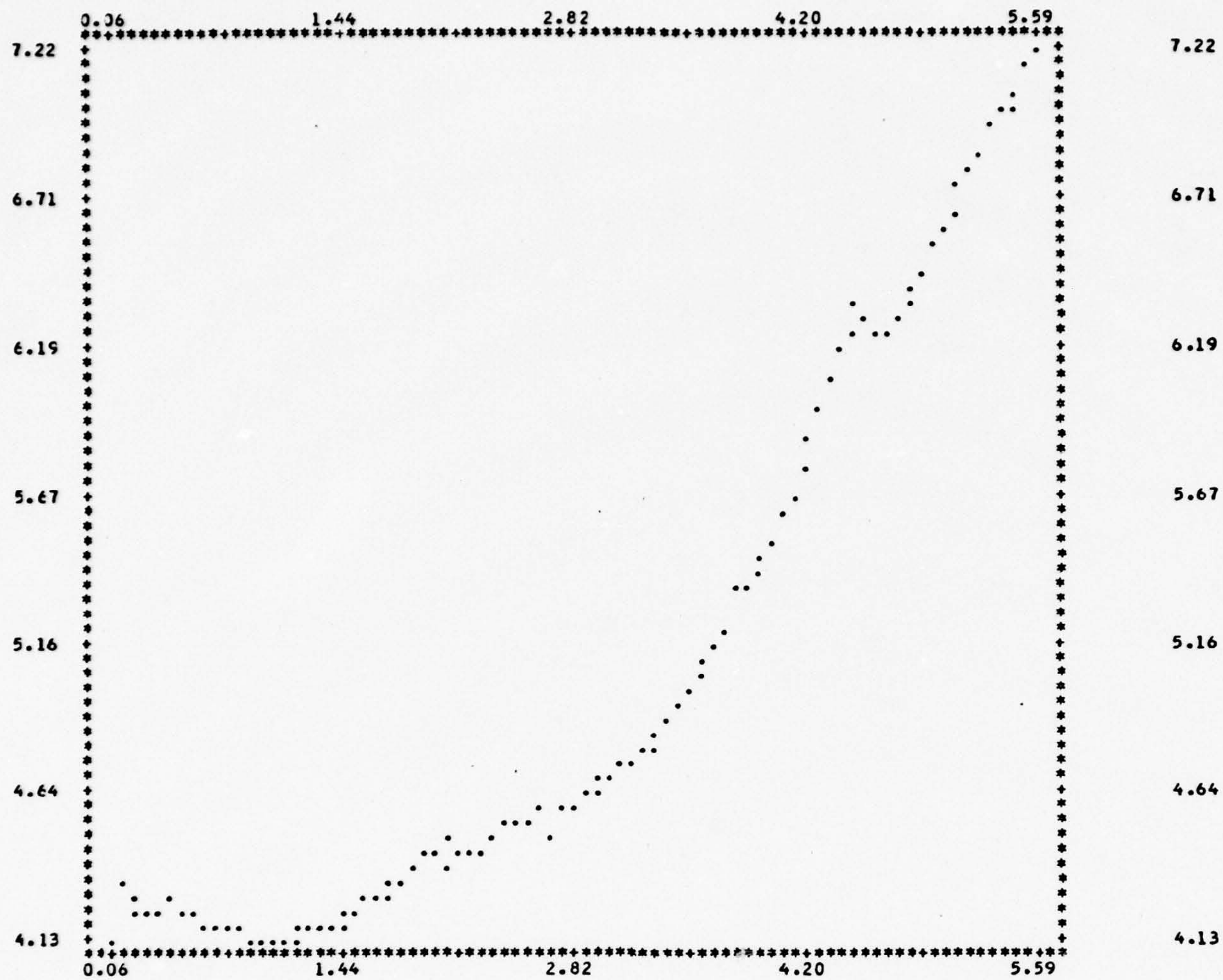



X-SCALE: "*"= 0.218E-01 UNITS

Y-SCALE: "*"= 0.117E-01 UNITS

PLOT OF DELTA TIME(SECS) VS MEAN DEVIATION BETWEEN TURRET AZIMUTH RATE(MILS/SEC) AND TARGET AZIMUTH RATE(MILS/SEC)
(TURRET RATE BEFORE LEAD INSERTION;TARGET RATE DURING PROJECTILE TIME OF FLIGHT)

Figure 12

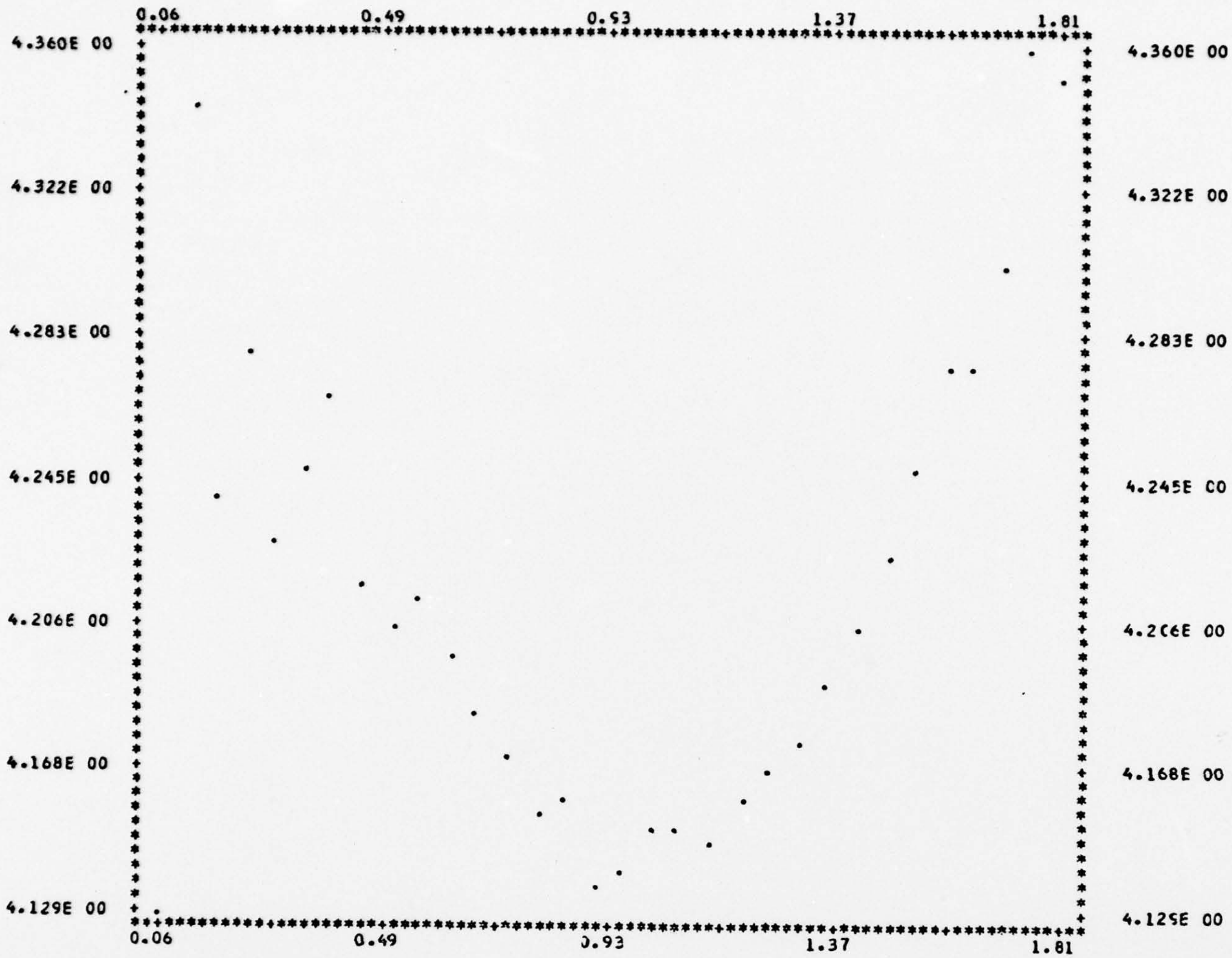



X-SCALE: "*"= 0.691E-01 UNITS

Y-SCALE: "*"= 0.515E-01 UNITS

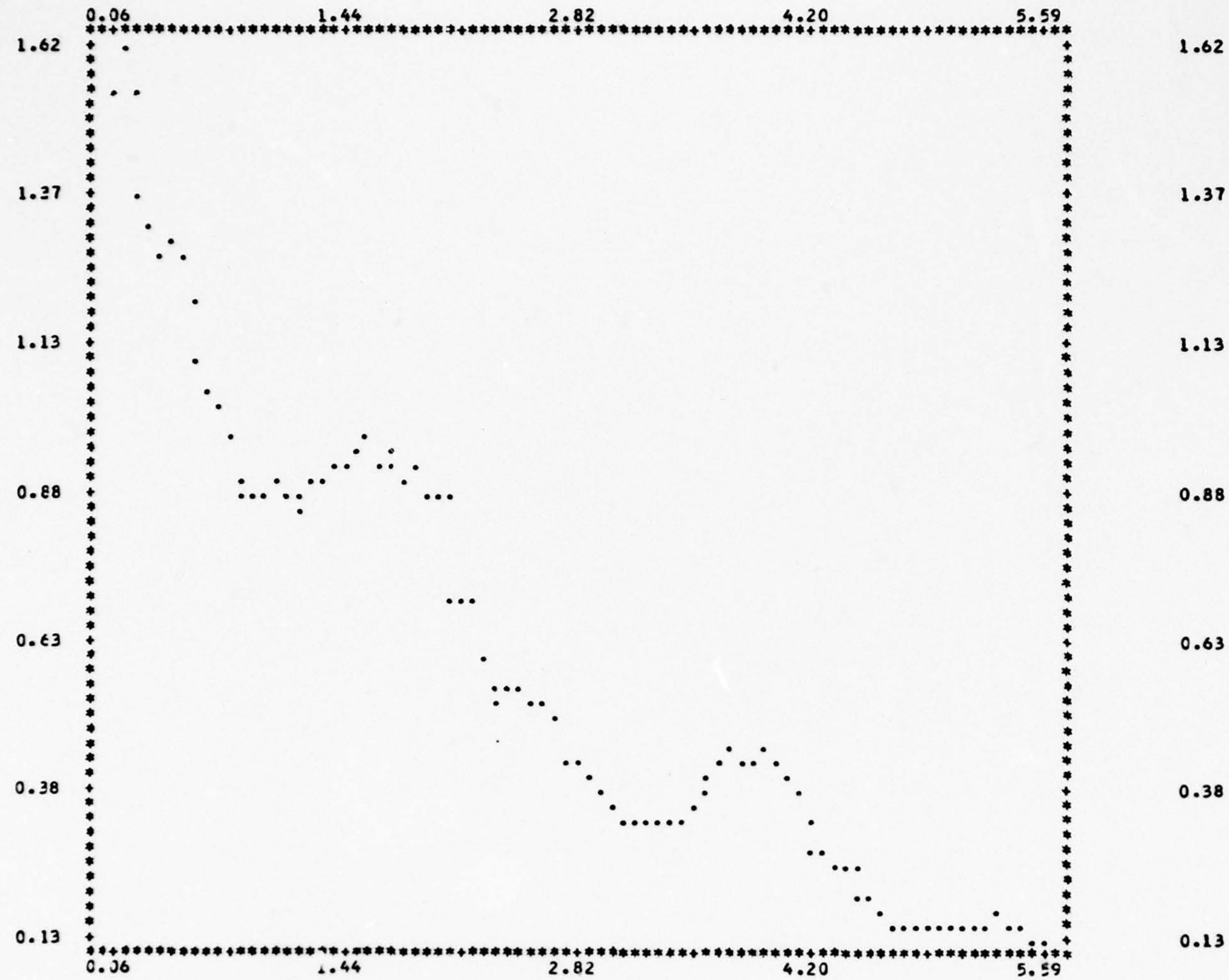
PLOT CF DELTA TIME(SECS) VS MEAN TARGET INDUCED AZIMUTH ERROR(MILS)

Figure 13




X-SCALE: "*"= 0.218E-01 UNITS
Y-SCALE: "*"= 0.384E-02 UNITS
PLOT OF DELTA TIME(SECS) VS MEAN TARGET INDUCED AZIMUTH ERROR(MILS)

Figure 14




X-SCALE: "*"= 0.691E-01 UNITS

Y-SCALE: "*"= 0.248E-01 UNITS

PLOT OF DELTA TIME(SECS) VS MEAN DEVIATION BETWEEN TURRET AZIMUTH RATE(MILS/SEC) AND TARGET AZIMUTH RATE(MILS/SEC)
(BEFORE LEAD INSERTION)

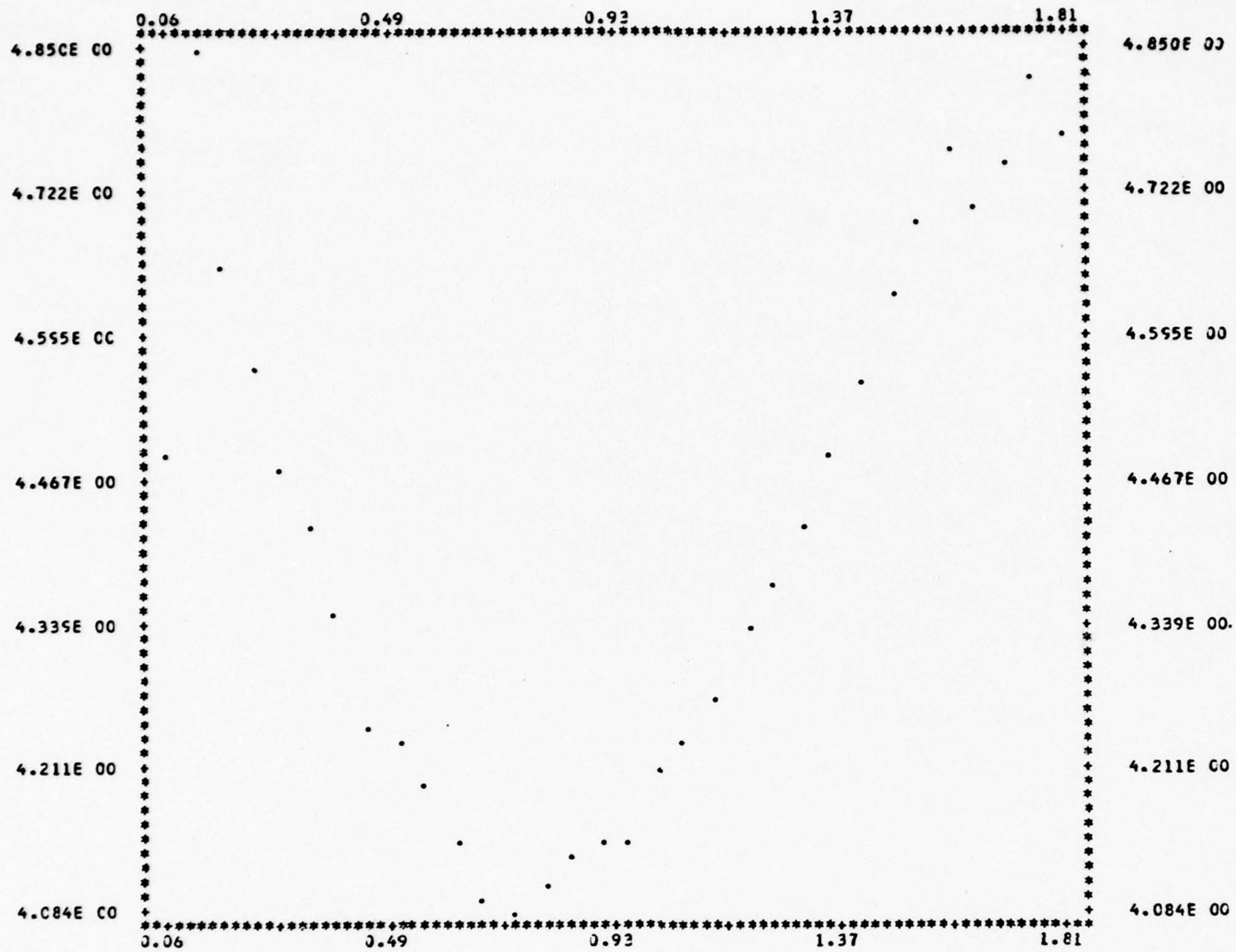
Figure 15


X-SCALE: "*"= 0.691E-01 UNITS

Y-SCALE: "*"= 0.517E-C1 UNITS

PLOT OF DELTA TIME(SECS) VS TOTAL TARGET AZIMUTH ERROR(MILS)
(ZERO GUNNER ERROR ASSUMED AT TRIGGER PULL)

Figure 16

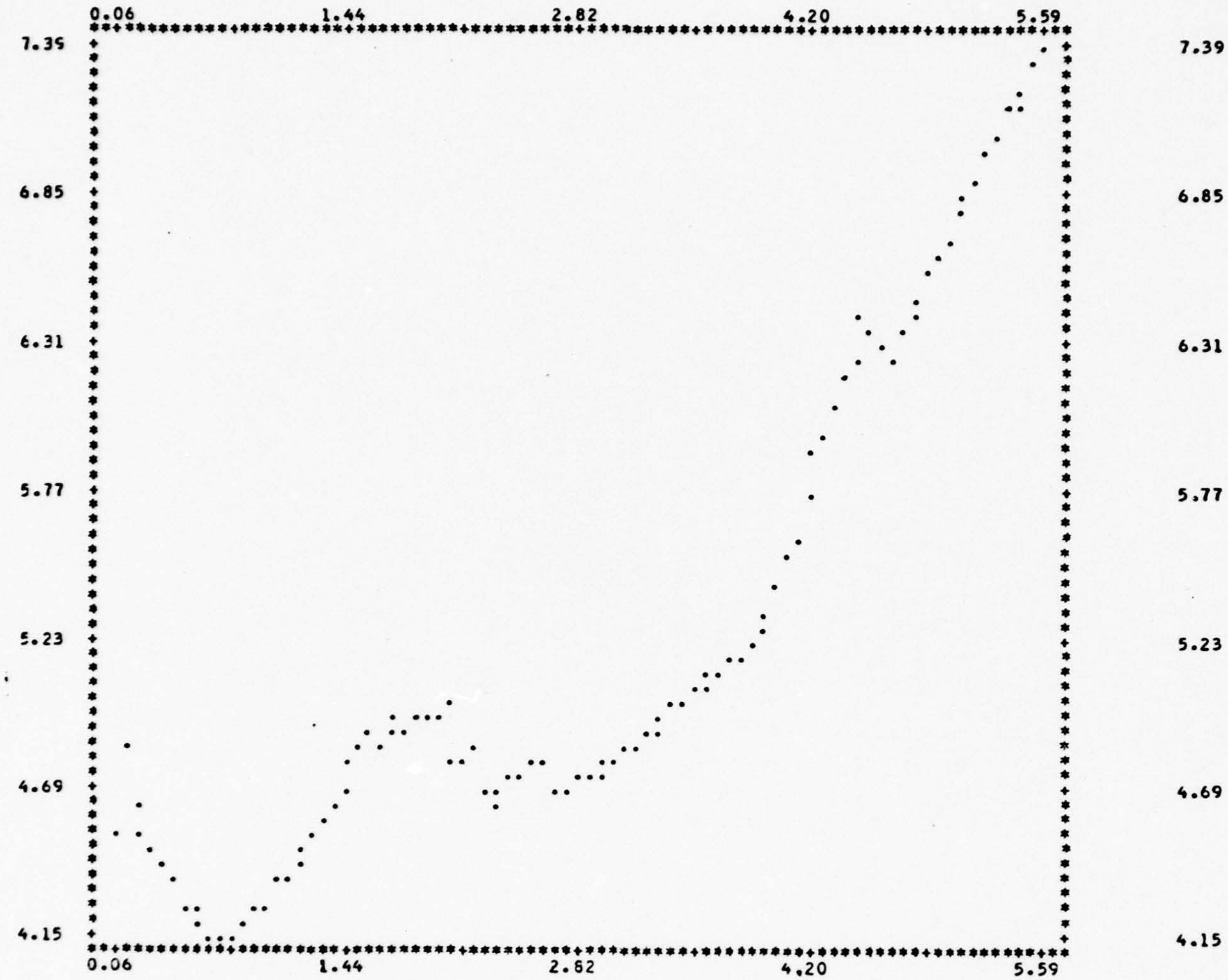



X-SCALE: "*"= 0.218E-01 UNITS

Y-SCALE: "*"= 0.128E-01 UNITS

PLOT OF DELTA TIME(SECS) VS TOTAL TARGET AZIMUTH ERROR(MILS)
(ZERO GUNNER ERROR ASSUMED AT TRIGGER PULL)

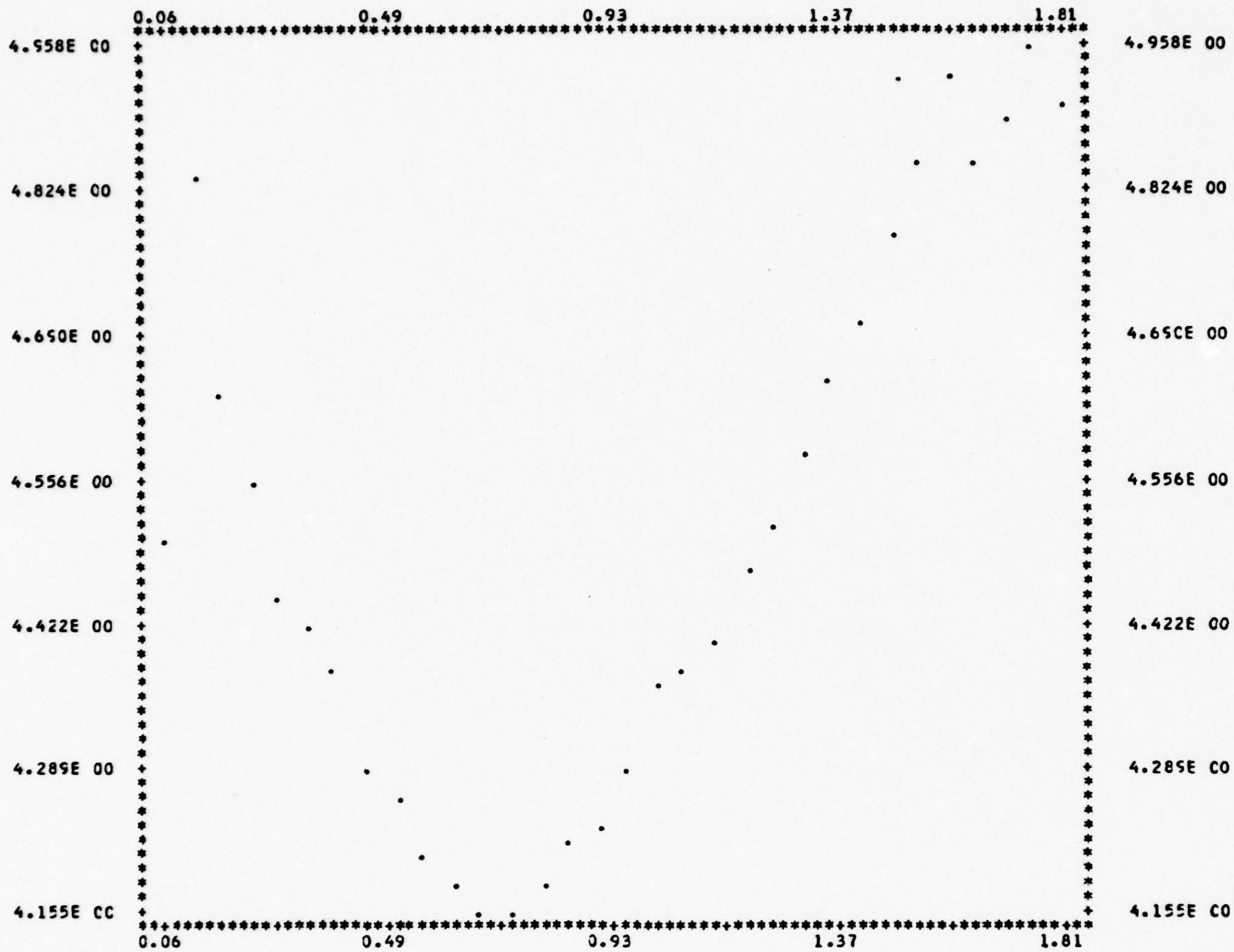
Figure 17




X-SCALE: "*"= 0.691E-01 UNITS
Y-SCALE: "*"= 0.539E-01 UNITS

PLOT OF DELTA TIME(SECS) VS TOTAL TARGET AZIMUTH ERROR(MILS)
(GUNNER ERROR AT LEAD INSERTION)

Figure 18

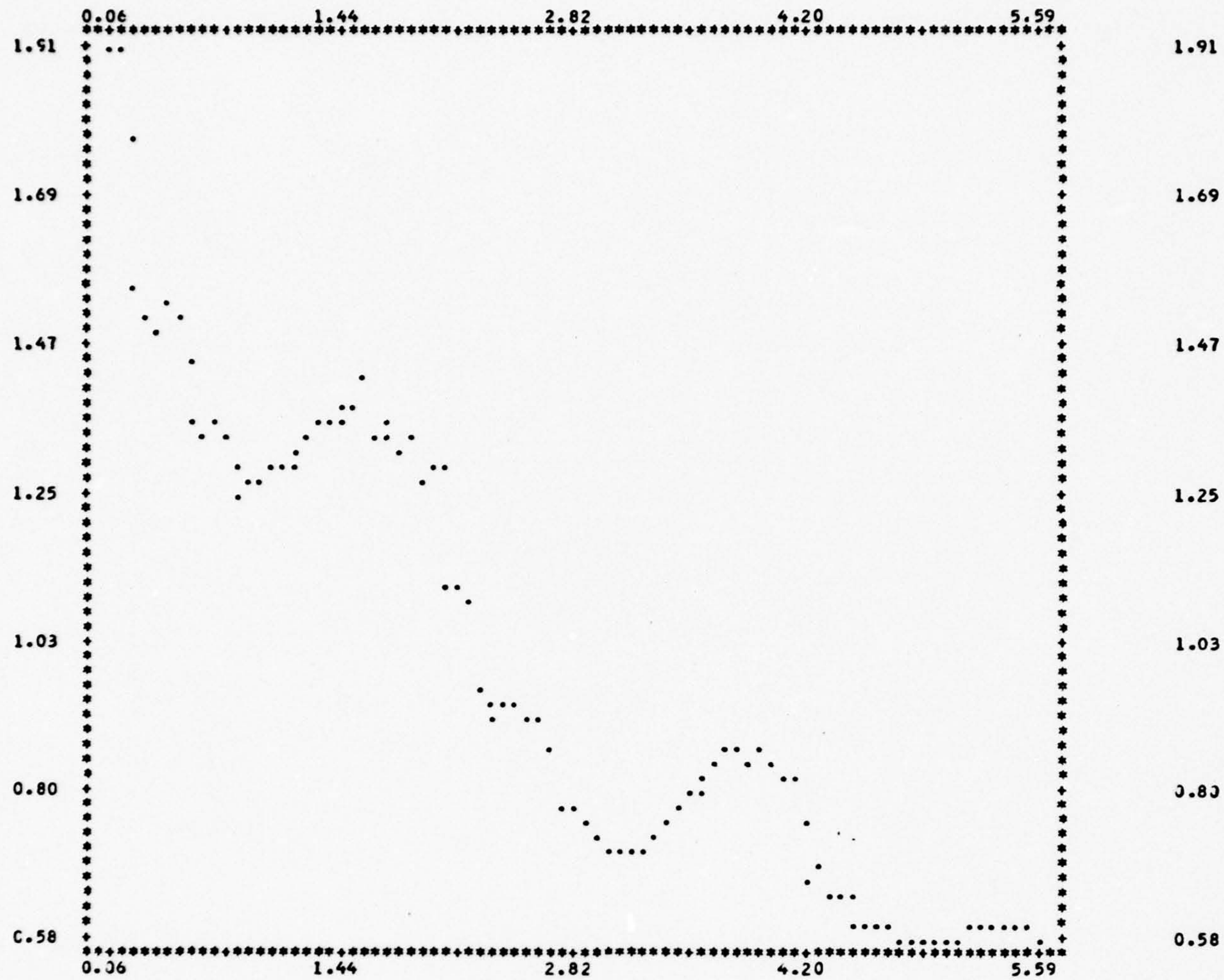



X-SCALE: "*"= 0.218E-01 UNITS

Y-SCALE: "*"= 0.134E-01 UNITS

PLCT OF DELTA TIME(SECS) VS TOTAL TARGET AZIMLTH ERRGR(MILS)
(GUNNER ERROR AT LEAD INSERTION)

Figure 19




X-SCALE: "*"= 0.691E-01 UNITS

Y-SCALE: "*"= 0.221E-01 UNITS

PLOT OF DELTA TIME(SECS) VS TOTAL TARGET AZIMUTH ERROR(MILS)
(GUNNER ERROR AT LEAD INSERTION AND EXCLUDING TARGET INDUCED AZIMUTH ERROR)

Figure 20

## APPENDIX B. FLOWCHARTS

The flowcharts contained in this Appendix provide a verbal description of the two Fortran computer programs used in the analysis of the fire control test data. The analysis concerned with the computation of azimuth tracking error and azimuth tracking rate error is described in flowcharts 1 through 7. Analysis procedures 1 through 4 are explained in flowcharts 2, 4, 3, and 5 respectively.

Flowcharts 8 through 15 describe the computer program written to execute analysis Models 1 and 2.

## FLOWCHART 1. MAIN PROGRAM

(Analysis Procedures 1 through 4)

Read data from magnetic tape 1. Each logical record read contains the following information:

Azimuth tracking data (mils)
Elevation tracking data (mils)
Mirror drive position data (radians)
Recording time of the logical record (0.2 sec)

↓

Record the number of logical records which were read (N).

↓

Specify the number of iterations (ITIMES) which are to be accomplished within each subroutine. This specification will cause mean azimuth error and mean azimuth rate error to be computed by averaging over delta times ranging from approximately 0.2 seconds to the product of (ITIMES) (0.2 seconds) in increments of 0.2 seconds.

↓

Call Subroutine BLKERR. This subroutine computes mean azimuth tracking error beginning with tracking data following a trigger pull, working forward in time.

↓

Call Subroutine AVRATE. This subroutine computes mean azimuth tracking rate error beginning with tracking data following a trigger pull, working forward in time.

↓

Call Subroutine ETUPLE. This subroutine computes mean azimuth tracking error beginning with tracking data just prior to lead insert, working backward in time.

↓

Call Subroutine RTUPLE. This subroutine computes mean azimuth tracking rate error beginning with tracking data just prior to lead insert, working backward in time.

↓

Call Subroutine OUTPUT. This subroutine provides a printed output of the data calculated in previously called subroutines.

↓

Call Subroutine PLOTS. This subroutine creates scatterplots of the data calculated in previously called subroutines.

↓

End

FLOWCHART 2. SUBROUTINE BLKERR

Enter loop 20 which will be iterated ITIMES starting with L=1. Index L is incremented in steps of 1. The product (L)(0.2 seconds) equals the delta time increment under consideration for any given iteration of loop 20.

↓

Enter loop 10 which will be iterated N times as specified from the main program. The constant N corresponds to the number of logical records to be processed.

↓

Identify the beginning of each tracking sequence which follows a simulated trigger pull by locating successive logical records which are separated in time by more than (L)(0.25 seconds).

↓

Enter loop 6 which will be iterated L times as specified by the index of loop 20.

↓

Calculate the cumulative sum of azimuth tracking error from each successive logical record proceeding forward in time. Maintain a count of the number of sums taken.

↓

Exit loop 6

↓

Calculate the mean of the cumulative sum recorded in loop 6. Calculate the absolute value cumulative sum of the mean computed in this step.

↓

Calculate the time interval over which the cumulative tracking error computed in loop 6 was taken. Maintain a cumulative sum of these times.

↓

Exit loop 10

↓

Calculate the mean azimuth tracking error from the cumulative sum computed in loop 10. Calculate the mean time interval over which the tracking error was computed.

↓

Record these values in vectors whose index value is equal to L.

↓

Exit loop 20

↓

Return

FLOWCHART 3. SUBROUTINE AVRATE

Enter loop 20 which will be iterated ITIMES starting with index L=1. Index L is incremented in steps of 1. The product (L)(0.2 seconds) equals the delta time increment under consideration for any given iteration of loop 20.

↓

Enter loop 10 which will be iterated N times as specified from the main program. The constant N corresponds to the number of logical records to be processed.

↓

Identify the beginning of each tracking sequence which follows a simulated trigger pull by locating successive logical records which are separated in time by more than (L) (0.25 seconds).

↓

Enter loop 6 which will be iterated L times as specified by the index of loop 20.

↓

Calculate the cumulative sum of azimuth tracking rate error from each successive logical record proceeding forward in time. Rates are calculated by subtracting the i'th azimuth error from the j'th azimuth error and dividing this sum by the time between these successive errors. Maintain a count of the number of sums taken.

↓

Exit loop 6

↓

Calculate the mean of the cumulative sum recorded in loop 6. Calculate the absolute value cumulative sum of the mean computed in this step.

↓

Calculate the time interval over which the cumulative tracking rate error computed in loop 6 was taken. Maintain a cumulative sum of these times.

↓

Exit loop 10

↓

Calculate the mean azimuth tracking rate error from the cumulative sum computed in loop 10. Calculate the mean time interval over which the tracking rate error was computed. Record these values in vectors whose index value is equal to L.

↓

Exit loop 20

↓

Return

FLOWCHART 4. SUBROUTINE ETUPLE

Enter loop 10 which will be iterated N times as specified from the main program.

↓

Identify the last logical record in each individual tracking sequence by locating successive logical records which are separated in time by more than 0.25 seconds. Create a vector containing the location number of the logical records identified.

↓

Enter loop 30 which will be iterated ITIMES starting with index L=1. Index L is incremented in steps of 1. The product (L)(0.2 seconds) equals the delta time increment under consideration for any given iteration of loop 30.

↓

Enter loop 20 which will be iterated IA times. IA corresponds to the number of individual tracking sequences previously identified.

↓

Encounter logic to determine when the end of an individual tracking sequence is reached. When the end of a tracking sequence is identified, transfer back to the top of loop 20.

↓

Enter loop 25 which will be iterated L times as specified by the index of loop 30.

↓

Calculate the cumulative sum of azimuth tracking error from each successive logical record proceeding backward in time from the last record in each individual tracking sequence.

↓

Calculate the cumulative sum of the time between each successive logical record wherein tracking data was summed in the preceding step.

↓

Exit loop 25

↓

Calculate the mean of the cumulative sums recorded in loop 25. Calculate the absolute value cumulative sums of the means computed in this step.

↓

Exit loop 20

↓

Calculate the mean azimuth tracking error from the cumulative sum computed in loop 25. Calculate the mean time interval over which the tracking error was computed. Record these values in vectors whose index value is equal to L.

↓

Return

## FLOWCHART 5. SUBROUTINE RTUPLE

Enter loop 30 which will be iterated ITIMES starting with index L=1. Index L is incremented in steps of 1. The product (L)(0.2 seconds) equals the delta time increment under consideration for any given iteration of loop 20.

↓

Enter loop 20 which will be iterated IA times. IA corresponds to the number of individual tracking sequences previously identified in Subroutine ETUPLE.

↓

Encounter logic to determine when the end of an individual tracking sequence is reached. When the end of a tracking sequence is identified, transfer back to the top of loop 20.

↓

Enter loop 25 which will be iterated L times as specified by the index of loop 30.

↓

Calculate the cumulative sum of azimuth tracking rate error from each successive logical record proceeding backward in time. Rates are calculated by subtracting the i'th azimuth error from the j'th azimuth error and dividing this sum by the time between these successive errors. Maintain a count of the number of sums taken.

↓

Calculate the cumulative sum of the time between each successive logical record wherein tracking rates were computed and summed in the preceding step.

↓

Exit loop 25

↓

Calculate the mean of the cumulative sums recorded in loop 25. Calculate the absolute value cumulative sums of the means computed in this step.

↓

Exit loop 20

↓

Calculate the mean azimuth tracking rate error from the cumulative sum computed in loop 20. Calculate the mean time interval over which the tracking rate errors were computed.

↓

Record these values in vectors whose index value is equal to L.

↓

Exit loop 30

↓

Return

FLOWCHART 6. SUBROUTINE OUTPUT

Create a printed output of mean azimuth tracking errors and the corresponding delta time data computed in Subroutine BLKERR.

↓

Create a printed output of mean azimuth tracking rate errors and the corresponding delta time data computed in Subroutine AVRATE.

↓

Create a printed output of mean azimuth tracking errors and the corresponding delta time data computed in Subroutine ETUPLE.

↓

Create a printed output of mean azimuth tracking rate errors and the corresponding delta time data computed in Subroutine RTUPLE.

↓

Return

FLOWCHART 7. SUBROUTINE PLOT

Create a scatterplot of delta time versus mean azimuth tracking error as computed in Subroutine BLKERR.

↓

Create a scatterplot of delta time versus mean azimuth tracking rate error as computed in Subroutine AVRATE.

↓

Create a scatterplot of delta time versus mean azimuth tracking error as computed in Subroutine ETUPLE.

↓

Create a scatterplot of delta time versus mean azimuth tracking rate error as computed in Subroutine RTUPLE.

↓

Return

FLOWCHART 8. MAIN PROGRAM

(Analysis Models 1 and 2)

Read data from magnetic tape 2. Each logical record read contains the following information:

Azimuth tracking data (mils)
Elevation tracking data (mils)
Mirror drive position data (radians)
Event code designation
Recording time of the logical record (0.06 sec)

↓

Record the number of logical records which were read (N).

↓

Subtract a constant K from each logical record recording time so that the resulting times can be represented more accurately in the binary number system.

↓

Call Subroutine LOCPUL. This subroutine locates the first logical record in each firing sequence and creates a vector KTPULL (I) which records the location of each record identified. A count of the number of firing sequences detected (NPULL) is computed.

↓

Specify the value of the constant NDELTA. This value determines the length of the delta time interval to be considered in the analysis. The delta time interval will equal (NDELTA) (0.06 seconds).

↓

Enter loop 5 which will be iterated once for each firing sequence of which there are NPULL.

↓

Call Subroutine SILEAD. This subroutine performs computations relative to the location and movement of the tank turret (sight) and simulated target a variable time interval prior to the gunner's insertion of azimuth lead.

↓

Call Subroutine LASER. This subroutine performs computations relative to the location and movement of the simulated target after the gunner's insertion of azimuth lead.

↓

Call Subroutine ERROR. This subroutine computes total target azimuth error as a function of delta time based on input data from subroutines SILEAD and LASER.

↓

↓

Call Subroutine ABSDIF. This subroutine computes the mean deviation between the turret rate and the target rate as a function of delta time.

↓

Enter loop 10 which will be iterated NDELTA times in increments of 1.

↓

Calculate the cumulative sum of the times between successive logical records and maintain this result in the vector STIME.

↓

Calculate the cumulative sum of the target azimuth errors computed in subroutine ERROR.

↓

Exit loop 10

↓

Exit loop 5

↓

Calculate the mean time interval between successive logical records by using the cumulative time data in vector STIME. The times computed in this step represent the mean intervals in which delta time is incremented as it is increased from 0 to (NDELTA)(0.06 seconds).

↓

Call Subroutine OUTPUT. This subroutine provides a printed output of selected data previously computed.

↓

Call Subroutine PLOTS. This subroutine creates scatterplots of selected data previously computed.

↓

END

FLOWCHART 9. SUBROUTINE LOCPUL

Enter loop 5 which will be iterated N times as specified from the main program. The constant N corresponds to the number of logical records to be processed.

↓

Check the event codes of each logical record to determine if they are code 2038. Event code 2038 corresponds to a firing sequence trigger pull. When a trigger pull event is detected jump out of loop 5 and record the logical record number where the trigger pull occurred in vector KTPULL(I).

↓

Return to loop 5 and start the search for subsequent trigger pull event codes beginning at the point where the loop was exited.

↓

Exit loop 5 when the last logical record to be processed has been reached.

↓

RETURN

FLOWCHART 10. SUBROUTINE SILEAD

Enter loop 5 for the purposes of locating the logical record at which the gunner engaged the lead lock enable switch thereby inserting lead into the firing azimuth. Exit loop 5 with the number of the logical record where lead was inserted.

↓

Compute the elapsed time between lead insertion and the gunner trigger pull.

↓

Enter loop 15 which will be iterated NDELTA times in increments of 1.

↓

Create a vector SPOTML which represents the coordinate of the simulated target in mils beginning at the time of lead insert to the time equal to time of lead insert minus (NDELTA)(0.06 seconds). Hereafter, for the purpose of brevity, this time interval will be referred to as time interval ALPHA.

↓

Create a vector APRIME which represents the coordinate of the turret (sight) in mils in the target coordinate system for time interval ALPHA. Both vector SPOTML and APRIME have a maximum length of NDELTA and contain coordinate data for each logical record within time interval ALPHA.

↓

Enter loop 19 where the gunner azimuth error is computed for time interval ALPHA. Gunner azimuth error is positive if the gunner is tracking in front of the target and is negative if the gunner is lagging the target.

↓

Exit loop 19

↓

Enter loop 30. Within this loop the vector AZRTUP and SPOTRT are computed. Vector AZRTUP represents the azimuth traverse rate of the turret in mils/sec for time interval ALPHA. The vector SPOTRT represents the azimuth rate of the target in mils/sec over time interval ALPHA.

↓

Calculate the cumulative sum of the time interval between successive logical records within time interval ALPHA. Store this result in vector DELTMI.

↓

Exit loop 30

↓

Enter loop 40 which is iterated NDELTA times in increments of 1.

↓

Calculate the cumulative sum of the deviation between the turret rate and the target rate in time interval ALPHA.

↓

↓

Exit loop 40

↓

If the firing sequence is the last one in the series of firing sequences enter loop 45 and compute the mean deviation between the turret rate and target rate in time interval ALPHA.

↓

Exit loop 45

↓

If the variable JRITE is set equal to 1 enter loop 55 which will cause data cards with gunner target error and target apparent velocity to be punched.

↓

If the variable JPLOT is set equal to 1 create a scatterplot of target apparent velocity versus gunner target error.

↓

RETURN

FLOWCHART II. SUBROUTINE LASER

Enter loop 1. Compute a vector TGTLD which represents the coordinate of the target in mils beginning at the time of lead insertion through the time at which the gunner initiates a trigger pull. Vector TGTLD will be of variable length which is dependent on the time interval between the insertion of lead and the initiation of a trigger pull. Coordinate data is calculated for each logical record within this time interval.

↓

Exit loop 1

↓

Enter loop 2 and compute the azimuth rate of the target in mils/sec from the time that lead is inserted through the time of trigger pull. Store the cumulative sum of the rates computed.

↓

Exit loop 2

↓

Compute the mean azimuth rate of the target from the time of lead insert through the time of trigger pull.

↓

Enter loop 5. This loop will be iterated 25 times. Compute a vector TGTMIL which represents the coordinate of the target in mils beginning at the time of trigger pull through the next successive 25 logical records. The computation of 25 target coordinates will permit subsequent computation of the target rate through a simulated projectile time of flight of 1.0669 seconds.

↓

Exit loop 5

↓

Enter loop 10 and compute the target rate in mils/sec over an interval of time corresponding to a simulated projectile time of flight of 1.0669 seconds. Maintain a cumulative sum of the computed target tracking rates.

↓

Exit loop 10

↓

Compute the mean target rate from gunner trigger pull through a simulated projectile time of flight of 1.0669 seconds.

↓

Enter loop 18 and compute the target induced error from the time of lead insertion through the time of simulated projectile impact. Projectile impact is assumed to have occurred 1.0669 seconds after firing.

↓

Exit loop 18

↓

↓

Enter loop 20 which will be iterated NDELTA times in increments of 1.

↓

Using 3 different computational formulas compute target error in mils and store the results of each computation in a separate vector. Calculate the cumulative sum of the target errors for each firing sequence.

↓

Exit loop 20

↓

If the firing sequence is the last one in the series of firing sequences enter loop 25 and calculate the mean target error for each of the 3 target error sums accumulated in loop 20.

↓

Exit loop 25

↓

RETURN

FLOWCHART 12. SUBROUTINE ERROR

Compute the variable TARGET which is equal to the product of the target rate after firing times the projectile time of flight.

↓

Enter loop 5 which will be iterated NDELTA times as specified from the main program.

↓

Compute the vector SIGHT which is equal to the product of the turret rate prior to lead insertion times the projectile time of flight. The vector SIGHT has length NDELTA.

↓

Compute total target azimuth error in mils by subtracting the quantity TARGET and the gunner azimuth error at the time of lead insertion from the vector SIGHT. The resulting vector is total target azimuth error in mils as a function of increasing delta time.

↓

Exit loop 5

↓

If the variable IPRT is set equal to 1 output selected computational results from subroutines SILEAD, LASER and ERROR.

↓

RETURN

FLOWCHART 13. SUBROUTINE ABSDIF

Enter loop 5 which will be iterated NDELTA times in increments of 1.

↓

Compute the cumulative absolute value difference between the turret rate before gunner insertion of lead and the rate of the target after firing. Maintain a count of the number of sums taken.

↓

Exit loop 5

↓

If this firing sequence is not the last in the series of firing sequences return to the main program.

↓

Enter loop 10 which will be iterated NDELTA times in increments of 1.

↓

Compute the mean deviation between the turret rate prior to lead insertion and the target rate after firing as a function of delta time.

↓

Exit loop 10

↓

RETURN

FLOWCHART 14. SUBROUTINE OUTPUT

Create a printed output of the logical record location of all simulated firings.

↓

Create a printed output of selected variables computed in subroutines SILEAD, LASER and ERROR.

↓

Create a printed output of selected variables computed in the MAIN program.

↓

Create a printed output of selected variables computed in subroutine SILEAD.

↓

RETURN

FLOWCHART 15. SUBROUTINE PLOT

Create a scatterplot of delta time versus mean total target azimuth error as computed in Subroutine ERROR.

↓

Create a scatterplot of delta time versus the mean deviation between the turret rate prior to lead insertion and the target rate after firing as computed in Subroutine ABSDIF.

↓

Create a scatterplot of delta time versus the mean deviation between the turret rate and target rate prior to lead insertion as computed in Subroutine LASER.

↓

Create a scatterplot of delta time versus the mean target induced error as computed in Subroutine LASER.

↓

Create a scatterplot of delta time versus the mean total target azimuth error (TGTER2) as computed in Subroutine LASER.

↓

Create a scatterplot of delta time versus the mean total target azimuth error (TGTER3) as computed in Subroutine LASER.

↓

Create a scatterplot of delta time versus the mean total target azimuth error (TGTER5) as computed in Subroutine LASER.

↓

RETURN

# LIST OF REFERENCES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