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A Stereoscopic Display for On-Line Monitoring of Simulated Terminal Engagements

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MASSACHUSETTS INSTITUTE OF TECHNOLOGY

LINCOLN LABORATORY

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ABSTRACT

A stereoscopic, dynamic display of re-entry bodies is described. Information for the display is generated by a simulation program on an IBM 7094 and is fed to a D. E. C. PDP-1 computer. The PDP-1 drives a D. E. C. Type 340 CRT display which is viewed through a special device by a systems analyst. The body of the report gives the philosophy of the need for on-line analysis and a general description of requirements for the display. Appendices give details about the optical viewer, the mathematics of stereoscopic viewing and a set of operational instructions for the display.

Accepted for the Air Force
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I. SUMMARY

This report is on a display for simulated engagements of ballistic missiles. The reasons for the development are threefold: (1) It is part of a larger effort to evaluate techniques for on-line control of large computer programs that simulate systems and analyze systems data. (2) It is intended as a test of the feasibility of generating on commercial equipment a display that will give an immediate perception of depth. (3) The display is to be used in a study of terminal defense doctrine with an existing simulation program.

The first section is a brief review of the context in which the display was developed; it explains the philosophy of on-line operation and describes the breadboard system that is being developed to explore this mode of operation. The second section gives a general description of the display. The third makes a few remarks about the value of such a display, apparent even before it has been put into operation.

There are three appendices: (1) the optical design of the Viewer, (2) the equation for calculation of stereoscopic disparity, and (3) the instructions for operation of the display controls. These technical appendices are intended to provide certain details needed by an experienced computer engineer to estimate the magnitude of the task of implementing such a display with similar equipment. Details of the display programs have been excluded; they are largely routine and are unique to the application and the equipment.

II. BACKGROUND

A principle objective of the Lincoln Laboratory efforts to develop new computer techniques is to replace the present awkward procedures for using computers in the analysis of data and the simulation of systems. At present the analyst is subject to delays of a day to a week in obtaining results from a particular computer run. If he could monitor his program during the run and intervene on-line, then it is clear that advantages of both speed and efficiency would be achieved. For example, whenever he perceived the effects of an error of procedure or judgment, he would be able to stop the run, correct the error at once and begin again. During the run, especially with good on-line displays, he would get an immediate appreciation of the significance of the results. Often the analyst is testing an hypothesis about the nature of his data or about the effect of a system parameter. If the results come back when the rationale that led to the hypothesis is still fresh in his mind, his appreciation of the results is likely to be more rapid and more profound. For these reasons an on-line facility should provide a marked improvement in efficiency and speed over the present methods of computer analysis.

Moreover, on-line analysis has a unique advantage: the analyst may become an active participant in the process. When it reaches a given point, the program may display relevant information, relinquish control to the analyst, and wait for orders as to the next course of action. It is not difficult to imagine instances in which this kind of facility would be of great value — in the development of new procedures of data analysis or in the invention of new system doctrine.

A breadboard computer and display system for on-line analysis of systems is being readied for a test of the validity of these ideas. No effort is being made to develop prototype equipment or programs. Rather this is a test facility, assembled largely from existing machinery and programs, where the systems analyst can work on substantive problems on-line with the computer. The essential product of this effort is an understanding of the advantages and costs of on-line procedures. Of course, it is hoped that a useful interim capacity to accelerate progress in selected areas will be achieved.

One of the areas is a study of terminal defense doctrine using a previous developed simulation program. A gross block-diagram of the system for this study is shown in Fig. 1. During live operation, calculations are made on the 7094 in Building J at Lincoln Laboratory and sent by wide-band link to the PDP-1 computer in Building L. The current data are shown on the display in the form of a dynamic picture of RV's and interceptors. The operator makes decisions relevant to intercept assignments. His orders are sent back to the 7094 via typewriter, PDP-1, and data-link and cause new

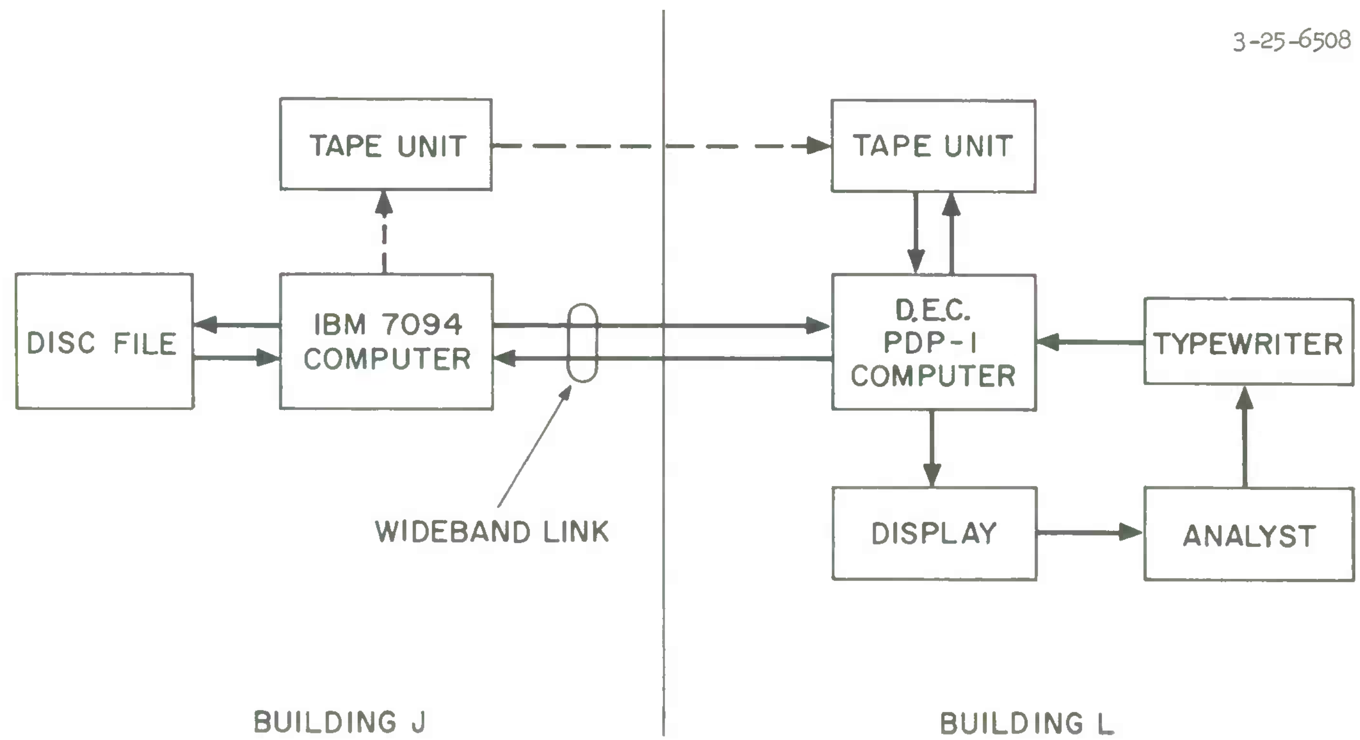

Fig. 1. Block diagram of the experimental on-line system.

interceptor launches in subsequent steps of the game. Efficient use of the 7094 is achieved by dumping the simulation program onto the disc file and making routine calculations of other kinds during the relatively long waits between orders from the analyst at the PDP-1. During the display-development phase reported here, output of the 7094 simulation program was recorded on tape and run off-line at the PDP-1 to test the display techniques. The dotted lines in Fig. 1 indicate the tape links between the computers.

A simulation program was selected which provides a valid simulation of engagements, is an operating program, and is written for the available computer, the 7094.

III. DESCRIPTION OF THE DISPLAY

The input to the display consists of two kinds of information, the locations of objects at successive times and a table of interceptor assignments. The position of each object, RV or interceptor, is given in three coordinates of space at one-second intervals, beginning at the time of appearance of the first RV. A table, which is kept up to date second by second, shows the number of the RV to which each interceptor is assigned.

The most difficult display requirement is to achieve a complete picture of an engagement — one that presents objects in three-dimensional space and changes over time as the engagement progresses. Several techniques were considered. For example, considerable work has been done recently on the use of relative motion as a method for obtaining a perception of depth with a computer-driven display. This method consists of showing the changing two-dimensional projection of a cluster of lines while the cluster is rotating in space. Previous research at Lincoln Laboratory by Green *et al.** showed that depth is readily perceived during rotation, even if the cluster is made up of a haphazard arrangement of elements. However, in the case where the elements move with respect to one another, as do RV's and interceptors in a terminal engagement, the change due to rotation is confounded with change of relative position among the objects. Thus, an accurate

* Figure coherence in the kinetic depth effect. *J. exp. Psychol.*, 1961, Vol. 62, No. 3, 272-282.

perception of the position of the objects over time seemed out of the question for this application.

The only reasonable way to achieve depth perception appeared to be to use the time-honored principle of the stereoscope. A separate view was presented to each eye. Appropriate geometrical discrepancies were introduced — discrepancies in keeping with the slightly disparate views of two eyes viewing objects distributed in depth and viewed at short range — about thirty inches. The equation by which the disparity was calculated is given in Appendix 2. The two views were painted on the CRT in an unusual orientation that is explained in Appendix 1, and were seen through a viewing device that is explained in Appendix 1 and illustrated in Fig. 2.

Looking through the viewer, the analyst sees a side view of the engagement, like that shown in Fig. 3, except that his view of course includes depth. The target and the interceptor farms are at the bottom near the left-hand margin. Re-entering objects enter at the upper right, and the nominal trajectory to the target is in the frontal plane. The "standard picture," the largest area available to the operator, is about 250 km wide and 120 km in height, and depth is perceived readily in the range between 50 km in front of the re-entry plane and 50 km behind it. The display is quantized, and the unit of quantization (which is set by the logical circuitry that drives the CRT) is 1/4 km in width and height, and 2 km in depth.

There is a X2 expanded view. A selected volume 125 km wide by 60 km high is expanded by a factor of two in each of the three dimensions — width, height, and depth — and fills the entire display. Off-centering of the expanded area is provided in the lateral and vertical dimensions, but not in depth. Expansions of X4 and X8 are also provided. Since the unit of quantization is fixed distance on the face of the CRT, the quantization error in kilometers decreases by a factor of two in all three dimensions with each factor of two in expansion.

The current (or latest) position of each object is represented by a point, as in Fig. 3. Directly below the point, and perceived at the same depth, is a number tag representing the depth of the object in kilometers. (The number "50" is arbitrarily set to represent the depth of the nominal trajectory plane.)

Fig. 2. An operator is shown looking at the display through the viewer. The controls are at the left. The viewer is shown in the insert at the right. The masking polarizers were removed when these pictures were taken.

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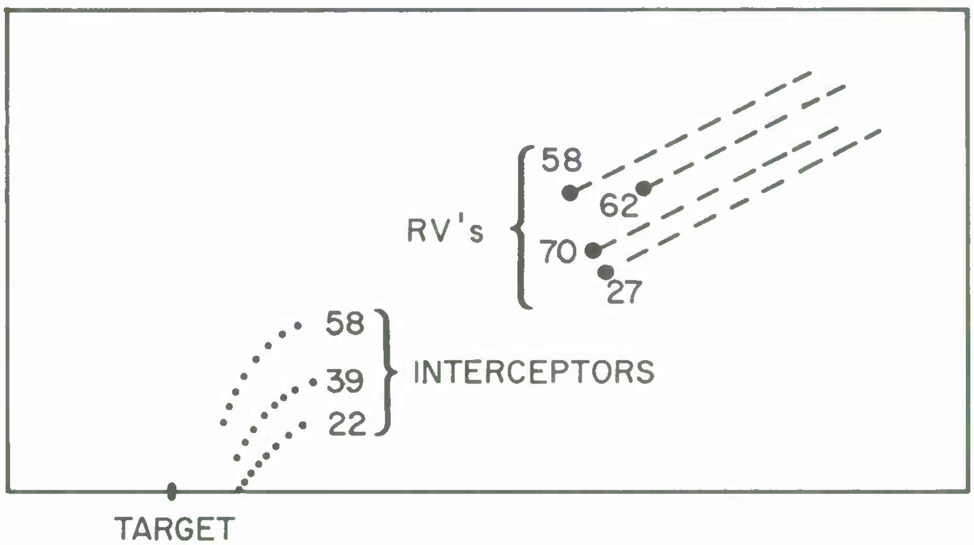

Fig. 3. Analyst's view of re-entry events.

Alternatively, the tags may be changed so that they refer to the number of the objects in the simulation program.

The dynamics of the engagement are presented by showing the analyst eight seconds of history for each object. The RV trails are dashes; the length of the dash is proportional to depth — the longer dashes indicating closer objects. Interceptor trails are represented by a series of dots. Current position and the number tag are bright and steady, but the trails of interceptor dots and RV dashes are presented in rapid sequence. The timing is such that there are repeated cycles of apparent movement along the trail up to the current position. If the analyst wants to review an earlier portion of the engagement, i. e. back up in time, he may temporarily designate any earlier second as "current time." He will then see the positions of the objects at that time, with the usual eight seconds of history behind them.

A maximum of 32 RV's and 32 interceptors may be shown. With that many objects on the display, the analyst needs some way of clarifying the picture. Besides off-centering and expansion, important aids to sorting out the objects, there is another feature: the analyst may devise his own scheme of brightness coding. By way of an example, he can set objects of little interest — e. g., those of low β or those outside the threat tube — so that they and their histories will be dim. All other objects can be made to appear at a normal level, except for a designated object: it and its history can be especially bright. Any brightness coding scheme of the three levels can be established with one restriction. When an object is set to a given brightness level, any object (interceptor or RV) that is paired with it will automatically be set to the same brightness.

Further details of the analyst's options in selecting and suppressing information are given in the operating instructions in Appendix 3.

IV. DISCUSSION

The display features described in the preceding section were specifically designed for the study of interceptor assignment doctrine. The utility of brightness coding has already been discussed. The eight seconds of history indicate the direction of flight and reveal changes of speed, such as those that RV's of low β exhibit on re-entry. If the analyst wishes to take action on an object he can ask that its number be shown beside it on the display. (Alternatively, he can read its number from the selector switch if it is selected by brightness coding.) The overall representation in four dimensions of space and time, with the off-centering and expansion features, would seem to provide a complete picture of the relation of interceptors to RV's, in position and by assignment, of the kind the analyst requires.

There is another sense in which the development of this display seemed to fit well with the study of intercept doctrine. Because of the uncertainties in stereoscopic phenomena and in cathode ray tubes, the precision of depth perception could not be predicted with confidence. It therefore seemed wise to choose a problem area that did not demand extreme precision in the perception of depth. This consideration was one factor in the decision to study intercept doctrine.

As it turned out, the quality of the stereoscopic effect is very satisfactory. People with normal vision (wearing their usual glasses if they need them) have no difficulty in perceiving the depth effects. There is, of course, the drawback that people with vision in only one eye cannot see stereoscopic depth. Indeed, one indication of the value of the third dimension is that a view with one eye is often difficult to interpret because of objects that fall on top of each other.

When the display is used on-line with the simulation program, evaluative experiments and observations will be carried out. Several questions need to be studied. They range from technical questions about the accuracy of depth perception to broad questions about the value of the display as an aid to solving intercept assignment problems.

APPENDIX 1

STEREO VIEWER

It was decided to present a "side" view of the simulated engagement; that is, range would be represented along the abscissa and the nominal RV trajectory would lie in a plane perpendicular to the line of regard. In a typical engagement, range will be large relative to altitude and, therefore, efficient use of the square area available on the CRT dictates that the pair of pictures should not be placed side-by-side as in the usual stereo viewer.

The arrangement that was chosen seems at first rather unlikely. The pictures were drawn with their range axes vertical, and with one image reversed and inverted with respect to the other, as shown in Fig. 4. They are viewed through a pair of Dove prisms* whose mirror faces are at right angles to each other and at 45° to the median plane of the user's head, as shown in the insert in Fig. 2.

Through the viewer the two pictures produce <u>two</u> complete three-dimensional visual images with their range axes horizontal. If the pictures are drawn as in Fig. 4, they are seen as in Fig. 5: the upper image is erect and with the proper right-left orientation; the lower is inverted and reversed. (If it is desirable to use the lower image instead of the upper, it can be made erect by interchanging the two pictures drawn on the CRT.) When the upper image is used, the right eye views the left picture on the CRT and the left eye, the right picture.

The lower, unused image was suppressed by covering the right picture on the CRT with a vertically oriented polarizer** and placing a horizontally oriented polarizer in front of the right Dove prism. Polarizers with reversed orientations were used with the left picture and left prism. The relationship of the eyes, prisms, polarizers, and CRT face is shown in Fig. 6.

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* Edmund Scientific Co., Catalog No. 3241.

** Polaroid Corporation, No. HN38.

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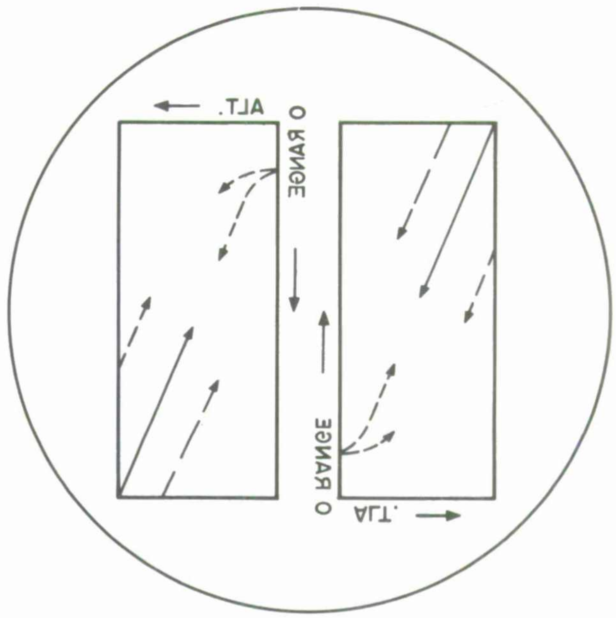

Fig. 4. Stereo pair of pictures as drawn on CRT.

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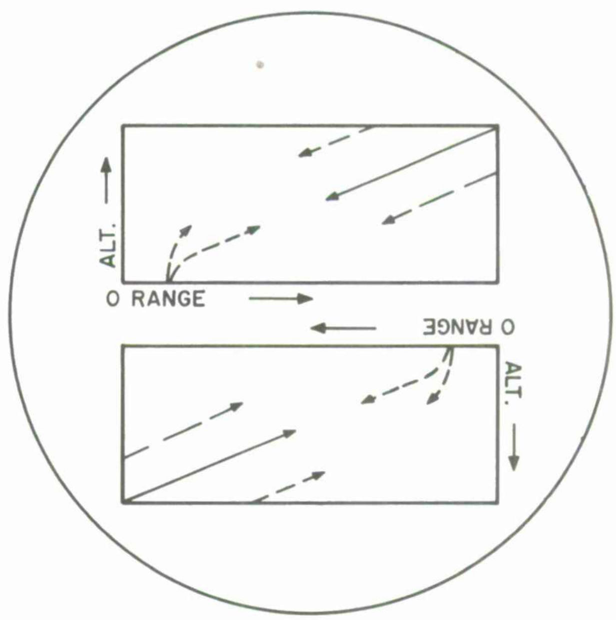

Fig. 5. Binocular view of CRT as seen through pair of dove prisms.

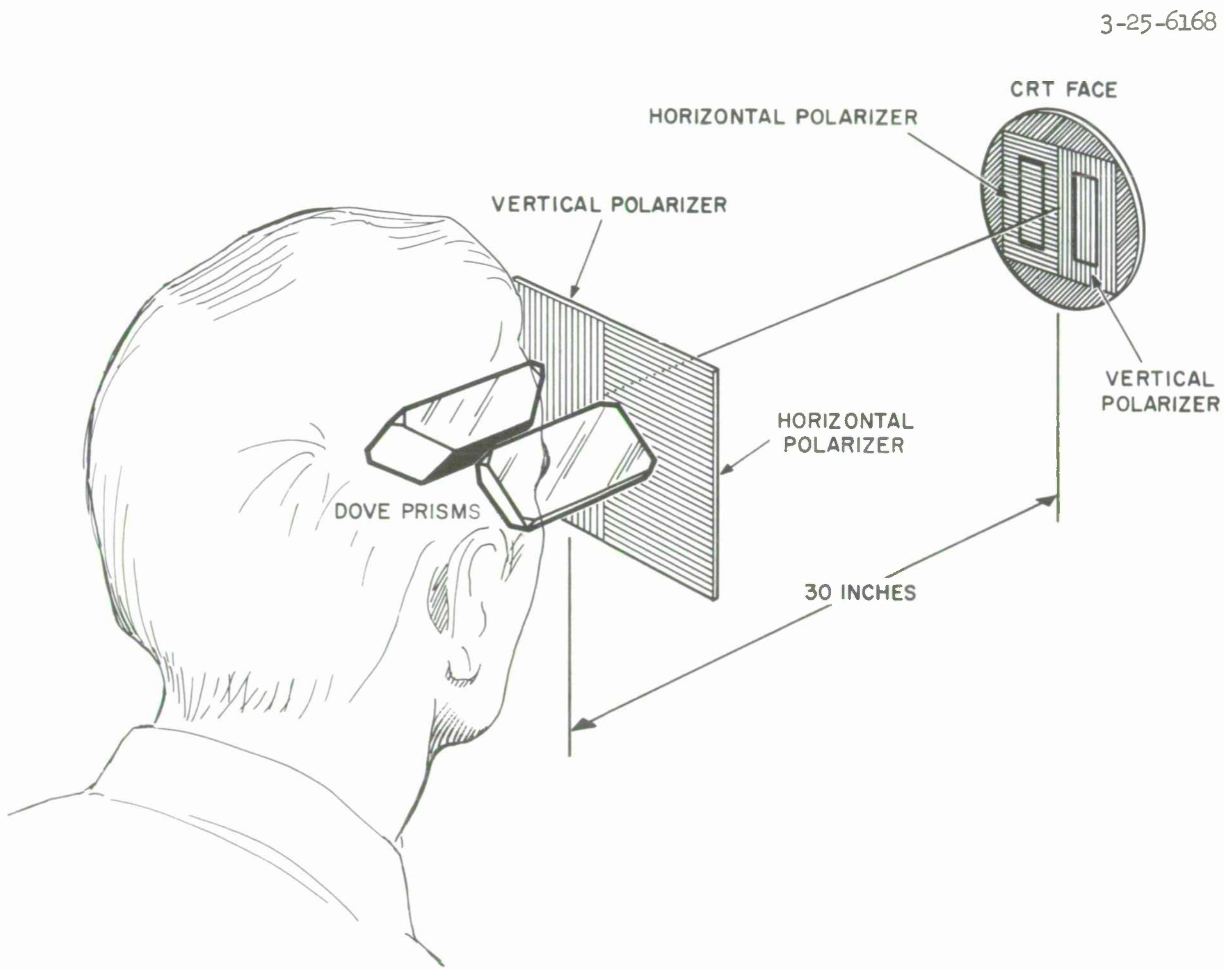

Fig. 6. Schematic drawing of the optics, showing the masking polarizers.

The prisms were mounted on sliding ways to permit lateral movement to accommodate various interpupillary distances. The ways were mounted on a geared instrument head* with three degrees of freedom: vertical translation, rotation about the vertical axis, and tilt about a horizontal axis parallel to the face of the CRT. Vertical translation adjusts the apparatus to the seated height of the user. The other two motions accomplish registration of the two images so that binocular fusion of the images occurs and a three-dimensional image is perceived. Rotation about the vertical axis translates the members of the stereo pair vertically with respect to each other. Tilt on the horizontal axis translates them horizontally. These four adjustments are all that are required for proper viewing.

The viewer is shown in Fig. 2. It is moved up to the counter of the DEC Type 340 display console on a small table** that can be immobilized by retracting its casters.

There are other solutions to the problem of superposing two images painted on a CRT. The present approach was chosen because (a) the distortion near the edges of the tube is matched in the stereo pairs, (b) the optical paths for the two eyes are symmetrical (for example, there is no extra mirror in one of the paths), (c) of the designs that have those first two advantages, the present seems to require the smallest number of optical elements, and (d) adjustments to accomplish registration are simple and show a negligible amount of interaction. Another practical feature is that people who need corrective eyeglasses have found little difficulty in using them with this viewer. A potential disadvantage of the design is the rather narrow angle of view. The effective field of view of the prisms is approximately 28°. In order that a 10" by 10" image be included, the viewing distance must be at least 30". This is a comfortable viewing distance, but it does preclude the use of a light-pen because of the long reach. In fact, the light-pen is ruled out altogether on other grounds — i.e., because of the scrambled relationship between the visual cues and the kinesthetic cues of hand and arm movements.

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* Quick-Set, Inc., Hercules column unit No. 5900.

** A modified typewriter table of the Tiffany Stand Co.

Experience to date has been very satisfactory. Naive observers experience little difficulty perceiving depth at their first look through the viewer. Adjustments are seldom required.

Two kinds of distortion of the total field have been observed, a tilt of the field and an exaggeration of depth effect. Both effects are somewhat different for different observers. Since neither seems to have any functional significance for present purposes, no attempt to reduce these effects has been made. All in all, this optical technique is a relatively simple and practical solution to achieving depth perception on a computer-driven CRT.

APPENDIX 2

CALCULATING THE STEREOSCOPIC DISPARITY

The primary cue to perception of depth in the CRT display was the spatial disparity between corresponding points in the images presented to the two eyes. This appendix explains the geometric disparity relations used to construct the images.

Figure 7 illustrates the calculation of the displacement for the observer's right eye. For ease of exposition, the figure is drawn as though the eye were viewing the display directly, not through the prism described in Appendix 1. (There is no loss of generality since the picture rotation and reversal due to the prisms, are compensated out in the program.) The eye is located at a distance $\underline{s}$ to the right of the center of the picture, and at a distance $\underline{d}$ from the face of the CRT. (In these calculations — indeed, throughout the program — the face of the CRT is treated as if it were a flat surface.) The observer perceives a point at a distance $\underline{x}$ to the right of the center of the picture and at a distance $\underline{z}$ in front of the face of the tube. If the spot that represents this point is painted on the face of the CRT at distance $\underline{x} + \Delta$ to the right of the center of the picture, what is the formula for the displacement Δ?

By similarity of the triangles,

$$\frac{\Delta}{z} = \frac{x - s}{d - z};$$

thus,

$$\Delta = \frac{z(x - s)}{d - z}$$

In this expression, the sign of $\underline{z}$ is negative when the point appears behind the face of the tube, and the sign of $\underline{x}$ is negative when the point is to the left of the center of the picture.

The displacement for the left eye is computed from the same formula, except that $\underline{s}$ is negative. When Δ is added to $\underline{x}$ for each point in each view, the result of the relative disparity between the images in the two eyes is a perception of depth. Since it is necessary for the same point to be viewed by both eyes in order to perceive depth, the limits on the display are set in terms of $\underline{x}$, rather than $(\underline{x} + \Delta)$, so that any point appearing in one view appears in the other.

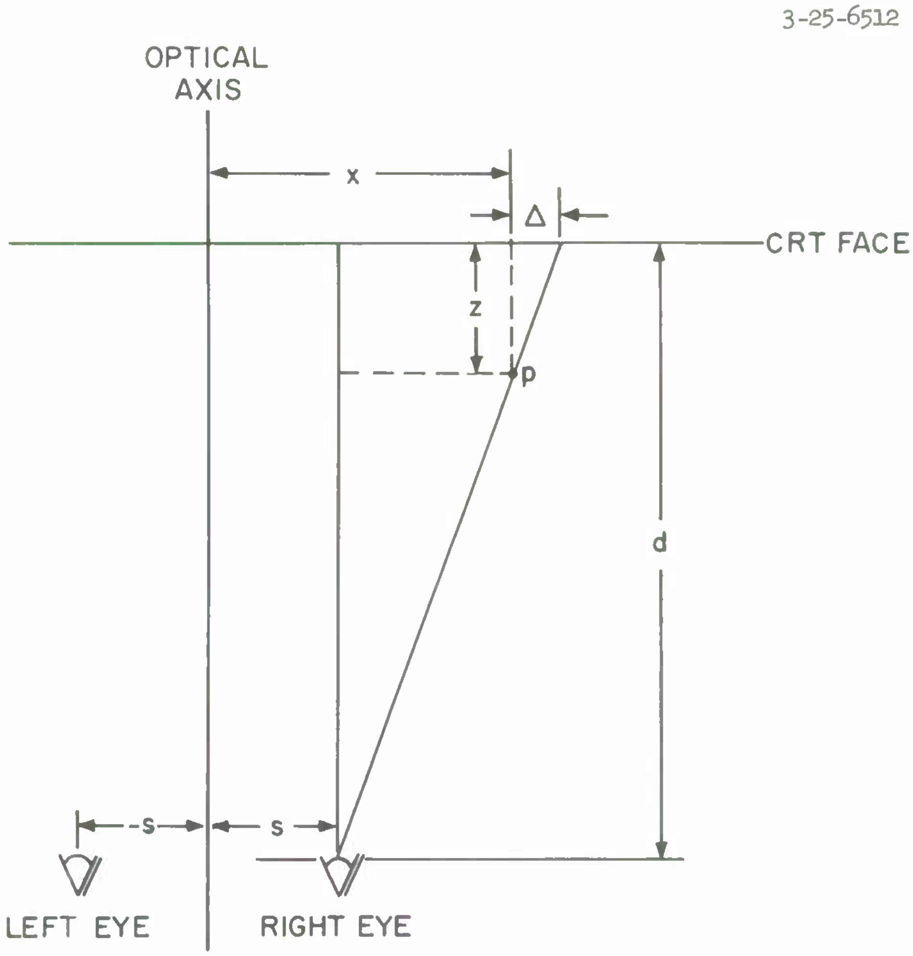

Fig. 7. Geometry underlying the disparity calculations.

APPENDIX 3

OPERATING INSTRUCTIONS

The control box is shown at the left in Fig. 2. The large knob at the right being turned by the operator is called the Rotor — it is a shaft encoder with sixty-four, detented positions. To the left is an eight-position Selector switch and, below it, five Toggles, numbered 1 to 5 from left to right. The arrangement and procedures for using these controls are not optimum. They developed in this form as the display developed and improvements will be made when the display is put into operation and users demand them.

The Selector sets up a mode of operation of the display. The functions of the other controls change according to the position of the Selector. The modes and switch functions are summarized for reference in Fig. 8 (page 21). To illustrate these functions, instructions were written specifying a series of display operations used to gain an appreciation of the results of a BAG run recorded on magnetic tape. These instructions may be useful to the general reader as a detailed explanation of the current features.

INSTRUCTIONS

1) Play Specified Second. To begin, set the Rotor on number 5 and the Selector to position 2. Press T_1 and a first display will appear. It shows the situation 5 seconds after an arbitrary Time 0. The time appears as "05" in the lower right-hand corner of the display.

2) Fly-By Mode. To obtain an over-view of what is on the tape, switch the Selector to 7 and Rotor to, say, 5. Press the action button T_1 and watch the raid fly in. (All numbers are suppressed in this mode.) The position of the Rotor determines the interval between steps in .05 second steps. Thus position 5 is one-quarter second, an interval corresponding to four times the rate missiles would actually fly in. The action will continue to the last second on the tape and automatically re-cycle. If a change of the Rotor position is made it will affect the re-cycle time only if T_1 is pressed again and the current cycle has run its course.

3) Changing Labels. Return the Selector to 2, adjust the Rotor to a convenient time in mid-game — say, 25 — and press the action button T_1. If T_5 is down, object labels indicate depth. Place T_5 in the Up position and observe that the number tags correspond to the game object number. To prove this, set the Selector on 6 and objects selected by the Rotor will dim out one by one. Note that the setting of the Rotor and the RV numbers correspond. Note also that interceptors (Rotor positions of 33 and above) have numbers of their assigned objects. (Object number "00" is the label for unassigned interceptors.) Set the Selector to 2 and press T_5 down to restore the depth numbers.

4) Altering Brightness Coding. Some objects are not of interest. For example, let objects outside ± 25 km in depth be suppressed. The depth number "50" is the nominal trajectory plane. Set the Selector to 6. Search through the RV's, starting with the rotor at 1, and if the label is less than 25 or greater than 75, obviously it is outside the threat tube as defined above. To suppress the object, i. e. to permanently alter its brightness code, turn the rotor to its object number and press T_1. The RV and its paired interceptor (or, if an interceptor, its paired RV) will be dimmed out permanently. In the event of an error, however, it may be restored by moving the Selector to position 5, moving the Rotor to its number and pressing T_1. Objects of special interest can be made permanently bright by pressing T_1 with the Selector in position 4. As before, interceptor-RV pairs are both brightened if either one is.

(The brightening is useful for coding — e. g., assigned versus unassigned interceptors, alternate tiers of RV's in an attack, and so forth. It is a relatively novel feature of this display that brightness coding is a flexible feature. Its exact use is left to the operator, who may want to use it differently for different problems. This is one respect in which a system analyst's display is likely to be quite different in design philosophy from an operational unit.)

To restore all objects to normal brightness, set the Selector at 5, hold T_1 down with the left hand while turning the Rotor fairly rapidly through all of its positions, with the right hand. The brightness code established in modes 4, 5 and 6 holds in other modes except in 7, the Fly-By mode.

5) Changing Off-Center and Expansion. Move the Selector to position 1 and press T_1. A small plus sign will appear at the center. Turn the Rotor. If T_2 is "Up" the plus will move in the vertical; if "Down," horizontal. Center the plus in the region of interest. Press T_3 down once and observe that the digit "1" in the lower right-hand corner changes to "2". It indicates a change of expansion level from X1 to X2. (Successive presses of T_3 cause the level to cycle through the 1, 2, 4, 8; 1, 2, 4, 8; . . . levels.) Press T_1 and the expanded display will appear at the new center. The expansion level and off-centering selected is permanent for Selector positions 2-6, unless altered in mode 1. To correct an off-centering or expansion error, set the Selector at 1 and press T_1. The plus will appear on the expanded display. Move it to the correct place on the present picture. Change expansion level with T_3, if desired, and press T_1 again to get the altered display.

The depth labels change scale with expansion level. The reciprocal of the scale factor is the distance in kilometers corresponding to a unit change of depth number. Thus, for example, at X4 the distance from 53 to 61 is 2 km. In contrast the nominal trajectory plane is always represented by "50". The origin in the depth dimension does not change with expansion level and no provision for depth off-centering is provided.

To restore the display to normal centering and X1 expansion, set the selector to 1. Press T_1, then T_4.

6) Next-Second Mode. Position 3 of the Selector is a second-by-second mode for use during live operation. On this position, a press of the action button T_1 will cause a display of the next second of data which the operator has not yet called for in this mode.

7) Note. The conditions for changing the labels from object number to depth or vice versa with T_5 are somewhat more elaborate than implied above. In Selector positions 2 or 3 the effect of T_5 is instantly effective. The same is true in position 1 unless the plus is present; if it is, pressing T_1 will remove the plus and effect a label change if it has been called for. In positions 4, 5 and 6 of the Selector, a somewhat curious feature is that

the state of T_5 is sensed only if a change of the Selector or of the Rotor is made. In that event, a convenient way to effect a change of label is to flick either switch one position and then back after changing T_5.

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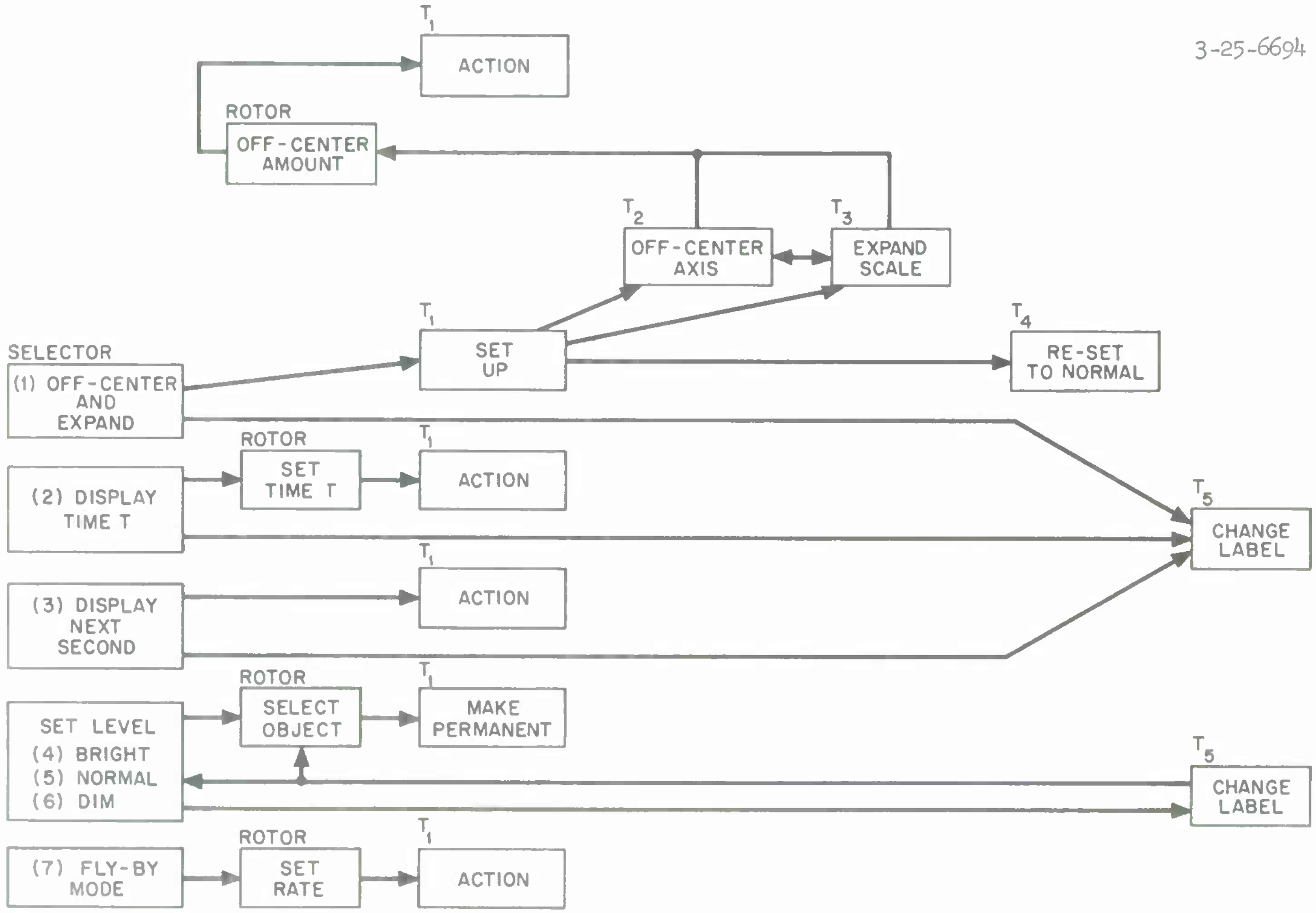

Fig. 8. Flow chart of actions on the display. The arrows define all the normal sequences.

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13. ABSTRACT

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14. KEY WORDS

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