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NAVAL RESEARCH LABORATORY

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Preliminary Report

of

Anti-Aircraft Fire Control Studies — Testing Methods and Apparatus

NAVAL RESEARCH LABORATORY
ANACOSTIA STATION
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I. AUTHORIZATION

1-1. The investigation of fire control problems in general is authorized by Bureau of Ordnance Project 30199 as covered by reference letter from the Bureau of Ordnance to the Naval Research Laboratory, C-S67-7(Re4f) dated August 31, 1942. This includes comprehensive tests on directors and computers. To study such problems the Naval Research Laboratory has organized a Fire Control Section in the Radio Division. The procedures adopted by this section for testing directors evolved from cooperative efforts by engineers and officers of the laboratory and the Bureau of Ordnance through actual conduct of tests on a new anti-aircraft director. This director was an early production unit which had seen some service prior to test and required certain modifications which were not made at the time of test. The curves shown, therefore, serve to illustrate the method rather than to evaluate the director.

II. INTRODUCTION

2-1. General Remarks:

2-1-1. In this country there has been little organization of material related to the anti-aircraft fire control problem. The information repeated here has been obtained from widely scattered sources and presumably is not complete.

2-1-2. In the Navy, development of gun directors and associated radar equipment has been accomplished almost entirely by the manufacturers in cooperation with the Bureau of Ordnance. Acceptance of directors has been on the basis of

(a) Factory tests by the Naval Inspector of Ordnance.
(b) Relative performance in actual firing tests using a towed sleeve as a target.
(c) Relative performance in service with the fleet.

Firing tests have been conducted at the Naval Proving Grounds (Dahlgren, Virginia), at the Naval Training Center (Dam Neck, Virginia), and recently at the Chesapeake Bay Annex of the laboratory. True target position and computer performance have also been obtained at the Chesapeake Bay Annex by the method described in this report.

2-1-3. The Army uses phototheodolite methods to provide synchronized records of true target position and of shell bursts, employing both towed sleeves and rocket targets. A phototheodolite is a recording instrument provided with a camera to photograph the airplane and a sighting telescope mounted with its axis parallel to that of the camera to permit the operator to keep the airplane target within the field of view of this camera. An additional optical system is used to indicate directly on the film the bearing and elevation angles of the sighting telescope. The angular position of the aircraft is obtained from the line of sight of the telescope and the relative angular position of the target in the camera field of view. To determine the altitude and horizontal range of the target, it is necessary to record the angles measured synchronously by a phototheodolite placed at each end of a long base line which is used as a reference distance. The Army at present conducts such tests at Fort Monroe, Camp Davis, Aberdeen Proving Ground, and the United Shoe Machinery Company.

2-1-4. Photographic methods similar to those employed by the Army have also been used abroad. In addition to these experimental methods theoretical studies have been described in foreign publications.

2-1-5. At this laboratory an extensive bibliography of material on the anti-aircraft fire control problem is being prepared. Every effort is being made to provide a complete source of information which will include progress made by the enemy as well as that made by this country and its Allies.

2-2. Possible Methods for Testing Directors:

2-2-1. Tests for determining the effectiveness of a given director can be divided into the following three general types: (A) sleeve firing tests, (B) actual target tests with complete data record, and (C) standard input tests.

2-2-2. Sleeve firing tests, Method (A): A cylindrical cloth sleeve is towed at a safe distance behind an airplane and fired upon by anti-aircraft guns controlled by the director on test. The relative merit of the director is determined in actual firing tests simply from the percentage of hits made on the moving aerial target. This method tests simultaneously the combination of the director (with computer), the gun and the operating personnel. If the percentage of hits is considered unsatisfactory, the director is not accepted, but there is little possibility of determining the real reasons for poor performance. No continuous record is kept of the inputs of the computer mechanism, nor of the outputs to the servo-drive of the gun.

2-2-3. Actual target tests with complete data record, Method (B): During the test, a synchronized photographic record is made of target position, of the director tracking errors, of all the computer outputs to the gun, of the gun follow-up errors, and of the position of shell bursts if the gun is fired. A comparison of firing and non-firing runs will indicate the effect of own gun's blast on the director mechanism and operating personnel. The effect of tracking errors due to the pointer-trainer can also be separated from the operation of the director, but because of the great amount of work involved and because of the fact that the operator is inseparable from the director in service, it is doubtful whether such a separation would be justified. As a matter of fact, the ease with which the director can be made to track a target is an important factor and should be considered a significant part of the performance of any production model of a director. If, however, it is desired to study the operation of the computer alone, as in the case of a director which needs to be re-designed, it will generally be necessary to correct the computer's solution for the tracking error both in displacement and rates.

2-2-4. Particular means for achieving this type of test include:

(a) Tracking an airplane (for high speed non-firing runs) or towed sleeve (for firing runs) as target. The photographic record of true target position may be taken by using a "spherical coordinate system" as described at length in this report. This method obtains present target range from an auxiliary precision radar and present angular position from a camera mounted on the director under test. An alternative means of determining true target position is the phototheodolite method, employing a long fixed reference base line between two observation stations where target elevation and bearing angles are synchronously recorded photographically.

(b) Use of a small scale target constrained to move at a prescribed speed along a fixed path. The actual distance to this target can be made as small as desired for convenience, as within a room while an artificial range can be put into the computer to correspond to normal target distances. A particular target behavior can thus be reproduced at will, providing convenient means, for example, to compare different modes of operation.

2-2-5. Standard input tests, Method (C): A study is made of the tracking rates and accelerations encountered at various director elevations for various types of target courses. This study, in conjunction with tracking data from the test set-up of Method (B), will indicate what frequencies and amplitudes of oscillatory motion are most characteristic of the normal inputs to the director. On this basis suitable artificial mechanical inputs may be chosen, whereby the response of the director can be critically examined. These inputs may be either impulsive or continuous or both. After an extensive comparison of the results of Method (B) with the results obtained by this method, the response to these standard inputs can be analyzed to indicate both the tracking capabilities and the most appropriate solution time for a particular director. This method inherently removes the effect on the director's performance due to the operating personnel and, in a simplified form, might provide a valuable dynamic test which could be performed comparatively rapidly at the factory. Once the criteria for standard inputs have been established, the tests can be:

(a) Experimental: Standard inputs are applied to a director and the outputs are recorded simultaneously

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with the inputs to be analyzed for correlation. These inputs can be impulses, continuous oscillations, or complete artificial target courses derived from mechanical cams. These may be described as follows:

(1) Impulses: For example, a "square wave" of displacements or of displacements or of rates is put into the control elements of the director, and the response of the director follow-ups and computer is analyzed. The steep transient wave-front contains many frequency components, and the sensitivity of the director control mechanism to these can be measured, as well as spurious responses such as "hunting." Likewise the stability of the computer can be studied, and the time of solution determined for the particular conditions.

(2) Continuous Oscillations: Sine waves of varying frequency and amplitude are used as inputs to the control elements of the director. The response of the director power units is studied for critical conditions of "resonance", or of extreme lag. For the ordinary type of computer, the time of solution can be adjusted to smooth most suitably the outputs resulting from such inputs, if the frequency amplitude curves representative of expected operation are known. For special types of computers there may be regions of critical frequencies for the computer output, corresponding to exaggerated roughness in gun orders, and the design of mechanical filters may be indicated. Such experiments are not very closely related to the actual anti-aircraft performance.

(3) Artificial Target Course: Inputs are supplied to the computer so that they are the same as would occur if the director were tracking a target perfectly along a given course. The apparatus which supplies these inputs can be provided with additional cams to give the true gun orders (correct anti-aircraft solution) as well as the inputs of the target's present position and rates. If these inputs are sent to a computer, the output of the computer can be compared with the correct solution and the difference between the two can be recorded as an error in the solution of the computer being tested.

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(b) Theoretical: Electromechanical equations need to be developed for the whole director or for the portion under study. The functions appearing in these equations must be supplied from experiment and from the manufacturer's design data. They involve the dynamic properties of all the components of the computer and director and so include the Class "A" errors as well as the Class "B" errors which have been tolerated in the design of the apparatus. If it were possible to obtain constants for such complicated equations and to approximate the solution of these equations with reasonable simplicity, some idea of the practicability of the director might be obtained before construction is completed. However, it should be noted that such equations cannot be used without possessing a great amount of experimental data among which might be listed all time constants in the system, the backlash in the gears, the moments of inertia of the moving components, and the characteristics of the compensated servomechanisms.

2-3. Evaluation of These Methods:

2-3-1. A list of the various methods which can be used for testing directors is included here for quick reference in the present discussion.

Method A - Sleeve Firing Test.
Method B - Actual Target Test with Complete Data Record.
(a) Tracking an airplane or sleeve, firing and non-firing.
(b) Tracking a small scale target moving on a fixed path.
Method C - Standard Input Test.
(a) Experimental.
(b) Theoretical.

2-3-2. Of these methods, the first can show approximately whether or not the combined system including guns, director, and personnel is adequate for fleet service, Provided the effect of compensating errors can be disregarded, the performance of the director cannot be worse than the overall performance of the combined system. However, the performance of the director itself cannot be described with any degree of precision, nor can the effect of the gun blast on the director be determined. Such tests are limited to courses and speeds possible with target sleeves. Performance against planes flown as an attacking enemy can therefore not be determined. The correlation between hits on a sleeve and probable hits on a live target with very different size and shape also is uncertain. Since there is no quantitative measure of the errors due to the director alone there can be little progress made in determining just how to make improvements on the director.

2-3-3. Method (B, a) permits tests on the director and computer independently of gun follow-ups and ballistics. It also provides data from which evaluation of the contributions of all the principal factors including operating personnel and gun follow-up can be made. It does not yield response characteristics for the various components of the computer and it is subject to vagaries of the weather in that it can be used only in weather good for flying and for outdoor photography.

2-3-4. Once the necessary testing equipment has been built, Method (B, b) is very rapid and convenient, since the true target position and rates can be calculated beforehand and used for all runs. This is a very useful feature in developmental studies. However, the choice of target courses is greatly limited since range cams are required to give an artificial range input for each course. Furthermore, simultaneous firing tests are generally not possible with such a set-up since the test is carried on within a building.

2-3-5. Method (C, a) is very rapid (provided the director is constructed so that a mechanical input is easily introduced into it), and revealing (provided the significance of the standard inputs has been made sufficiently obvious). In general, the significance can only be obtained from a comparison of the data of method (C, a) with those of method (B, a). The outputs can be compared with the true theoretical solution, or with the intended designed output determined from the equations of (C, b), or with standard output curves determined by statistical analysis based on some arbitrary criteria of optimum performance. Nevertheless, deviations from these standard output, however determined, will be very difficult to interpret.

2-3-6. Standard inputs for different directors must of necessity vary widely since tracking may be accomplished by position control, rate control, or increment of rate control, and particularly since the control may or may not be regenerative. In addition, these inputs must vary to suit the requirements of different tactical designs, accordingly as the director is designed for own ship's protection or for screening, or for some more specific purpose. This method obviously cannot show what effect an actual operator will have on the director's performance.

2-3-7. Method (C, b) is a very desirable adjunct to any of the methods listed above, but it presents very grave difficulties even to the most capable mathematicians and will always be uncertain of realization.

2-4. Method now in Use at the Naval Research Laboratory:

2-4-1. It was necessary for the Naval Research Laboratory to develop a method to meet the following requirements:

(a) The equipment and procedure must be such that for any director results of the test can be obtained in a minimum of time.

(b) It must be capable of independent measurement of the important variables in control of anti-aircraft fire under actual operating conditions.

(c) It must show the performance of the anti-aircraft system under conditions as nearly as possible simulating actual attack.

(d) It should be capable of ready application to any director and any mode of operation.

2-4-2. Inspection of the methods outlined in paragraph 2-2-5 shows that simultaneous satisfaction of all these requirements is most nearly achieved in method (B, a). This method calls for photographic means of continuous determination of true target position. Either of two methods may be used for this, the spherical coordinate method or the phototheodolite method.

2-4-3. The spherical coordinate method is extremely flexible because target courses can be standardized as desired, guns may or may not be fired, and the system may be mounted on a roll and pitch platform. Work can be started immediately on any unusual design of director without having to make any elaborate changes in the testing equipment. Most of these features apply to the phototheodolite method, which gives somewhat more accurate data than that used for this report. However, the spherical coordinate method will be the more accurate of the two when the precision range radar now set up for this purpose is used. Also this method is far simpler, less expensive in time and labor, and more flexible than the phototheodolite method, and can be used where space is restricted.

2-4-4. It must be noted that the phototheodolite system can provide a stereoscopic record of projectile bursts, whereas the present Naval Research Laboratory method would require an additional camera and comparable calculations to achieve this. Instead of firing tests, however, a simple analysis can be made of the gun orders by use of the ballistic tables for the gun. This approach to the problem is very practical and possesses advantages pointed out later in this report. Likewise, the effects of dead time and fuse mechanism errors can be studied completely with fixed targets, and thus reduce the confusion resulting from too many variables to be positively accounted for in the study of a director.

2-4-5. To summarize, method of (B, a) can be made as mathematical as desired, or can be made to simulate service conditions as nearly as desired, even to the extent of setting up the photographic equipment on shipboard. It is undoubtedly the quickest way to determine the weaknesses in a director already in production and being supplied to the fleet. The laboratory has adopted this method but will continue to make every possible effort to improve the technique. In particular, if personnel is available, the methods of (C, a) and (C, b) will be used too, since they are especially valuable in connection with the design of new directors.

III. METHOD OF COLLECTING DATA

3-1. Organization of Test:

3-1-1. The persons connected with this test may be divided into three groups; namely, (1) the director group, (2) the photographic group, and (3) the calculating group. The director group is in charge of setting up the director and corresponding radar at the Chesapeake Bay Annex of the Naval Research Laboratory and is responsible for conducting the whole test of the director, including the treatment of the data and final analysis. The photographic group obtains a photographic record of the data appearing during operational tests and is in charge of maintaining the equipment for obtaining such data. The calculating group takes the data in the form of developed motion picture film and turns it into suitable charts, tables, and graphs, under the direction of the director group so that an analysis can be made.

3-1-2. A major portion of the test consists of making standard runs for approach torpedo and pass courses, employing both airplanes and surface craft as targets. In addition to these runs, courses are also chosen which will demonstrate the design limitations of the director. After all of these runs have been completed, both firing and non-firing runs are made using as a target a sleeve towed along an approach and a pass course.

3-2. Preparation of Director being Tested:

3-2-1. Whenever a director is set up at the Chesapeake Bay Annex of the Naval Research Laboratory, it is necessary to mount on it whatever synchros are necessary to ensure that the following quantities can be continuously recorded:.

Director Elevation
Director Train
Director Present Range
Auxiliary Precision Radar Range
Gun Train Order
Gun Elevation Order
Gun Traverse Order
Fuze Setting
Level
Cross level
Special functions under study, such as
advance range, range rate, etc.

3-2-2. For particular directors it may be that Fuze Setting, Gun Traverse Order, and special functions will not be involved; however, if the director is tested on a moving platform an additional record must be kept of

Level of Platform
Cross Level of Platform
Turn of Platform, or own ship's course

[redacted]

3-2-3. Suitable housing is required for all of the apparatus to protect it from the weather. This has taken the form of a small house, the sides of which can be let down and the roof of which can be taken off. This house can be completely removed from the director in about two minutes.

3-2-4. To assure the validity of the operational tests and to determine also how well the computer stays in adjustment, standard computer "A" tests are made both morning and evening of each day of tests. When radar tracking is used, the radar is lined up with the optics before tests and checked for errors after tests. When firing runs are to be made, the roller paths of director and gun are adjusted to parallelism and director and gun are bore-sighted at average firing range, or as nearly thereto as convenient. These adjustments are also checked for errors after the day's runs.

3-2-5. Facilities for maintenance of the radars and of the mechanical equipment are provided. For the firing runs the naval personnel have provided a sound power telephone system, a pelorus, spotting circuits, and a sky control. Radio communication with the target or towing aircraft is maintained. A fast cabin cruiser (the "Navajo") which is attached to the station, serves as a surface target for non-firing runs as well as to clear the firing range of boats and to pick up sleeves that have been dropped in the bay after firing tests.

3-3. Apparatus Required for Test:

3-3-1. The photographic equipment and remote indicating dials form the basic test apparatus. Adaptations of autoloading cameras are employed, using 16 mm film and interchangeable lenses. One camera is mounted upon the director and is adjusted to have its optical axis parallel to the director line of sight. A lens of six inches focal length is standard, providing a field of view of 2.71 degrees vertically and 3.54 degrees horizontally. This lens and camera must be rigidly mounted to prevent vibration during firing tests. Another camera is mounted within the director to record quantities which cannot be properly transmitted by synchros.

3-3-2. A third camera is mounted within the control building to photograph the outputs of the computer, together with such computer inputs as can be transmitted from the director. The panel carrying the dials appearing in this photographic record includes meters to indicate the rate of increase either of gun order quantities or of director quantities. The rate measuring instrument providing these values was recently completed at the Naval Research Laboratory, and used on the first director analyzed in this program. This instrument requires further development to achieve useful sensitivity and stability. It is felt that rates are most accurately and quickly obtained directly from the photographic record of position angles.

3-3-3. All three cameras used are driven by oversize synchronous motors at 20 frames per second. The exposure time for the cameras is about 1/600 second so that the moving dials can be photographed without Strobolux illumination and its attendant complications. Zero time for the three cameras is indicated by the extinction of neon signal lights and subsequent synchronism is indicated by quick-action counter mechanisms mounted in each field of view and tripped immediately after every fifth frame. Normally only every tenth frame is read to provide data at half-second intervals. Of necessity the data films will be synchronized with one another within one-fortieth of a second or less for an entire run. The high picture speed is employed chiefly to enable studies to be made of the fine structure of rates, gun orders, and director response. For the camera speed used the fifty-foot magazines of Super X film chosen as standard last about 100 seconds.

3-3-4. The photographic data for all angles is readable to one minute and range can be read at one yard. The chief source of error in measuring angles came from lack of synchronism in the cameras, since the back lash in director gearing is within one minute error. Evaluation of the asynchronism error can be made only on the basis of consistency of the data. The estimated error in angular measurements using the older camera system (described below) was a maximum of one mil after appropriate smoothing. The error in measurement of the present target range is determined by the errors present in the standard range radar used, which in this case is the Mark 9 mounted on the power-driven pedestal designed for the Mark 5 automatic radar. The specifications for the Mark 9 radar call for a range accuracy of ± 15 yards, and previous Naval Research Laboratory tests have shown this figure to be fairly reliable. This radar has been increased in sensitivity for this work, and efforts are being made to increase the stability of the range circuits. It is particularly interesting that the chief source of error in the radar is the zero setting and that at large ranges the absolute error is nearly the same as for short ranges. This is a great improvement over the method used to obtain present target range in the early test work at the Naval Research Laboratory, when only the radar of the director itself was used.

3-3-5. A very rapid photographic method for repeatedly calibrating the standard range radar has been used. This method is very simple since it depends only on the angle subtended at the radar by the wings of an airplane. The basic data for a continuous range calibration within 4000 yards can be obtained within a few minutes' time and analyzed in a few hours. The method requires that a plane equivalent to the PBY be flown on a bearing toward the radar, while the radar reading and director tracking are simultaneously recorded by cameras. After the angle subtended at the radar by the wing span of the airplane target has been obtained from measurements made on the tracking film, the distance to the target can be calculated if the exact wing span is known. This method of calibration is accurate to about 5 yards at 1000 yards, and correspondingly more accurate with decreasing range.

IV. TREATMENT OF THE RECORDED DATA

4-1. General Outline:

4-1-1. For each airplane run made during a director test, the tracking film is read to obtain the angular displacement of the director line of sight from the target line of sight. This angular deviation of the target is then plotted against time to give Tracking Error Curves similar to those illustrated in Plate 1. The films from the other cameras are also read to provide a simultaneous record of director and gun quantities as listed in Paragraphs 2-4-1 and 2-4-2. All of these basic data are recorded on the first of a series of large standard tabular forms. A Target Course Plot against time (see Plate 1) is also made from these data so that, by comparing it with the Tracking Error Curves, the tracking errors can be correlated with the motion of the target.

4-1-2. A second form is used to record the various calculations necessary for making a ballistic analysis plot (see Plates 2 and 3 and the explanation given on page 12). For numerous points along the target's course this plot provides a graphic record of the director's misses, that is, of the vertical deviations of the projectiles from the target as measured in a vertical plane passing through the target line of sight. Finally, a third form is employed for calculations of the lateral deviations of the projectiles from the target in the slant plane of sight.

4-1-3. Upon the completion of these forms, the following curves are plotted against time: director elevation, gun elevation orders from the computer, and gun elevation orders required to hit the target. These are simply referred to as the Gun Elevation Order Curves and are illustrated in Plate 4. Similar graphs which are made using equivalent quantities for train instead of elevation are called Gun Train Order Curves (see Plates 6 and 7). The Mean Point of Impact (MPI) of the various outputs on this plot, together with the Apparent Mean Dispersion (AMD), is taken as a figure of merit for the director controlling the fire against an attacking aircraft flying on a particular course. Additional plots to show the position of the MPI for various ranges are also of interest in analyzing the performance of a director. (See Plates 8 through 11 and Plate 18.)

4-1-4. On the basis of the design data, calculations can be made to show how the director should be expected to perform. These calculations take account of the Class "B" errors built into the director and they can be represented by a Class "B" Error Splotch Plot (Plates 12 and 13), which can be sub-divided by range groups to give the curves of Plates 14 through 17 and Plate 19. A detailed study of these results in comparison with the actual performance of the director will show in what ways the director fails to meet its design specifications.

4-1-5. The three most important steps in treating the data are discussed more fully under the sub-headings of Tracking Error Curves, the Ballistic Analysis Plot, and the Splotch Plot.

4-2. Tracking Error Curves:

4-2-1. Tracking error curves are illustrated in Plate 1. (If the director line of sight is above or to the right of the target line of sight the deviation is positive.) They can be analyzed to indicate the comparative effectiveness of several modes of director operation, such as the use of aided or unaided tracking, the use of radar, optical, or estimated range, and the use of radar, telescope, or open sight pointing. Suitable mathematical averages and their corresponding dispersions are taken as measure of this effectiveness. These quantities represent the percentage of the total time that the target is within certain error limits.

4-2-2. These curves may be analyzed further to show the relative contribution of the tracking errors to the overall performance of the director. Although the tracking error displacements may be easily taken into account, it is very difficult in the case of some directors to make a correction for the rate errors introduced by tracking deviations.

4-3. Ballistic Analysis Plot:

4-3-1. The ballistic analysis plot (see Plates 2 and 3) consists of graphing the course of the target in the vertical plane passing through the line of sight of the director. To aid in determining the time of flight of the projectile fired from the anti-aircraft gun, there are superimposed on this plot the time of flight curves for whatever gun is being used with the director. Then, by counting time along the target's path as well as along the path (trajectory) assumed for the projectile, it is possible to mark on the target's path a point at which the projectile and target should meet in time and space. From the value of the slant range to this point and from the value of the appropriate gun elevation order of the computer, the position of the projectile at this time can be plotted after it has been calculated by making use of the range tables for the gun.

4-3-2. The procedure involved in making one of these ballistic analysis plots can best be described with reference to Plate 2. With the altitude as the ordinate and the horizontal range as the abscissa, time of flight curves have been drawn on the graph for every half second as marked along the horizontal axis. In this particular case the ballistic assumed was that of the 40 mm Bofors Anti-Aircraft Gun so that the time of flight is indicated by concentric circles. Successive photographically recorded positions of the airplane target are plotted as plus (+) signs. The course of the target for Run #00 consisted of a pass about 1500 yards abeam and at an altitude of 2000 feet; Plate 2 represents the approaching portion (IN) of the course while Plate 3 represents the receding portion (OUT).

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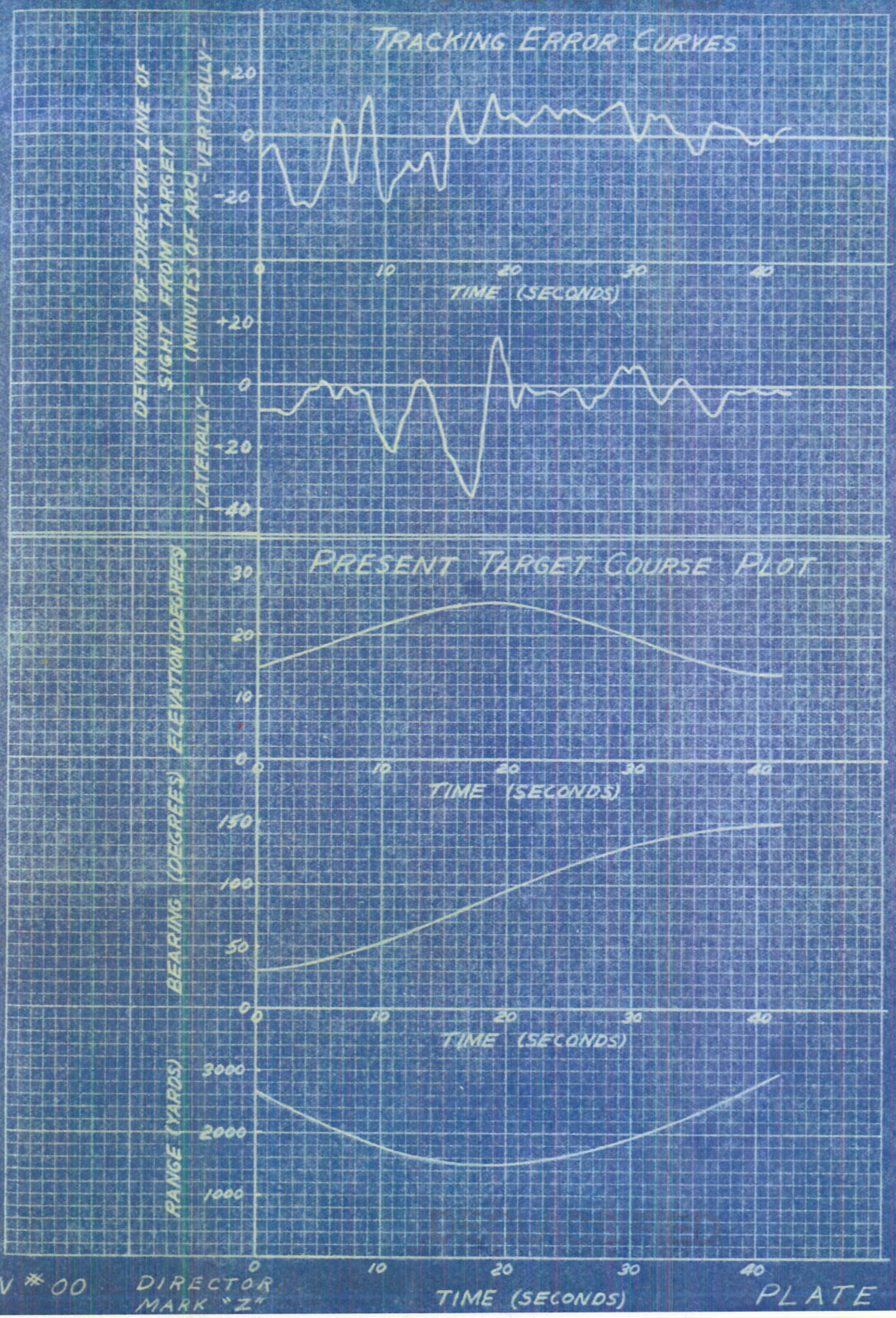

RUN * 00 DIRECTOR MARK "Z"

PLATE 1

4-3-3. After the target's course has been plotted, the next step is to determine where a projectile will cross the target's path, if the gun is fired at a time corresponding to a plus mark and has been correctly aimed. Let us consider the first plus mark appearing on the right hand side of Plate 2. When the target is at this position we will fire the gun and start counting time from this point along the target's path and from the origin (the gun position) along a radius vector. At the end of 2.0 seconds the target has reached the position indicated by the second plus mark and projectile is somewhere on the 2.0 second time of flight circle. By letting the target and the projectile approach one another in small increments of time, we find that their point of intersection occurs at 3.4 seconds as shown by the position of the small circle (o).

4-3-4. By repeating this process for each plus mark, we arrive at a series of small circles which correspond to the true advance target positions. Since the trajectory of the 40 mm gun is very nearly flat within the ranges for which it is used, there is only a negligible range error introduced in determining the advance target position for this gun by assuming that the projectile travels at right angles to the time of flight curves.

4-3-5. To determine the position of the projectile at the time of the advance target position, it is necessary to find the position angle of the projectile at this time. This position angle is found in a standard trajectory table (commonly called a gun elevation order table) by finding the entry listed for the gun elevation order given by the computer and for the slant range to the advance target position. Knowing this position angle and the corresponding slant range, the horizontal range and altitude of the projectile are easily calculated so the position of the projectile can be plotted as an asterisk (*) as illustrated in Plates 2 and 3.

4-3-6. To determine, in the vertical plane of sight, the distance of nearest approach of the projectile to the target, it is simply measured on the ballistic analysis plot as the distance between the circle and the asterisk. There is only a small error introduced by the assumption that the target and projectile are nearest one another when they are at the same slant range.

4-3-7. The ballistic analysis plot used for the actual computation is plotted on a scale of fifty (50) yards to the inch and the time of flight circles are drawn for every 0.1 second so that the time of flight can be very easily read to 0.01 second.

4-3-8. Since a standard trajectory table was not available for the 40 mm anti-aircraft gun, such a table had to be made by interpolating the sight angle table presented on O.P. 867 ("Ballistic Data for 40 mm Anti-Aircraft Guns - July 1942"). The standard trajectory table which has been constructed gives the position angle of the projectile for a given gun elevation order at intervals of five minutes of arc and for a given range at intervals of ten yards.

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4-4. The Splotch Plot:

4-4-1. The splotch plot is a representative of the deviations of the projectiles from the target at the point of closest approach. The axes chosen for measuring these deviations are in a plane passing through the target and perpendicular to the target line of sight. The horizontal axis used is the intersection of this plane with the slant plane of sight while the vertical axis is the intersection of this plane with the vertical plane of sight. These coordinates are the most obvious ones to use for contact-fuzed projectiles. They are also the most useful for time-fuzed projectiles since the accuracy of the fuzes is generally expected to be far less than that of the fuze orders from the director.

4-4-2. The splotch plot may be made for any of several modes of operation of the director during actual test (Performance Splotch Plot as in Plates 6 and 7), or it may be made to show the performance of the director according to its theoretical design (Class "B" Error Splotch Plot as in Plates 12 and 13). Thus, for example, the errors may be plotted for runs using combinations of radar range, optical range, fixed range, radar tracking, aided tracking, or delayed rate computing. Graphs are normally made for overall performance; i.e., including the tracking errors due to the operators.

4-4-3. It is expected that the graphs showing the shift of the MPI of the splotch plot with range to the target will provide the most concise and significant data for a "figure of merit" ascribable to a particular director controlling gun fire against a target moving on a particular course. Plate 18 shows the course of the MPI with respect to the target during Run #00. To obtain it, splotch plots are made for slant range groups of 500 yards and the MPI and AMD for both the vertical and lateral misses of the projectiles are computed for each group, as shown in Plates 8 through 11. The AMD for each group is indicated by the length of the bracketed lines. Plates 14 through 17 and Plate 19 are a similar treatment of the inherent Class "B" errors. Differences between the plots of Plates 18 and 19 are due to combined Class "A" and Class "C" errors.

V. ACKNOWLEDGMENTS

5-1. Much of the historical information presented in this report has been derived from conversations with officers in the Bureau of Ordnance. The phototheodolite method of determination of target position was developed by the Fire Control Research Group of Princeton University. The dynamic tester which supplies artificial target courses for testing computers was developed by Dr. Stewart of Div. 7, NDRC, and the Barber-Colman Co., for the Army. The application of Fourier Analysis to director input data and correlation with frequency response characteristics of the director-computer combination was suggested by Dr. Wiener's group, also Div. 7, NDRC, and Dr. Bigelow of the Applied Mathematics Panel of the NDRC.

VI. SUMMARY

6-1. The possible methods of studying the performance of anti-aircraft gun directors are listed as follows:

Method A - Sleeve Firing Test.
Method B - Actual Target Test with Complete Data Record.
  (a) Tracking an airplane or sleeve, firing and non-firing.
  (b) Tracking a small scale target moving on a fixed path.
Method C - Standard Input Test.
  (a) Experimental.
  (b) Theoretical.

These methods are compared and evaluated. Method (B, a) was chosen for use at the Naval Research Laboratory for the following reasons:

6-1-1. It yields data on director and computer performance uncontaminated by variables of exterior ballistics and gun follow-up mechanisms, while at the same time permitting independent evaluation of those variables.

6-1-2. It is the most rapid of all methods to give a quantitative check on the overall performance of the director and computer.

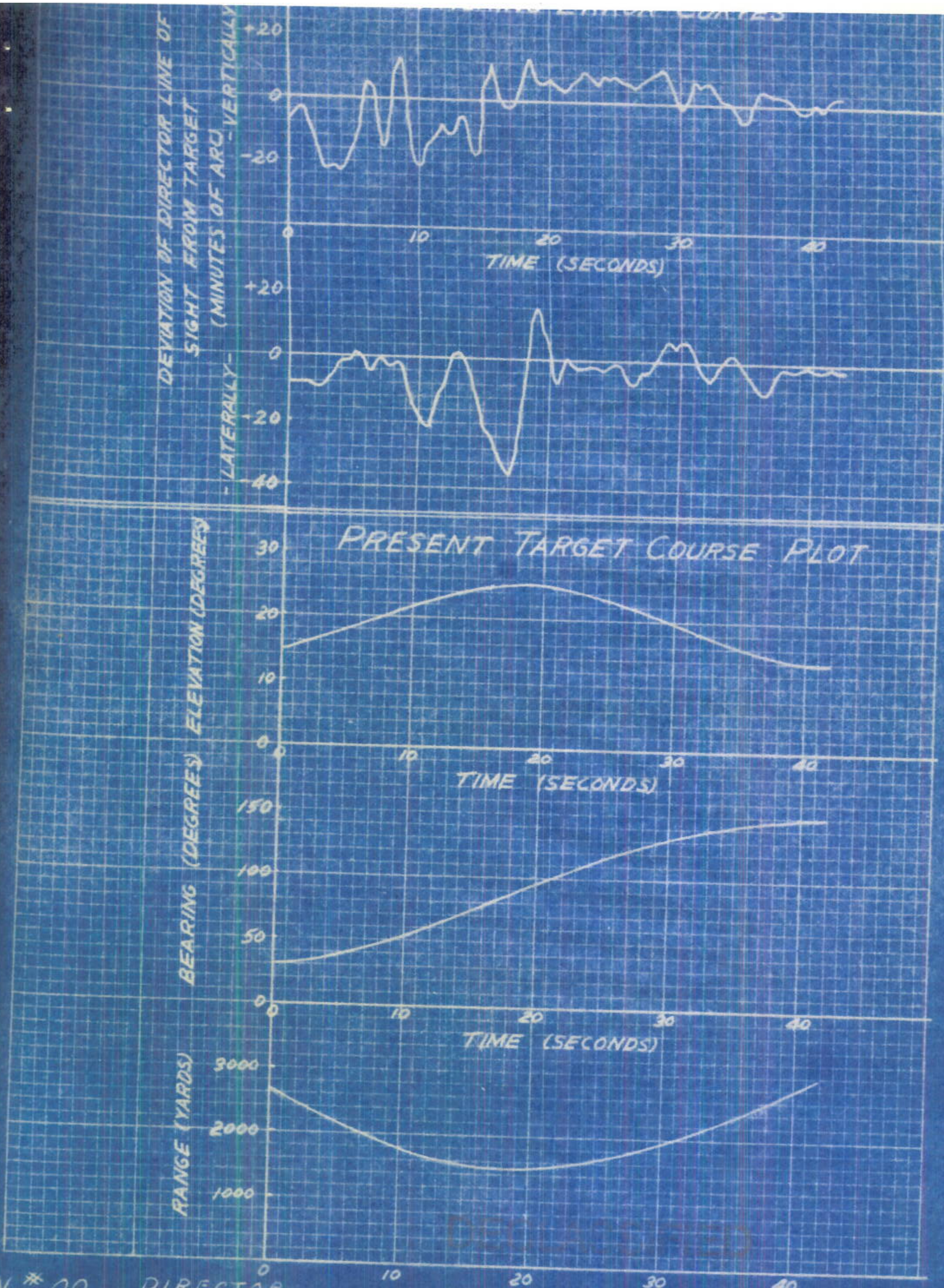
6-1-3. It is the most comprehensive of all methods in that it evaluates the contribution of all factors, such as operation personnel, ease of operation of director, all errors of the computer with and separately from Class "B" errors, radar control, gun follow-up mechanisms and exterior ballistics.

6-1-4. It is the most flexible of all methods in that course and speed of target, and type of target may be chosen at will without modification of test apparatus and technique.

6-1-5. It is the most realistic of all methods in that it may be used with targets simulating enemy attack even to the extent of using evasive tactics.

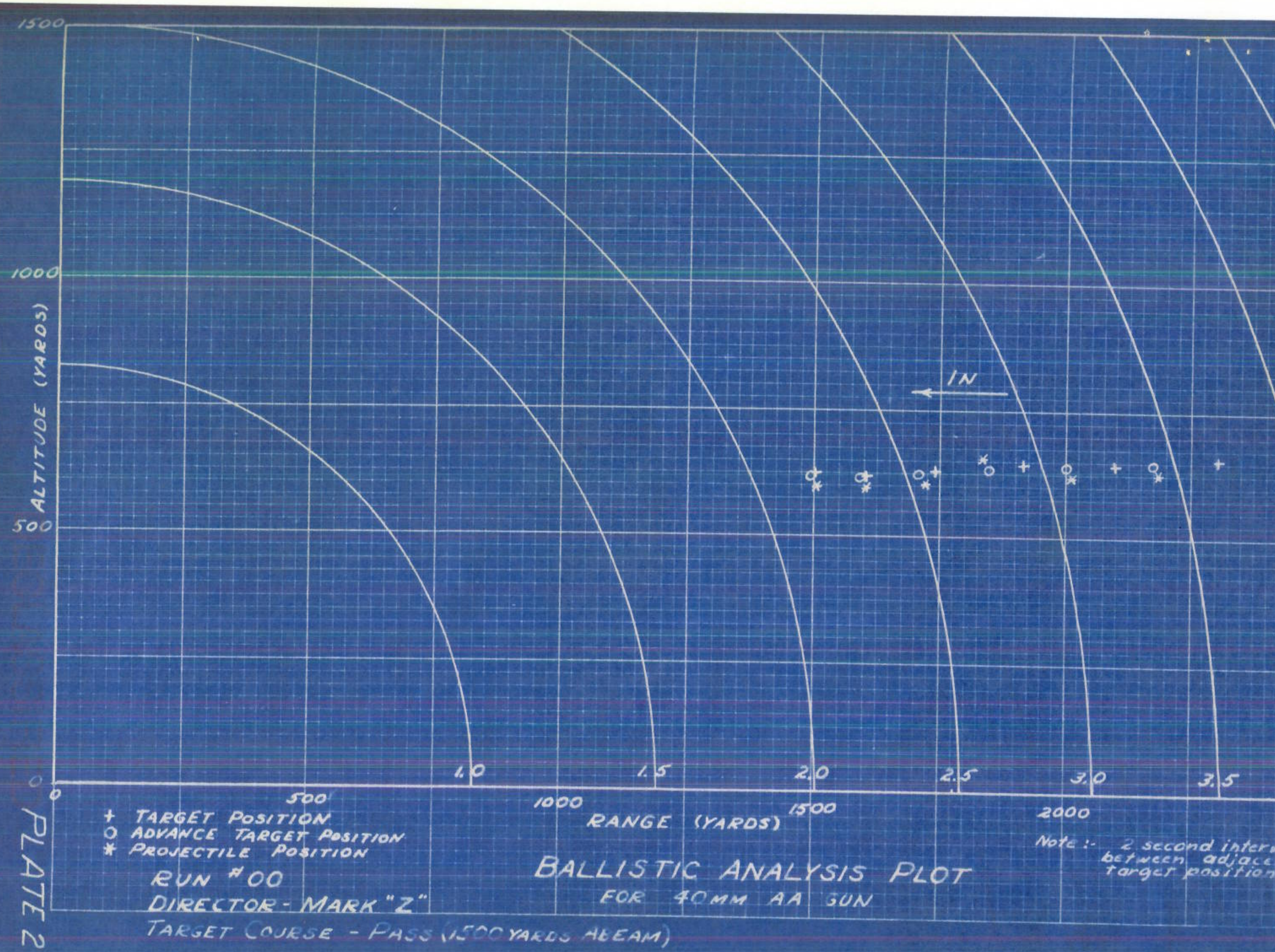
6-1-6. The method may be applied to any type of director in any mode of operation, and is useful in developmental studies as well as for acceptance tests.

6-1-7. In the final presentation of data the ballistic analysis plot and the splotch plot give vivid geometric illustration of the performance of the director, while the splot of mean point of impact and apparent mean dispersion versus range gives a highly significant graphical "Figure of Merit" of the director for any particular target path.



RUN # 00 DIRECTOR MARK "Z"

PLATE 1



1500
1000
500
0
ALTITUDE (YARDS)
0
500
1000
1500
2000
RANGE (YARDS)
1.0
1.5
2.0
2.5
3.0
3.5
IN
+ TARGET POSITION
O ADVANCE TARGET POSITION
* PROJECTILE POSITION
RUN #00
DIRECTOR - MARK "Z"
TARGET COURSE - PASS (1500 YARDS ABEAM)
BALLISTIC ANALYSIS PLOT
FOR 40MM AA GUN
Note :- 2 second interv
between adjacen
target position

PLATE 2

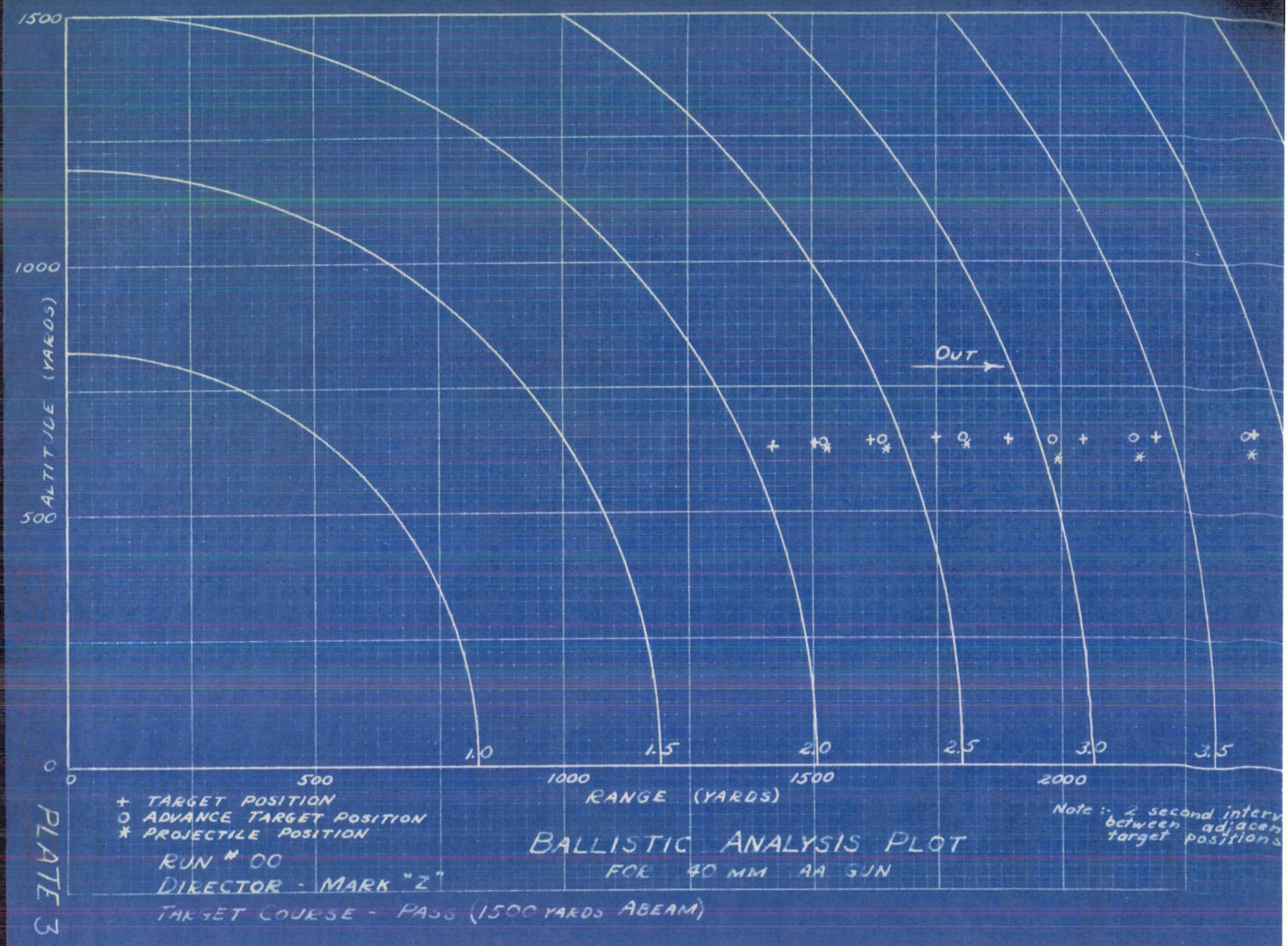
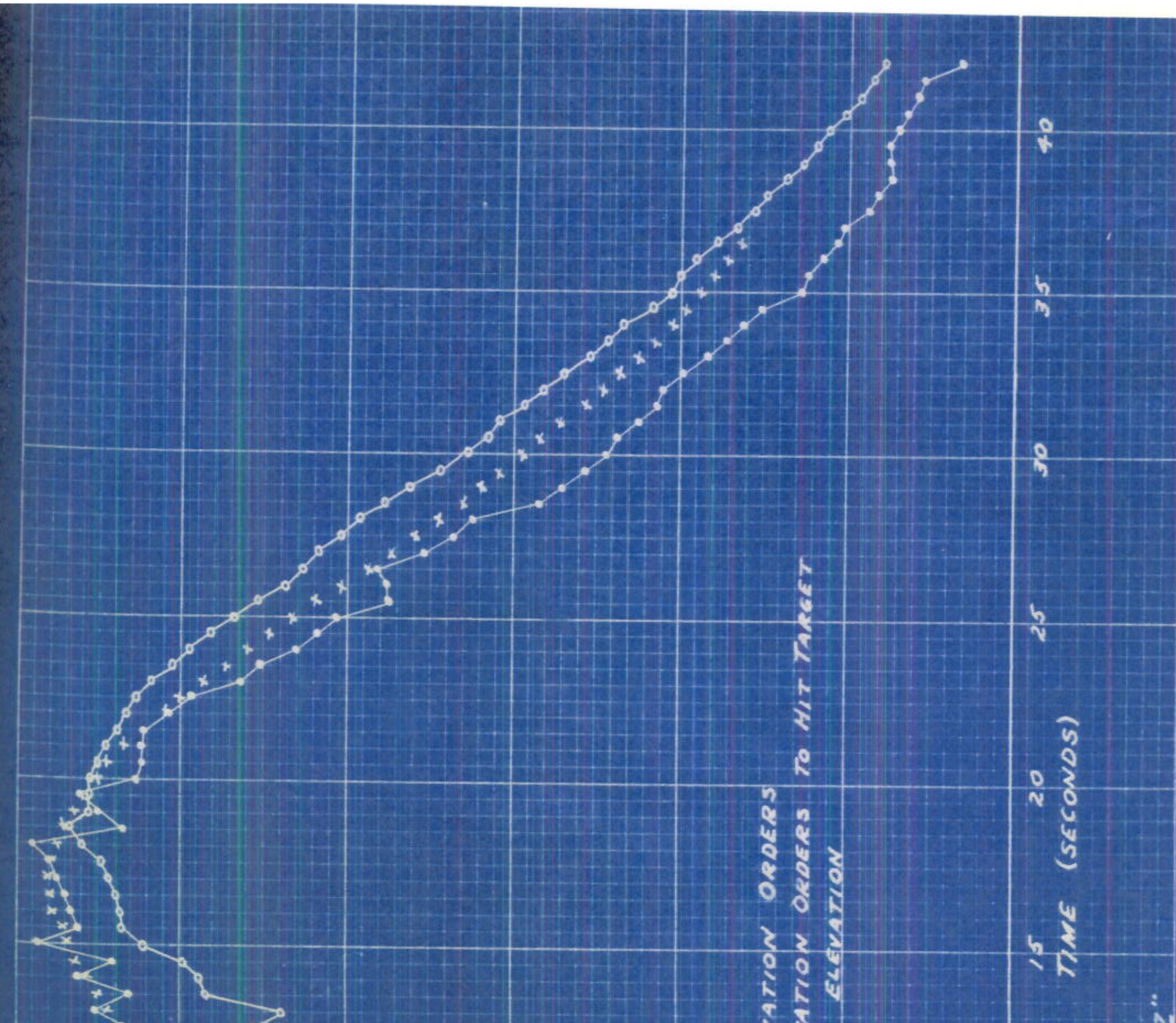
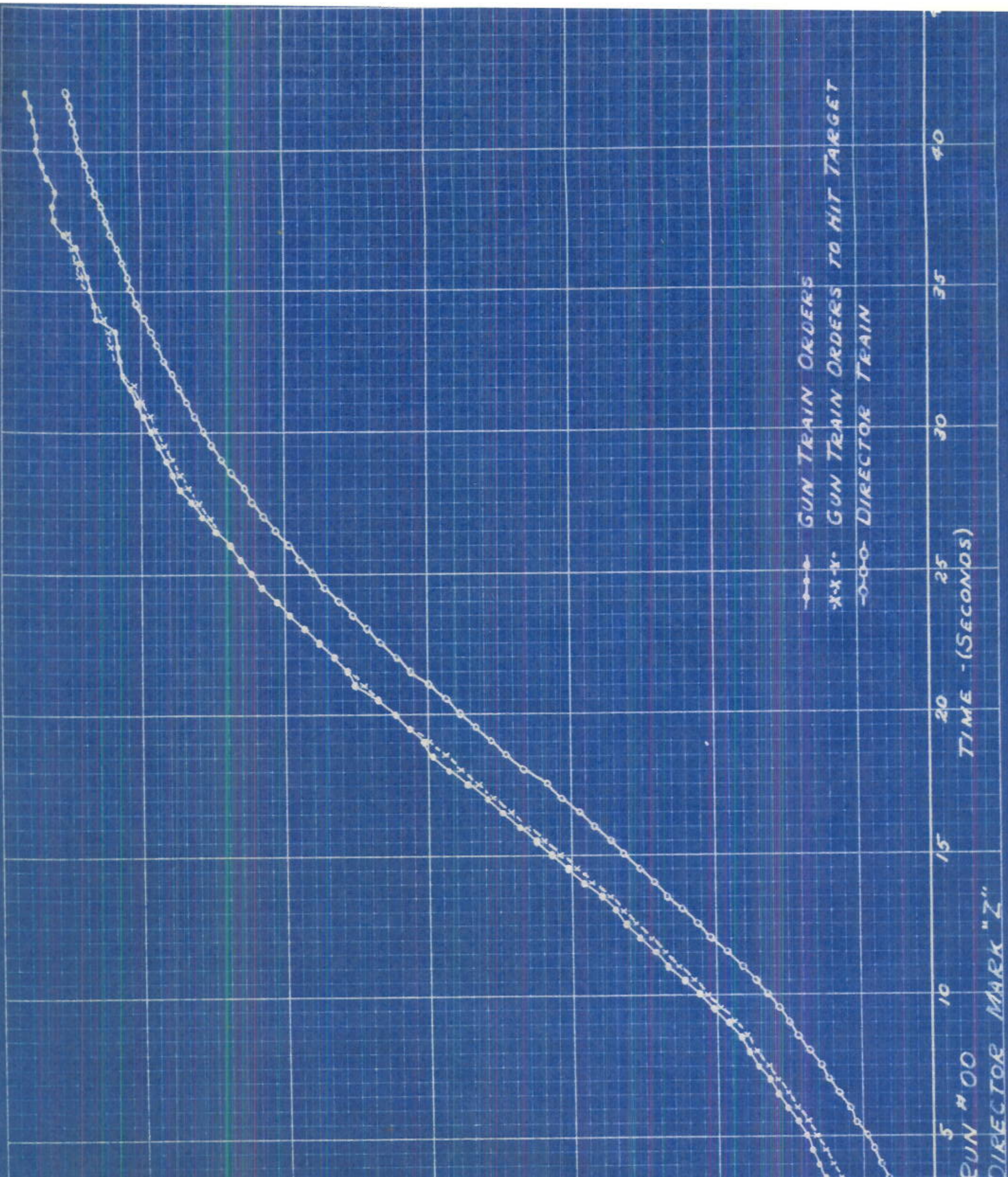

1500
1000
500
0
ALTITUDE (YARDS)
0
500
1000
1500
2000
RANGE (YARDS)
1.0
1.5
2.0
2.5
3.0
3.5
OUT
+ TARGET POSITION
O ADVANCE TARGET POSITION
* PROJECTILE POSITION
RUN # 00
DIRECTOR - MARK "Z"
TARGET COURSE - PASS (1500 YARDS ABEAM)
BALLISTIC ANALYSIS PLOT
FOR 40 MM AA GUN
Note :- 2 second interv
between adjacen
target positions

PLATE 3



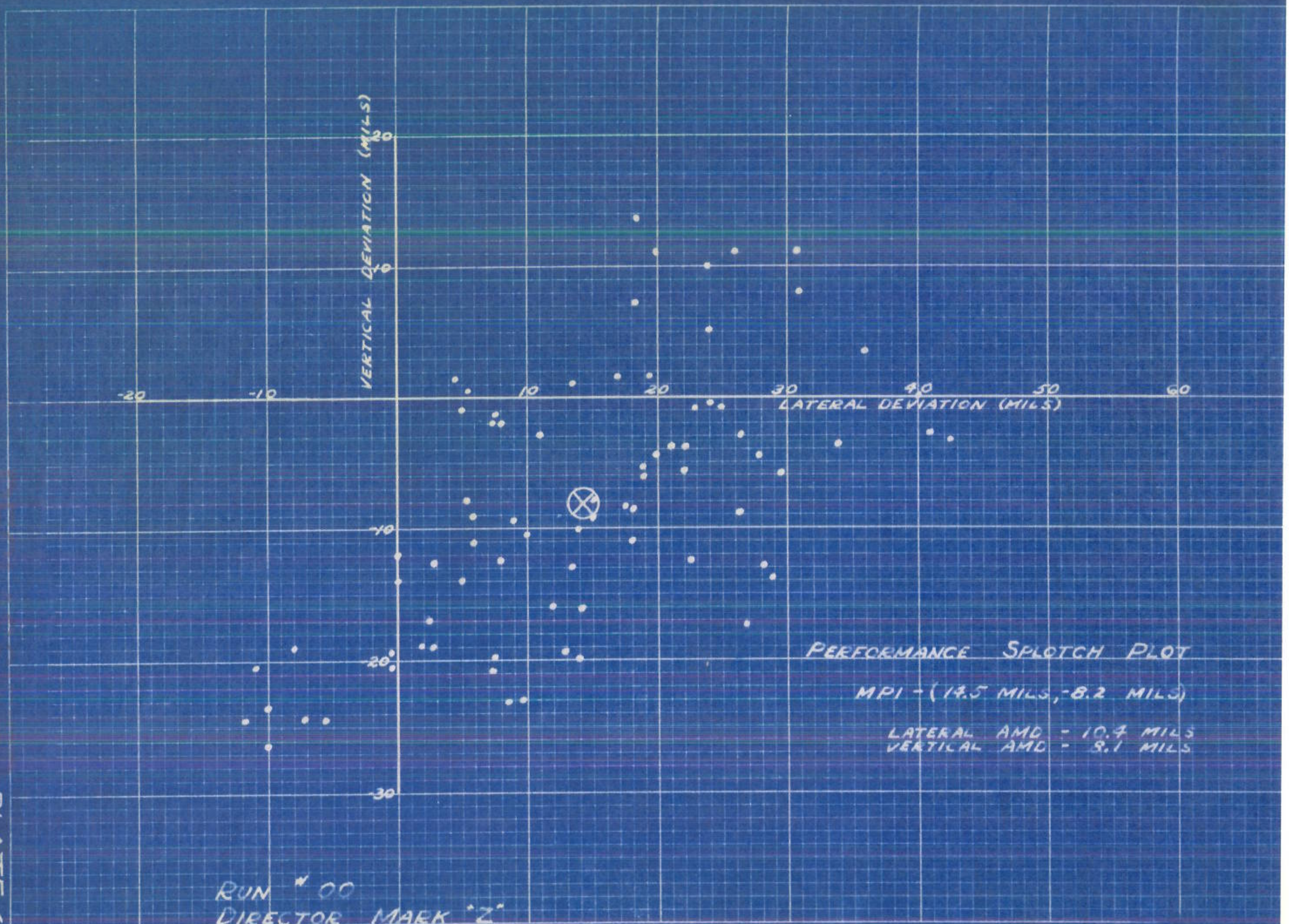
GUN ELEVATION ORDERS
GUN ELEVATION ORDERS TO HIT TARGET
DIRECTOR ELEVATION
TIME (SECONDS)
DEGREES
0
5
10
15
20
25
30
35
40
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
RUN #00
DIRECTOR MARK "Z"

PLATE 4



GUN TRAIN ORDERS
GUN TRAIN ORDERS TO HIT TARGET
DIRECTOR TRAIN
TIME - (SECONDS)
RUN #00
DIRECTOR MARK "Z"
DEGREES

PLATE 5



VERTICAL DEVIATION (MILS)
LATERAL DEVIATION (MILS)
-20
-10
10
20
30
40
50
60
-30
PERFORMANCE SPLOTCH PLOT
MPI - (14.5 MILS, -8.2 MILS)
LATERAL AMD - 10.4 MILS
VERTICAL AMD - 8.1 MILS
RUN # 00
DIRECTOR MARK "Z"

PLATE 6

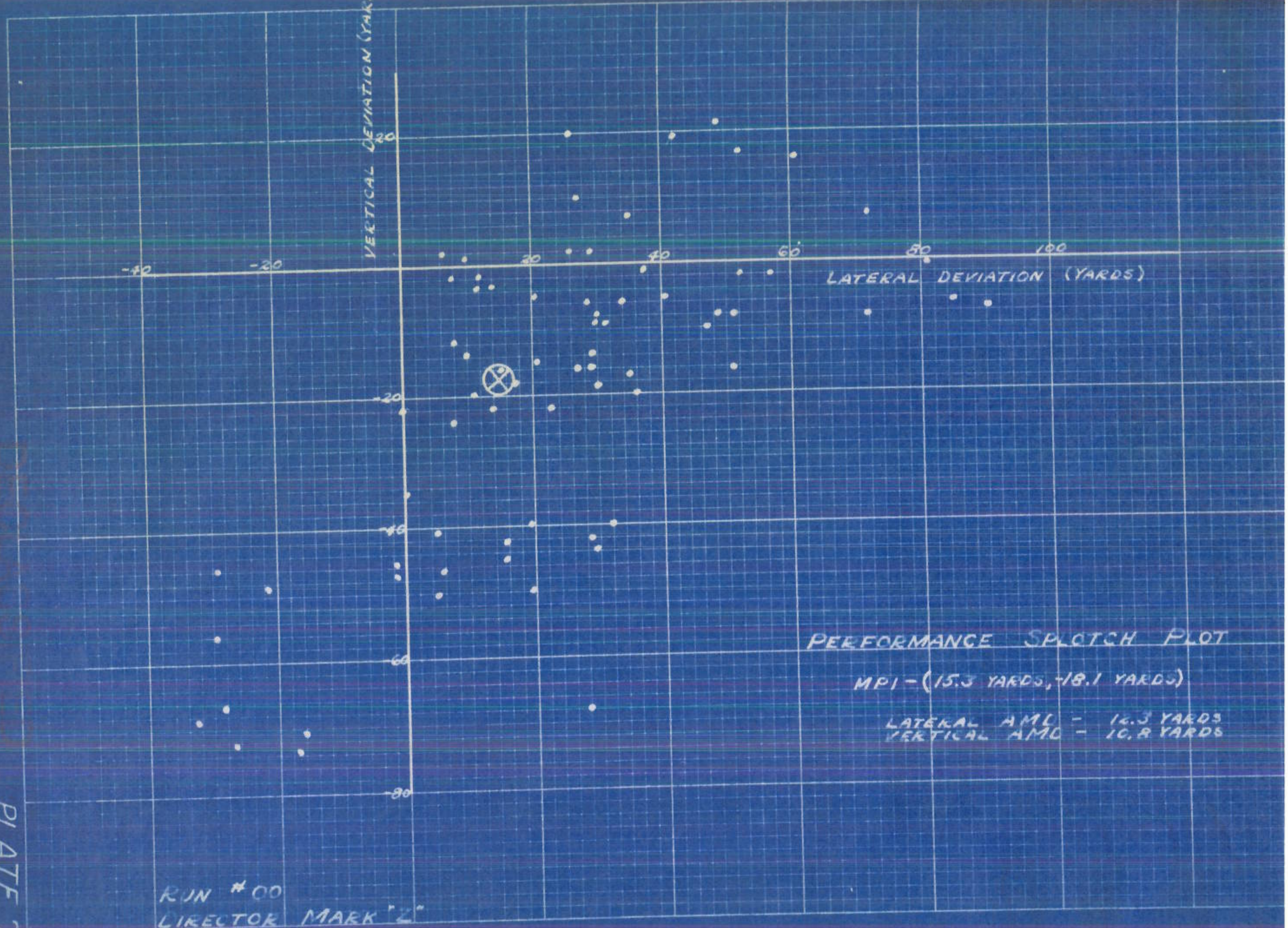
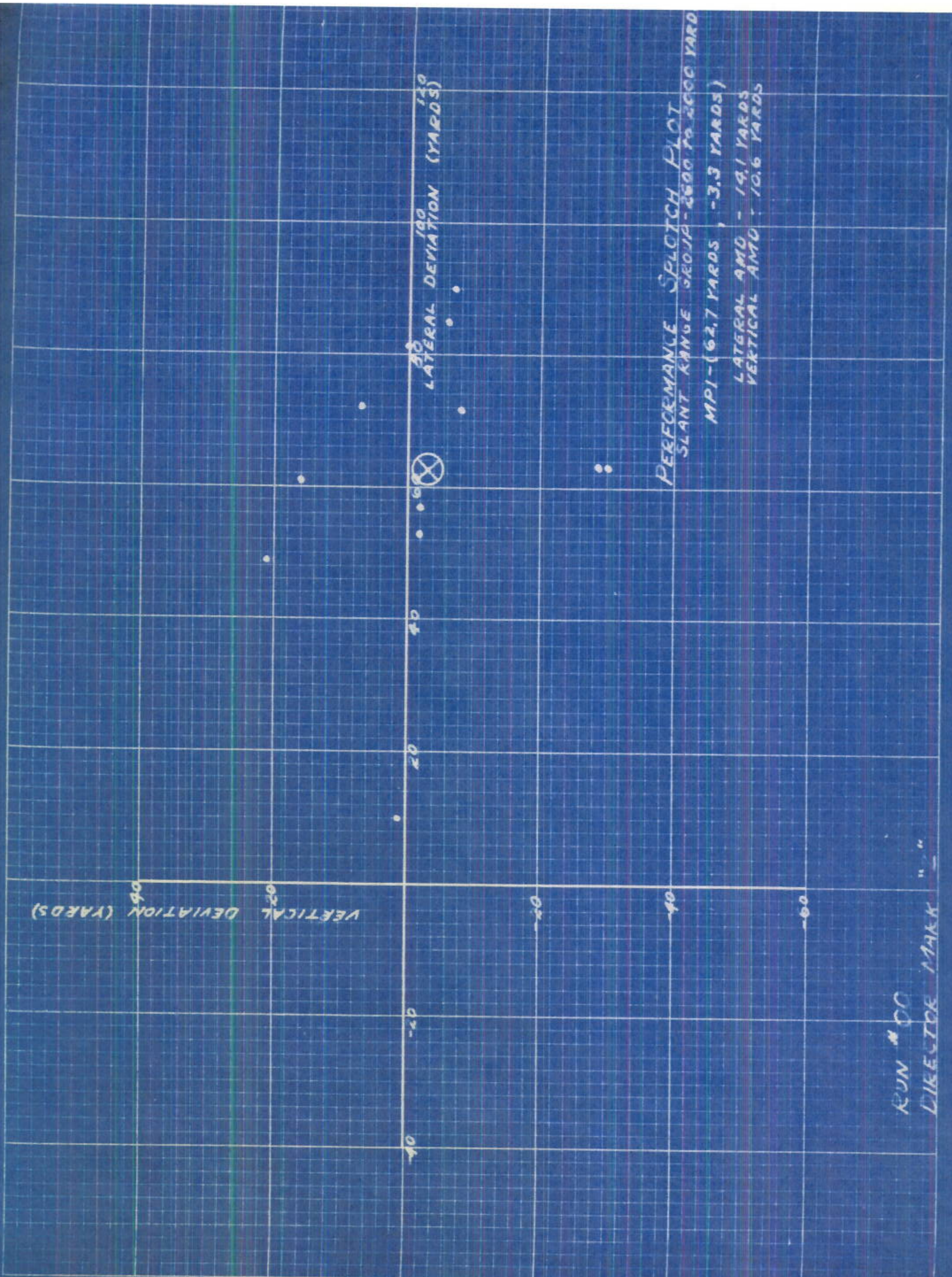
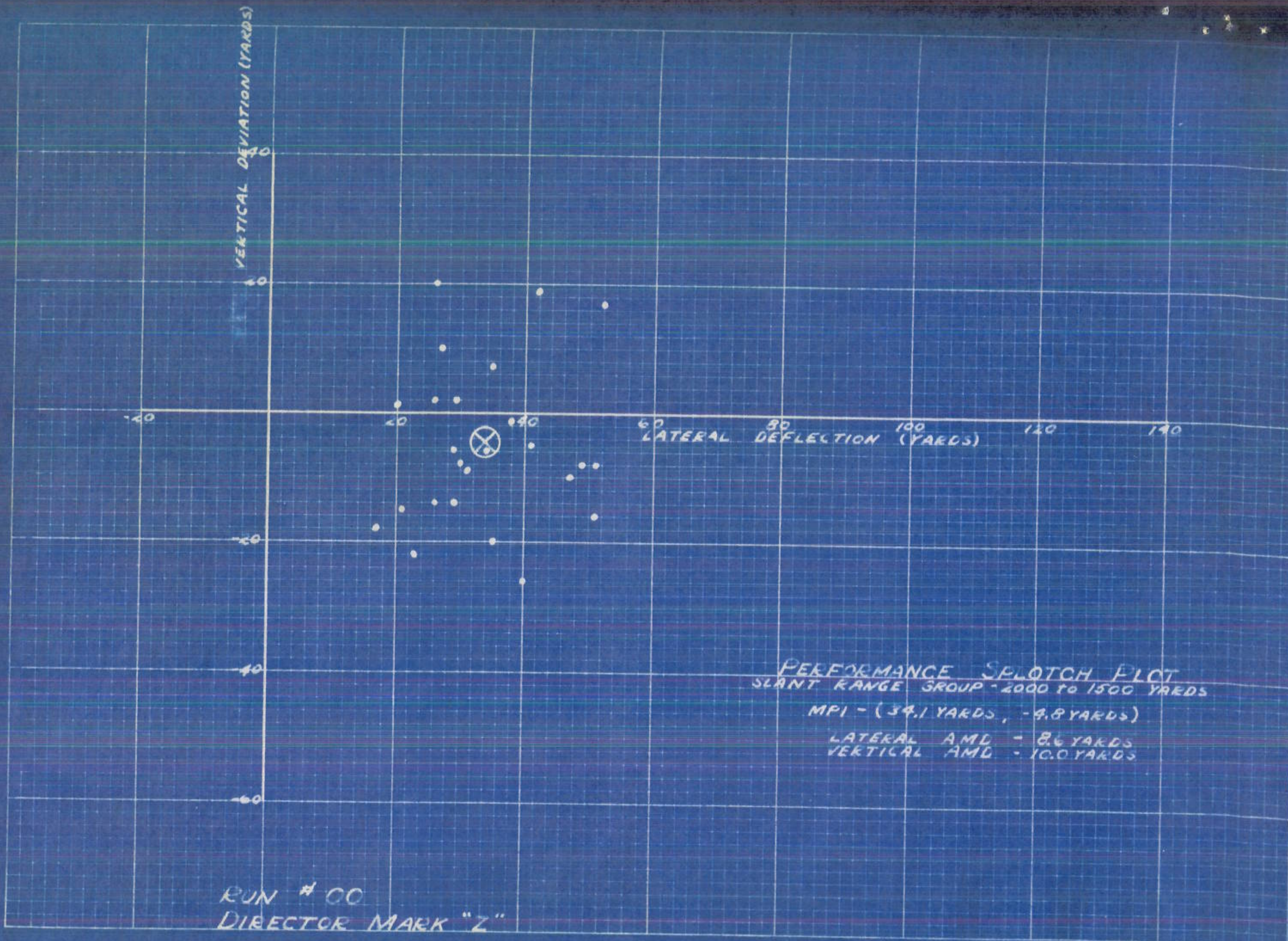

VERTICAL DEVIATION (YARDS)
LATERAL DEVIATION (YARDS)
-40
-20
20
40
60
80
100
-60
-80
PERFORMANCE SPLOTCH PLOT
MPI - (15.3 YARDS, -18.1 YARDS)
LATERAL AML - 16.3 YARDS
VERTICAL AMD - 10.8 YARDS
RUN #00
DIRECTOR MARK "2"

PLATE 7



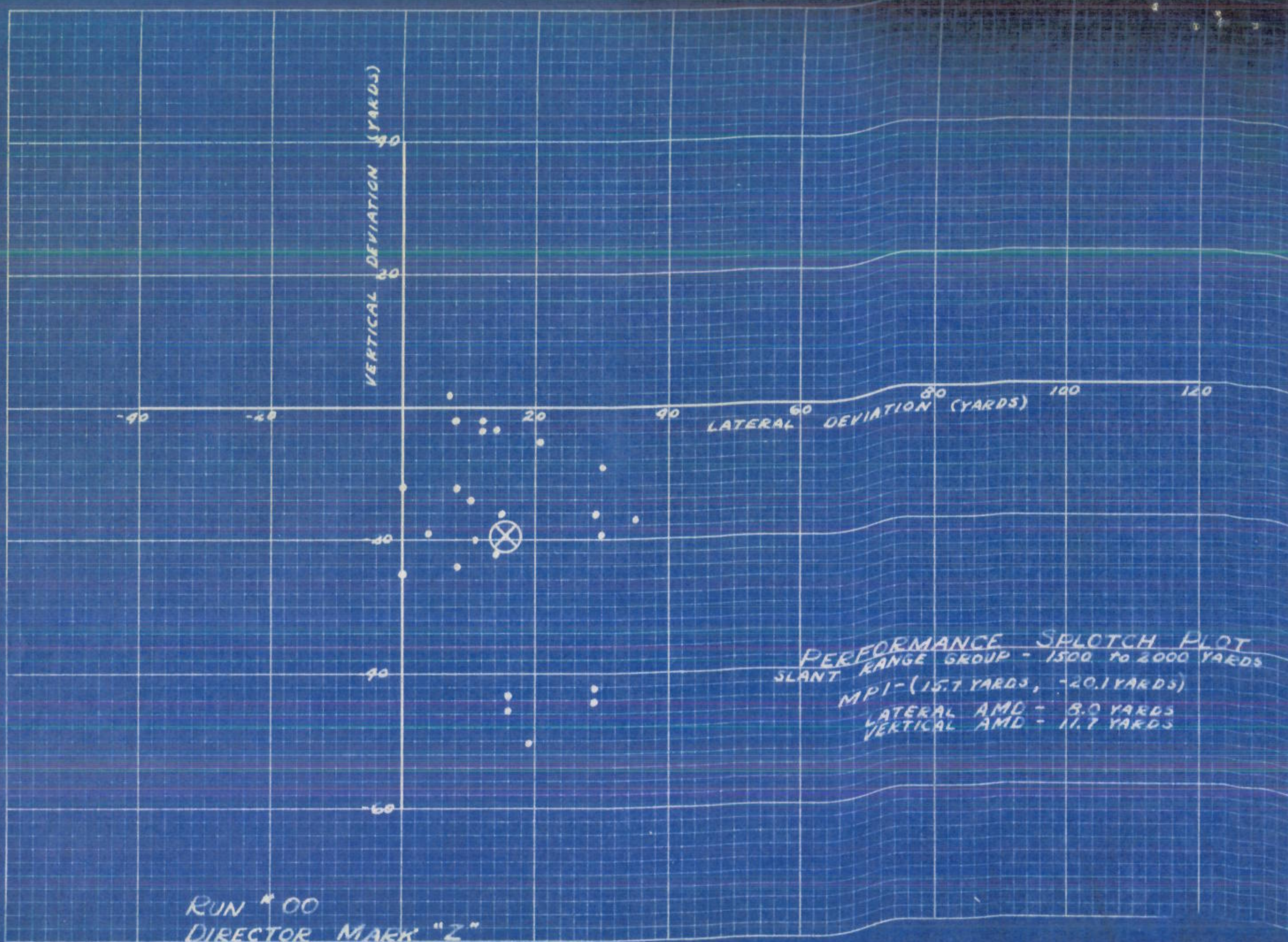
PERFORMANCE SPLOTCH PLOT
SLANT RANGE GROUP - 2600 TO 2000 YARD
MPI - (62.7 YARDS , -3.3 YARDS)
LATERAL AMD - 14.1 YARDS
VERTICAL AMD - 10.6 YARDS
LATERAL DEVIATION (YARDS)
VERTICAL DEVIATION (YARDS)
RUN #
DIRECTOR MARK

PLATE 8



VERTICAL DEVIATION (YARDS)
40
20
-20
-40
-60
-20
20
40
60
80
100
120
140
LATERAL DEFLECTION (YARDS)
PERFORMANCE SPLOTCH PLOT
SLANT RANGE GROUP - 2000 TO 1500 YARDS
MPI - (34.1 YARDS, -4.8 YARDS)
LATERAL AMD - 8.6 YARDS
VERTICAL AMD - 10.0 YARDS
RUN # 00
DIRECTOR MARK "Z"

PLATE 9



PERFORMANCE SPLOTCH PLOT
SLANT RANGE GROUP - 1500 to 2000 YARDS
MPI-(15.7 YARDS, -20.1 YARDS)
LATERAL AMD - 8.0 YARDS
VERTICAL AMD - 11.7 YARDS
LATERAL DEVIATION (YARDS)
VERTICAL DEVIATION (YARDS)
-40
-20
20
40
60
80
100
120
-60
RUN # 00
DIRECTOR MARK "Z"

PLATE 10

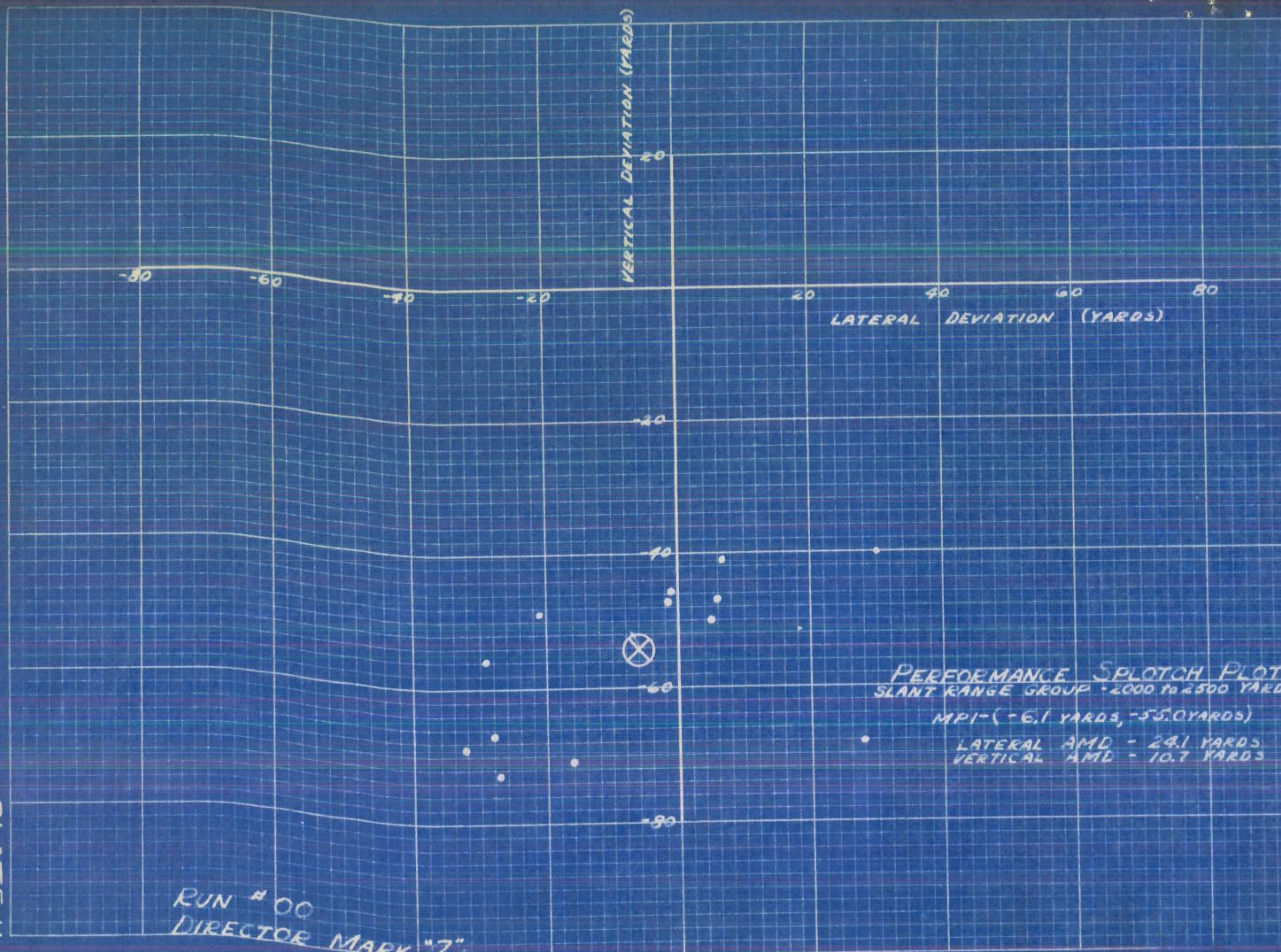

VERTICAL DEVIATION (YARDS)
LATERAL DEVIATION (YARDS)
-80
-60
-40
-20
20
40
60
80
PERFORMANCE SPLOTCH PLOT
SLANT RANGE GROUP - 2000 to 2500 YARDS
MPI - (-6.1 YARDS, -55.0 YARDS)
LATERAL AMD - 24.1 YARDS
VERTICAL AMD - 10.7 YARDS
RUN # 00
DIRECTOR MARK "Z"

PLATE 11

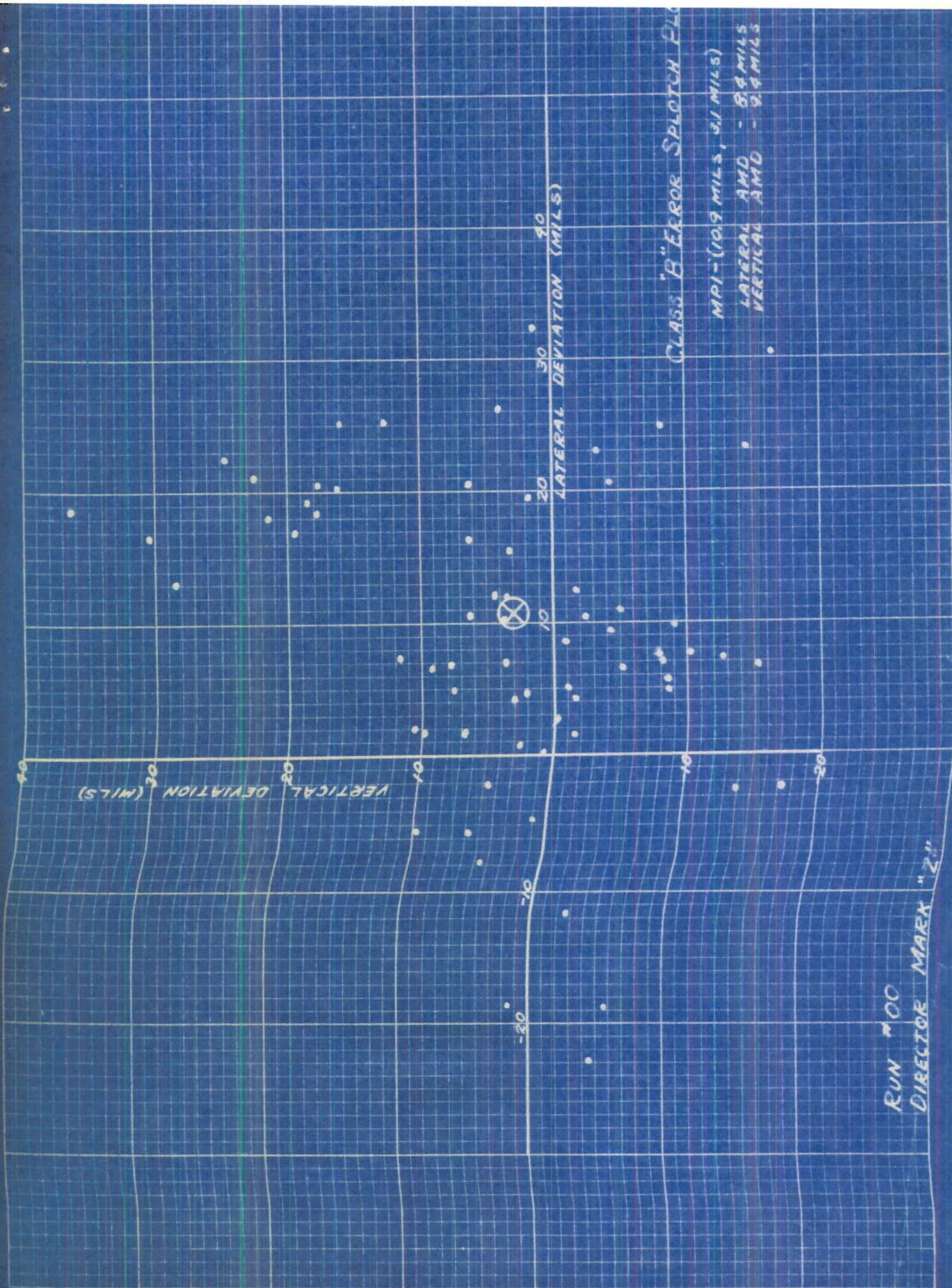

CLASS "B" ERROR SPLOTCH PL
MPI-(10.9 MILS, 3.1 MILS)
LATERAL AMD - 8.4 MILS
VERTICAL AMD - 9.4 MILS
LATERAL DEVIATION (MILS)
VERTICAL DEVIATION (MILS)
RUN #OO
DIRECTOR MARK "Z"

PLATE 12

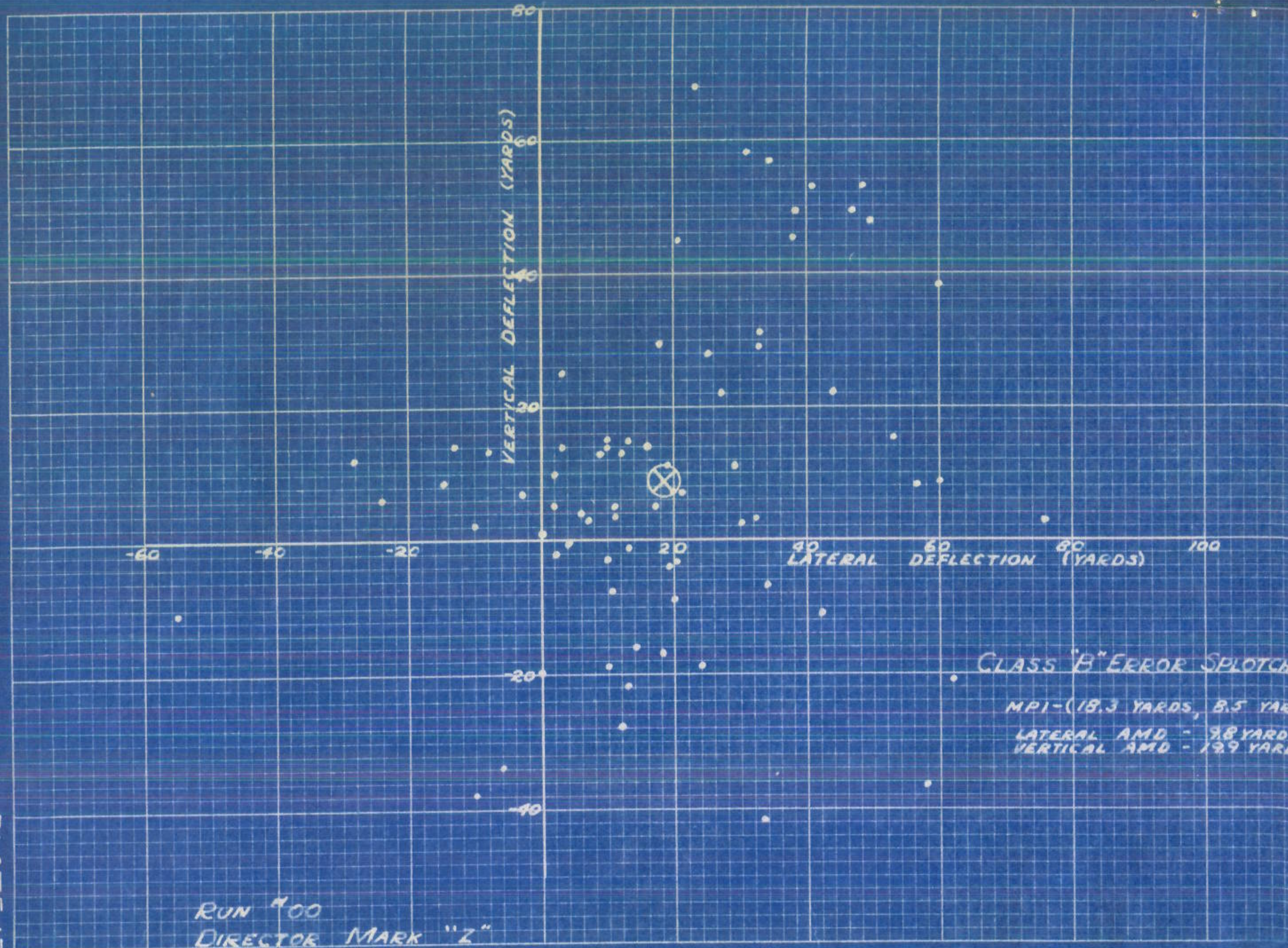

VERTICAL DEFLECTION (YARDS)
LATERAL DEFLECTION (YARDS)
-60
-40
-20
20
40
60
80
100
CLASS "B" ERROR SPLOTCH
MPI-(18.3 YARDS, 8.5
LATERAL AMD - 9.8 YARDS
VERTICAL AMD - 19.9
RUN #00
DIRECTOR MARK "Z"

PLATE 13

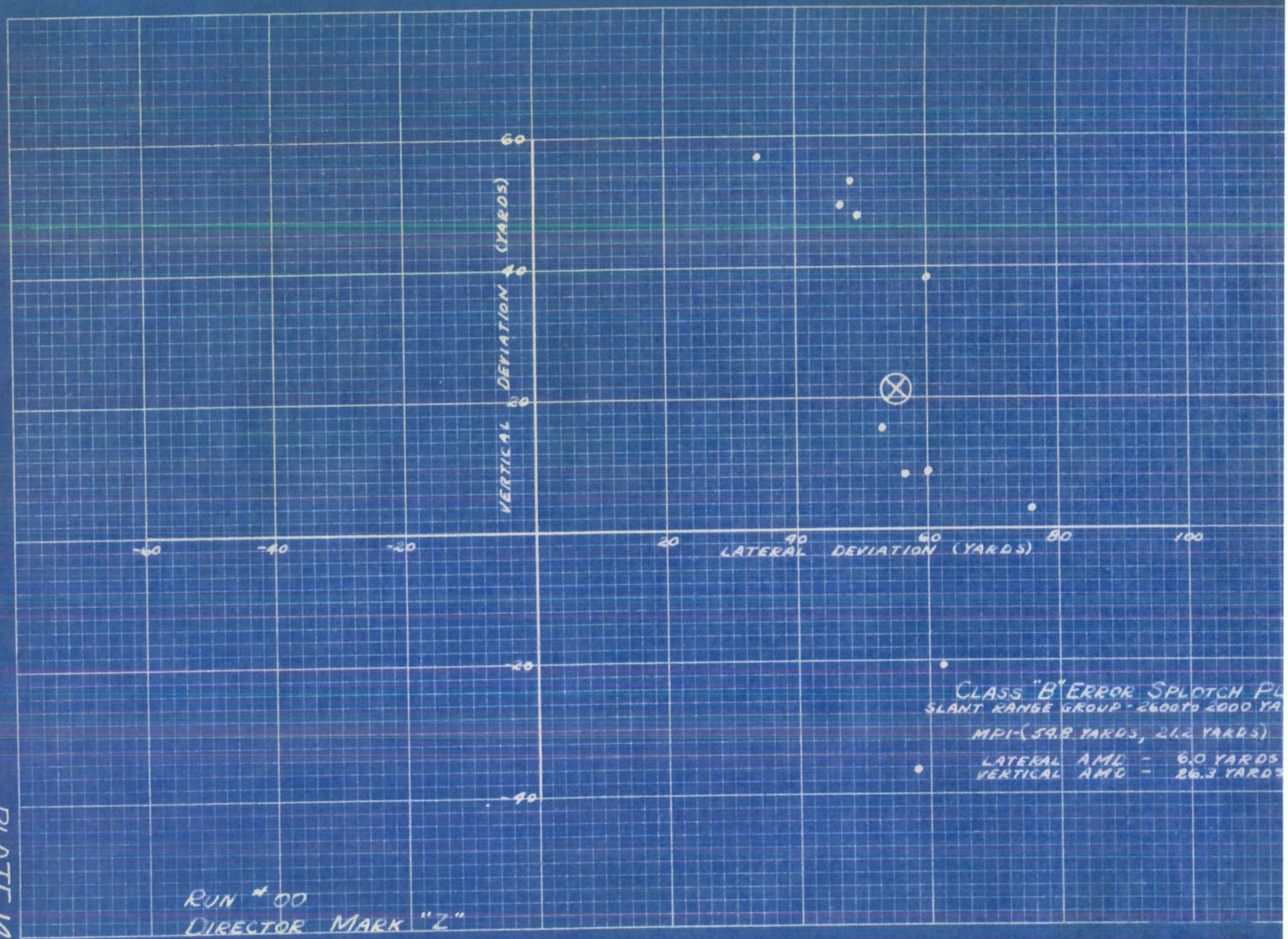
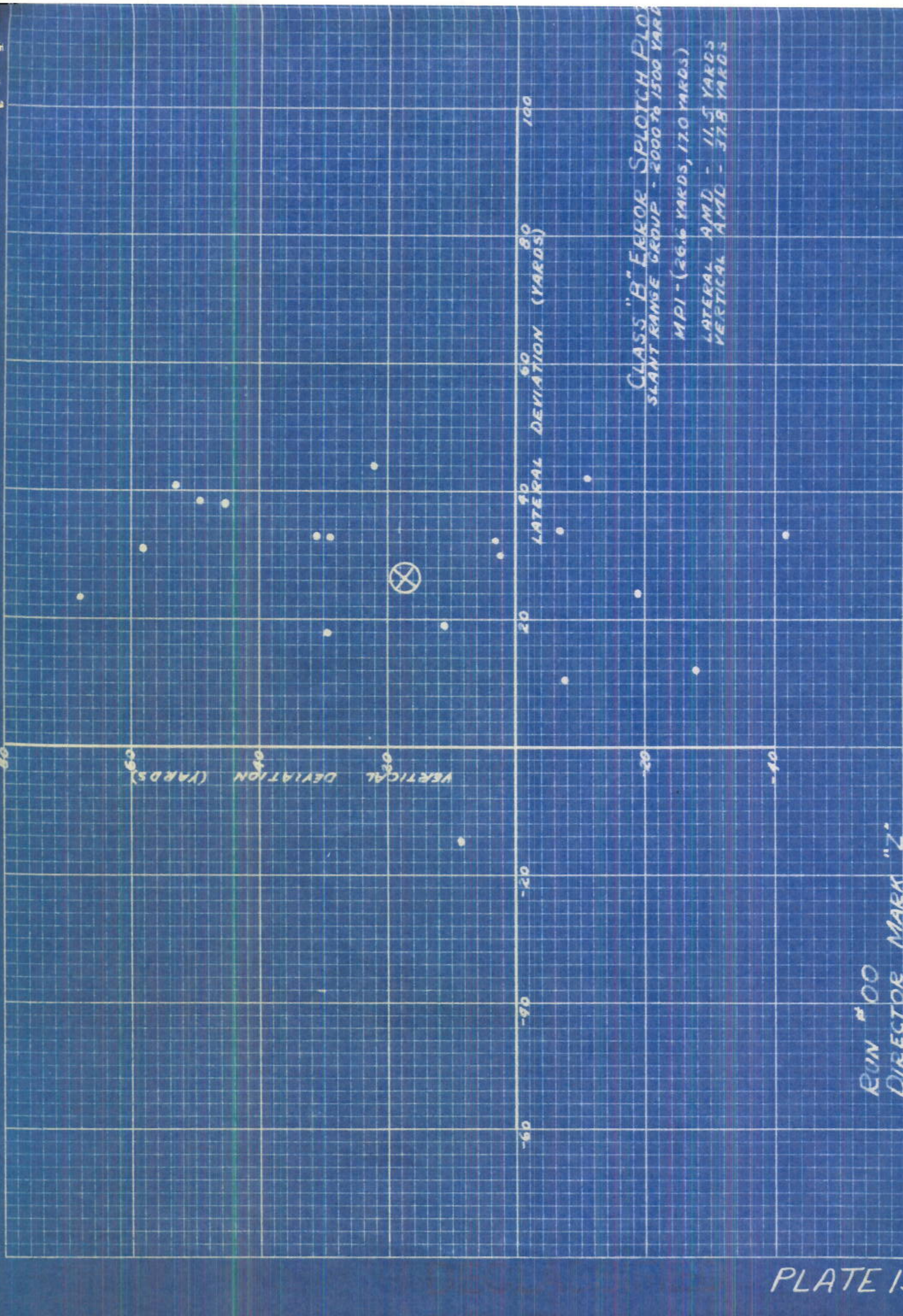

VERTICAL DEVIATION (YARDS)
LATERAL DEVIATION (YARDS)
60
40
20
-20
-40
-60
-40
-20
20
40
60
80
100
CLASS "B" ERROR SPLOTCH PL
SLANT RANGE GROUP - 2600 TO 2000 YA
MPI-(59.8 YARDS, 21.2 YARDS)
LATERAL AMD - 6.0 YARDS
VERTICAL AMD - 26.3 YARD
RUN # 00
DIRECTOR MARK "Z"

PLATE 14



CLASS "B" ERROR SPLOTCH PLO
SLANT RANGE GROUP - 2000 TO 1500 YAR
MPI - (26.6 YARDS, 17.0 YARDS)
LATERAL AMD - 11.5 YARDS
VERTICAL AMD - 37.8 YARDS
LATERAL DEVIATION (YARDS)
VERTICAL DEVIATION (YARDS)
100
80
60
40
20
-20
-40
-60
RUN #00
DIRECTOR MARK "Z"

PLATE 15

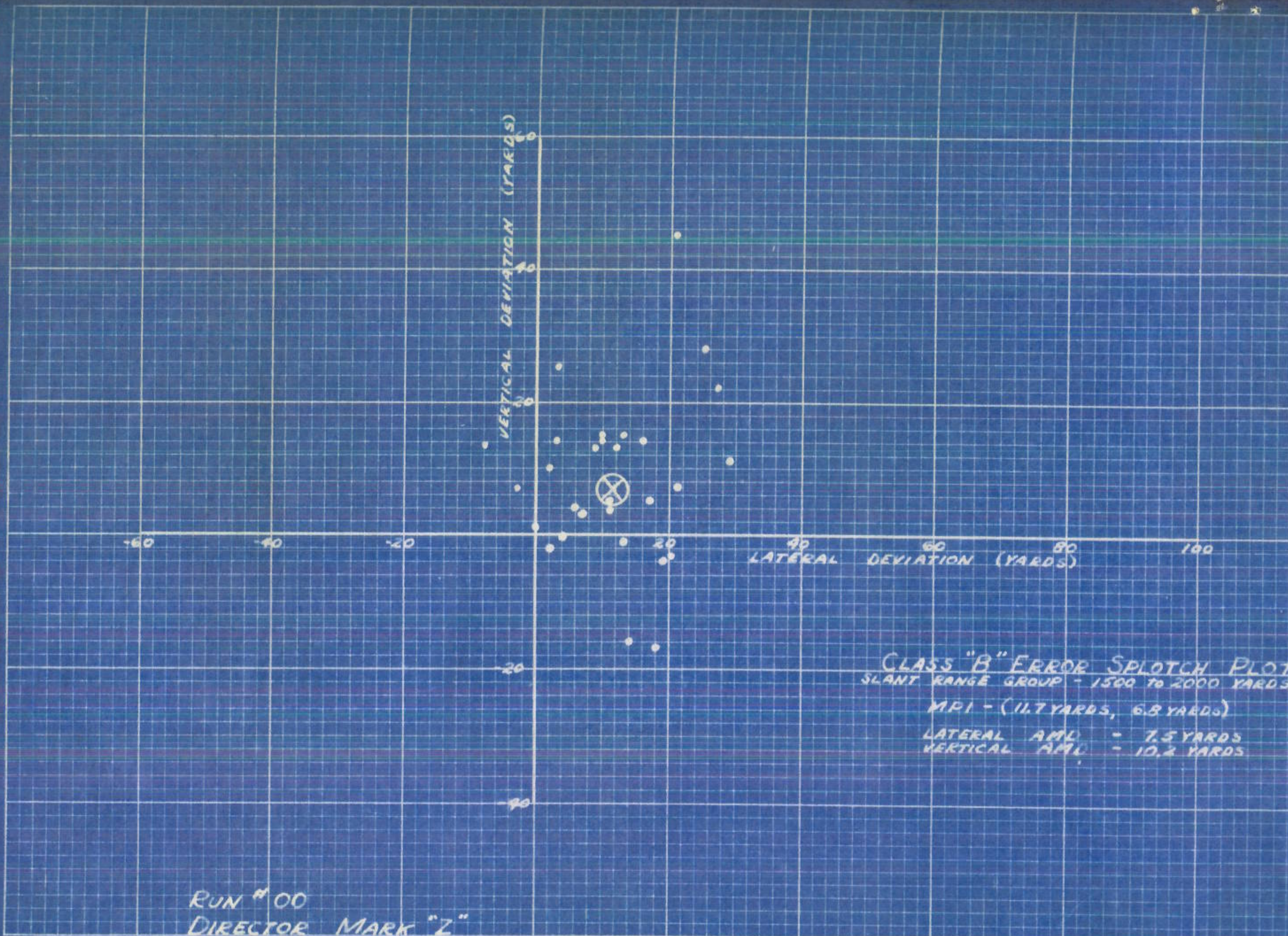
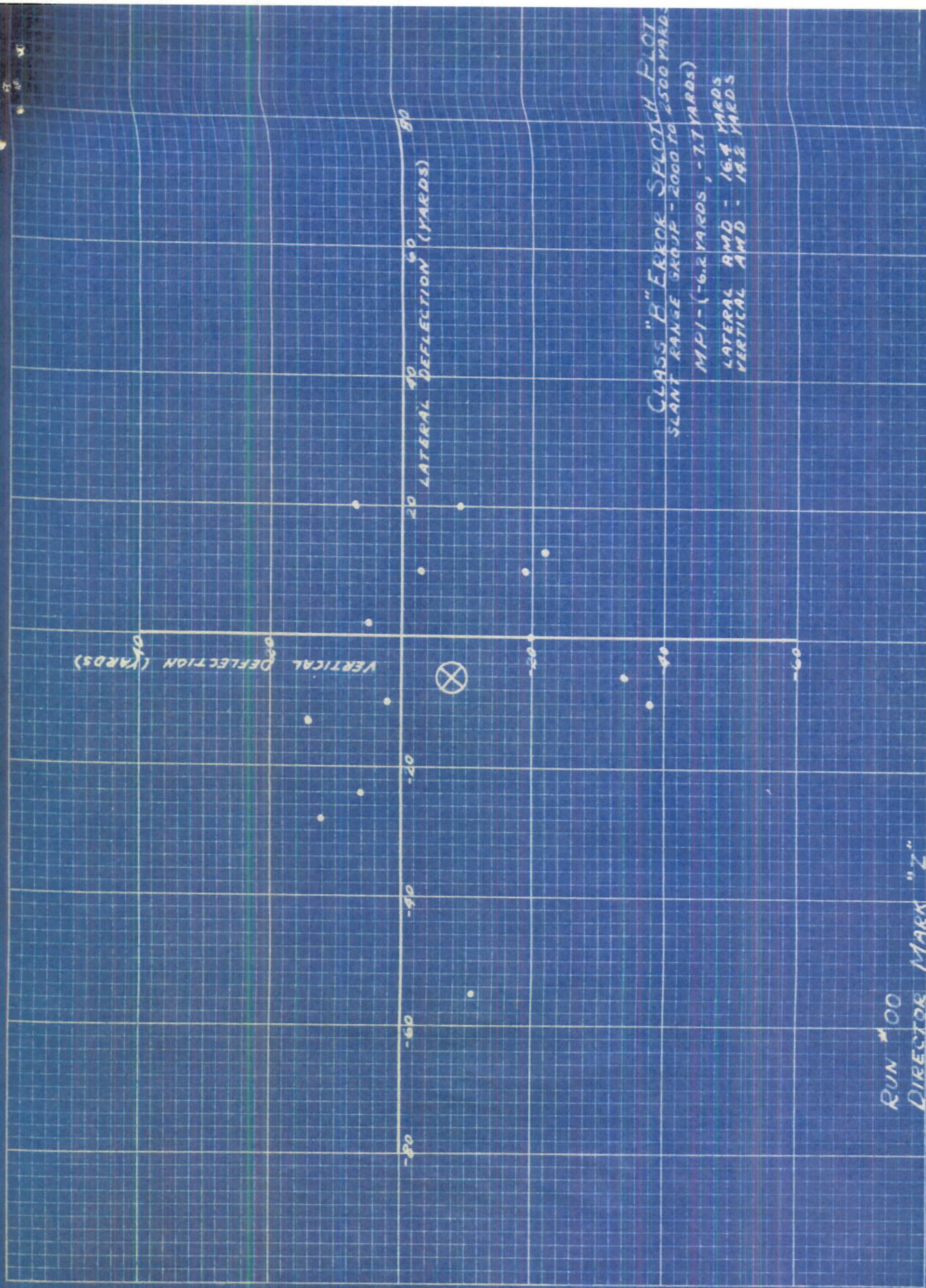

VERTICAL DEVIATION (YARDS)
LATERAL DEVIATION (YARDS)
-60
-40
-20
20
40
60
80
100
CLASS "B" ERROR SPLOTCH PLOT
SLANT RANGE GROUP - 1500 TO 2000 YARDS
MPI - (11.7 YARDS, 6.8 YARDS)
LATERAL AML - 7.5 YARDS
VERTICAL AML - 10.2 YARDS
RUN # 00
DIRECTOR MARK "Z"

PLATE 16



CLASS "B" ERROR SPLOTCH PLOT
SLANT RANGE GROUP - 2000 TO 2500 YARDS
MPI - (-6.2 YARDS, -7.7 YARDS)
LATERAL AMD - 16.4 YARDS
VERTICAL AMD - 14.8 YARDS
LATERAL DEFLECTION (YARDS)
VERTICAL DEFLECTION (YARDS)
RUN # 00
DIRECTOR MARK "Z"

PLATE 17

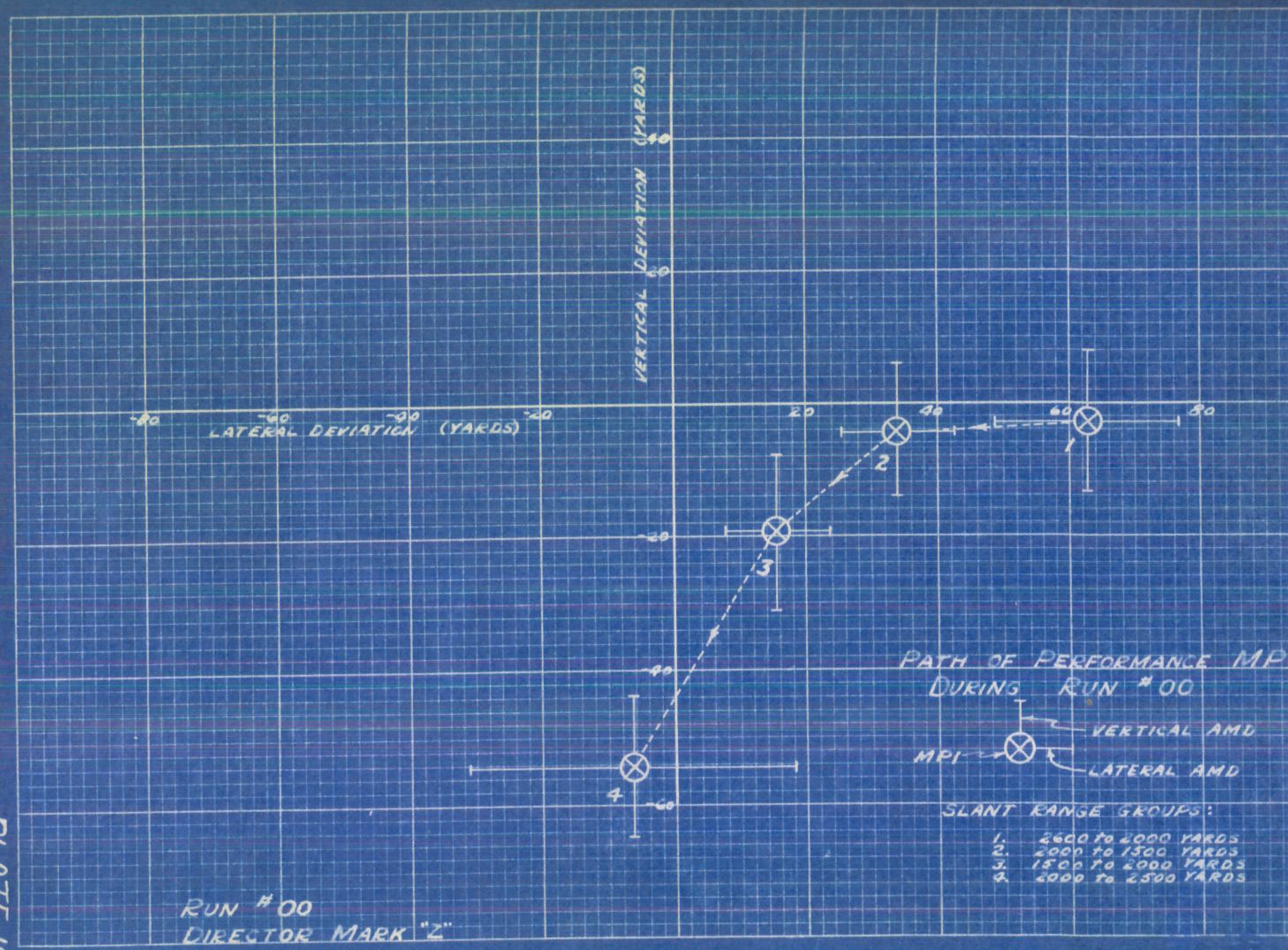
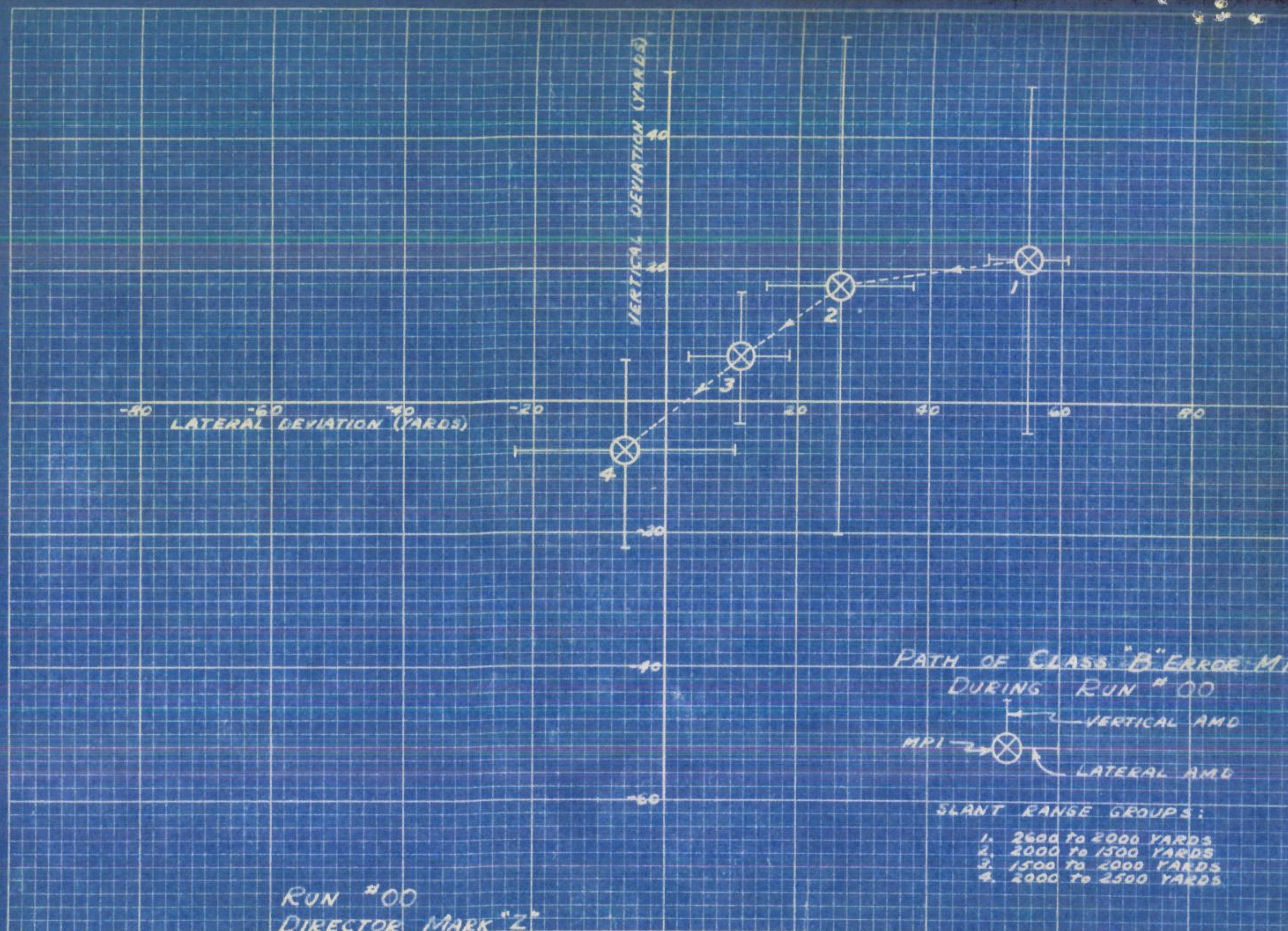

PATH OF PERFORMANCE MP
DURING RUN #00
VERTICAL AMD
MPI
LATERAL AMD
SLANT RANGE GROUPS:
1. 2600 to 2000 YARDS
2. 2000 to 1500 YARDS
3. 1500 to 2000 YARDS
4. 2000 to 2500 YARDS
LATERAL DEVIATION (YARDS)
VERTICAL DEVIATION (YARDS)
-80
-60
-40
-20
20
40
60
80
40
20
-20
-40
-60
1
2
3
4
RUN #00
DIRECTOR MARK "Z"

PLATE 18



VERTICAL DEVIATION (YARDS)
LATERAL DEVIATION (YARDS)
-80
-60
-40
-20
20
40
60
80
-20
-40
-60
1
2
3
4
PATH OF CLASS "B" ERROR MP
DURING RUN # 00
VERTICAL AMD
MPI
LATERAL AMD
SLANT RANGE GROUPS:
1. 2600 TO 2000 YARDS
2. 2000 TO 1500 YARDS
3. 1500 TO 2000 YARDS
4. 2000 TO 2500 YARDS
RUN #00
DIRECTOR MARK "Z"

PLATE 19