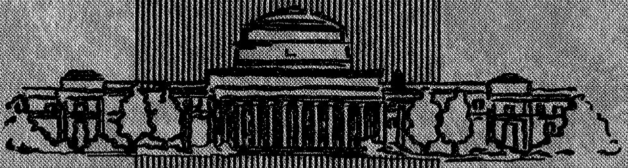

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

STUDIES OF HUMAN DYNAMIC SPACE ORIENTATION USING TECHNIQUES OF CONTROL THEORY

Principal Investigators : L.R. Young
Y.T. Li

June 1967

Seventh Semi-Annual Status Report on
NASA Grant NsG-577

MAN-VEHICLE CONTROL LABORATORY
CENTER FOR SPACE RESEARCH
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
CAMBRIDGE, MASSACHUSETTS 02139

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I. INTRODUCTION

During the first half of 1967 the Man-Vehicle Control Laboratory continued its investigation of the problems of dynamic space orientation with approximately 16 graduate students working under the supervision of Professors Yao T. Li, Laurence R. Young, and Jacob L. Meiry. The major single effort during this period was devoted to development of new 3-D display techniques for use in possible vehicle application. By using head movement cues to generate a moving image, we succeeded in attaining a certain effectiveness of depth representation on a cathode ray tube display. The body of this report is devoted to a brief review of some of the approaches and problems associated with this project, which concerned the majority of the Man-Vehicle Control Laboratory staff members at one time or another. In addition to this research, a number of other areas of investigation were continued, the results of which will be reported in subsequent technical reports. These areas include the following:

Our approach to the modelling of learning and adaptive systems using Bayesian updating of a discrete stochastic model continued. The model developed by Preyss was extended for use in the situation of learning to control a plant with other than $1/s^2$ dynamics. In addition, the computer program for the learning model was rewritten for our hybrid computer in an effort to develop a real time learning model which would duplicate the learning and adaptive control characteristics of the human operator.

Experiments were completed during this period on quantization of the effects of roll motion cues on the performance and describing function of the human operator controlling a variety of vehicle dynamics. This constitutes an important data base for control experiments on motion cues. It will be the basis for the development of techniques to predict the effects of motion, in order to extrapolate from fixed base simulation to actual flight.

Our research on adaptive control techniques, using man as a monitor, continued into investigation of chatter-mode adaptive control in which a system limit cycles to the origin along a preselected switch curve in the phase plane, regardless of changes in the plant dynamics.

Significant advances were made in our research on eye movement models, including the exposition of the importance of the synchronization between the sampling time in the sampled data model and the time of occurence of transient movements of the visual target being tracked.

A variety of experiments continuing our effort to define control models of the vestibular system were carried out. Among the important ones were the quantification of the response to caloric stimulation and the experimental verification of a theory for the effects of rotating linear acceleration on the semicircular canals. These latter experiments were carried out by measuring eye movements during counter-rotation of subjects placed on the arm of the MIT

Instrumentation Laboratory centrifuge. In addition, our single axis rotation simulator for vestibular studies involving rotation about the vertical axis was completed. A series of experiments were run with the object of uncovering the differences between nystagmus and rotational perception responses, and the source of the nonlinearity was noted in semicircular canal function. During this reporting period, one doctoral thesis and one masters thesis resulted from research carried on under the subject grant.

II. THREE DIMENSIONAL DISPLAYS

1. General

Since September 1966 the Laboratory has worked on the development of a hybrid computer generated contact analog visual display in which various perceptual "depth cues" are included on a two dimensional CRT screen. This display format was chosen for a number of reasons:

With the increasing complexity of modern V/STOL aircraft, helicopters, undersea vehicles and spacecraft, and the precision maneuvering requirement which is being placed upon them, there is clearly a need for more advanced display systems than are available today. These displays must convey information, in an integrated and visually compelling fashion, about the vehicle's position and orientation in space.

The concept of the incorporation of multiple depth cues in contact analog displays is certainly not new. Indeed, the term "contact" implies that the pilot will be presented with a display which appears to be, insofar as is possible, a view of the real world as seen from his cockpit while flying contact VFR and navigating by looking out the window.

Early studies with simple contact displays often were more subjective than objective in nature; and because of the large differences in display format and task difficulty between experimenters, it has been difficult to evaluate various contact analog display techniques in more than a general way. This "hit or miss" approach has led to a certain compromise in the original concept of the contact analog display. In recent years, contact analog displays have been incorporated in submarines and in several military aircraft, but because the displays themselves have not been completely visually compelling, the trend has been to a system which not only shows a two dimensional approximation of the view of the real world as seen from the cockpit, but also presents quantitative readouts of vehicle position, attitude, systems status, and various forms of navigational and collision avoidance information. In a certain sense, though, these "integrated" displays have been unsatisfactory, because they accomplish the integration of information in a topological sense only. Much of the perceptual integration of information must still be consciously performed by the pilot.

It was felt that, regardless of the requirements for direct parameter readout, the basis for more advanced display systems would be a truly realistic contact analog display; one which is truly integrated and visually compelling. Incorporation of third dimension information into the display in a realistic way is essential.

The most straightforward way of including three dimensional information in a display is to create a stereoscopic view. Several techniques are available to do this, but all of them generally have multiple disadvantages which make them impractical for displays of this type. Stereopsis may be created with polaroid and head mounted TV techniques, but aside from interfering with the normal visual field, they involve considerable objectionable encumbrance of the pilot's head. Holographic display techniques, while making rapid advances, have not yet been developed to the stage where they may be considered practical.

Consequently, it was decided that the most useful area of investigation, given these constraints, would be to examine the possibility of including other "depth cues" in a display with two dimensional format.

2. Depth Cues

It has been pointed out (ref. 1) that stereopsis (the psychophysical perception of depth associated with binocular vision) and the related clarity of the image on the retina (depth of focus) are not the only means which a vehicle pilot employs to obtain depth information from his normal visual field. Some of the known effects may be identified as follows:

1. "Deflection" cues; due to
   a. Scene rotation and translation
   b. Observer rotation and translation
   c. Movement parallax between objects in the visual field
2. "Non-Deflection" cues; due to
   a. Inverse square law of illuminance
   b. Aerial perspective (loss of image clarity due to intervening air mass)
   c. Linear perspective
   d. Interposition effects (where closer opaque portions of a scene hide more distant points located behind them in the visual field)

3. Preliminary Experiments

When one "perceives" depth in a visual field, stereopsis alone is not responsible. Rotation and translation of a simple two dimensional perspective representation of a three dimensional scene (such as in the shadow cast on a screen by a moving three dimensional object) is well documented (ref. 2). It seemed likely that head motion would provide as powerful a cue at close ranges. In an attempt to make an assessment of head motion as a depth cue, experiments were performed with different sized cubes and spheres held motionless in a dark room. It was verified that:

1. Binocular vision (stereopsis) provides a very strong depth cue; but
2. Monocular vision with head movement gives a depth cue which is nearly as compelling as binocular vision.
3. If no deflection cues are present, monocular vision with the absence of observer head movement gives a poor depth cue.

These experiments were performed with the objects illuminated with ultraviolet light and no more than fifteen feet away from the viewer. It was concluded that head movement provides a strong cue to the depth of an object being viewed when at close range.

4. Construction of a Display System for Depth Cue Evaluation

On the basis of these preliminary experiments, it seemed useful to investigate the possibility of building a visually compelling "three dimensional" contact analog display system in which the non-stereoscopic deflection and non-deflection cues alone were incorporated.

Consequently, four graduate students were assigned to develop a prototype display system using the Laboratory's own

GPS-290T hybrid computer, and to investigate pilot head position measurement techniques.

The apparatus developed, as shown in figures 1-3, consists of a computer generated CRT display of a cube, presented in perspective, with inverse square law line intensification. The cube appears as a solid object, as all lines leading to hidden vertices are blanked. Typical display scenes are shown in fig. 4. The display operates continuously, showing the "updated" scene thirty two times per second. The pilot has full six degree of freedom control over the scene through simulated vehicle dynamics. Ultimately, an ultrasonic head position sensor will track the pilot's head motion, and the computer will use the information to produce the proper change in aspect and screen parallax to make it appear to the observer that he can "look around" the cube. Head position sensor development is discussed in section 5 of this chapter.

The overall approach used in this particular system is relatively simple and is shown in fig. 5. The pilot watches the CRT, which he might imagine to be an artificial window in a hypothetical vehicle whose dynamics are simulated on the analog half of the computer. On the basis of the pilot's control inputs, the analog computer determines how the hypothetical vehicle would move and feeds this information on digital computer request, through an Analog to Digital converter, and to a program in the digital half of the machine which keeps track of all the points in the visual field which are to be displayed, and performs rotations and translations on this field in three dimensional body coordinates (see fig. 6) to account for the motion of the vehicle. This digital program operating continuously also calculates, on the basis of the current three dimensional field, what the field would look like if seen through the display "window" from the pilot's current head position, and prepares a two dimensional display list for the analog machine, on the basis of the equations shown in fig. 7.

The display itself is generated on a Tektronix 565 Oscilloscope by a hybrid program which runs simultaneously and in parallel with the digital calculation program. Most of the computer time required for this program is used by the analog computer actually to draw the scene on the CRT screen.

This analog line drawing can occur simultaneously with the digital calculation program, but when the analog computer is ready to draw a new line in the display, it must request the information about the line from the digital computer. Since the digital computer is, by nature, a serial machine, and is capable of performing only one set of instructions at a time, the system is programmed so that the digital computer will normally perform the digital calculations required for scene rotation and display list generation, but when the analog computer needs to take data from the display list in order to continue on and draw a new line, an "interrupt" is created. This is essentially a control pulse which interrupts the digital machine to stop what it is doing, and instructs it to jump to a subroutine which stores away current machine status and then "services" the analog line generator by passing information to it through a Digital to Analog converter.

Except for the rotation algorithm employed, the programming of the vector translations and the calculation of the screen coordinates based upon the perspective equations is straightforward. The inertial coordinates of each vertex are stored with 36 bit precision. Each of the eight corners of the cube is considered by itself, and is translated, rotated, and translated, and then stored. The three dimensional coordinates are used to calculate a set of horizontal and vertical screen coordinates. An "intensity value" for each vertex, inversely proportional to the square of the slant distance to the vertex is also computed.

After all eight cube corner coordinates have been calculated, the digital computer determines which vertices are, in fact, hidden from the observer's view. The machine keeps track of the scalar product of the outward pointing normal vectors of each face of the cube with a pointing vector from a point in the plane to the observer's eye. If this dot product is negative, the side faces away from the observer. If it is zero, the observer has an edge view of the plane, and if positive, the plane can be seen, as shown in fig. 8.

Scene rotation of the three dimensional coordinates required careful review of mathematical techniques: A rotation transformation was required which would express a vector

X in one coordinate system as X' in a new coordinate system which differs from the first only by some small arbitrary rotation. If the three coordinates of each corner of the cube are operated upon successively by an orthogonal coordinate transformation matrix

$$\begin{vmatrix} \cos\theta & \sin\theta & 0 \\ -\sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{vmatrix}$$

any arbitrary rotation in space can be reduced to the resultant of a single pitch, roll, and/or yaw maneuver using the product of these rotation matrices. Unfortunately, matrix multiplication is not, in general, commutative, so the magnitude of the roll, pitch, and yaw angles necessary to achieve a given arbitrary rotation depends very much on the order in which they are performed. For the purposes of the display calculations, a given rotation would have to be built up out of a series of small symmetrical roll, pitch, and yaw transformations, since the matrix product of these transformations does commute to the first order. By using small angular increments, a reasonable approximation to a given rotation can be achieved by a series of nearly simultaneous rotations through small angular increments about the observer's coordinate axes.

Since a table look up technique could not be used conveniently for sine and cosine terms, a mathematical investigation of approximations to the orthogonal rotation transformation was made in search of a substitute. Analysis of the errors arising out of both the form and the digital implementation of various types of nearly-orthogonal transformations led to the choice of an alternating order, serial updating difference equation procedure: for a nearly orthogonal transformation, the magnitude of the Eigenvalues of the transformation may be considered as a representation of the length of a unit vector when portrayed in an orthogonal coordinate system. In a similar sense, the difference between the "input" rotation and the angle of the complex Eigenvalue reflects a phase error in an orthogonal interpretation. It turns out that if

$$X' = CX$$

and if the Eigenvalue is a complex quantity and X is a unit vector, the requirement that the length of the unit vector be stable for monatonic repetitions leads to the requirement that

$$\det C = 1$$

$$a + b + c \lesssim 3$$

(where a, b, and c are the diagonal terms of a 3 x 3 rotation transformation). A further requirement for the transformation is that if the coordinate system is subjected to an oscillatory control, i.e., a series of $d\theta$, $-d\theta$ sequential rotations, no errors develop. This is equivalent to saying

$$C\, C^{-} = I$$

where C^{-} is $C(-d\theta)$.

A transformation which satisfies all these requirements is

$$C = \begin{vmatrix} 1 & \frac{d\theta}{2} & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{vmatrix} \begin{vmatrix} 1 & 0 & 0 \\ -\frac{d\theta}{2} & 1 & 0 \\ 0 & 0 & 1 \end{vmatrix} \begin{vmatrix} 1 & 0 & 0 \\ -\frac{d\theta}{2} & 1 & 0 \\ 0 & 0 & 1 \end{vmatrix} \begin{vmatrix} 1 & \frac{d\theta}{2} & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{vmatrix}$$

This algorithm will not diverge and is reversible, although it is not exactly orthogonal. Hence small radial distortions will be introduced during a rotation, but as rotation is continued, these errors cancel out. Phase errors accumulate, but they are of the order of $d\theta^3$. Fortunately, digital implementation produces a phase error of opposite sign, and when calculated to 36 bit precision, the results of the inertial coordinate rotation proved entirely satisfactory.

The hybrid line generation routine developed by the laboratory actually to draw the cube shown in the display consists of three parts. The analog patch board of the computer is wired with the display generation circuitry. The output of these circuits is the horizontal, vertical, and intensity voltages which are applied to the CRT to control beam position and brightness. The logic board on the analog computer is used to generate the control signals for the generation circuitry, synchronize all programs precisely to a clock signal, and generate interrupt signals which request the digital machine to "service" the analog circuitry by performing the digital display program.

Since the display was to be used exclusively for experimental purposes, a cube seemed to be the ideal object to display, because of its simple, linear shape and its symmetry, which could be exploited: by representing the cube (in two dimensions) on the screen as four triads of three lines each, as shown in fig. 9, only minimal data transfer between the digital display program and the analog display circuits is required. This is because each triad can be conveniently drawn if the coordinates of the vertex point are known, and the slopes of the lines joining it are also obtained.

The bases of the analog display generation circuitry are two circuits which produce the horizontal and vertical beam position, as shown in fig. 10. To draw a given triad the following procedure is used:

The analog control logic circuits request a digital interrupt. The digital display program enters the display list and finds the horizontal and vertical screen coordinates of the vertex of the triad; these values are converted D-A and sent as initial conditions to integrators 1 and 2 in fig. 10. Integrators 1 and 2 are then set in the compute mode, but since there is no input and only an initial condition specified, the outputs are simply voltages representing the horizontal and vertical triad vertex position on the screen. These are fed as initial conditions to "line drawing" integrators 3 and 4. Once this has been done, the analog logic board initiates another interrupt. This time, the digital display routine enters the display list and finds the horizontal coordinates of the endpoints of the first line to be drawn in this triad. The digital program subtracts to find the difference in the horizontal coordinates and sends it across D-A where it is set as the input to integrator 3. The digital program repeats the process for the vertical coordinates, and enters the difference in integrator 4. While the digital computer then proceeds with the rotation and display list calculation program, both integrators 3 and 4 are put into the compute mode for a finite period of time, T. The potentiometers in the circuits are set at 1/T. The resulting x(T) and y(T) trace out, parametrically, the correct line. This process is then repeated twice more with the same initial conditions, and then integrators 1 and 2 are reset for a new triad. The output of a circuit is shown in fig. 11. When these horizontal and vertical signals are cross plotted on the CRT, the proper figure results, as shown in fig. 12.

A circuit entirely analogous to those in fig. 8 is used to create the intensity signal for each line, so that lines running "away" from the viewer become dimmer. However, because there is a series capacitor in the CRT intensity circuit (in the scope itself) the intensity signal must be modulated by a sine wave. In order to prevent the beam from creating a trace during the reset period, the modulated intensity signal is passed through an electronic switch which passes the signal to the CRT grid only during the compute periods of integrators 3 and 4 in fig. 10. This switch will also remain open <u>during</u> a compute period if the digital display program has discovered that the line leads to a vertex which should not be seen. One of the properties of a cube when seen in perspective is that if a part of a line can be seen then all of the line is visible, and vice-versa. Hence if either endpoint of a line in a triad cannot be seen, then the whole line is blanked. A typical intensity signal as it is finally sent to the grid is also shown in fig. 12.

Summarizing, then, the lines of the cube are drawn by producing voltages which are proportional to the slopes of the lines of the triads and are parametric in time. To be above the critical flicker frequency for most human observers, at least thirty complete pictures must be shown per second.

Each frame requires 12 compute and 12 reset times, and the integration period for each line was taken to be 1.3 milliseconds, so 31.2 milliseconds are required per frame.

5. Development Work on an Ultrasonic Head Position Monitor

A method of monitoring the observer's head position was needed in order to include the head movement depth cue. An accurate, simple system was required, one which did not encumber the pilot's head.

Experimentation was undertaken with an ultrasonic sound transmitter mounted on the pilot's helmet. As shown in fig. 13, if two ultrasonic receivers are mounted on either end of a polystyrene rod mounted overhead, and the transmitter is pulsed periodically, the difference between the arrival times of the transmitted pulse at the two receivers is directly proportional to the distance of the transmitter from the center of the rod, measured along the axis of the rod (ref. 3). Notice that ideally this is independent of the absolute distance of the transmitter from the rod.

A prototype system was constructed utilizing several inexpensive transducers, cemented directly to the rod to minimize the loss in amplitude of the received waveform. Unfortunately, electrical and acoustical problems have been a constant source of trouble thus far, and results have not yet been satisfactory. The transmitter proved to be too highly directional for this particular application, and acoustic transients and standing waves set up in the rod made accurate measurement of the transmitted waveform unreliable.

In general, however, the technique appears promising, and arrangements have been made with the MIT Instrumentation Laboratory to complete the development work on this system within the next several months.

6. Conclusions

To date no systematic study has been made of the combined man-vehicle performance of the system with a given set of vehicle dynamics. However, individuals "flying" the present system without the head position monitor report that in general perception of the orientation and range of the cube are unambiguous and maneuvers are quite easy to perform once one has become accustomed to the six degree of freedom movement and the various stick force peculiarities of the hand and foot control sticks used in this particular system.

Observers do report that occasionally they do experience the phenomenon similar to "Necker Cube Reversal" as a result of occasional ambiguities in the depth cues presented by the non-stereoscopic display. Under the usual circumstances, one looks at the display and sees the two dimensional figure shown thereon as a solid object, but without stereopsis; this is probably because one's perception of the form of the figure is strongly influenced by the way that one has been interpreting the available depth cues for the last few moments before the time in question. One's perception of the cube as a solid object is strongly influenced by an extrapolation of the perceived orientation of the object during the previous few moments. If one looks away from the display for a moment and then looks back, one is forced to develop a new perception of the figure solely on the basis of the immediately available depth cues. If the available depth cues are ambiguous, as they might be if the "vehicle" is not moving and head motion is not included in the display, one is forced to work with only the available non-deflection depth cues, and as Necker has shown, one is just as likely to perceive the figure "reversed" as not in such a situation. Given that one perceives it reversed, this perception is bound to continue for some time until one either looks away or conciously decides to try to perceive the figure in a different way.

Most observers felt that intensity modulation with depth and elimination of hidden lines was of considerable value in deterring cube reversal, and that if reversal could be completely prevented, the display would certainly be compelling. Work in the coming months will be directed toward this end: our objectives are to assist in the refinement of the head position sensor, so that it may be incorporated in the laboratory display system as soon as possible. In the interim, it may be possible to translate the hybrid programs into the language of the MIT Lincoln Laboratory's computer and make a preliminary evaluation of the efficacy of the head motion cue by using the "Lincoln Wand," a three dimensional sonic display pen available for use with that computer.

At the same time, an investigation will be made of ways to reinforce the available non-deflection cues so they will be less ambiguous. Perhaps this may be accomplished by producing a continuous apparent small oscillation of the cube, thus producing a continuously operating "kinetic depth effect."

Starting in September, studies will be made of the possible application of three dimensional display techniques to the blind take-off and landing problem, particularalaly with reference to V/STOL applications.

III. PUBLICATIONS OF THE MAN-VEHICLE CONTROL LABORATORY

through September 1967

Papers and Reports

Young, L. R., and J. L. Meiry, "Manual Control of an Unstable System with Visual and Motion Cues," presented at IEEE International Convention, New York, March 1965

Young, L. R., and J. L. Meiry, "Bang-Bang Aspects of Manual Control in High Order Systems," IEEE Transactions on Automatic Control, July 1965 (Also presented at the 1965 Joint Automatic Control Conference)

Meiry, J. L., "A Model for Otolith and Its Implication on Human Spatial Orientation," Proceedings of the International Astronautical Federation, Athens, Greece, September 1965

Li, Y. T., L. R. Young, and J. L. Meiry, "Adaptive Functions of Man in Vehicle Control," IFAC (Teddington) Symposium, September 1965, also in Theory of Self Adaptive Control Systems (Plenum Press, 1966)

Li, Y. T., "Stability and Controllability of Vehicles for High Speed and High Traffic Permeability," IFAC Systems Symposium, Tokyo, Japan, August 1965

Li, Y. T., L. R. Young, and J. L. Meiry, "Control Engineering Approaches to Human Dynamic Space Orientation," National Academy of Sciences Workshop-Orientation in the Exploration of Space, NASA Ames Research Center, January 1966, NASA SP-115

Young, L. R., "Some Effects of Motion Cues on Manual Tracking," MIT-NASA Working Conference on Manual Control, Cambridge, Mass., February 28-March 2, 1966, NASA SP-128, and also Journal of Spacecraft and Rockets (in press)

Young, L. R., "The Dead Zone to Saccadic Eye Movements," June 1966, Symposium on Biomedical Engineering, Marquette University (Charles C. Thomas, in press)

Li, Y. T., and J. L. Meiry, "An Active Roll Mode Suspension System for Ground Vehicles," presented at JACC, August 1966, and also ASME Transactions (in press)

Li, Y. T., "Design Optimization of a Multimode Hydraulic Vehicle Suspension System," presented in AGARD Lecutre Series, September 1966, Turin, Brussels, London

Young, L. R., and R. Winblade, "MIT-NASA Working Conference on Manual Control," IEEE Spectrum, Nov. 1966, pp. 88-93

Steer, R. W., Y. T. Li, L. R. Young, and J. L. Meiry, "Physical Properties of the Labyrinthine Fluids and Quantification of the Phenomenon of Caloric Stimulation," Third Symposium on the Role of the Vestibular Organs in Space Exploration, Pensacola, Florida, January 23-27, 1967

Young, L. R., and J. L. Meiry, "A Revised Dynamic Otolith Model," Third Symposium on the Role of the Vestibular Organs in Space Exploration, Pensacola, Florida, January 23-27, 1967

Yasui, S., and L. R. Young, "Manual Time Optimal Control for High Order Plants," presented at the USC-NASA Conference on Manual Control, Los Angeles, California, March 1967

Preyss, A. E., and J. L. Meiry, "Stochastic Modelling of Human Learning Behavior," USC-NASA Conference on Manual Control, Los Angeles, California, March 1967

Theses

Duke, C. M., Capt. USAF, and M. S. Jones, Capt. USAF, "Human Performance during a Simulated Apollo Mid-Course Navigation Sighting," S.M. Thesis, M.I.T., June 1964

Johnson, I. S. C. Jr., "Human Response to Variations of Simulated Control Stick Forces," B.S. Thesis, M.I.T., May 1964

Kilpatrick, P. S. II, "Comparison of Relay and Manual Controllers for Systems with High Order Dynamics," B.S. Thesis, M.I.T., May 1964

Schulte, R. J., 1st Lt., USAF, and R. E. Vreeland, Jr., Capt., USAF, "The Design and Construction of an Acceleration Cart," S.M. Thesis, M.I.T., June 1964

Meiry, J. L., "The Vestibular System and Human Dynamic Space Orientation," Sc.D. Thesis, M.I.T., June 1965. Also NASA CR-628

Vuorikari, V. O., "Human Role in the Control-Loop of the Automatic Landing Aircraft," S.M. Thesis, M.I.T., September 1965

Kilpatrick, P. S. II, "Bending Mode Acceleration Influence on Pilot Control of Flexible Booster Dynamics," S.M. Thesis, M.I.T., September 1965

Benjamin, P., "Visual and Motion Cues in Helicopter Flight," S.M. Thesis, M.I.T., January 1966

Preyss, A. E., "A Theory and Model of Human Learning Behavior in a Manual Control Task," Sc.D. Thesis, M.I.T., February 1967

Friedman, G. R., "Helicopter Control: A Multi-Loop Manual Control System," S.M. Thesis, M.I.T., June 1967

Steer, R. W., "The Influence of Angular and Linear Acceleration and Thermal Stimulation on the Human Semicircular Canals," Sc.D. Thesis, M.I.T., September 1967

Yasui, S., "The Use of the Chatter Mode in Self-Adaptive Systems," S.M. Thesis, M.I.T., September 1967

Katz, G. B., "Perception of Rotatio - Nystagmus and Subjective Response at Low Frequency Stimulation," S.M. Thesis, M.I.T., September 1967

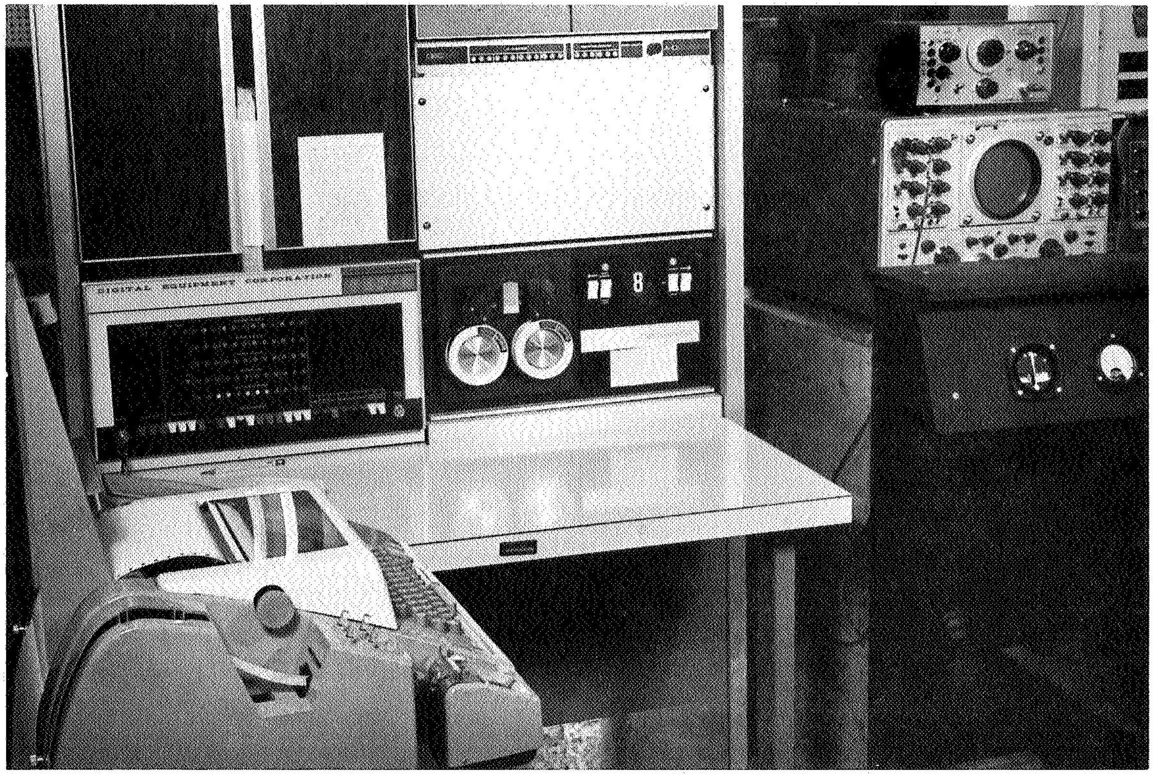


Figure 1
GPS 290T Hybrid Computer, Digital Portion

Figure 2
Observer's station. Six degrees of freedom of control are available

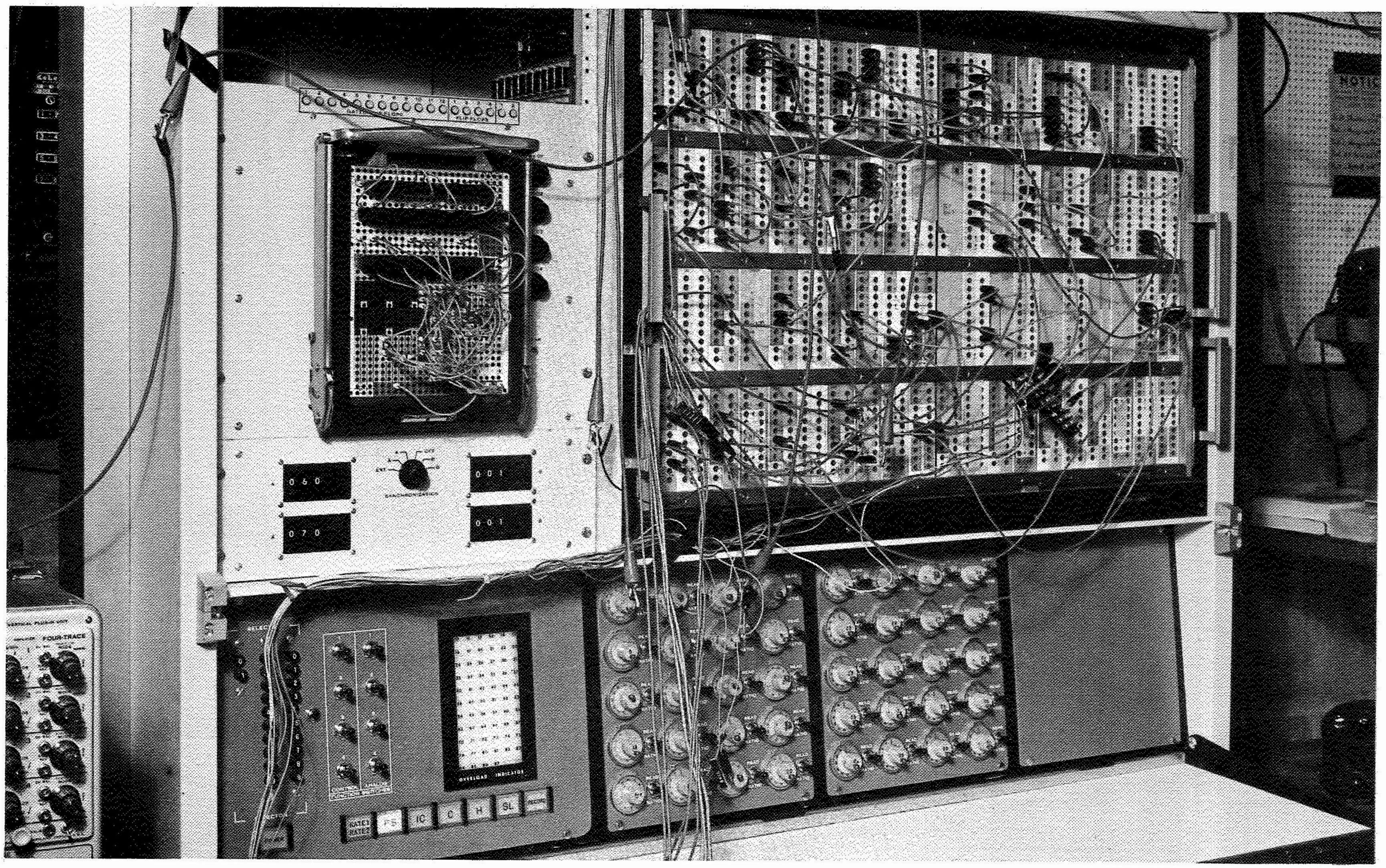


Figure 3
GPS 290T Hybrid Computer Analog Portion

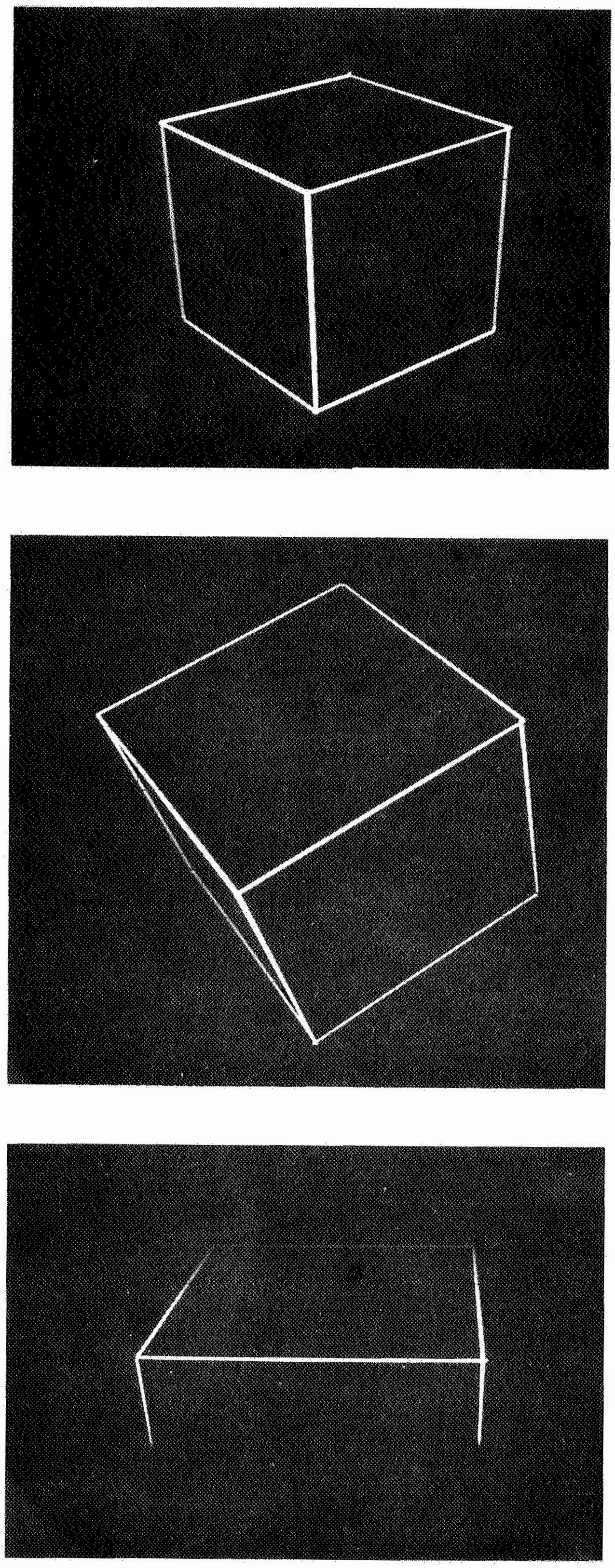


Figure 4
An "approach" to the top of the cube

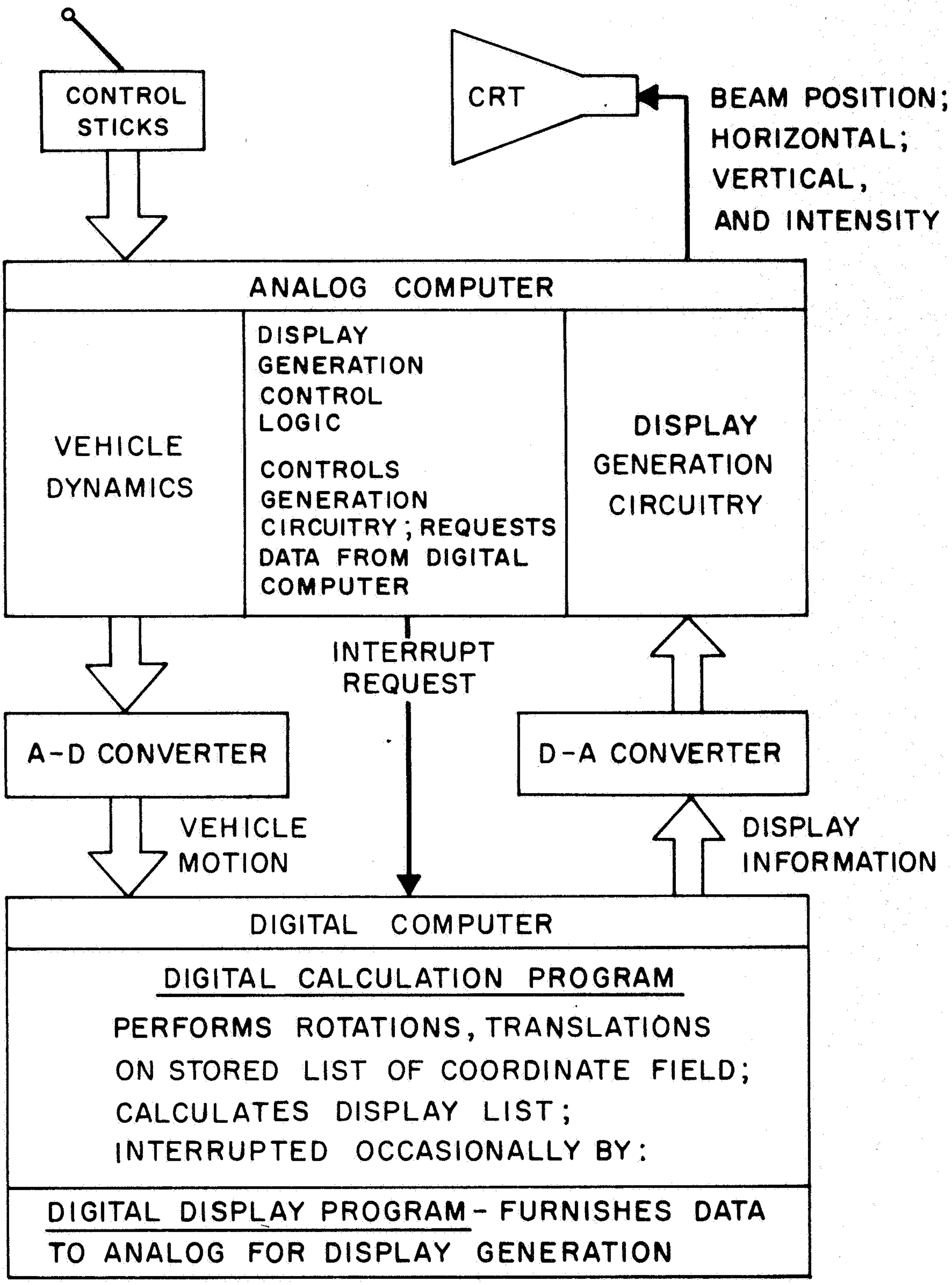


FIGURE 5 DISPLAY GENERATION SCHEMATIC

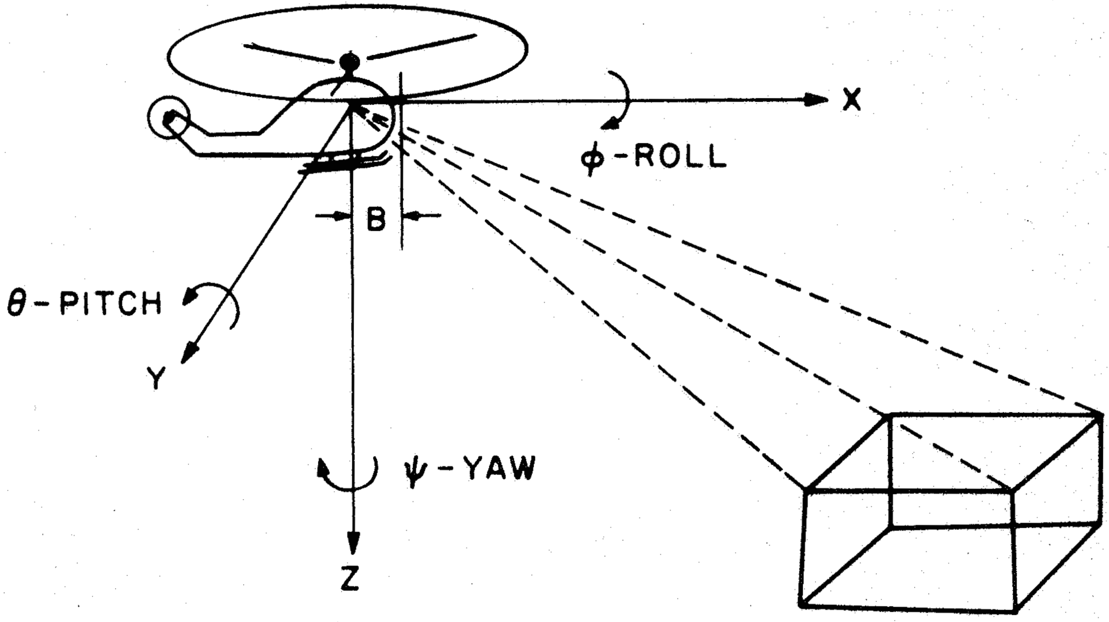
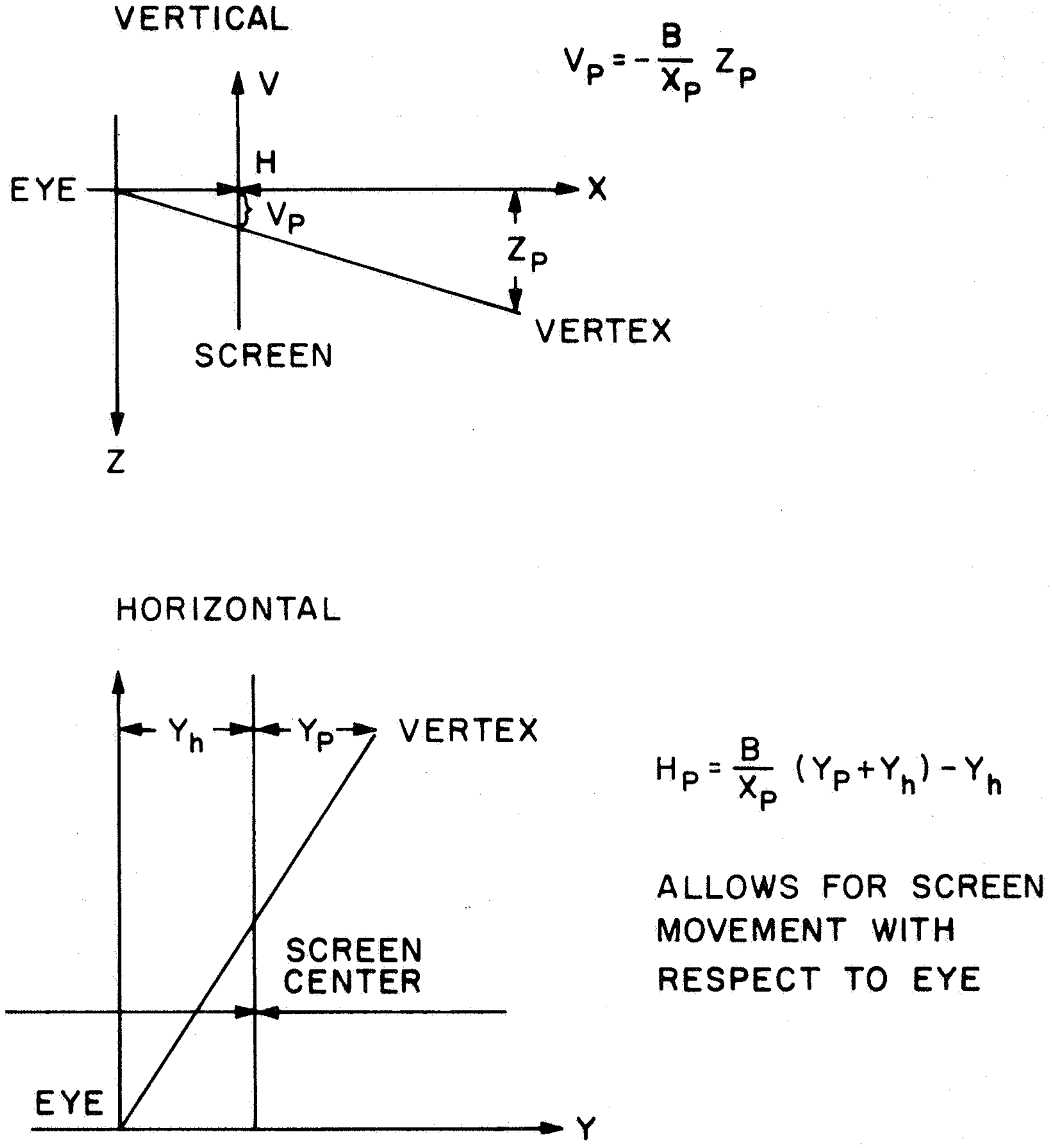


FIGURE 6 COORDINATE SYSTEM NOTATION. TRANSLATION OF THE COORDINATE AXES CONTROLS THE LOCATION OF THE OBSERVER'S EYE, WHILE ROTATION OF THE AXES INDICATES THE ORIENTATION OF THE OBSERVER'S WINDOW.

H,V SCREEN AXES--DISPLACED FROM X,Y,Z AXES BY Y_h ALONG Y AXIS AND EYE-SCREEN DISTANCE B ALONG X AXIS



$$V_P = -\frac{B}{X_P} Z_P$$

$$H_P = \frac{B}{X_P} (Y_P + Y_h) - Y_h$$

ALLOWS FOR SCREEN MOVEMENT WITH RESPECT TO EYE

FIGURE 7 PERSPECTIVE EQUATIONS

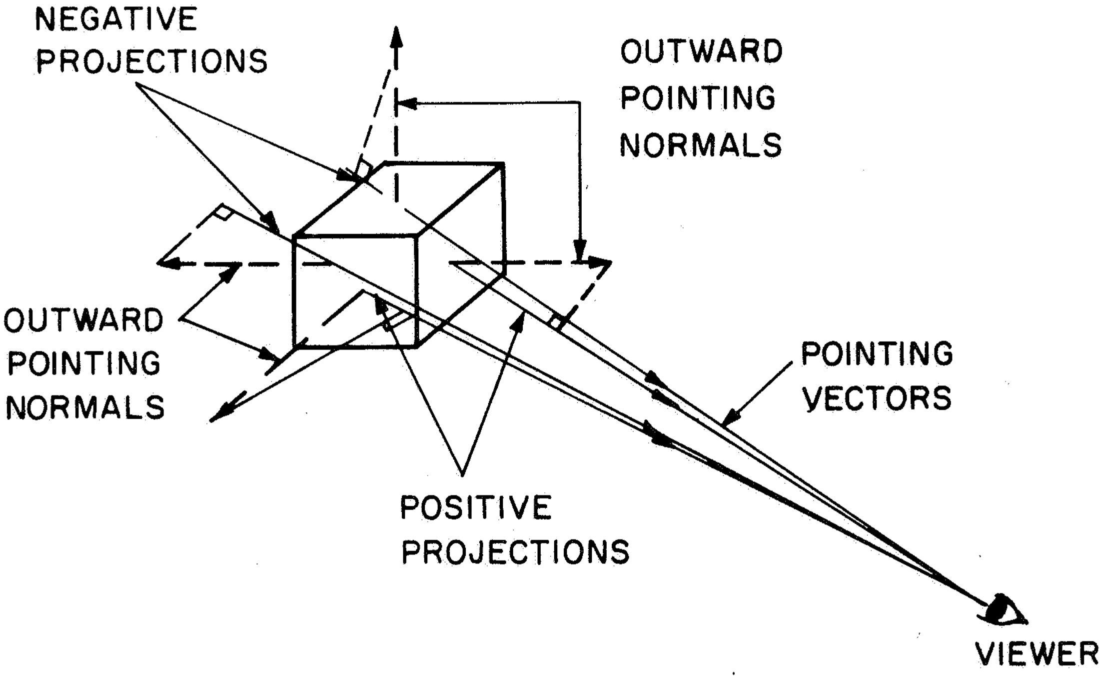


FIGURE 8 BLANKING OF HIDDEN LINES. NEGATIVE PROJECTION OF THE OUTWARD POINTING NORMAL VECTOR ON THE POINTING VECTOR INDICATES SIDE CANNOT BE SEEN.

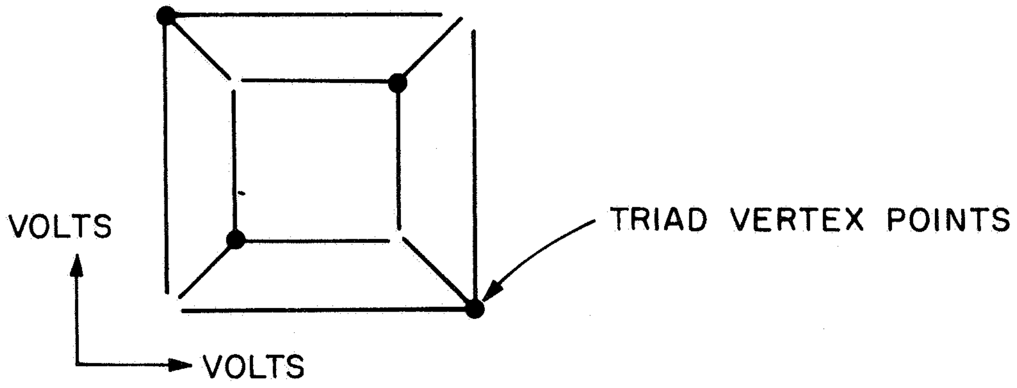


FIGURE 9 FOUR TRIAD CUBE "HIDDEN" LINES ARE SHOWN

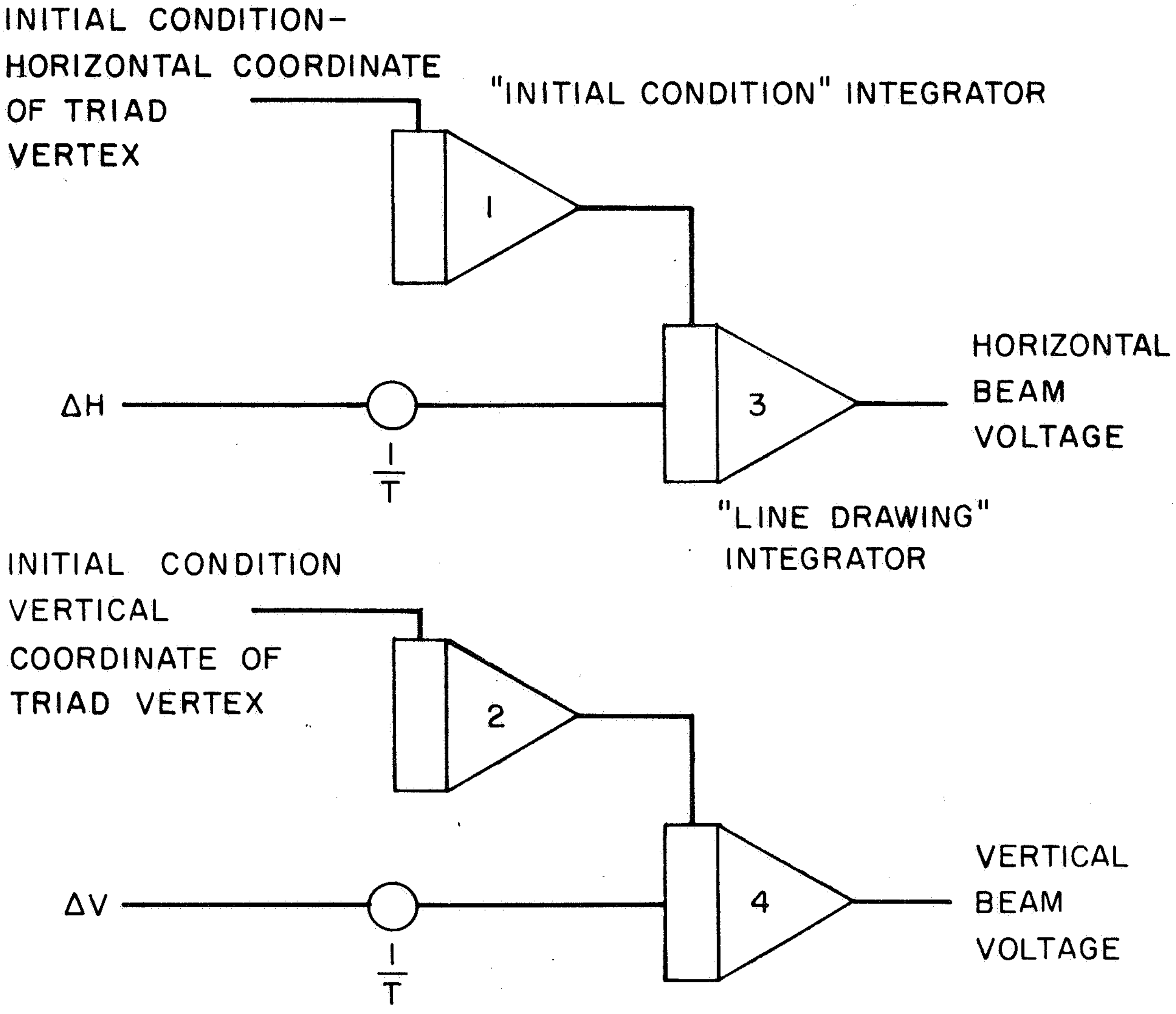


FIGURE 10 BASIC DISPLAY CIRCUIT

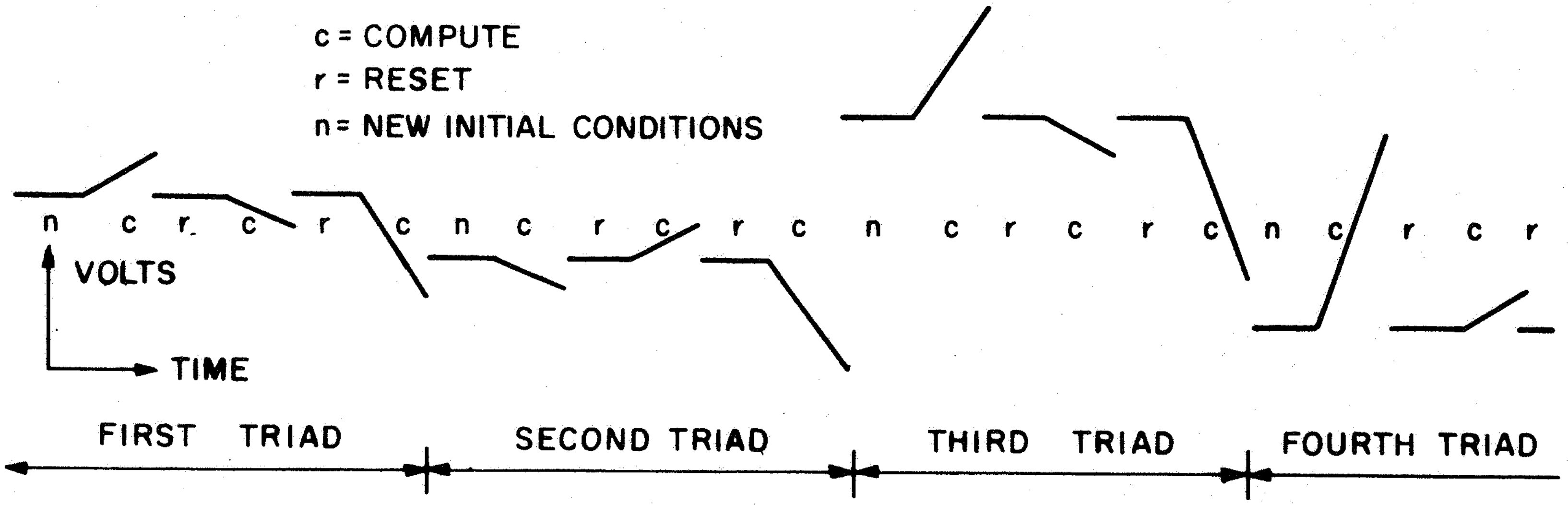

c = COMPUTE
r = RESET
n= NEW INITIAL CONDITIONS
n c r c r c n c r c r c n c r c r c n c r c r
VOLTS
TIME
FIRST TRIAD
SECOND TRIAD
THIRD TRIAD
FOURTH TRIAD

FIGURE II

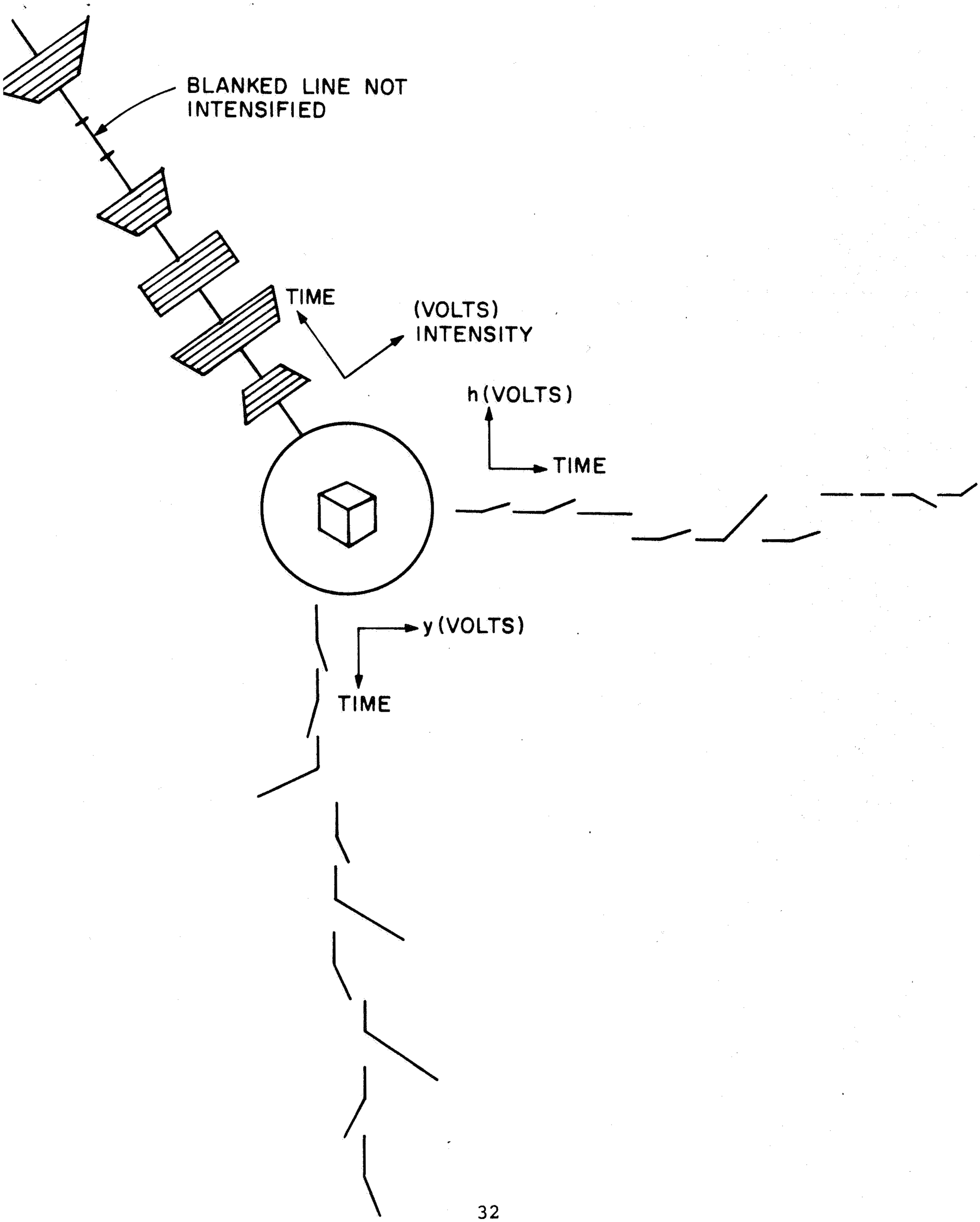
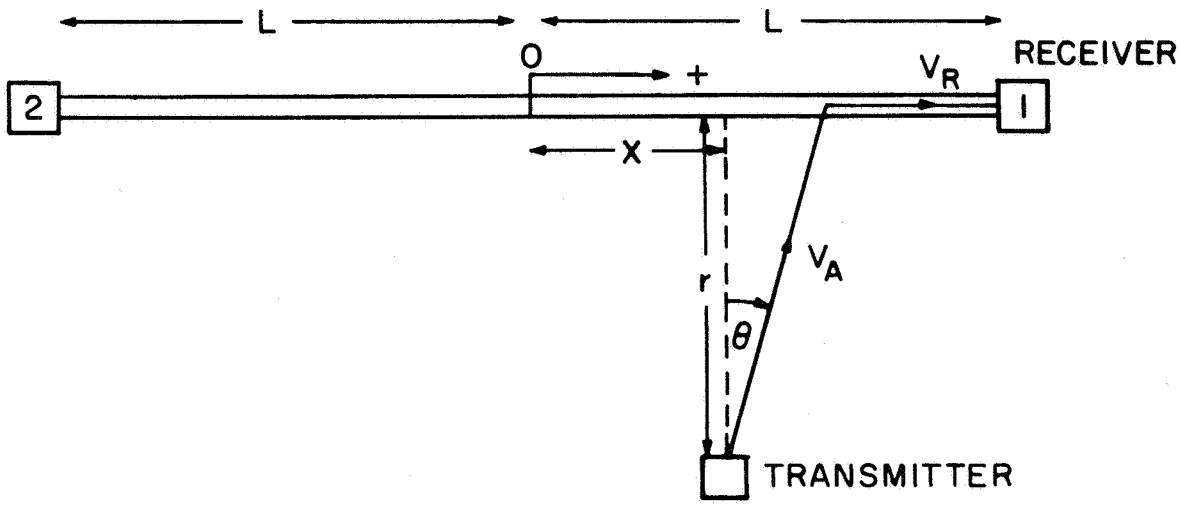

BLANKED LINE NOT INTENSIFIED
TIME
(VOLTS) INTENSITY
h (VOLTS)
TIME
y (VOLTS)
TIME

FIGURE 12



T_1 = TIME OF ARRIVAL AT RECEIVER 1

T_2 = TIME OF ARRIVAL AT RECEIVER 2

V_A = SPEED OF SOUND IN AIR

V_R = SPEED OF SOUND IN ROD

$$T_1 = \frac{r}{V_A} \text{ SEC } \theta + \frac{1}{V_R} \left[L - X - r \text{ TAN } \theta \right]$$

$$T = \frac{r}{V_A} \text{ SEC } \theta + \frac{1}{V_R} \left[L + X - r \text{ TAN } \theta \right]$$

WE WANT TO FIND THE MINIMUM TIME PATH WITH RESPECT TO θ

$$\frac{dT_1}{d\theta} = \frac{r}{V_A} \frac{\text{SIN } \theta}{\text{COS}^2 \theta} - \frac{r}{V_R} \frac{1}{\text{COS}^2 \theta} = 0 \Longrightarrow \text{SIN } \theta = \frac{V_A}{V_R}$$

$$T_1 = \frac{1}{V_R} \left[L - X + r\sqrt{(V_R/V_A)^2 - 1} \right]$$

$$T_2 = \frac{1}{V_R} \left[L + X + r\sqrt{(V_R/V_A)^2 - 1} \right]$$

$T_2 - T_1 = \frac{2X}{V_R}$ = DIFFERENCE IN ARRIVAL TIMES FOR RECEIVERS 1 AND 2

FIGURE 13

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3. Landsman, E., Sc.D. Thesis, M.I.T.Electrical Engineering Department, 1966