VOLUME I

REPORT OF A STUDY ON

A VIRTUAL IMAGE OUT-THE-WINDOW DISPLAY SYSTEM

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VIRTUAL IMAGE OUT-THE-WINDOW

DISPLAY SYSTEM STUDY

Volume I

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ABSTRACT

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A study of virtual image out-the-window display systems has been completed. A variety of configurations has been analyzed and three basic forms were selected as representative variations of the infinity image system. Each of these three characteristic designs was studied to determine its applicability to the parameters and characteristics defined by the statement of work. The recommended design is shown to emerge from a thorough consideration of the trade-offs and compromises necessary to achieve the desired characteristics. A design specification is included as a part of this report.

In addition to recommendations for a display system, the study explores a variety of possibilities for the input or image generation end of the simulation system. Particular attention is paid to high resolution TV techniques, which together with several other methods of image generation are exhaustively examined with an eye towards expected future capabilities.

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SECTION I

INTRODUCTION

This report represents the results of the work performed under NASA Contract NAS-9-3678, "A Virtual Image Out-the-Window Display System Study", for the Manned Spacecraft Center, Houston, Texas.

The work that was to be performed is described as follows:

Phase I

1. "A comprehensive survey shall be made of the state-of-the-art of virtual image out-the-window display systems. Information contained in previous surveys shall be included with a bibliography, abstracts and a detailed analysis of pertinent data."

2. "A detailed study shall be performed to define significant parameters such as those that follow. Also an evaluation of the trade-offs or compromises that may be necessary to achieve a set of desired characteristics shall be included:

(a) Field of view and format of field.

(b) Exit pupil and exit volume.

(c) Eye relief and clearance problems in inserting an image into a simulator cockpit.

(d) Image quality, contrast and resolution.

(e) Image illumination.

(f) Distortion control - the correction of system distortions such as that resulting from a cathode ray tube face plate curvature.

(g) Virtual image distance and control of the distance at which the image appears.

(h) Multiple image input and superimposition.

(i) Insetting methods for various types of input devices such as cathode ray tubes, film, direct projection from models, etc."

3. "Method of construction and the economics of building virtual image systems shall be investigated. Size limitations due to manufacturing techniques, cost or mechanical implementation problems shall be detailed."

4. "An analysis and technical discussion of virtual image systems previously built shall be presented."

<u>Phase II</u>

1. "Practical television video bandwidth is presently limited to approximately 30 megacycles equivalent to about 1200 TV lines for a standard 30 cycle frame rate with two interlaced fields. This imposes an information limitation which for wide fields of view restricts the amount of detail that may be shown. A solution to this problem may be mosaic implementation, which implies matched multiple pickup devices. A detailed design study shall be made of optimum implementation of mosaic systems with matched pickups for television information transfer.

2. "A study shall be made of methods of implementing ultrawide displays greater than 110° in the horizontal plane with lesser fields of view in the vertical plane to be supplied with information by advanced single channel television systems in anticipation of advancements in the art of high resolution television."

3. "Preliminary designs shall be made in sufficient detail to establish optical and mechanical features of a mosaic system as in paragraph 1 and an ultra-wide single channel system as in paragraph 2. The specific characteristics of these designs shall be established during Phase II in concurrence with NASA."

4. "At the end of the Phase II period, a Statement of Work shall be prepared for the design, development and construction of a very wide field of view display system whose configuration will be established at that time in concurrence with NASA."

In accordance with the statement of work, a comprehensive survey was conducted of the available pertinent literature, and since virtual image systems are relatively new devices in the art of simulation the survey also included questionnaires and personal visits to various facilities active in either optical design and manufacture or simulation work or both:

LITERATURE SEARCH

A search of available, pertinent literature was conducted by a study of the bibliographic files of the following sources:

Defense Documentation Center

Document Service Center, Dayton Ohio

U.S. Patent Office, Washington, D.C.

Engineering Societies Library, New York, N.Y.

Farrand Optical Co., Inc., New York, N.Y.

Reference was also made to a selected group of current periodicals, foreign journals and textbooks, and bibliographic references included in the sources reviewed were also investigated. A relatively small percentage of all the literature reviewed was abstracted and made a part of this report. Only that literature having a direct bearing on the objectives of this program was selected for inclusion.

SURVEYS OF ORGANIZATIONS

One hundred and five organizations active in television development were surveyed by questionnaire. Fifty six organizations active in the art of visual simulation were surveyed by questionnaire. The questionnaires and the responses thereto are catalogued in Volume II of this report.

FACILITY VISITS

Visits by a Farrand Optical Company study team were made to all cooperating organizations. Their individual contributions to the field of visual simulation are summarized in Section V of Volume II of this report.

ARRANGEMENT OF THIS REPORT

The results of the study program and the considerations leading to these results are presented in Section I of this report for the convenience of the reader who is not concerned with the background study and analysis from which they were derived. Sections II and III are arranged, insofar as practicable, in a sequence effecting a logical development of the study results. In particular, Section III summarizes the state-of-the-art of visual simulators and attempts to predict the direction and extent of future developments. The development of the design of the virtual image display system defined by the study program is described in Section IV of this report. Section V attempts to define the visual simulation system of the future based on current advanced concepts.

For the sake of continuity, technical terms and statements of optical theory germane to the optical simulation art are not defined or explained in the body of the report. In the interest of completeness, Section VI of this report comprises a glossary of optical terms, while Section VII contains schematic drawings illustrative of the basic types of optical systems discussed throughout the report.

The study effort, as originally specified by the referenced contract, was confined to the consideration of virtual image display systems and the television type of image generation. It was soon found necessary, however, to consider elements of other types of display systems, as well as means other than television image generation, to analyze and evaluate all possible combinations leading to visual simulation systems. This expanded effort resulted in the section of this report on the state-of-the-art of the modern visual simulator and its predicted future capability. It is well to note, however, that because of the recent increased interest in the visual simulation art, rapid progress is being made, and many of the new developments are considered proprietary by the organizations fostering these advances. For this reason, several of the organizations surveyed declined to reveal their current programs. This report, therefore, cannot be said to contain a complete survey of every organization engaged in the field of visual simulation.

REFERENCE MATERIAL

Abstracts of all material reviewed, reports of all surveys of organizations contacted, and reports of all the simulation facilities visited, as well as a complete bibliography, have been included as Volume II of this study program.

CONCLUSIONS AND RECOMMENDATIONS

1. A comprehensive survey of the state-of-the-art of virtual image out-the-window display systems was completed in accordance with the Phase I requirement of the work statement.

As a result of the detailed analysis of virtual image systems in Phase I of the program, a set of desirable characteristics for a general purpose, wide field, long eye relief, out-the-window display system was formulated in conjunction with NASA personnel in Phase II. These characteristics are listed in Section IV of this report. Section IV also develops the final design of an out-the-window virtual image system which fulfills the desired characteristics. A set of specifications governing the design and performance of this system as well as a schematic layout of the optical components are included in Section IV. The proposed system represents this contractor's recommendation for display equipment fulfilling that requirement of the study contract.

2. This study program also called for an investigation of techniques aimed at the development of closed circuit television systems of increased data content in order to implement ultrawide displays with good resolution. Particular attention was paid to single channel television systems and to mosaic implementation. It was found that the single channel television systems suffer most at the pickup or camera end in terms of resolution. Aside from amplifier bandwidth considerations, the camera tube itself represents the most se-

vere limitation and unfortunately there seems to be no improvement of any consequence on the horizon.

Mosaic systems encompass a host of different schemes and the reader will find most of them fully described and evaluated in this report. Although the principles of several of the mosaic systems are sound, their implementation becomes impractical. The study shows that the most promising system using television displays resides with image generation by computation of pictorial elements. For this reason a considerable portion of Section III is devoted to the theory of several computational approaches. It will be found that even though computation of pictorial elements holds the greater promise as far as image generation is concerned, it too is limited (as are other techniques) by the display CRT. The display CRT must provide both resolution and brightness in sizes of 21" and over to provide inputs serving fields of view over 110° in infinity display systems. Unfortunately, increased resolution on a display CRT is obtained with loss of brightness and vice-versa. After considerable evaluation of television image generation and display techniques this contractor feels that the best prospect for future improvement in resolution lies with the computing of pictorial elements technique, and therefore recommends a concentrated development effort in this area as well as in the area of display - CRT resolution and brightness.

The Farrand Optical Company also recommends that continual development be exercised with an unprogrammed color film projection technique such as the "Mission Effects Projector", described in Section III, which can provide unprogrammed, real time displays in full color, with resolution surpassing television systems.

SECTION II

BACKGROUND OF THE STUDY PROGRAM

A. GENERAL

Although cockpit simulators have been developed to the point where aircraft dynamics and response to both external and pilot inputs are reproduced in a most realistic fashion, the same cannot be said of the corresponding visual display made available to the pilot undergoing training. This deficiency is rapidly being overcome at the present time. This section of the report will attempt to develop the current and future requirements of both spaceflight and aircraft flight visual simulation and to define the method of approach used in arriving at the recommended system parameters.

B. EVOLUTION OF THE VISUAL SIMULATION ART

In order to fully appreciate the rapid strides that have occurred over the past six years it is necessary to review the state of the art of visual simulation prior to this period.

Various devices termed "aircraft flight simulators" have been in use for several decades. Generally speaking these machines were used for pilot training in tasks of a particular nature. They were not capable of accurately reproducing all aircraft responses to pilot initiated stimuli, nor were they capable of introducing all the visual cues which a pilot requires to initiate the proper stimuli. Hence the "transfer" value from simulator to real flight was admittedly low. Recognizing these drawbacks, designers concentrated on optimizing the simulator for intensive training of a particular task. These simulators then, should have been termed "part task" simulators.

Recent examples of part task trainers include radar navigation trainers, instrument trainers, cockpit procedural trainers and visual specific task trainers such as gunnery trainers or target acquisition trainers. All part task trainers are designed to increase operator proficiency in a specific task, be it speed of response, interpretation, or visual acquisition, in order that he may properly and efficiently cope with any problems that may arise due to either the external environment or machine malfunctions.

More recently, the part task trainer has found widespread use in the science of human engineering. For example, the procedural trainer is admirably suited to studies leading to optimization of controls design and location, to better weld the man to the machine. Other part task trainers, because they emphasize a specific problem, ideally isolate the stimuli and human respones to those specific stimuli so that the proper psychomotor skills can be examined and optimized through training. Many psychomotor responses, however, are dependent on human evaluation of many simultaneous cues, and these experiments are not readily performed on part task trainers. If the multiple cues leading to a more skilled response requiring a higher degree of judgement could be reproduced in a simulator, the usefulness of part task trainers could be extended tremendously. Unfortunately, it is extremely difficult to scientifically separate and artificially weigh in quality, quantity and time, the variety of physical, psychological and visual cues that are utilized by the complicated human in arriving at a decision for the execution of a particular response. The interrelation of variables is so complex, especially when visual simulation is involved, that the task of reproducing the required cues in their proper proportion is a formidable one.

If it were possible to reproduce the external world scene faithfully then one could avoid defining visual cues or interrelating visual cues that could not be assigned individual weighing factors. If this visual simulation could be made dynamically accurate and the motion system were made equally accurate with respect to given aircraft or space vehicle characteristics, we would arrive at the ideal simulator suitable either for part task work or for whole task or full mission work. Once the training value of such a full mission or whole task simulator were proved out, it would be possible to degrade the simulation in calculated steps to determine by actual trial the necessary cues for individual part task trainers. This should be a more desirable approach to part task trainer design. Should one question the advisability of resorting to part task trainers when the ideal full mission or whole task simulator exists, the answer as always, lies in the lesser cost of part task simulators.

In summary, continued effort is recommended in setting out to achieve visual scene fidelity in terms of resolution, contrast, full color, and controlled parallax to duplicate the real world as closely as possible. Recent achievements in these areas will be examined in detail as this report progresses.

1. The Requirement For Visual Simulation

Despite apparent deficiencies, the role of visual simulation in both aircraft and spaceflight training continues to gain increasing prominence in the overall simulator. This fact by itself may appear surprising when the simulated scene offered to the pilot is far from ideal. However, when one considers that the ultimate objective of aircraft and spacecraft designers together with the human factors people is to provide the optimum man-machine system within the current technological framework, the importance of simulating visual cues with fidelity is obvious. We can do nothing to improve the human being physiologically. On the other hand we can optimize the man-machine system by tailoring the machine to the human psychmotor response skills. To achieve this end, we realize that the complex man-machine servo loop, of which the human operator is an integral part, depends on the operator's psychomotor skills. The pilot, in turn, represents a complex servo system whose psychomotor responses depend wholly on the inputs or stimuli. While these stimuli or cues depend on varied physiological sensing elements that result in both kinesthetic and visual stimuli used to initiate responses in the man-machine system, it is largely the visual cues that provide the error sensing and correction.

The visual cues may result from cockpit instruments or from direct observation of the external world scene or both. While both types of visual stimuli will always be required, dependence on the external scene is continually increasing because of the high performance machines currently employed in the field of aircraft and because of certain vital maneuvers such as rendezvous and docking that are required in the field of spaceflight. It is obvious, therefore, that we must strive to provide means for generating the external scene in full fidelity and in real time.

From a totally different viewpoint, the requirement for visual simulation is becoming increasingly apparent because of the high cost of in-flight training. This is especially true in spaceflight. Systems development and evaluation would also profit from the availability and reproducibility offered by simulators both in the aircraft and spaceflight fields. More important, emergency procedures training could be effected without danger and at minimal costs.

Considering the aircraft field in particular, systems such as Head-Up Displays, weapon delivery systems, and reconnaissance systems could be evaluated under repeatable conditions. Finally, pilot transfer training from one type of aircraft to another would be accomplished at minimal cost and in a minimum of elapsed time.

2. Visual Simulator Performance Objectives

In order to achieve the foregoing objectives, the performance of the visual simulator must be specified. Specifications for both aircraft and spaceflight visual simulators will be developed in the paragraphs that follow.

To attempt to discuss a visual simulator in detail as a single unit is unwieldy. Hence to simplify all subsequent discussions we will arbitrarily classify a visual simulator as comprising two separate and distinct components; a display end and an image generation end. Except for the matching of focal surfaces at the interface, these two portions of a typical system may be considered independent of each other.

In order to effectively describe visual scene requirements for both aircraft flight and spaceflight, it will be necessary to consider the overall scene as the sum of its component parts. In addition, we should attempt to specify the physical characteristics of the visual simulator as they affect the overall simulator.

Display End of the Visual Simulator

The display end of a visual simulator must provide the indicated performance in the following areas:

a) Resolution - Although the normal resolution capability of a human being is usually quoted as one minute of arc, most pilots and astronauts exhibit a far better capability. In addition, the human eye can see elongated detail whose width is far below an equivalent angle of one minute subtended at the eye. On this basis, the ideal visual simulator scene should, therefore, provide images whose resolution is better than one minute of arc. The display end should also be capable of relaying a full color image from the generating elements to the observer without noticeably affecting the color balance. Equally important, the optical system and/or the final display technique should not degrade the contrast rendition of the generated visual scene to any large extent. It is a well known fact that "seeing" depends not only on resolution but also on contrast.

An additional requirement of the display end of a visual simulator concerns the acuity of human stereoscopic vision. The eyes are sensitive to differential divergence angles of a point source as small as 10 seconds of arc, therefore stereo depth distortions must be kept low for a system with optically combined multiple images. In addition, convergence of light entering the eye must be avoided. The same type of disparity in a plane orthogonal to the eye plane is called dipvergence. Convergence and dipvergence are very critical since the eyebrain system finds it more difficult to allow for these conditions as compared to the divergence. Obviously therefore, the optical system must be of such quality as to prevent such conflicts from arising in the eye-brain system, in order that the visual scene will not be rejected as unreal, or that unintended visual cues are not aroused.

b) Field of View - In aircraft flight the importance of peripheral vision as a velocity cue has been well established. Many studies have been conducted aimed at determining the minimum acceptable field of view and although no single conclusive horizontal field of view has ever been arrived at (probably because of the variation in simulator detail and resolution), it appears as a general concensus that a 100° horizontal field of view is necessary for most tasks. The vertical field of view is fairly well restricted in modern flight vehicles except for the helicopter type aircraft. It appears, therefore, that a vertical field of view of 60° would suffice in most cases. For the particular case of aircraft carrier landings where a turn-around maneuver is necessary, the horizontal field of view must be enlarged or the frontal field of view must be displayed to favor the pilot's left field of vision. Most pilots would prefer vision out to 90° from the forward direction through the lefthand window. Ideally, therefore, a 180° horizontal field of view by 60° vertical field of view visual simulator would be optimal.

In the field of spaceflight there has not been developed a sufficiently complete set of requirements for field of view. Earth orbital vehicles are limited in window size because of the structural and weight requirements associated with window size. In this case, the pilot's field of view is determined by the distance of his eye location from the window. The field of view must, however, be large enough for visual acquisition of rendezvous and docking targets, for navigation with handheld devices, and for eyeball acquisition of orbital landmarks. Based on this contractor's experience, in the design, development, and fabrication of visual space-flight simulators for the Mercury, Gemini, Apollo and LEM programs, it appears that a 100° horizontal field of view by an 80° vertical field of view suffices for the accomplishment of all required tasks.

c) Eye Relief and Operator Clearance - Most visual simulators require equipment in the proximity of the pilot. In projection systems utilizing a screen as the final output, the projector is ideally located at the pilot's eye. Such devices utilize a beamsplitter mirror to elevate the projector away from the pilot's head position, or they effect a compromise by locating the projector above the pilot's head. In the more recently developed virtual image systems of the reflective mirror type, a beamsplitter is required forward of the pilot's eye position, while in the lenticular type of virtual image systems, a large lens is required forward of the observer's eye position. Because of the geometry, the closer these devices are located to the observer, the smaller, and therefore the more economical the system becomes for equivalent fields of view. These elements should, however, be located forward of the instrument panel in aircraft simulators, and external to the window in spaceflight simulators. In simulators of the general purpose type, the eye relief distance, which may be defined as the real clearance between the pilot and the closest optical element, should be made as large as possible, in order that a variety of aircraft cockpit or space capsule configurations can be accommodated.

d) System Size and Weight - In the virtual image type of simulator, where the image generation input is directly attached to the visual display end, it is important to limit the total number of separate inputs when the simulator is to be of a moving base type. The overall simulator is greatly simplified when the visual display system can be attached directly to the moving base, for in this manner no differential motions of the visual scene need be provided. In other words, the visual scene may be driven directly from the signals driving the moving base. This simplification, however, must be paid for by the moving base actuating system, which must now drive not only the simulator, cockpit, and pilot, but also the visual display system with attached image generation.

Image Generation End

It is generally acknowledged, that in many areas of the visual simulation field, technological limitations exist in the techniques of image generation. Because of these limitations, and also for economic reasons, part task trainers have flourished. There exist at least two definitions of visual fidelity which must be considered. The physical fidelity of a simulator which concerns the cockpit environment and its motion cues does not concern us at this time. Visual fidelity, however, comprises not only perceptual fidelity but also psychological fidelity that is in question. It has been explained that psychological responses and the interrelated visual cues that govern human psychomotor responses of a complex nature cannot be definitely attributed to specific cues such as would be required for part task simulations. Determination of these visual cue interrelationships and relative weighings, to assure good part task training value and transfer value, cannot be established simply, reliably, and economically. For this reason, we will resort to perceptual fidelity, which implies the optimum degree of equivalence between the real scene and the simulated scene. It is on this basis that we will attempt to define the optimal visual simulator:

a) Resolution - Regardless of viewing conditions such as visibility, relative velocity, brightness, etc., image generation of the external world scene must be capable of a resolution sufficiently high to accommodate the human observer's capability. Resolution, however, is not all there is to "seeing". The eyes and the brain function as a system, and recognition is a good part of seeing. Other parameters, such as contrast, color, shadows, relative size, etc., in turn affect recognition, so that provision of one arc minute of resolution does not by itself make a good visual simulator.

Although in aircraft flight the relative angular velocity between observer and the external scene is higher than in orbital spaceflight conditions, the aircraft pilot can fixate on a certain area and follow this for extended periods of time for critical examination. Therefore, both aircraft flight and spaceflight visual simulation require image generations of the external scene with resolutions exceeding those normally attributed to the human visual system. Additionally, resolution is intended here to apply to a random distribution of image forming points. For example, resolution limited by visible raster lines is not only inadequate if the raster lines are visible, but the very fact that a pattern is evident tends to destroy the apparent reality of a synthetically generated scene.

b) Perspective - Perspective describes the apparent distortion of the overall scene as one scans from the nadir to the horizon. This type of distortion is usually known as "Keystone" distortion because of the shape it assumes. Keystone distortion is a function of the elevation angle from the local vertical. The perspective point or the vanishing point to which all keystone lines are oriented always resides at the horizon and in the direction of the heading vector. Additionally, this type of distortion is independent of the observer's spatial orientation, and is equally important to spaceflight and to aircraft flight visual simulation, since both velocity and heading cues reside in it. In spaceflight simulation, both perspective distortion and the proper sphericity of the Earth view is provided when the viewing point is at the correct or scale altitude with respect to the model used for image generation when the model is of the three-dimensional type. In the case where a three-dimensional model is not a full model, or in the case of a two-dimensional film, an artificial horizon must be introduced. In cases where the view point is not at the proper or scale altitude, while correct perspective distortion can be introduced it will not by itself provide the proper sphericity. In such cases additional distortion, commonly referred to as spherical distortion, must also be introduced separately to combine with the perspective distortion to obtain a valid view.

c) Aspect - Aspect concerns the apparent shape of individual three-dimensional objects in the field of view. Like perspective distortion, it is independent of the observer's spatial orientation. Aspect, however, is completely dependent upon object location in the field of view with respect to elevation and azimuth angle. In order to convey the correct sensations of velocity, drift and flight pitch angle, aspect must be accurately displayed. Because this distortion is a function of both elevation angle from the nadir and azimuth angle, it is a continually changing cue with motion. Proper simulation of aspect requires that not only the aspect of three-dimensional objects change with velocities of approach, recession, and lateral drift, but also that such changes either cover or uncover additional detail beyond the three-dimensional objects as their aspect changes in the field of view. Aspect, as a cue, is more important in visual flight simulation of aircraft than it is in spaceflight. However, the degree of relative importance cannot be estimated at this time because of lack of comparative experimental values.

d) Color and Contrast - Contrast and color augment each other in rendering terrain details visible. It is generally true that a range of contrast of 10:1 is acceptable for faithfully simulating an external scene. If we implement such a scene with color, the visibility is greatly enhanced. A scene displayed in a full color range greatly enhances realism for aircraft flight simulation. It is felt at this time that color equally enhances orbital views in spaceflight simulation.

e) Cloud Cover - In order to faithfully reproduce the external scene, it is important to include variable cloud effects, ranging from solid cloud cover, through fog, to a variety of dispersed cloud effects. In aircraft flight simulation, cloud cover and fog are important from the point of view of target acquisition, target identification, terrain avoidance, and landing simulation. In spaceflight, fog is relatively unimportant, although cloud cover with its shadow effects adds another dimension to reality, while the perspective distortion permits a rough estimate of yaw attitude through observation of cloud formations.

f) Brightness - It will be found, that regardless of the image generating means employed, exact duplication of brightness levels in the real world is impossible to achieve. However, the eye-brain system operates on a proportional scale, and as long as the visual simulation system operates in the observer's photopic region of sensitivity, it is justifiable to lower all brightness values of the external scene proportionately, with the result that the illumination of bright sunlight may be achieved utilizing a maximum highlight brightness as low as 10 ft.-lamberts at the eye. Depending on the degree of dark adaptation, the acceptable highlight brightness value may be lowered appreciably. This compromise will be found to hold valid both for aircraft visual simulation and spaceflight visual simulation. This expedient offers a great advantage to the visual simulation art when multiple inputs are required to reconstruct a scene of optimal perceptual fidelity.

g) Seasonal Changes and Day-Night Generation - Seasonal changes may be incorporated where desired by altering the primary source of information, is this additional cost is justified. Day to night changes are important both to aircraft visual flight simulation and spaceflight visual simulation. Depending on the method of generating the external scene, there will be some minor advantages and disadvantages involved. Generally speaking, however, the lowering of the scene illumination can be gauged to effect a satisfactory transfer from the observer's photopic sensitivity to his scotopic or dark-adapted sensitivity without any great degree of difficulty. There should exist the capability of varying night-time illumination from full-moon, clear weather conditions, to starlight illumination conditions. In spaceflight visual simulation, there must be included the capability of generating an accurate terminator as well as special sunrise and sunset effects. In aircraft flight simulation, night operations must include a faithful reproduction of air field landing light displays.

h) Image Generation Response - With high performance aircraft and equally responsive spaceflight vehicles, the image generating means for all inputs at the display end of the system must operate in real time and within the calculated response framework of the simulated vehicle. If this is not achieved, the added delay in the man-machine response loop will compromise the training value or the transfer value or both. Additionally, if the final visual output scene comprises several input image generations, these generations cannot afford to vary in response, otherwise the final output scene may "tear" apart. Even if such discrepancies are minute, the human visual system is extremely sensitive to these variations and the realism is immediately sacrificed.

1) Celestial Presentation - In aircraft flight simulation, the use of a celestial presentation is not often required. However, for use in navigation training, the images of stars in sufficient quantity and of sufficient quality should be provided, without the parallax normally encountered in the screen type planetarium projection system. Star images should remain point sources even under reasonable magnification. Star magnitudes should be available ranging between -1 and +5. For such aircraft simulation, limited portions of the sky are required to be visible over any given flight program. The motion system for this display must operate without any perceptible jitter down to earth's rate and no singularities due to the gimballing arrangement should be encountered. Both partial and total occultation of the celestial presentation should be available to simulate cloud cover at the lower altitudes. In spaceflight simulation, the requirements are more stringent. Not only must the stars remain point sources, but the

celestial sphere must be capable of unrestricted motion about three axes (pitch, yaw and roll), with programmed excursions about the singular points of the gimballing system. In this case, the star images must be capable of being accurately occulted by wither the planets or other space vehicles. Additionally, the driving rates must now be extended to cover a velocity as low as 1/5 of earth's rate without any perceptual jitter. This contractor has found from experience that a total of approximately 1000 stars constitutes a realistic presentation. Fifty-seven navigational stars should be included as well as all stars sown to the 4th magnitude and some selected stars of the 5th magnitude, where they will aid in the recognition of certain constellations. In either the aircraft flight simulation or the spaceflight simulation case, very high accuracies must be maintained as stars translate across the field of view. In particular, the interstellar angles must be preserved with accuracy. It is felt that stellar location accuracies of 1 milliradian are sufficient to exercise navigational problems with hand-held devices. In cases where greater accuracies are desired, existing errors can be accurately recorded and sightings can be adjusted to reflect the pilot's navigational performance.

In certain isolated missions, the moon must also be accurately displayed. Similarly, for particular tasks, the sun's image must be presented in its proper location against the celestial sphere. The brightness of the sun, must, in certain cases, be such that it dazzles the astronaut. If the brightness of the simulated sun is insufficient to provide sunshafting, then this effect should be included as an additional input.

j) Targets - In aircraft flight simulation, airborne targets should be represented at their correct apparent distance; that is to say that if the background is projected to infinity at the display end, then the approaching target should be introduced into the display equipment to create the proper parallax between it and the background. Ground targets, however, need not be displayed with any parallactic difference. Cloud cover, on the other hand, should include this feature. In spaceflight simulation, it is of the utmost importance to reproduce this parallactic difference between a target vehicle and a background for rendezvous and docking maneuvers. It is also necessary in this mode of operation, to provide occultation of the background scene at infinity by the target vehicle, for proper training in the rendezvous and docking maneuver.

C. ORGANIZATION OF THE STUDY PROGRAM

The organization of the study program is aimed at a thorough investigation of the latest advances in the field of visual simulation, both in the display end, and in the image generation end, to conclusively establish the current state of the art. In Section A of Part 3, the critical review conducted of the various techniques employed in the visual simulation art will be summarized and examined in some detail. Those techniques that emerge as most closely fulfilling the aforementioned requirements, both in the display end, and in the image generation end of visual simulation, will be compared, and combinations of techniques will be sought, to arrive at recommendations for an optimal visual simulation system. Section B of Part 3 will describe the apparent visual simulation system with any required compromises carefully indicated, and all interface requirements where they exist between display end and image generation end completely specified.

Based on the requirements of this program, the recommended display end of the ideal system will be examined and developed into a working design. Image generation techniques will be developed only as far as the recommendations of Section 3, since the contractual obligation does not require design of image generators.

SECTION III

CURRENT APPROACHES TO VISUAL SIMULATION

A. GENERAL

For the purpose of examining current approaches to the art of visual simulation, we shall follow the division of a visual simulator into a display end and an image generation end, as advanced in Section III of this report.

The paragraphs that follow will describe virtual image displays first. This type of display system is generally acknowledged to represent the current state-of-the-art. However, there will also be included several simulation systems using other methods of display which are of recent design. Immediately following the discussion of displays, current techniques of image generation will be thoroughly examined. The results of this survey will be a series of recommendations for future research and development in the area of image generation. There will be no specifications evolved for an image generation system, since this is not a contractual obligation. Section III will, however, lead to the ideal type of virtual image display system based on the contractual statement of work. Section IV will examine the suggested type of virtual image display system, and a set of specifications describing the optimal system will be developed.

B. DISPLAY END

1. Large Eye Relief Virtual Image Displays

No attempt has been made to discuss all visual simulation devices ever built which provide a virtual image display. Nor would such a goal be particularly desirable.

Many devices and displays have been constructed for in-house purposes and, as such, lack the sophistication required of wide-angle, out-the-window displays for flight simulators.

Virtual image displays may be conveniently divided into two basic designs. There are (1) the magnifier type and (2) the large pupil, long eye relief eyepiece type. The magnifier type (see Section VII of this report) are not pupil forming. These systems locate one or more inputs in the focal plane of a weak magnifying lens so that light emanating from any point in the focal plane emerges as a directional, collimated bundle to the observer. These systems are usually limited in their maximum field of view for several reasons. In order to provide acceptable imagery, it is desirable to make the focal length of the magnifier lens long for purposes of folding other inputs into the optical path. Again the focal plane images become large for large fields of view and physical interferences soon result. The magnifier type system usually results in severe distortion and "swimming" except for limited head motion about the optical axis unless the focal length is unusually long or multiple elements are provided.

The eyepiece type of virtual image system is capable of being designed as either a pupil forming or non-pupil forming virtual image system. The refracting eyepiece type of system, although it results in better imagery and a much more compact design than the magnifier type of system, is heavier and much more expensive. The system is pupil forming if an aerial image is located in its focal plane. If the image in the focal plane is derived from a diffusing screen, then it is not pupil forming. Systems of this type, like the magnifier type are difficult if not impossible to make in very large diameters. If the eyepiece, however, is made reflecting rather than refracting then size limitations are essentially eliminated. Such reflecting type systems utilize an eyepiece type mirror and beamsplitter arrangement to achieve the effect of a refracting eyepiece (see Section VII of this report). It is obvious, therefore, that with reflecting eyepiece type virtual image systems extremely wide fields of view with very large exit pupils become feasible, since the eyepiece mirror can be made in very large diameters. If such a system were used as a non-pupil forming device then the very large eyepiece mirror would permit two pilots side-by-side to enjoy the benefits of very wide fields without restricting either their head motion or their overlap field of view. For a more thorough description of the variety of virtual image systems, the reader is referred to Section IV of this report and also to Section VII where the theory of infinity image display systems is illustrated.

The survey effort has been made to include major virtual image displays which, at the time of their development, represented significant advancement in the state-of-the-art for the basic simulation technique that was used. Devices of this type that were inspected by the Farrand research team on facility visits are described and evaluated. Information gleaned from previous surveys and reports, manufacturers' literature patents on simulator devices, and answers to the simulator survey were analyzed for pertinent data and additional findings. The same sources provided useful information about virtual image displays unknown to, or unavailable to, the Farrand research team. In general, most of the accumulated data is of a qualitative, rather than quantitative, nature.

a. Farrand Infinity Display System

Wide Angle Viewing System

A wide-angle system developed by the Farrand Optical Company has proven well suited to simulators requiring either window or windscreen type displays. Fields of view achieved in this type of simulator display had hitherto been impossible to achieve without resorting to a large projector-screen installation, where the large size was necessary to minimize undesirable motion parallax.

The Farrand Optical Company development permits an instantaneous field of view up to 110 degrees or more within a relatively small volume. The system provides the capability of producing accurate and realistic scenes, with the added feature of superimposing additional views. The simulated background scene is projected to infinity and therefore provides visual cues similar to those of the real world. Superimposed images such as rendezvousing vehicle, or close-up views of terrain during landing maneuvers, can be projected with variable focus to simulate object distances from infinity down to about four (4) feet without disturbing the infinity focus or proper parallax with respect to the background.

The image source can be any standard medium such as film, projection CRT, video tape, etc. Since an aerial image is produced at the display end, the resolution and contrast of the display is limited mainly by the quality of the image source, whether it be film, the face of a CRT, a rear projection screen image or a celestial sphere model.

This contractor has designed and fabricated virtual image systems for NASA, the Navy and the Air Force. Table I summarizes the important characteristics of these systems. The accompanying paragraphs describe very briefly each of the systems tabulated except for the breadboard model which is not used as an actual simulator.

Head Operated, 360° Visual Simulator (Figure 3-1)

A wide angle T.V. viewing system for training vehicle operators was developed for the U.S. Naval Training Device Center, Port Washington, New York under Contract N61339-799. The device provides for servoing pick-up camera and display projector to the operator's head

TABLE 3-I
VIRTUAL IMAGE VISUAL SIMULATORS

CONSTRUCTED BY THE FARRAND OPTICAL CO., Inc.

INSTRUMENT	PUPIL	DISTANCE ALONG AXIS PUPIL TO 1st BEAMSPLITTER	FIELD OF VIEW	INPUTS
1. Breadboard Model Infinity Display	4 inch	4 inches	70° vertical - 90° horiz.	Film or T.V.
2. Head Operated, 360° Visual Simulator	4 inch	4 inches	70° vertical - 90° horiz.	T.V.
3. Mercury Simulator	4 1/2" (Field defined by spacecraft window from pupil plane)	12 inches	40° vert. - 62° horiz.	Two. a) Celestial Sphere - 6" Radius b) T.V. - Flat
4. Interim Space Flight-Sim-Type I	8 inch	20.5 inches	50° vertical - 60° horiz.	Three. a) Cel. Sph. 13.5" Radius b) & c) 2 T.V. Inputs on one leg - normal 21" T.V. Tubes
5. Interim Space Flight-Sim-Type II	8 inch	50.5 inches	25° Round	Three. Same as Type I
6. Edwards T27 Spaceflight Simulator	12 inch	10.3 inch (Lens at Pupil)	80° vertical - 110° horiz.	Three. a) Celestial Sphere - 13.5" Radius b) M.E.P. - 13.5" Radius c) T.V. - 16.5" Radius
7. Apollo-Landing Windows	12 inch	13.6 inches	50° vertical - 88° horiz.	Two. a) Celestial Sphere - 13.5" Radius b) M.E.P. - 13.5" Radius

TABLE 3-1 (Continued)
VIRTUAL IMAGE VISUAL SIMULATORS

INSTRUMENT	PUPIL	DISTANCE ALONG AXIS PUPIL TO 1st BEAMSPLITTER	FIELD OF VIEW	INPUTS
8. Apollo Rendezvous and Docking Windows	6 inch vert. 12 inch horiz.	14.9 inches	70° vertical - 100° horiz.	Three. a) Celestial Sphere - 13.5" Radius b) MEP - 13.5" Radius c) T.V. - 16.5" Radius
9. Apollo - Hatch Window	11 inch	12.2 inches	78° vertical - 80° horiz.	Two. a) Celestial Sphere - 13.5" Radius b) M.E.P. - 13.5" Radius
10. Aids - Gemini Windows	8 inch (Field defined by spacecraft window from pupil plane)	23.5 inch	60° vertical - 90° horiz.	Three. a) Celestial Sphere - 13.5" Radius b & c) 2 T.V. inputs on one leg - normal 21" T.V. Tubes
11. LEM - Front Windows	12 inch (Field defined by spacecraft window from pupil plane)	10.2 inches to compressor lens	80° vertical - 110° horiz.	Two. a) Celestial Sphere - 13.5" Radius b) T.V. - 13.5" Radius
12. LEM - Overhead Window	8 inch (Field defined by spacecraft window from pupil plane)	19.5 inches	65° vertical - 40° horiz.	Two. a) Celestial Sphere - 13.5" Radius b) T.V. - 13.5" Radius

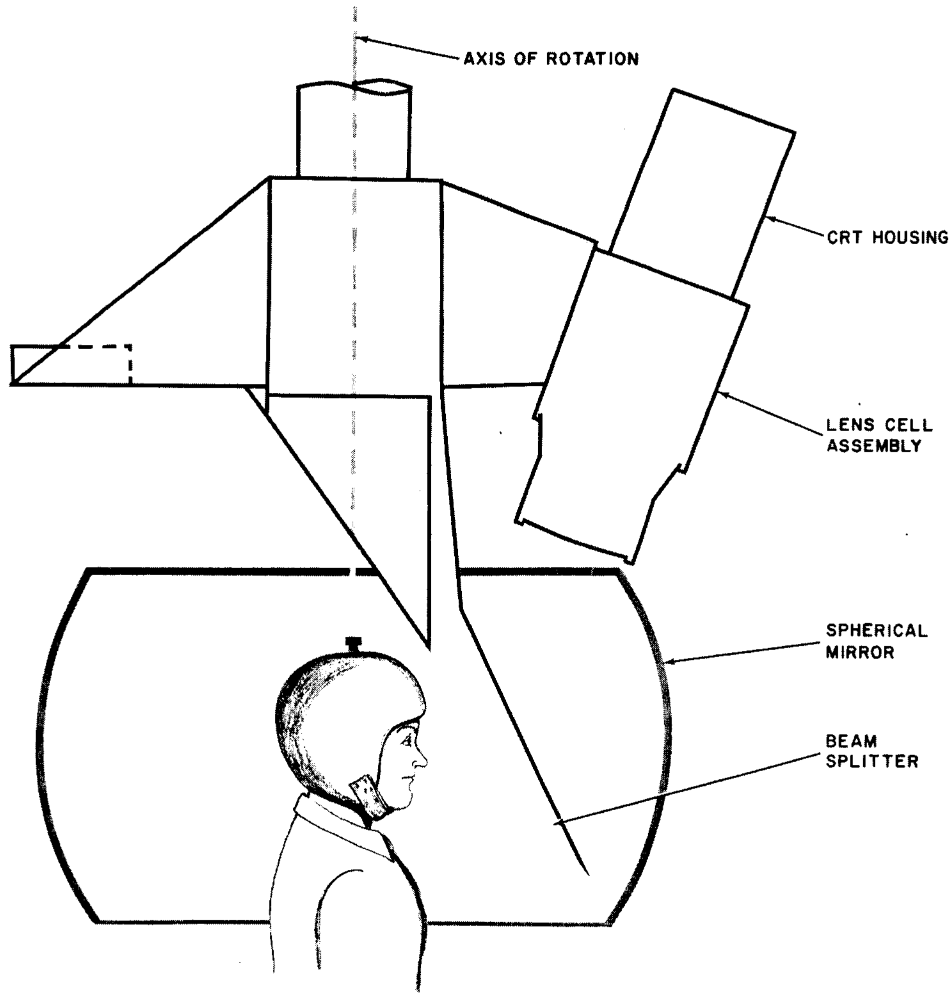


FIGURE 3-1 HEAD OPERATED 360° VIRTUAL IMAGE DISPLAY

movements so that while the instantaneous field of view is 90 degrees in the horizontal direction, the operator may view a full 360 degrees by pivoting about his seat. The optical axis of the pick-up camera at all times coincides with the observer's viewing direction. The terrain model and optical probe can be located at any convenient distance from the display unit.

Spaceflight Simulator for Mercury Capsule (Figures 3-2A & B)

The first true infinity display system for aerospace training was produced by the Farrand Optical Company for the National Aeronautics and Space Administration, Langley Field, Virginia, under Contract No. NAS 9-250. It was delivered in January 1963.

The equipment is an earth orbital flight simulator for the Mercury Capsule which mounts to the window of the training capsule. The system provides the astronaut with a most realistic window view of the stellar field as it would appear in an actual mission. The unit can simulate continuous rotation in roll, pitch and yaw and provides for occultation of the star field by the earth's disc from any direction from a 100 mile orbital altitude. The star images are generated by a 12 inch diameter celestial sphere on which the constellations and stars down to 5th mag-

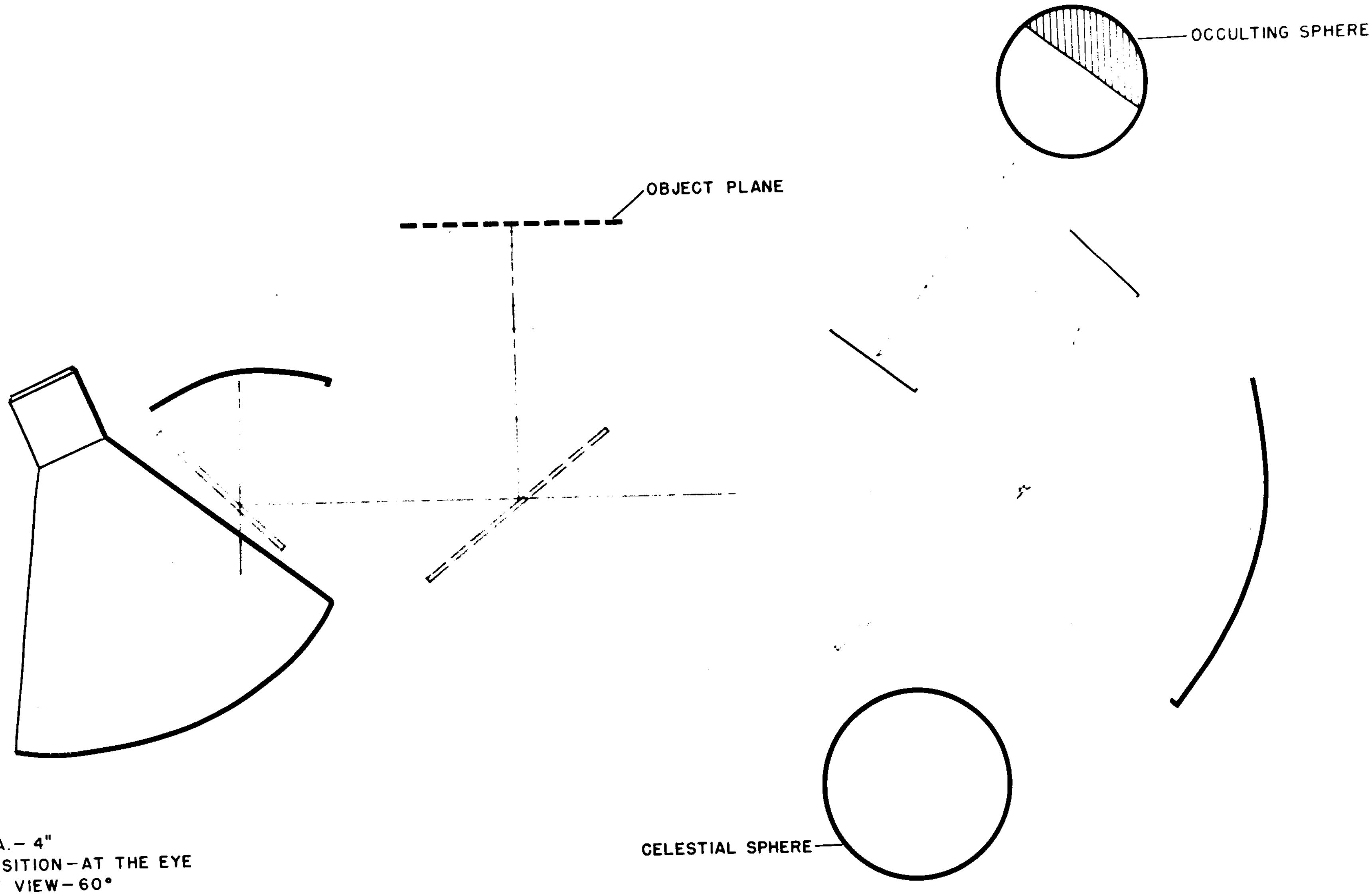


FIG. 3-2 MERCURY SIMULATOR SCHEMATIC

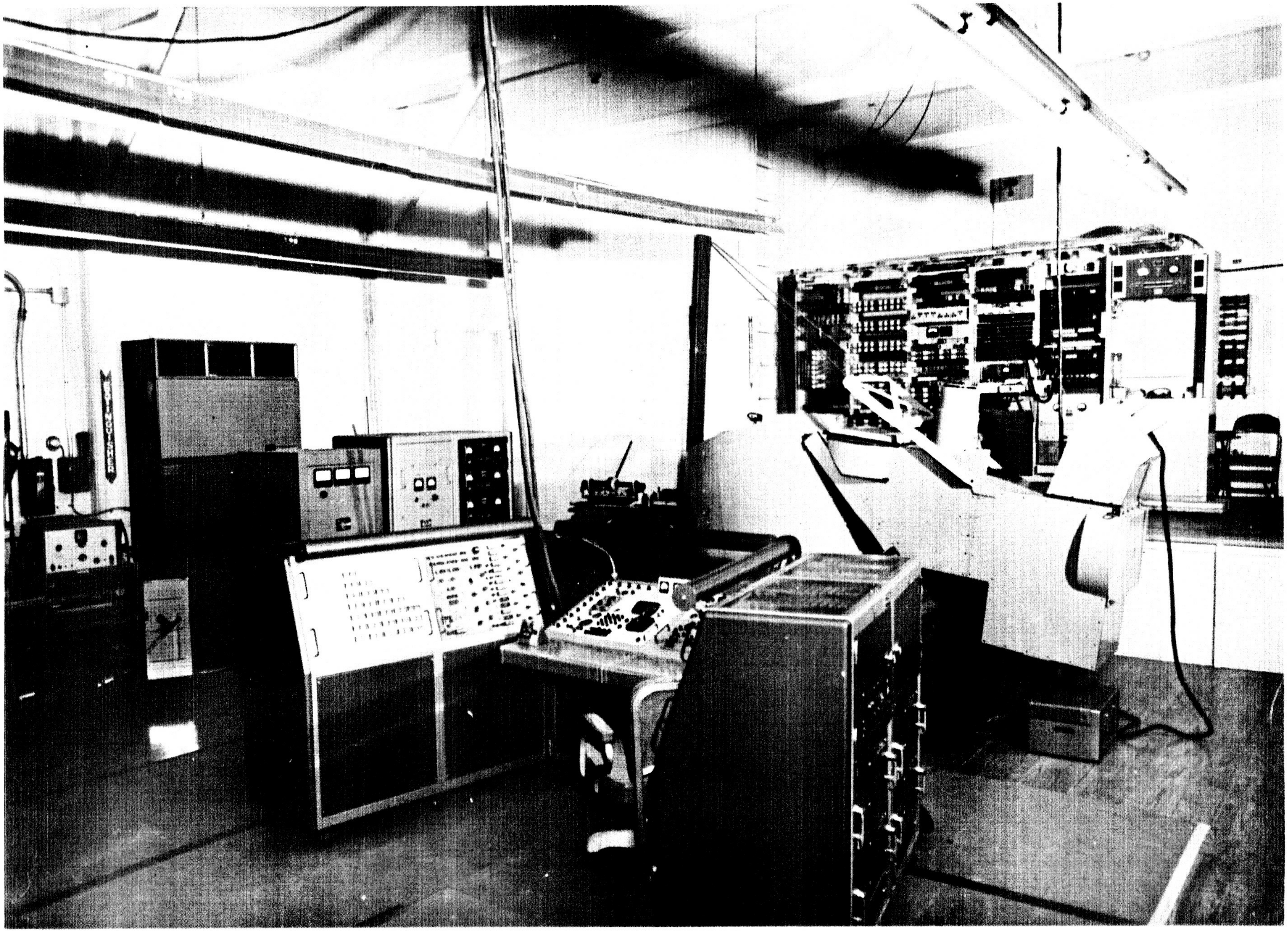


FIGURE 3-2B MERCURY SPACEFLIGHT SIMULATOR nitude are located with sufficient accuracy to permit celestial navigation practice. A second input provides the capability for superimposing an additional image (such as a space station or vehicle, or the Earth's view below) on the star scene. Figure 3-2B shows the display installed on the Mercury capsule.

Since the end of the Mercury Program the display has been converted by M.S.C. Houston for use as a part task Gemini Simulator, utilizing a computer generated T.V. image of an Agena Vehicle, built by Bell Aerosystems, plus the star field for astronaut training.

Interim Spaceflight Simulator (Figures 3-3A & B)

The purpose of this simulator is for research rather than actual astronaut training. It was developed and built by the Farrand Optical Company for M.S.C. Houston under a subcontract for Prime Contract No. NAS 9-1375 performed by the General Electric Company.

It consists of three window displays (two - Type I and one - Type II listed as Items 5 and 6 in Table 3-1).

Each window is designed to operate with three inputs:

1. Celestial Sphere
2. 21" color T.V. CRT
3. 21" black and white T.V. CRT

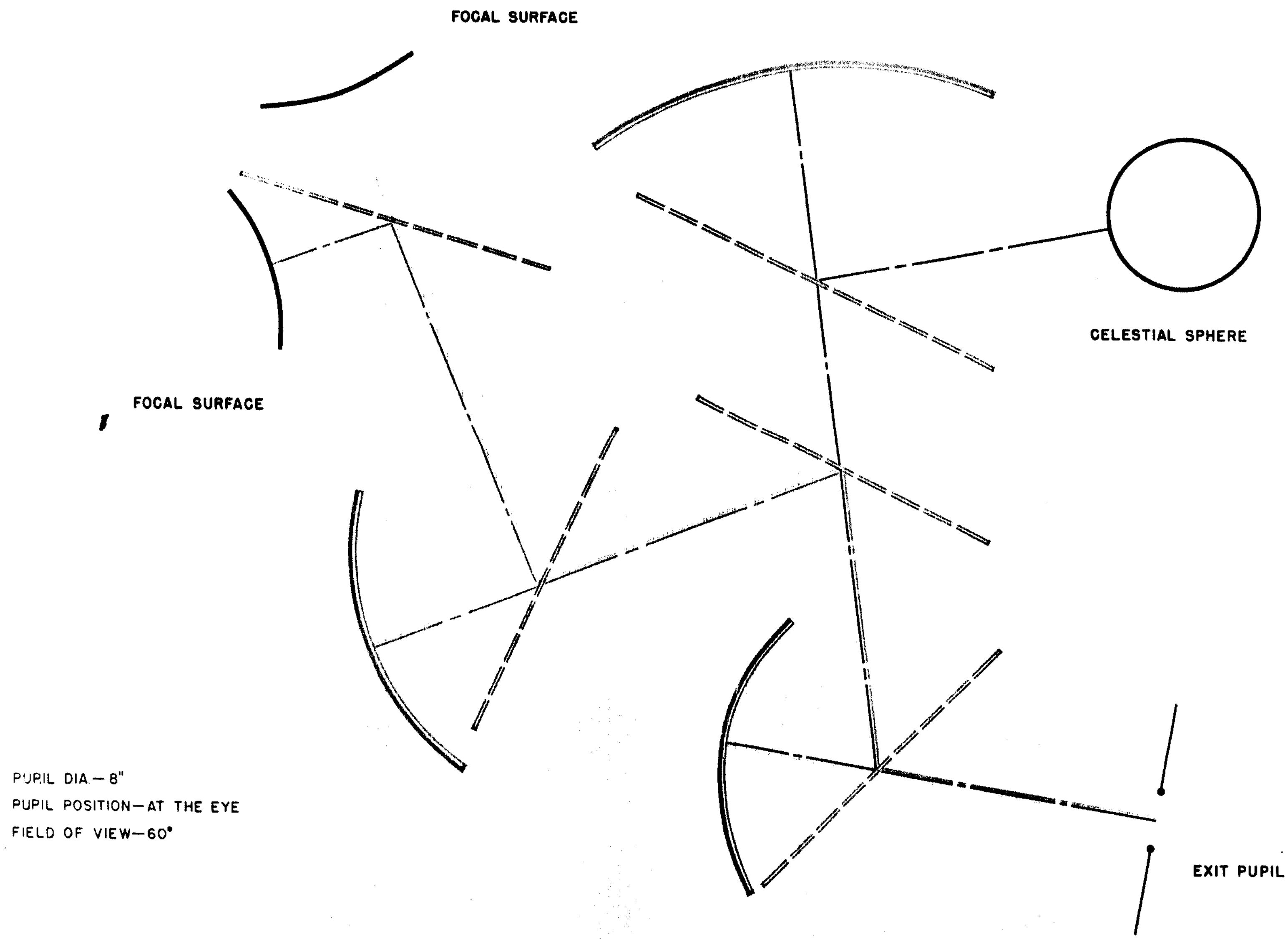


FIGURE 3-3A INTERIM SPACEFLIGHT SIMULATOR

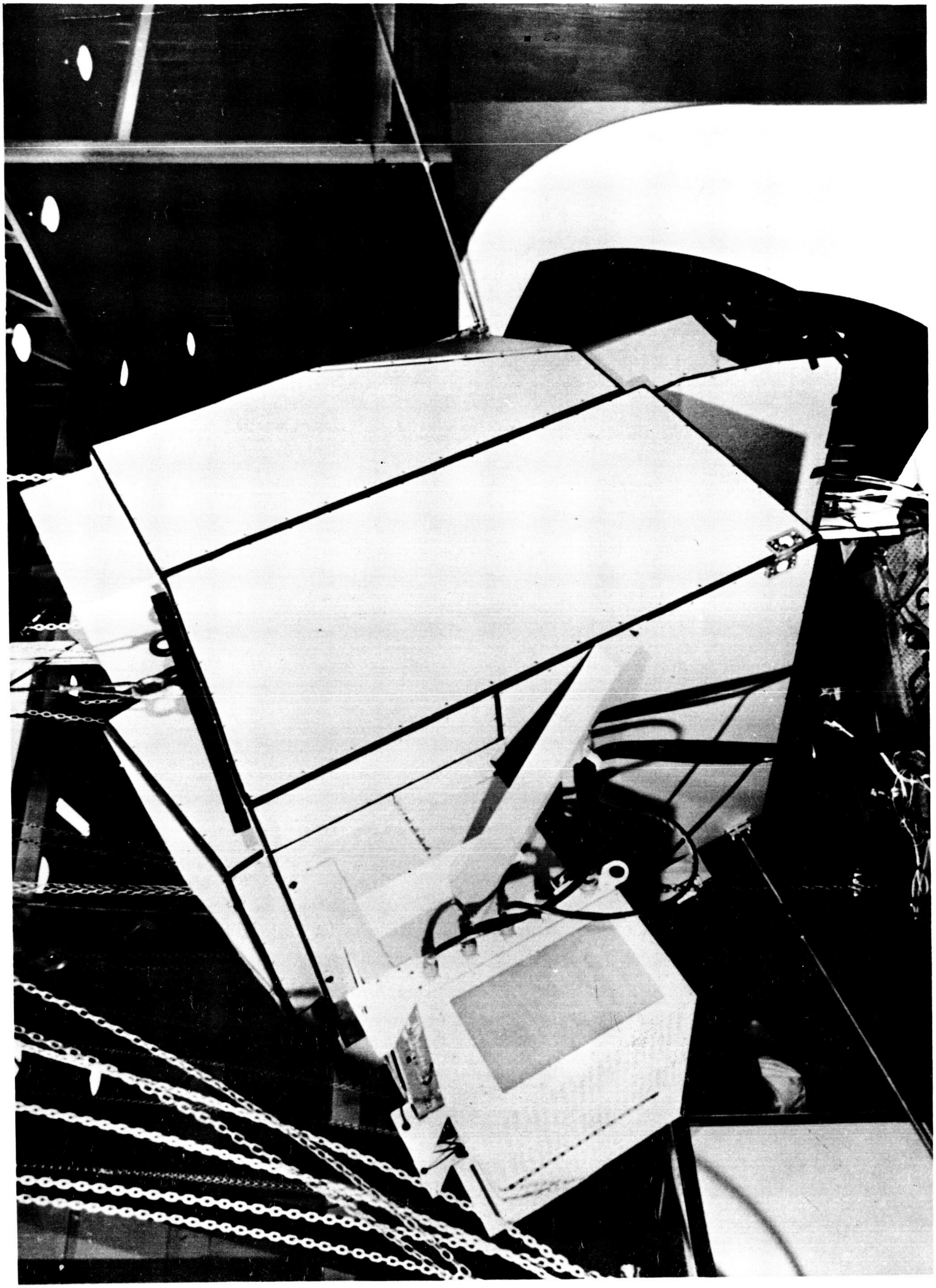


FIGURE 3-3B INTERIM SPACEFLIGHT SIMULATOR

The star input is the now standard 27 inch diameter Celestial Sphere.

The color T.V. input is the General Electric Contact Analogue Display.

The black and white T.V. input is a track and model Rendezvous and Docking System.

The system utilzing the Celestial Sphere and the color T.V. display has been in operation at M.S.C. Houston since 1964.

The Rendezvous and Docking system is being installed early in 1966. A picture of the system is shown in Figure 3-3B.

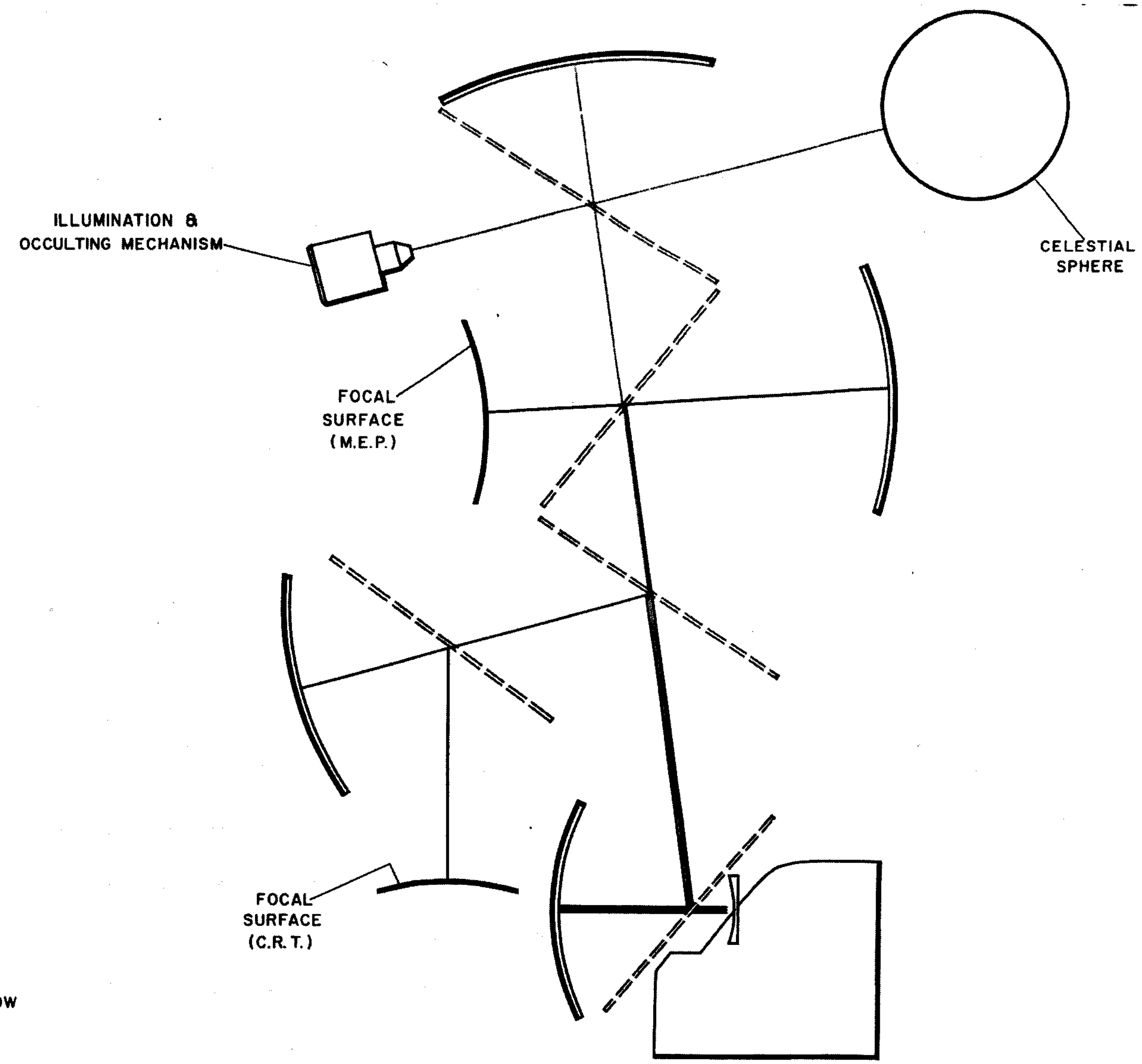
Edwards T-27 Spaceflight Simulator (Figures 3-4A & B)

A general purpose display for Air Force space vehicle training and studies has been developed and built by the Farrand Optical Company on a subcontract for Prime Contract No. AF 33(657)10317 performed by Link Division of General Precision Inc.

The system with a 12 inch diameter exit pupil has the largest field (80° x 110°) of all windows presently in operation.

It has three separate inputs:

1. Celestial Sphere
2. 16.5" radius T.V. for Rendezvous and Docking Simulation
3. 13.5" radius screen for input of earth orbital scenes using the strip film Mission Effects Projector (M.E.P.)



PUPIL DIA.—12"
PUPIL POSITION—AT THE WINDOW
FIELD OF VIEW—110° H x 80° V

FIGURE 3-4A EDWARDS T-27 SPACEFLIGHT SIMULATOR SCHEMATIC

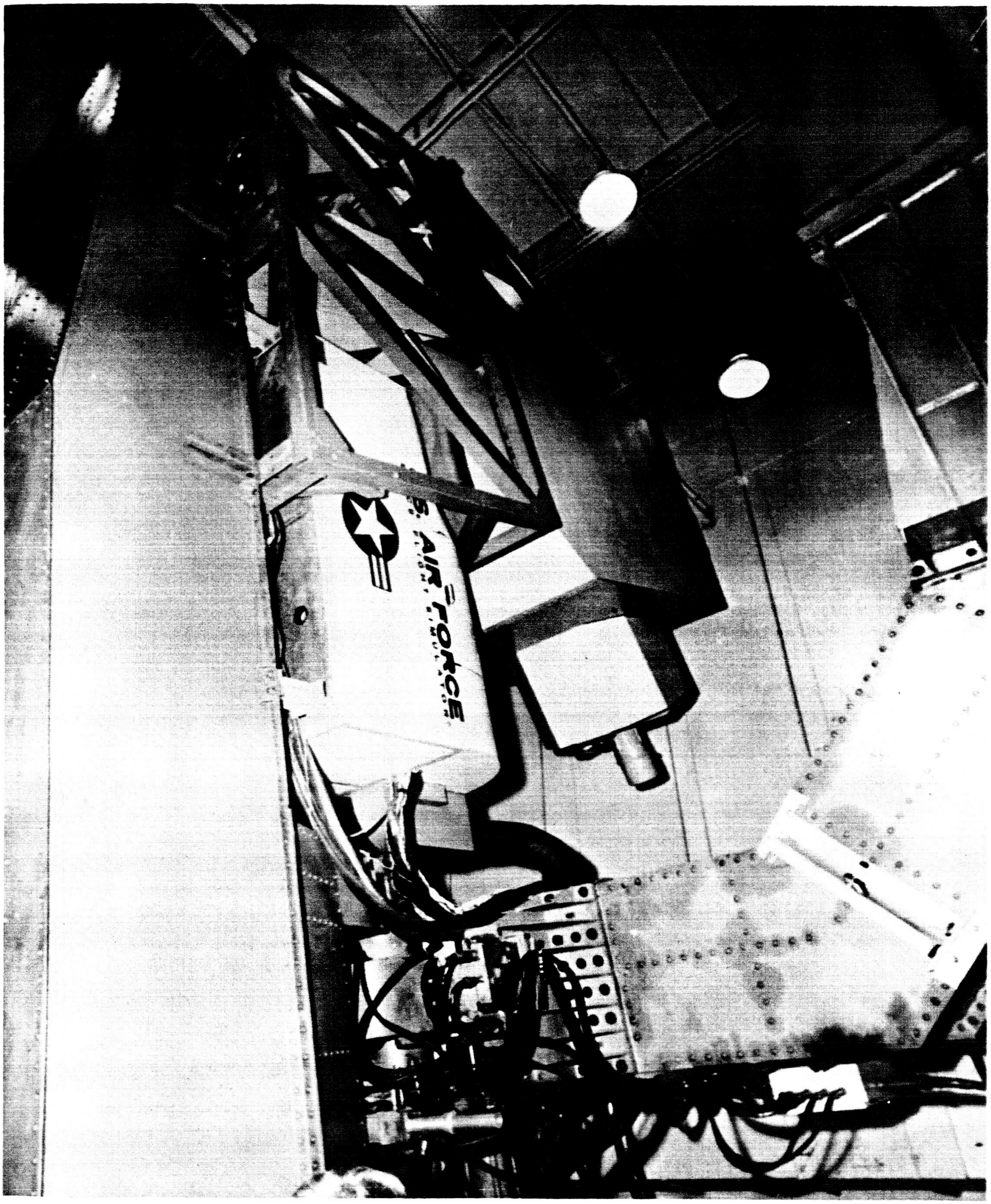


FIGURE 3-4B EDWARDS T-27 SPACEFLIGHT SIMULATOR

The celestial sphere system has a variable altitude earth's disc occulting system.

The whole system plus a capsule is mounted on a 3-axis motion system that permits change of altitude from vertical upward (launch) to horizontal (orbital) to vertical downward (re-entry). Additional motions of pitch, roll and yaw can be provided singly or in combination with maximum excursions of $\pm 15^{\circ}$.

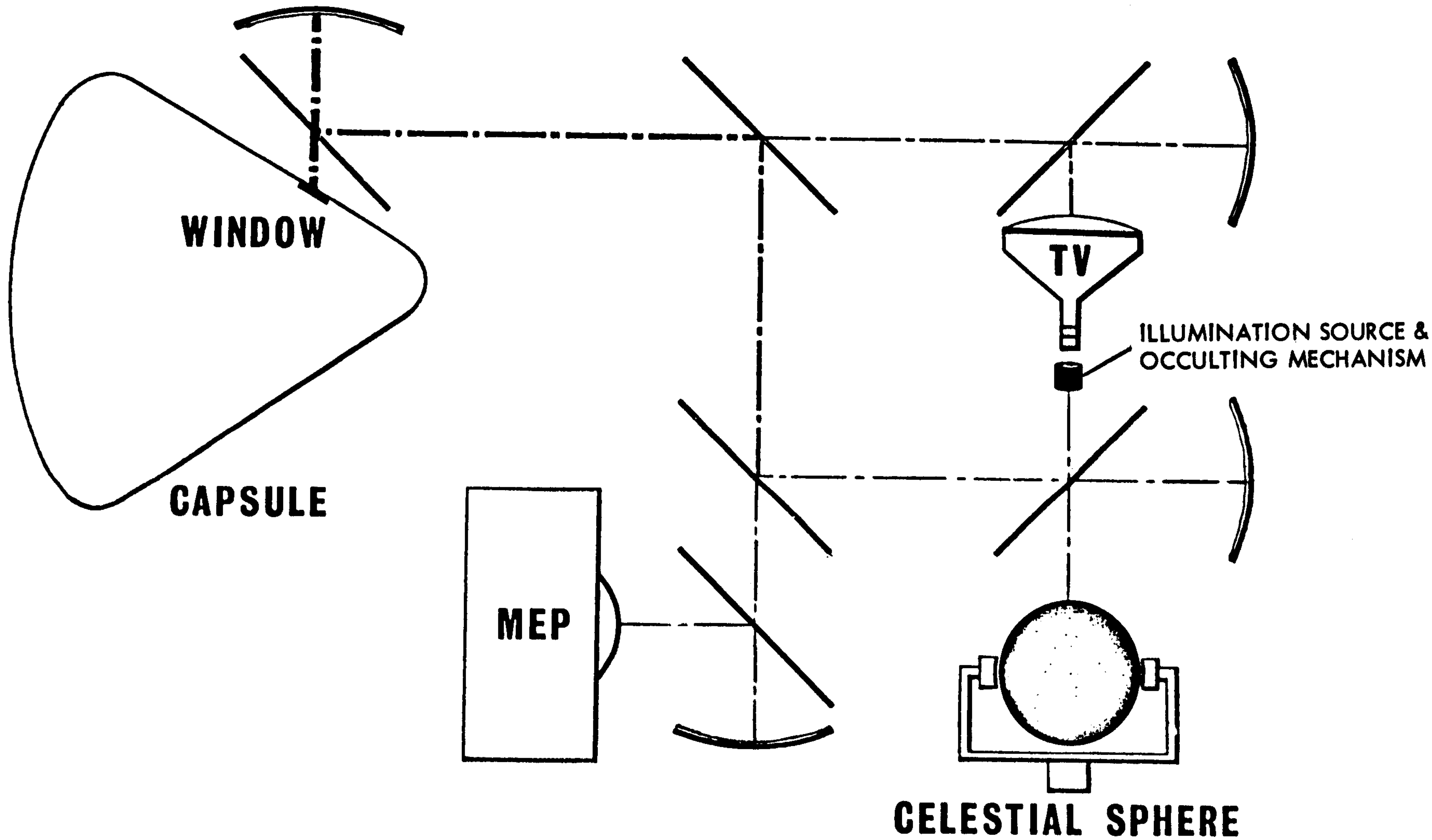
Gravity effects of up to 2g are also applied to the astronaut.

The system utilizing the Celestial Sphere and Rendezvous and Docking inputs has been in operation at Edwards Air Force Base since February 1965.

The Mission Effects Projector will be in operation in the middle of 1966. A picture of the system is shown in figure 3-4B.

Apollo Mission Simulator Visual Display System (Figure 3-5A & B)

Under a major subcontract from Link Division of General Precision Inc., The Farrand Optical Company has developed a display system providing synchronized displays through four (4) vehicle windows. These are the two Rendezvous and Docking windows and the two Landing windows of the Apollo capsule. Originally the fifth window of the capsule, namely the hatch window, also had a window display but this was eliminated to permit



APOLLO SIMULATOR, R & D WINDOW

FIGURE 3-5A APOLLO SPACEFLIGHT SIMULATOR (R & D WINDOW)

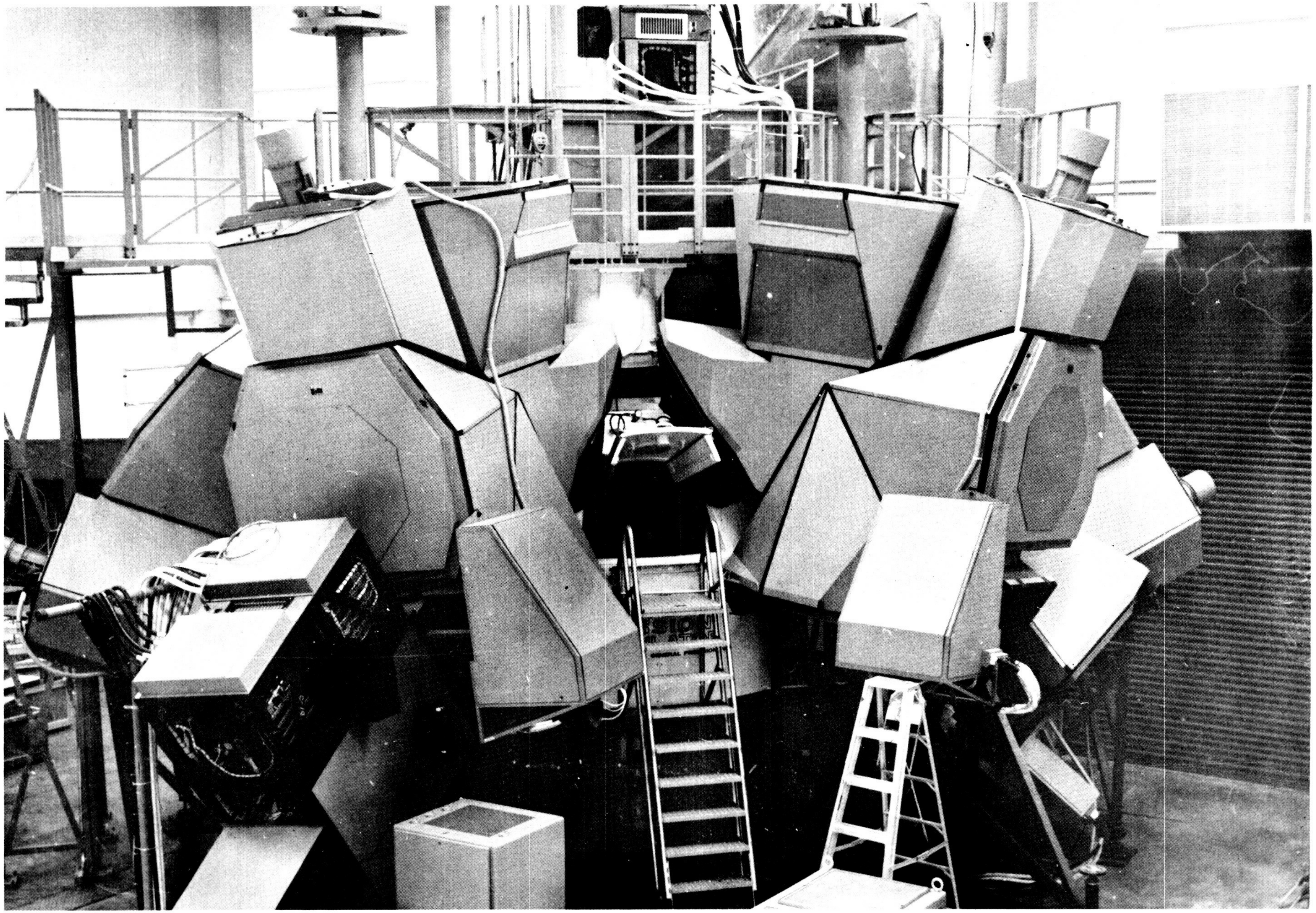


FIGURE 3-5B APOLLO SPACEFLIGHT SIMULATOR the use of the hatch for entrance to and exit from the capsule.

The Rendezvous and Docking windows each have three inputs:

1. Celestial Sphere

2. 16.5" radius T.V. for Rendezvous and Docking

3. 13.5" radius screen for the Mission Effects Projector

Occultation of the Celestial Sphere by the earth's disc with variable altitude and by the LEM vehicle with variable range are provided by separate occultation systems.

The T.V. tube is servoed to provide a correct parallax inside focus scene of the LEM during docking.

The Landing Window provides only the Clestial Sphere and the Mission Effects Projector inputs with variable altitude occulting for the earth's disc.

In addition, a sextant and telescope simulator built by Librascope Division of General Precision Inc. is provided. The telescope simulator utilizes the Farrand Celestial Sphere and Mission Effects Projector for inputs.

One Apollo Mission Simulator will be installed at Cape Kennedy and one at M.S.C. Houston. Both simulator complexes will be the same.

A view of the partially completed simulator at M.S.C. is shown in Figure 3-5B.

Advanced Infinity Display Systems (AIDS) (Figures 3-6A & B)

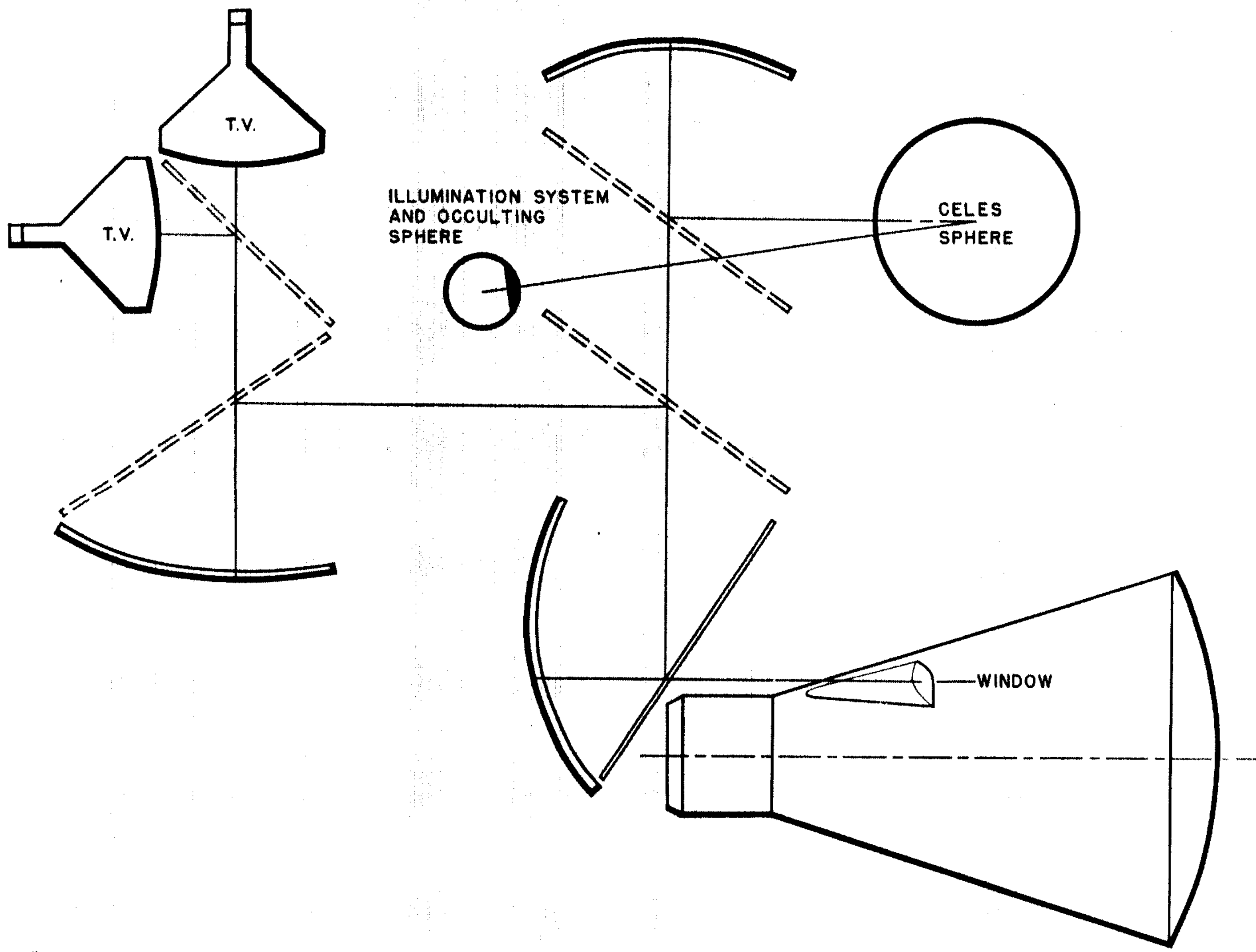
Two advanced visual simulators, suitable for training and studies for vehicles such as Gemini, have been developed and delivered to NASA by the Farrand Optical Company on Contract No. NAS 9-2034. The systems, now called Gemini Mission Simulators are now in operation at Cape Kennedy and M.S.C. Houston and have been in operation since October 1965.

Utilizing a pair of the same basic type of wide angle viewing systems as the previously described simulators, the system provides a 27" diameter Celestial Sphere with fixed altitude occultation and two T.V. inputs.

At the Cape Kennedy complex these two T.V. inputs are used with two different color phosphor T.V. tubes on which are displayed scenes of Earth orbital views generated from flying spot scanning of film. This input system built by Bell Aerosystems is known as GEOS (Generated Earth Orbital Scenes). In addition, a computer generated view of the Agena vehicle is utilized for Rendezvous and Docking simulation.

At Houston the Rendezvous and Docking simulation is provided by a track and model system and the orbital scene is generated by a probe and 6 foot diameter earth globe.

In both complexes the Rendezvous T.V. tube is in a focusing mount



PUPIL DIA.-8"
PUPIL POSITION-AT THE EYE
FIELD OF VIEW-88°×50°

FIGURE 3-6A GEMINI SPACEFLIGHT SIMULATOR (ONE WINDOW)

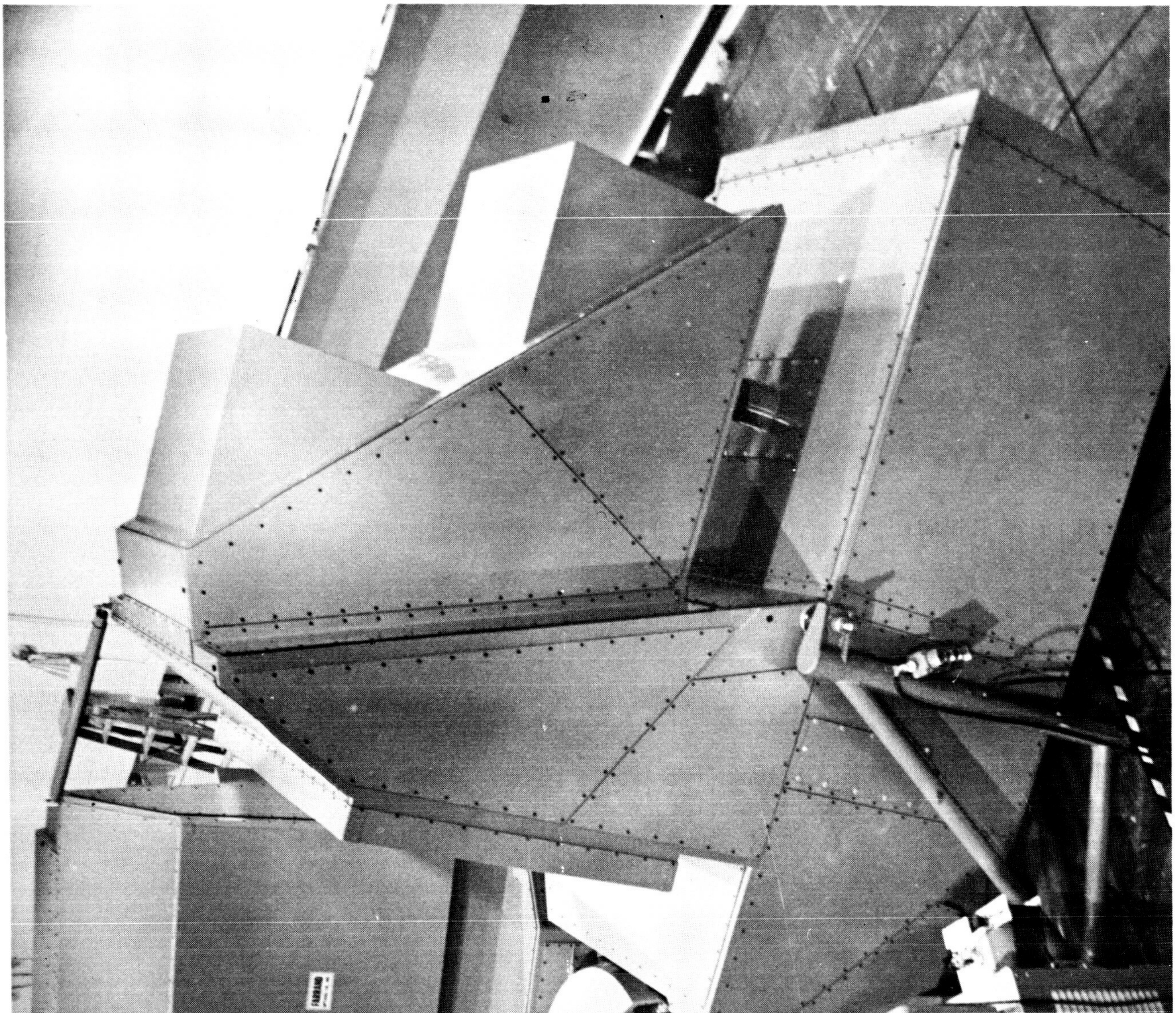


FIGURE 3-6B GEMINI SPACEFLIGHT SIMULATOR so that parallax and focus are exactly duplicated for the rendezvous vehicle against the stellar background during docking.

A photograph of the Gemini Mission Simulator at Cape Kennedy is shown in Figure 3-6B.

<u>LEM External Visual Display Equipment</u> (Figures 3-7A & B)

Under a subcontract from Grumman Aircraft Corporation (NASA Prime Contract No. NAS 9-1100) the Farrand Optical Company has developed the visual display systems for the LEM Mission Simulators.

Each system consists of four window display systems, namely:

1. Left Front Window
2. Right Front Window
3. Overhead Window
4. Telescope Display

Each display system has two inputs.

1. Twenty-seven inch diameter Celestial Sphere for the left, right and overhead window. Twelve-inch diameter super-accurate Celestial Sphere for the telescope.

2. Thirteen and one-half inch radius CRT for the left, right and overhead windows. Six inch diameter flat CRT for the telescope input. The window CRT's are focussable for simulation of docking

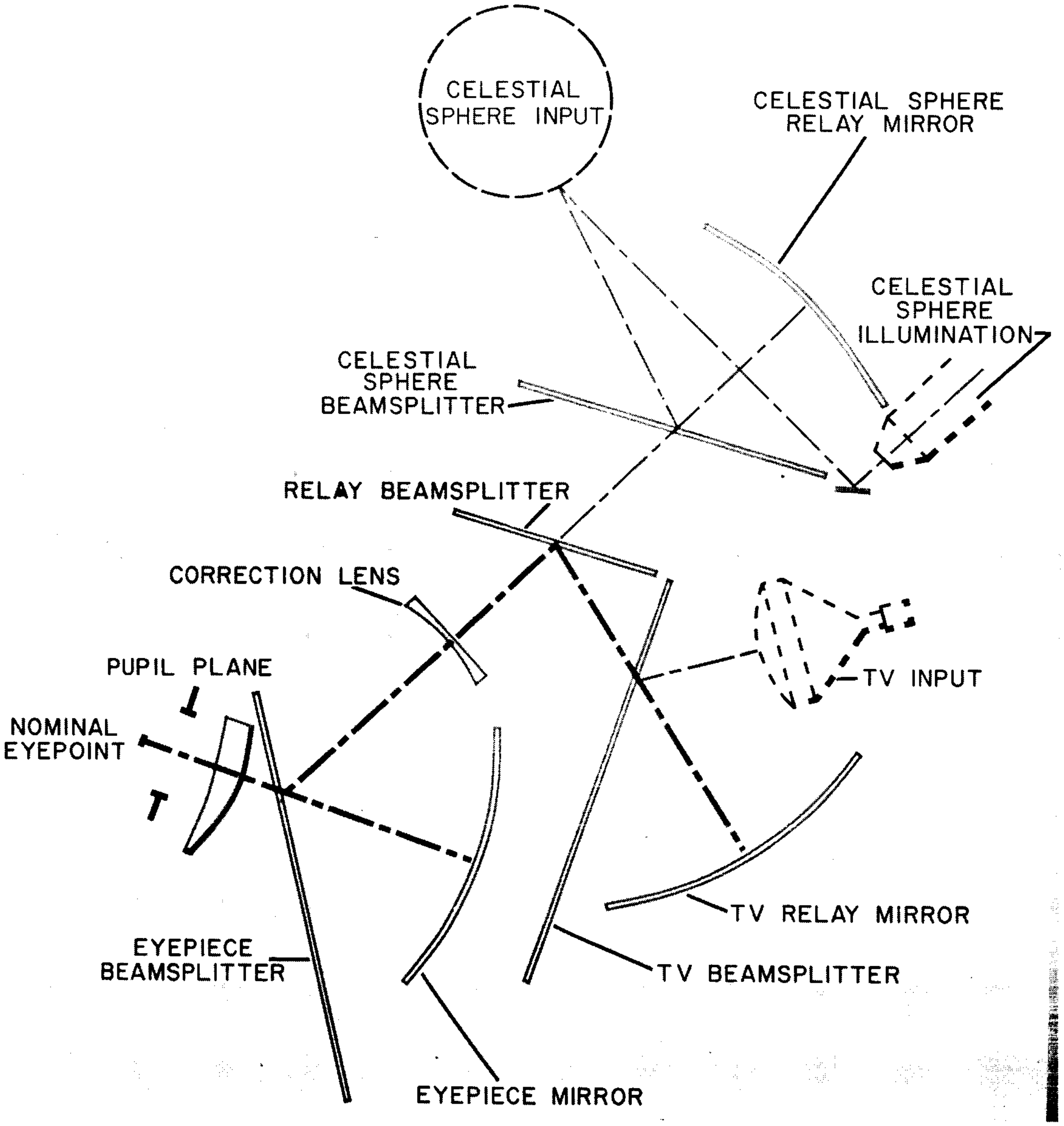


FIGURE 3-7A LEM SPACEFLIGHT SIMULATOR (ONE WINDOW)

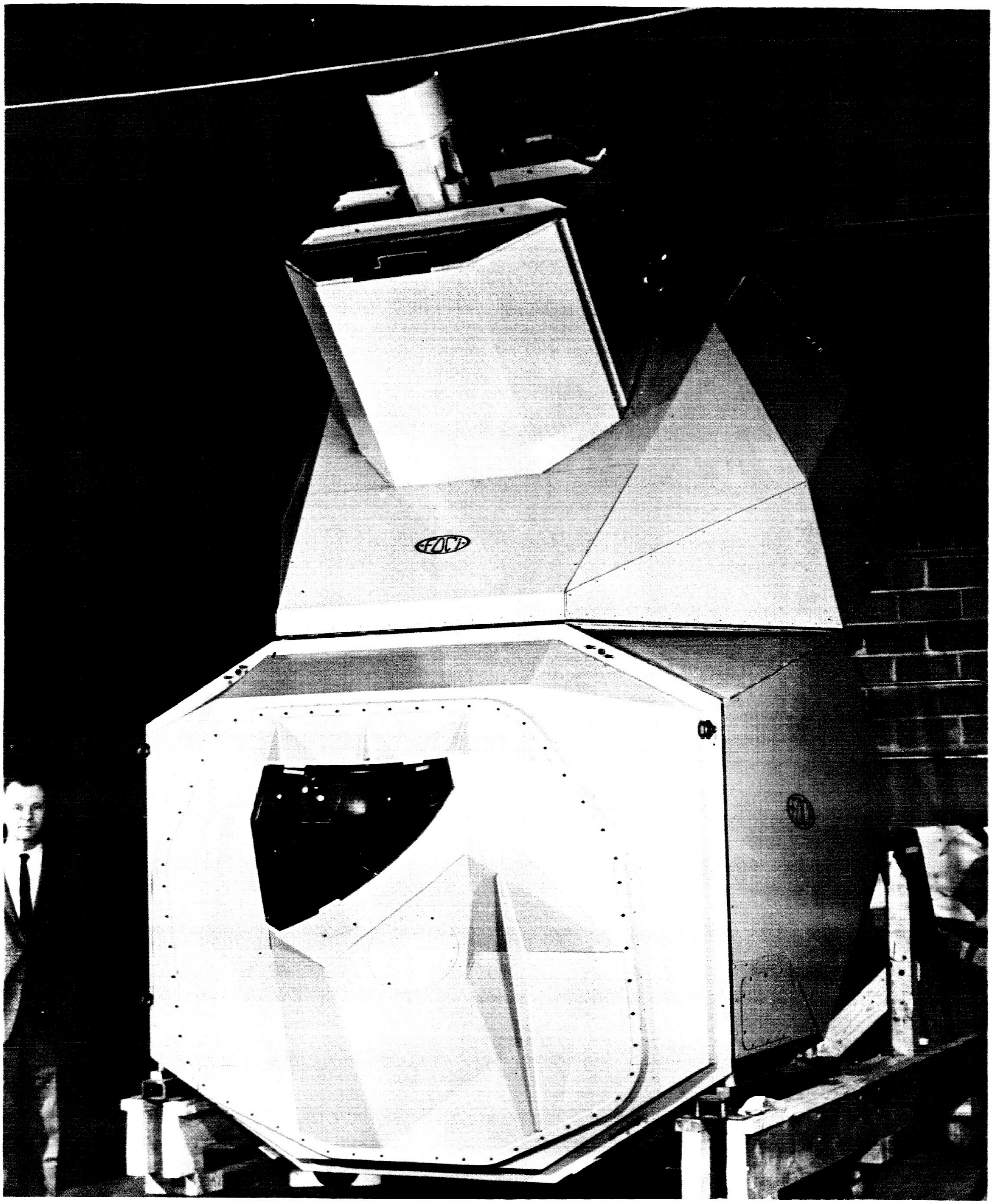


FIGURE 3-7B LEM SPACEFLIGHT SIMULATOR

with the Apollo Command Service Module.

Rendezvous and Docking images are generated by a track and model dual probe system.

Moon orbital and ascent and descent down to 1500 ft. are generated by a modified Mission Effects Projector system which provides altitude change from 350 feet to 190 nautical miles. The output of this strip film projector which is displayed on a flat screen is scanned by a fixed altitude probe that provides capsule orientation information.

Final descent to landing on the Moon is provided by a probe and lunar terrain model.

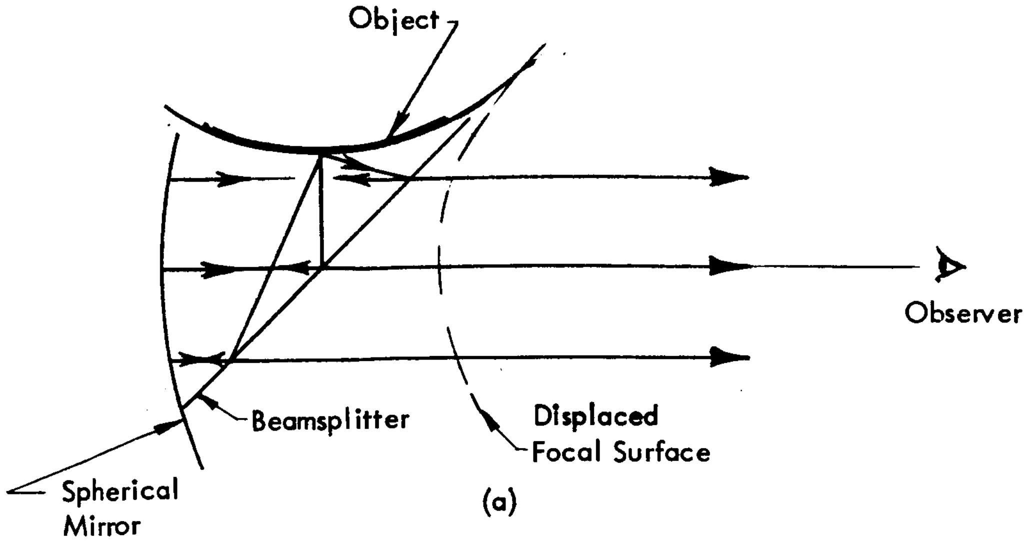
A photographic of a Right Front Window is shown in Figure 3-7B.

b. Austin Torpedo and Rocket Attack Trainer, Device 14B3 (Figure 3-8)

This device was invented by J.P. Laird, Jr. of the U.S. Naval Training Device Center in 1945, and built by the Austin Company as Device 14B3. It was designed to train pilots of fighter aircraft and to teach procedures for launching of airborne torpedoes and rockets.

The basic concepts for the system are discussed in Laird's patent (31). This patent describes an apparatus, optical system, and method for projecting an optical image that creates for the observer an illusion that the object being viewed is at or near infinity. In one form of the apparatus that is described, the optical system consists of a concave spherical mirror and a beamsplitter located between the mirror and its focal surface. The object, a portion of a spherical surface, is made to coincide with the displaced focal surface. Thus the object surface appears at infinity to an observer located in front of the spherical mirror, as shown in Figure 3-8 .

The author postulates a use for his invention as a visual training device. The object is shown as being a hemisphere located in a convenient arrangement in a trainer cockpit (Figure 3-8). The pilot sees the hemisphere as a virtual image at infinity through the windshield. An alternate form of object is provided with a three-dimensional surface, similar to a relief map.



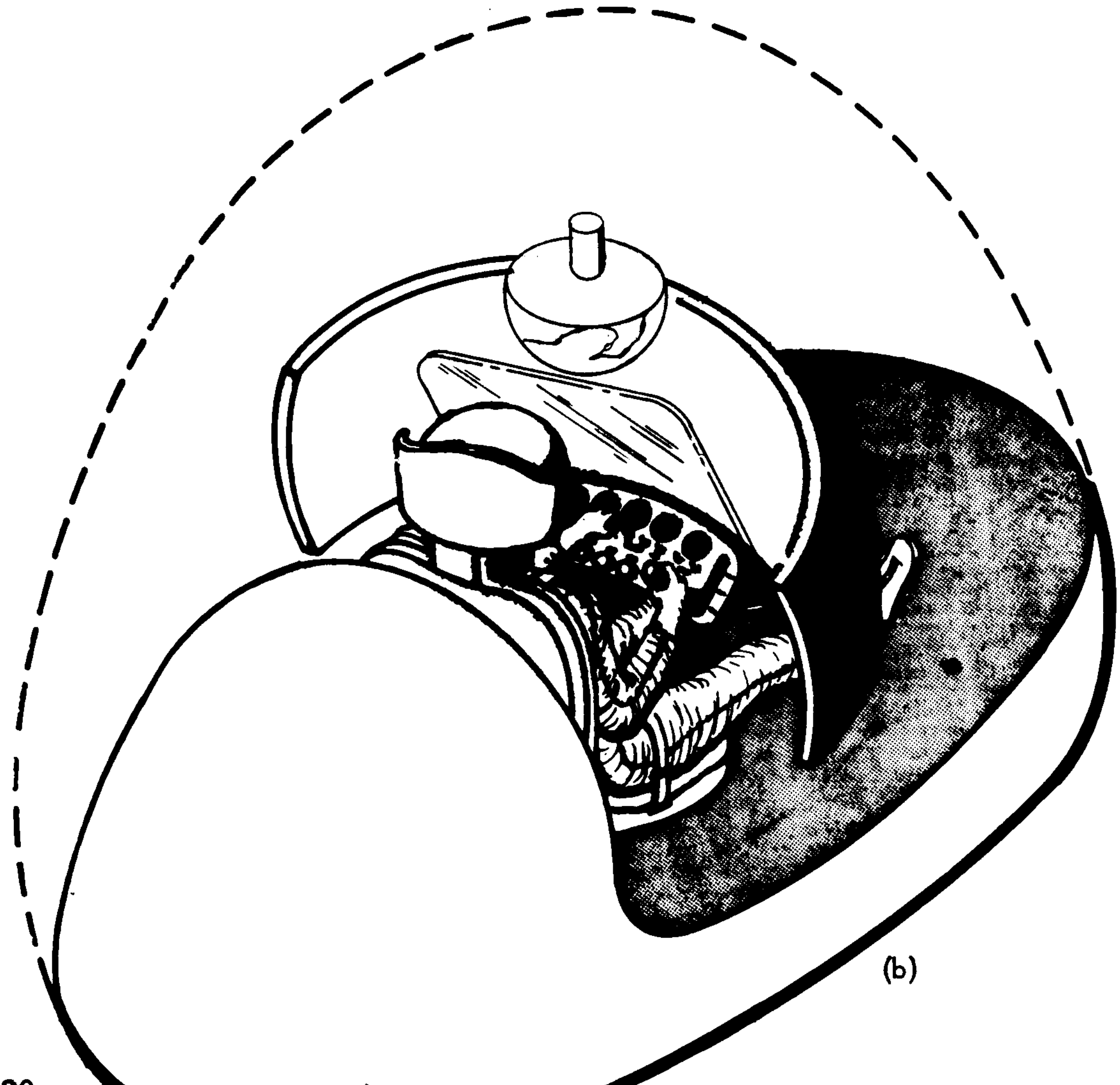


FIGURE 3-8 INFINITY PROJECTION CONCEPT (a) AND SYSTEM (b)

Portions of the image appearing at infinity appear to be flat or two-dimensional, while portions of the image appearing in relatively close proximity appear to have depth or to be three-dimensional. When the observer's eyes are moved from the normal point of observation, at the center of curvature of the mirror, there is no appreciable distortion of the image. There is proper apparent relative movement between near and distant object points in any part of the image that is three-dimensional.

Since the object sphere can be rotated relative to the other features of the simulator cockpit, it is possible to present to the observer an image of a changing panorama. This changing scene could consist of sky, clouds, land, and bodies of water that would be observed under actual flight conditions.

The Torpedo and Rocket Attack Trainer is described by Molnar and Lybrand (1). The device utilizes the operational flight trainer Device 2F2. It gives the optical illusion of a seascape and a floating target as viewed through the front of the aircraft cockpit.

The system is illustrated in Figure 3-9. A target is arranged in line with a 10:1 ratio variable magnification lens system, in front of, and above the line of sight of a trainee in an aircraft cockpit. The image of the target, varying in size between the simulated ranges of 1200 to 12,000 feet, is formed

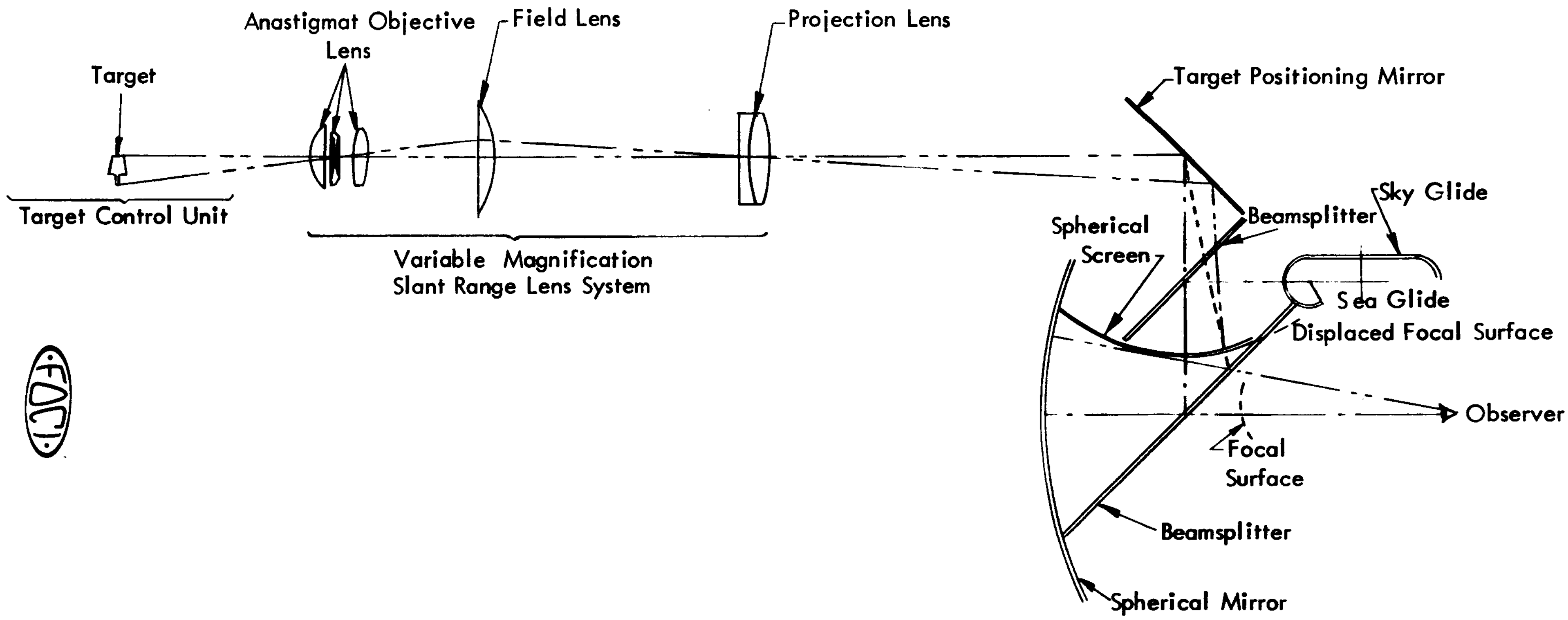


FIGURE 3-9 TORPEDO AND ROCKET ATTACK TRAINER, DEVICE 14B3

on a spherical screen. The screen coincides with the focal surface of a 36-inch radius stellite spherical mirror. The focal surface of the mirror is folded out of the observer's line of sight by means of a beamsplitter. A sea-and-skyscape scene, introduced into the optical system from a servo unit containing a point light source and transparencies, is superimposed on the target image on the spherical screen. The overall, out-the-window scene appears to the trainee to be at a great distance.

The seascape and target move in relative motion as they would under actual flight conditions. The motion of the target is controlled by a relative motion computer which gains its information from a flight computer which in turn responds to dynamic signals from the simulator cockpit. The motion of the servo unit associated with the sea-and-skyscape presentation is coordinated with that of the target unit by the same computer.

c. Carrier Landing Flight Simulator (Figure 3-10)

The Carrier Landing Flight Simulator was built by the Oxford Corporation, Buffalo, New York and delivered to Naval Air Test Center, (NATC), Patuxent River, Maryland, in 1961. It is a full color, wide field of view simulator of the external scene viewed by a pilot in making a carrier approach. Programmed and non-programmed simulated landings are used in the evaluations of various landing marking patterns and visual aids placed on the carrier deck.

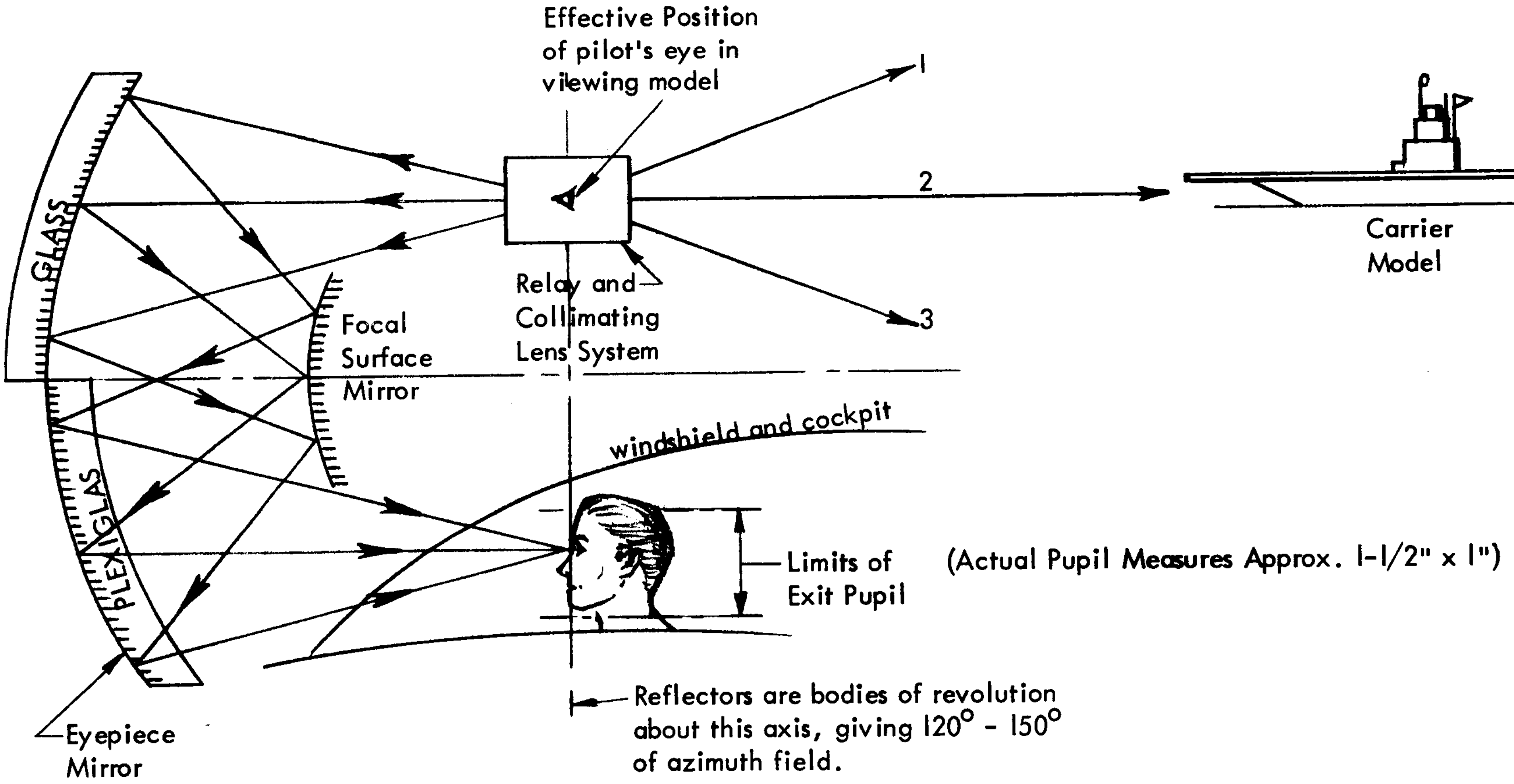


FIGURE 3-10 OPTICAL SYSTEM, OXFORD CARRIER LANDING FLIGHT SIMULATOR

The entire system employs a direct optical viewing technique.

The device at NATC is a slightly modified version of the simulator described in Oxford Report No. 6102 of August 1961 (9). The simulator consists of an A-4D aircraft cockpit, windshield and instrument panel, an infinity display optical system, day or night aircraft carrier models with associated illumination, drive mechanisms and electronics.

The optical system is illustrated in Figure 3-10. A subject in the cockpit looks into the lower off-aperture section of a hemispheric rear-coated Plexiglass "eyepiece" mirror. A smaller, convex reflector is aligned to coincide with the focal surface of the eyepiece mirror. Part of this focal surface mirror is painted blue to simulate the ocean and horizon. A 14-inch diameter, front coated glass mirror is mounted above the eyepiece mirror and is intended to form a continuation of the eyepiece mirror surface. (The glass mirror replaced the upper half of the original one-piece Plexiglass eyepiece mirror.) Basically, then, these mirrors act as one large mirror with a reflecting focal surface.

The entrance and exit pupils of the system lie at equal distances above and below, respectively, the center of curvature of the mirror system. Thus, the pilot's eye can, in effect, be transferred to another point in space about 2 feet above his head. A relay and collimating lens system at this upper point then sees the aircraft carrier model directly. The lens consists of a package of about 6-inch diameter and a foot long. It is linked to the position of the model so it can be continually refocused to keep the carrier model collimated over the 7-foot movement along its track.

The carrier models are scaled 1 inch to 50 feet, travel on a 7-foot bed, and are illuminated by four white, 6-foot-long, tubular fluorescent lamps. Illumination for the night model landing lights comes from the interior of the model.

The upper, glass surface of the large concave mirror re-images the carrier model on the reflective face of the convex mirror which is located at the prime focal surface of the former mirror. In turn, the lower, Plexiglass mirror re-collimates the carrier model image. This results in virtual images for the pilot which are located at infinity behind the lower portion of the large mirror surface.

The system was inspected by the Farrand research team at NATC. A three power diopter scope was used to measure the collimation of the carrier image at three positions. The results were:

Carrier Position	Image Distance	Approximate Pupil Size
Farthest position on track	-0.3 diopters	1.5" horiz. , 1" vertical
Center position on track	-0.5 diopters	1.5" horiz., 1" vertical
Nearest position on track	-1.4 diopters	1.0" horiz., 0.3" vertical

The pupil aberrations were apparently great enough to result in 3-inch horizontal and 1-inch vertical pupil motion with head motion. This had the effect of allowing both eyes to be used in viewing the model at the closer ranges. The three-dimensional effect, good resolution and unobtrusive color errors contributed to a realistic effect. Since the background was a solid blue, no real bleeding through of images was observed, although the carrier did appear misty or "ghostly". Roughness of the Plexiglass mirror surface was evident as spots in the field of view but this was not distracting.

The severe swimming of the pupil and its small size made finding and holding the carrier image very difficult. A head rest and electric control for pilot seat movement were provided and were necessary. Even slight head movements caused a loss of the image or an annoying amount of "swimming", which made the carrier appear to turn to the right or left. (Possibly the pupil stop was made small in order to minimize the image swimming.) The horizon image measured +0.2 diopters and was also affected by swimming.

Except for the wide horizon in the horizontal field (approximately 120°-150°), the field from the upper pupil was limited to the carrier and the area dead ahead with a maximum diameter of about 25°.

The operating personnel at NATC are well aware of the system's limitations, however, the equipment is only used for landing marking evaluations and is servicable for this purpose. There are no plans to build additional units.

d. <u>VueMarq Virtual Image System</u> (Figures 3-11, 3-12)

The VueMarq system developed by the Marquardt Corporation, Pomona Division, is based on a concept for gathering information from a spherical volume of approximately 3π steradians and forming it into a flat image surface for detection or recording. The flat image format can be reconstructed into a virtual image, out-the-window display of the original scene. Closed circuit television and optical display projection techniques are used throughout.

The VueMarq principle is illustrated in Figure 3-11. In its simplest form, the principle embodies the use of two mirrors that have conic sections of revolution with reciprocal eccentricities. The mirrors share a common focus and a common axis, and have an optical stop that passes only the rays reflected through the common focus. A ray approaching the mirrors at a given angle to the common axis makes the same angle to the axis after reflection from both mirrors, but rotated 180° about the axis from its original direction. Such an

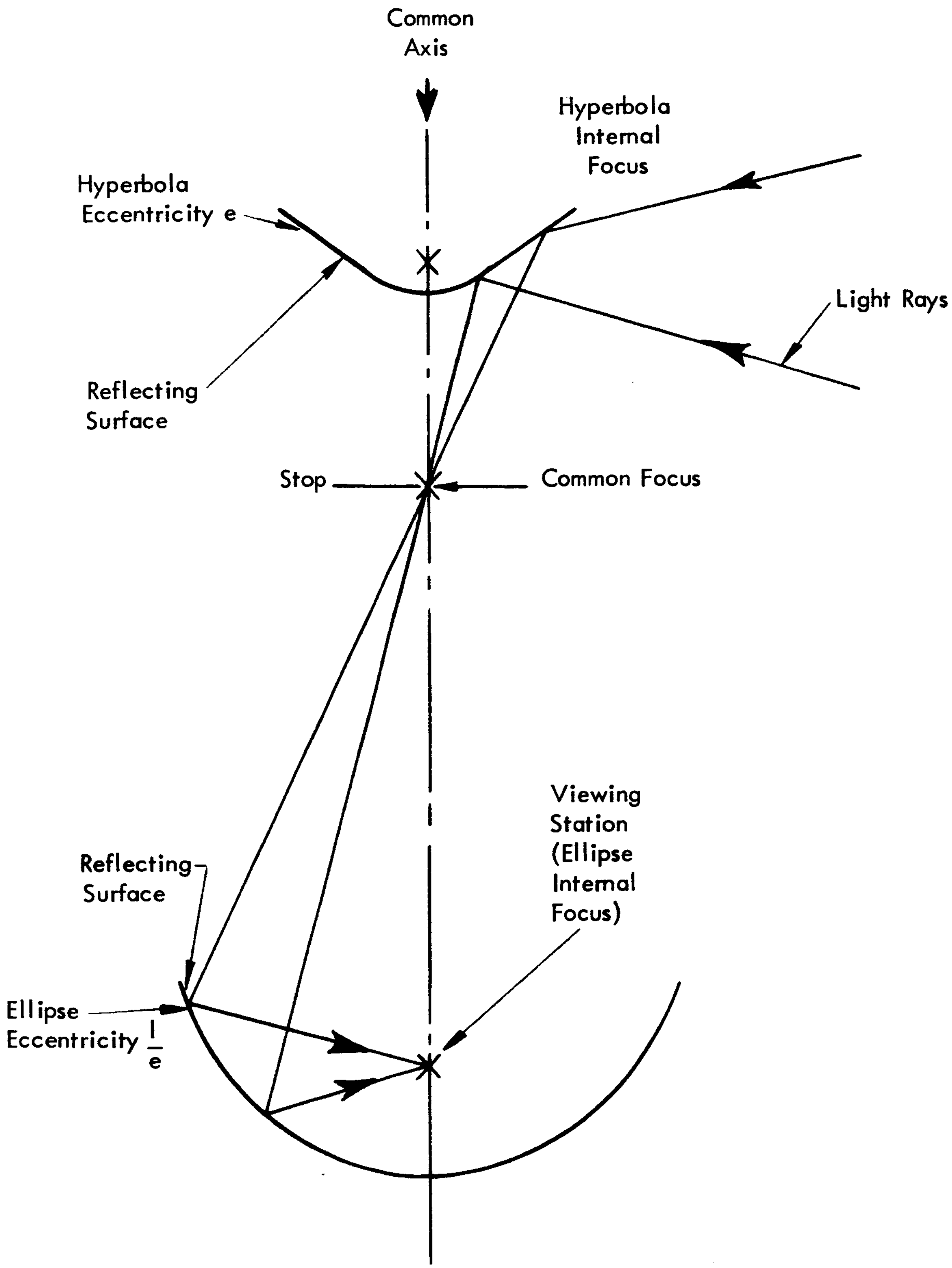


FIGURE 3-11 VueMarq BASIC PRINCIPLE

arrangement provides a distortion-free optical system.

The VueMarq technique uses a hyperbolic camera and elliptical viewer combination. The optical probe for the camera consists of a VueMarq hyperbolic element and associated field flattener optics. The simulated eyepoint is at the internal focus of the hyperboloid. Light rays from points on a model aimed at this point will be reflected through the aperture stop located at the external focus of the hyperboloid. The rays passing through the stop are reflected from the field flattener to form a primary image. This, in turn, is enlarged by a relay lens to just fill the active face of a vidicon tube.

The image display assembly of the VueMarq is shown in Figure 3-12. The video output of the vidicon is fed to a projection kinescope. The kinescope image is relayed by a projection lens and folding mirror to form a secondary image on a diffusing screen surface aligned with the focal surface of an elliposoidal mirror. Field shaping to fit the diffusion screen is accomplished by the shaping of the object plane (kinescope surface) and the longitudinal magnification function of the relay lens. The light from each image point on the diffusion screen spreads and is reflected off the ellipse in a collimated bundle. The central rays of all image bundles intersect at the focus of the ellipse which is the center of the exit volume. To

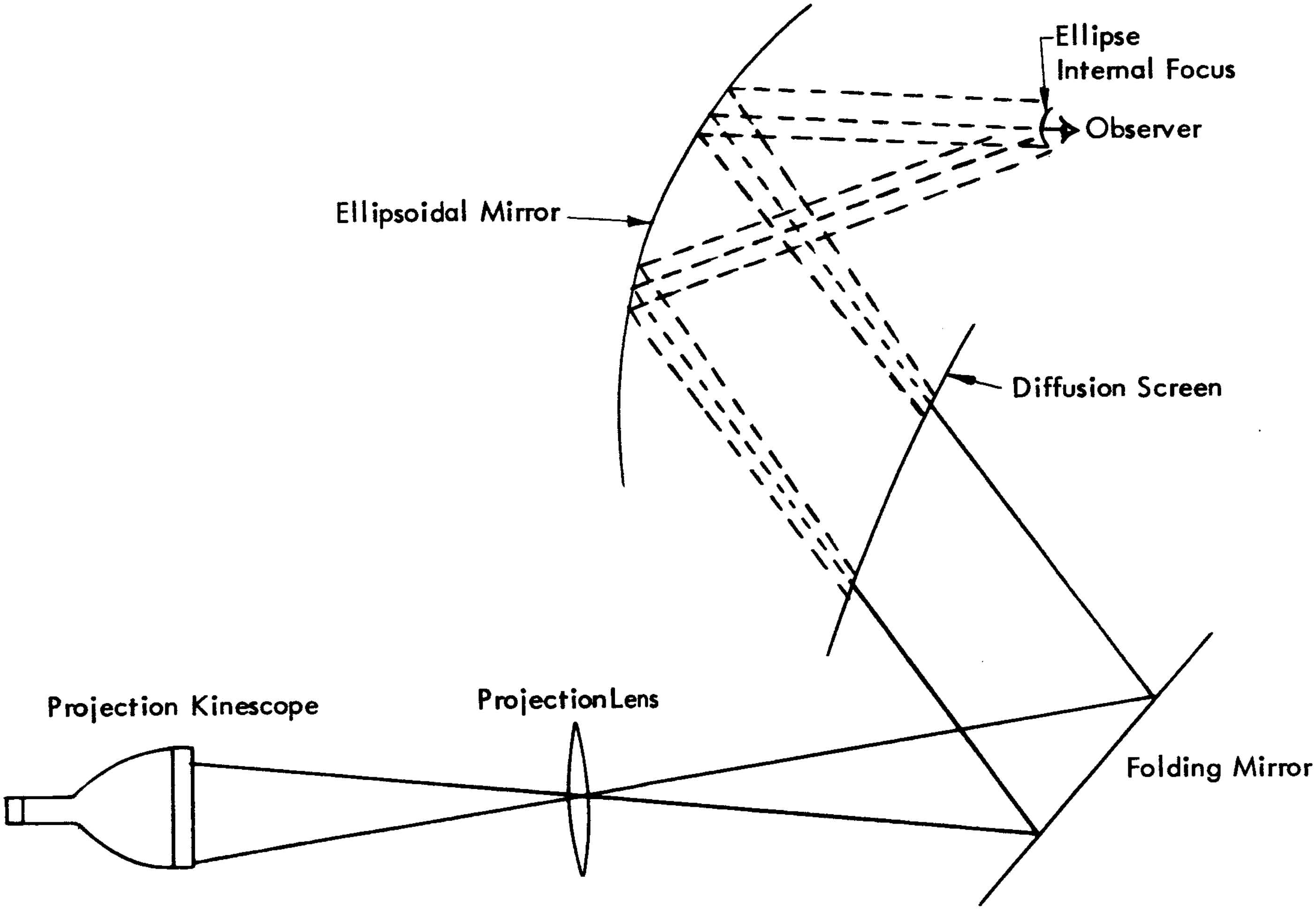


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FIGURE 3-12 VueMarq IMAGE DISPLAY ASSEMBLY an observer at the focus of the ellipse, the image appears at infinity (figure 3-12).

Performance data on the VueMarq is provided in a Marquardt report (32). An existent VueMarq feasibility model has a camera field of view of 345° azimuth by 120° elevation. The field of view of the viewer was set at 180° azimuth and 30° above and below the horizon to achieve an exit volume 6 inches in diameter.

A set of data was evolved in a ray trace of the elliptical mirror. The aberrations present are tangential and sagittal coma versus exit pupil position, which results in an angular deviation of rays as a function of incidence position in the exit pupil. The effect on the observer is an apparent shift of the image from infinity towards the observer, and a change in angular position of the image as a function of the observer's eye height. It is claimed that these effects are so small as to be unnoticed except for large and rapid motion of the observer within the exit pupil.

e. ACF Virtual Image Display (Figures 3-13, 3-14)

The ACF simulator at Wright-Patterson Air Force Base is designed to provide training for rendezvous against a star field background. The device uses a composite of optics, television, and computer techniques to achieve this objective.

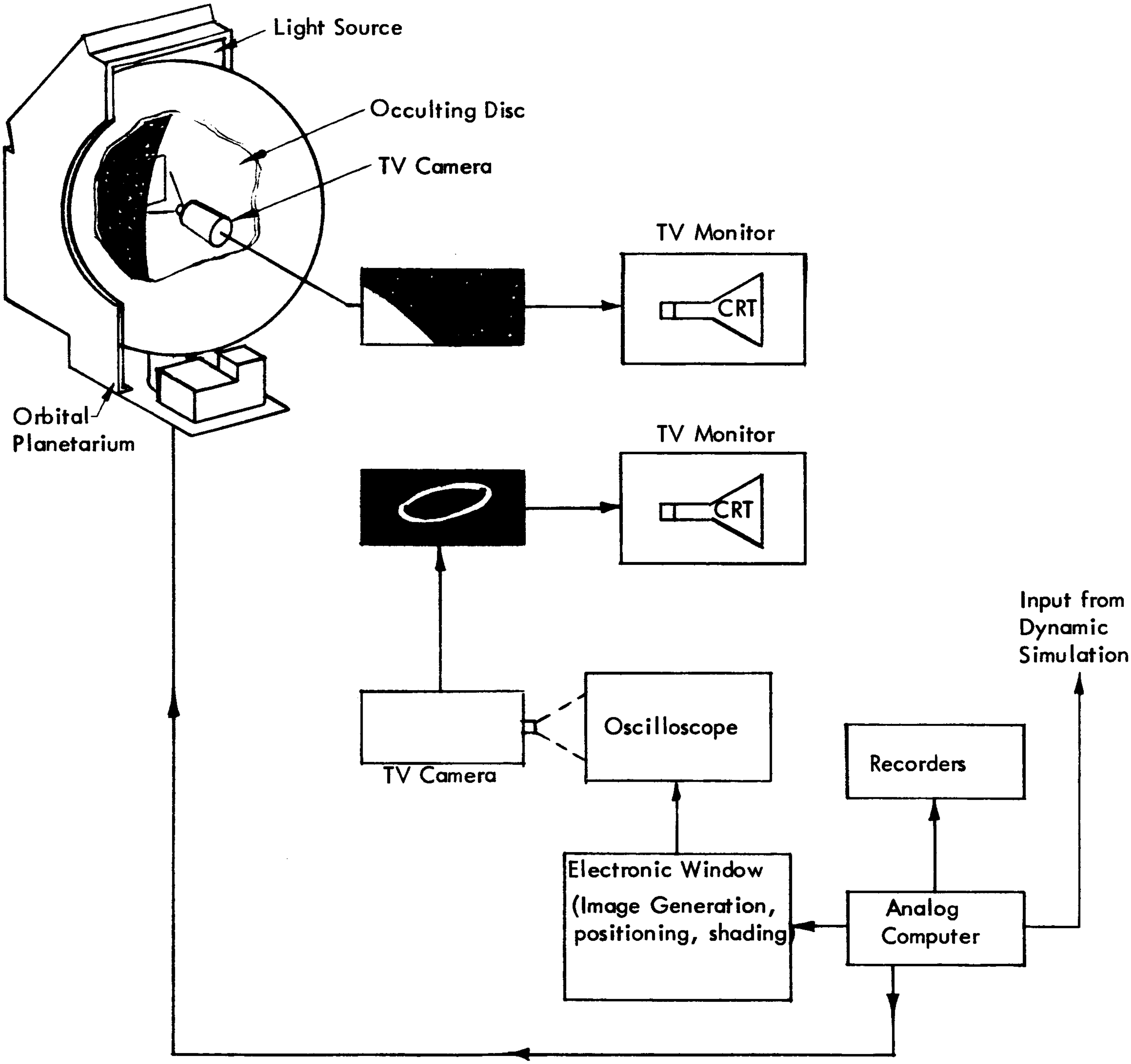

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FIGURE 3-13 ACF IMAGE GENERATION SYSTEM

The ACF image generation system is illustrated in Figure 3-13. An orbital planetarium, made by Bell Aerosystems, Inc., simulates a star background. This is a 4-foot diameter hollow sphere containing 463 apertures for stars, 0 to +4 magnitude. The stars are large and vary perceptibly in size. The sphere is externally illuminated by a blue fluorescent light source with porcelain reflectors. An axis of rotation simulates the polar axis. A TV camera, mounted inside the hollow sphere, is rotated to simulate the other axes. The planetarium pickup system employs a G.E. TV projector. Any one of three fixed masks inside the sphere occults the TV pickup of the star field.

An electronically generated image is prepared by an analog computer and displayed on an oscilloscope. (A doughnut-shaped lissajous image has the appearance of an orbiting space station. Control movements from the simulator cockpit modify the signals from the analog computer for change in perspective of the electronic image.) This image is picked up by a TV system similar to the planetarium pickup system.

An artist's concept of the ACF infinity display system is shown in Figure 3-14. The planetarium image is projected onto a fixed rear view screen. In like fashion, the lissajous pattern is displayed on another viewing screen. The

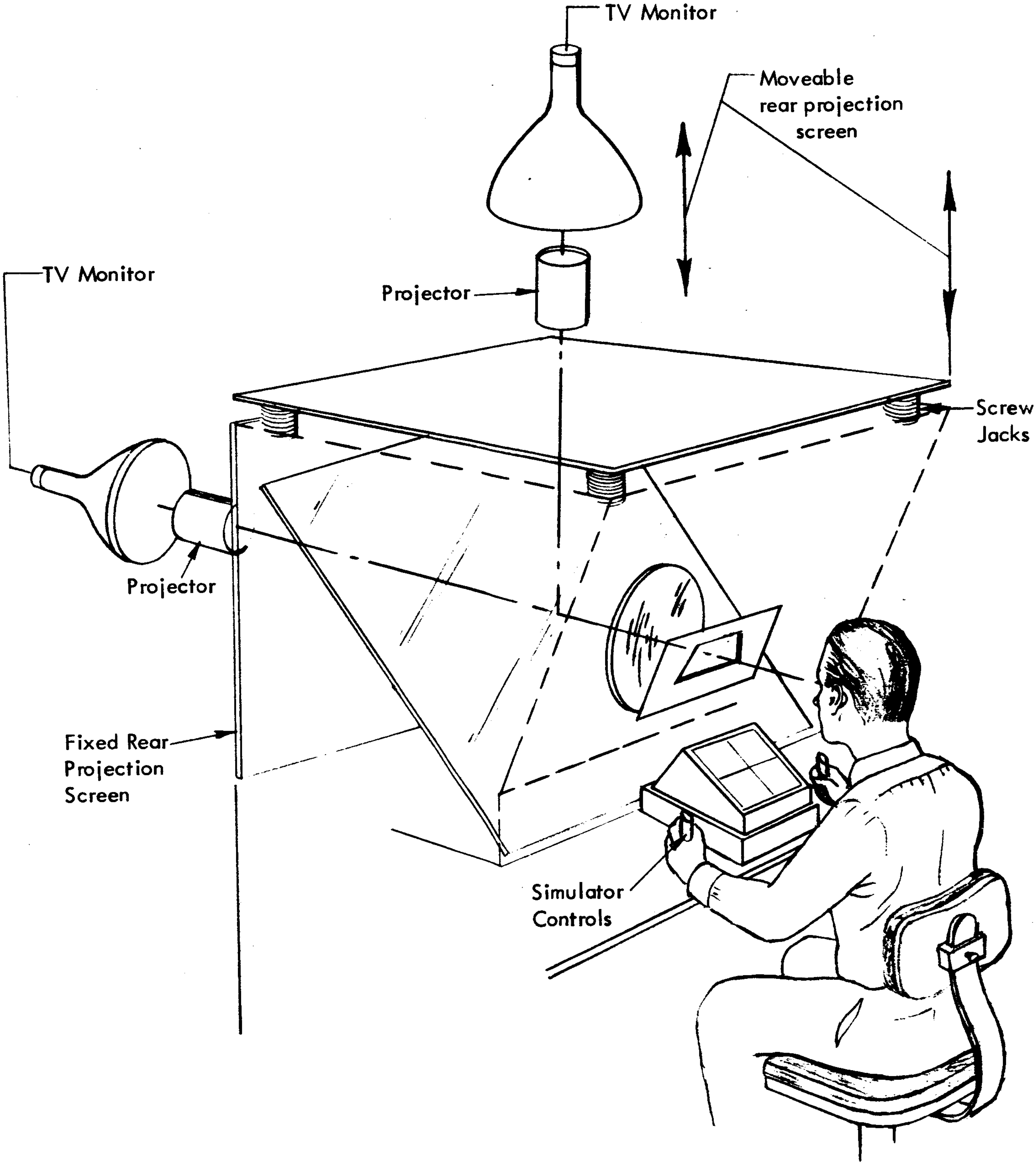

FIGURE 3-14 ACF INFINITY DISPLAY SYSTEM

scenes on the two screens are superimposed through a beamsplitter. A glass lens, approximately two feet in diameter, is used to project the two scenes at infinity. The second screen moves with respect to the first, to bring the docking target in from infinity. The movable screen is driven by four screw jacks and a chain drive. The focusing projector is driven by cables from the screen.

A solid model may be used in place of the electronically generated image, if the type of docking vehicle is too complex to be synthesized. Another possibility is to add in another background scene, such as the earth or moon globe, by resistively adding the new signal to the star signal in the TV amplifier.

The orbital planetarium and electronic image systems were originally made by Bell Aerosystems, Inc., and later integrated by ACF into a hardware system. The display end of the system, Figure 3-14, including the viewing screens, projectors and optics, is housed in a wooden and masonite package which has the outward appearance of a large, black box. The stellar field of view available to the simulator cockpit is approximately 52° on the diagonal. (It is reported that the price of a system with field of view greater than 60° would be prohibitive.)

The system was in process of assembly by ACF personnel at the time of the Farrand research team visit to WPAFB. System specifications were, in general, unavailable, except for resolution. Resolution over the field of view is claimed to be better than one minute of arc, not considering TV degradation (six minutes of arc).

Bell techniques used for image generation in connection with space simulation work are described more fully in a paper by Whitby (33). For the generation of simple forms, the system is highly efficient, but as the array of possible generated patterns becomes more complex, the advantages decline rapidly.

The first two techniques described are used to generate a toroidal-shaped space station (used as an input to the ACF simulator) and to generate an Agena-shaped cylindrical vehicle, used as an input to the Farrand Gemini Infinity Display System at MSC. From the description of the various factors which have been considered and corrected for, it would seem that the generation would be very realistic.

Analog computer simulation is used for generation of the geometry of the subject to be displayed. The coordinate systems of the subject and the viewing vehicle are related to inertial coordinates, and corrections made for perspective, distance, illumination source, beam spot velocity, etc. The main advantage over a conventional TV system with a model is that no model, gimballing system, camera or illumination system is necessary. The main disadvantage is that the programming becomes extremely complex if even moderately fine detail is to be presented in addition to the vehicle outline. (For instance, to have the letters NASA appear on the vehicle would require a highly involved system.)

The advantage of setting the scan pattern to conform to the image, rather than to use a fixed raster scan is very potent for images which do not fill the television display screen. A major limitation of the technique is the difficulty in matting multiple images, or in insetting the generated image into a raster-scanned TV background.

System advantages over the probe and model type of image generator are given by Whitby as follows:

a. Improved resolution in high data portions of the scene. (This results in better-than-TV resolution in distant subjects, but poorer than TV realism for subjects closer than about seven feet.)

b. High contrast ratios are possible, more nearly approaching the condition of the real space scene.

c. Full angular and positional freedom, without singular points.

d. Multiple-window generation with modest increases in system cost and complexity.

e. System economy in size and cost over that using a model and TV pickup.

f. Dalto Scanalog Trainer Attachment, Visual Simulator (Figure 3-15)

This device uses the flying spot scanner variation of the synthetic image generation technique to read information from a glass transparency. At the pickup end of the system, a 5-inch diameter transparency of a terrain scene is scanned with a trapezoidal raster. At the display end, a rectangular raster is used. By employing appropriate distortion coefficients on the flying spot scan to alter the aspect of the trapezoid, the display can be made to present a portion of the transparency in a wide variety of sizes, orientations, and perspectives. Rotation is accomplished by physical rotation of the flying spot scanner CRT. This rotation is about an axis just off the viewing area, which represents the "infinity point" in the display.

The Scanalog image generation concept is illustrated in Figure 3-15. Light passing through the transparency is collected by a Fresnel lens and directed by means of dichroic mirrors to three photomultipliers. These provide intensity signals for the three color kinescopes which are projected onto a rear screen display.

The Scanalog display system comes with an accessory attachment to display the strobe lights used to define the centerline of the approach path to an IFR runway. This consists of a neutral beamsplitter in the optical path between the

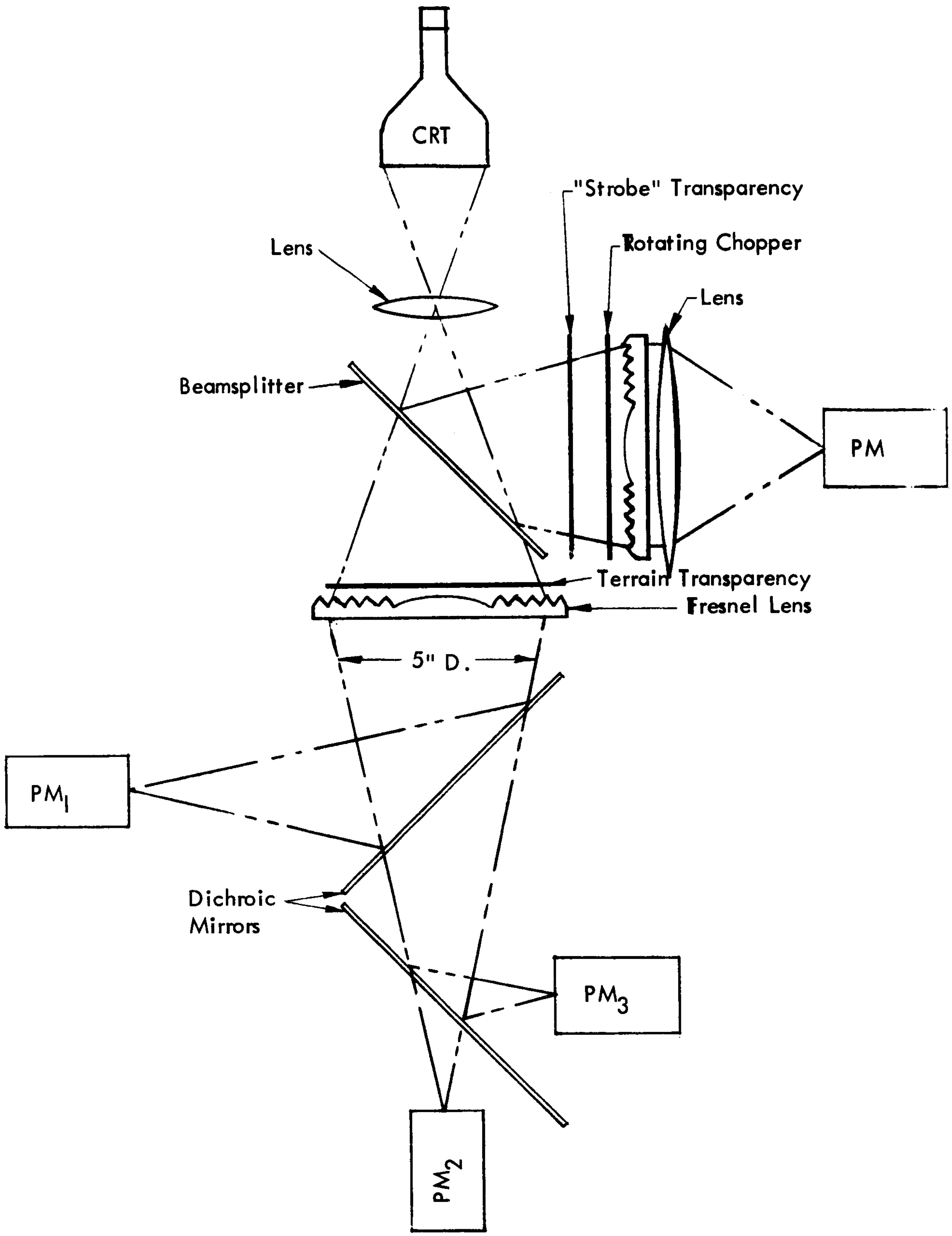

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FIGURE 3-15 DALTO SCANALOG IMAGE GENERATION TECHNIQUE

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flying spot CRT and the transparency; a second transparency; and an additional photomultiplier. The auxiliary transparency is opaque except for apertures located to correspond with the position of the strobe lights on the main transparency. A motor-driven occulting mask uncovers the strobe light apertures in repeating sequence at the appropriate rate, and the illumination is in turn presented to the strobe light photomultiplier. This signal is used to key all three color projector kinescopes which produce an intense white light to simulate the strobes.

The Scanalog technique permits display of an area surrounding the runway, about 5 miles diameter in all, and permits maneuvers such as complete fly-around the runway in sight at all times.

Resolution varies with altitude and orientation of the plane, with better resolution at higher altitudes.

The Farrand research team was able to inspect units of the Scanalog system at Federal Aviation Agency (FAA), Atlantic City, New Jersey, and at Wright-Patterson Air Force Base. The unit at FAA was modified to include a 24-inch diameter, plastic plano-convex lens to collimate the screen image. The square display screen covered at least a 70-degree field across its diagonal. The collimation appeared acceptable for a 40-degree or 50-degree field of view over a limited head motion. At larger fields and head motions of 3 or 4 inches, severe "swimming" of the image was apparent. Lateral color was evident at field angles 25 degrees or more off the axis, and was considered moderately objectionable. Within limited head motion, very little distortion was observed.

The scene being simulated was a night scene of an airport landing strip, including strobe lights. Color register and registration of the strobe lights were imperfect, but the overall impression was favorable.

The unit at WPAFB is similar to the Scanalog equipment in use at FAA, Atlantic City, New Jersey. The installation at WPAFB, however, was attached to a C-110 Flight Trainer, and was in better operating condition.

Within the confines of the trainer cockpit, the scene through the window subtended a smaller field of view, and head motion was limited, thus avoiding the "swimming" and the lateral color that impaired the FAA display. Color registration on the WPAFB model was considerably better.

Three transparencies were used during the demonstration. One transparency was a colored, painted night scene of an airport runway and nearby city lights. This transparency was similar to that used in the demonstration at FAA. The second transparency was a daylight view of the same scene. The effectiveness of the display depended to a large extent on proper color balance. At optimum balance, the color and gradation of the sky and horizon were very realistic.

The third transparency was a black and white aerial photograph of Wright Field in daytime. The white areas of the display had a definite greenish tint, and the black areas were very pronounced, giving excellent contrast. In attempting to compare two different daylight scenes, the general feeling was that the aerial photograph gave better results. A more significant test would have involved making comparisons among colored and black and white paintings and photographs, all four transparencies of the same scene.

A patent granted to Tucker and Weiss (34), and assigned to Dalto Electronics Corporation, describes an electronic system for generating a perspective image. The features described in this patent seem to be some of those used in the Scanalog simulator system. A flying-spot scanner is described in which a triangular raster is generated and used for scanning while the display is a conventional rectangular raster. This results in generation of a perspective display of a plane surface from a plan view of this surface. Several details relating to the spacing of raster lines and the distribution of detail are disclosed.

Yaw is accomplished optically by means of a pechan prism; translatory motions are accomplished by physical motion of the scanned transparency; and rotary motion is proposed to be achieved by means of a separate closed-circuit television link.

The Scanalog system has also been discussed by Wise, et al (2), Aronson (3), and Doty, et al (1).

g. Miscellaneous Virtual Image Display Systems

A number of virtual image displays have been developed or proposed about which scant information is available. Generally, this is because proprietary considerations are involved. Some of these will be briefly discussed:

Goodyear Aerospace Corporation has developed means for providing virtual image display systems with wide overlapping fields of view for two-man displays. No obstructing media are interposed between the men and display, which would require special compensation in vehicle components such as size, location or function. Their approach to this system is considered proprietary.

Wise and Whittenburg (2) summarize an Aerojet-General proposal to the Federal Aviation Agency for a virtual image projection display system. The proposal includes two system approaches. Each system operates in an unprogrammed mode utilizing the closed circuit television technique. The two systems differ primarily in cost.

The major components of the more expensive system are a 14-inch Kinescope projector with high brightness phosphor; a projection lens with 5-inch aperture, f/2.5 speed; a special lenticulated and ribbed, rear projection screen; and a 36-inch diameter, f/2.0 plastic lens for projecting the image to infinity.

The rear-projection system eliminates projector - displacement parallax completely since the viewing pupil is coaxial with the projector. Elimination of hotspots is proposed by making one side of the transparent screen of ribbed Fresnel ring construction; the other side is lenticulated and thus controls diffusion. The proposed screen is semi-specular because of the arrangement of the lenticular elements and provides a 14-inch observer pupil. The efficiency of this screen should be greater than 30 percent because of lower scattering and absorption losses.

This system provides a 53° horizontal by 45° vertical field of view.

The second proposed virtual image projection system, used in conjunction with a Schmidt projector, uses a high-brightness reflective-type lenticulated screen. The screen consists of a reflective liner glued to a concave spherical shell segment. An increase in image brightness is provided with this screen, as the gain figure is approximately 55. The observer has a viewing pupil of approximately 15 inches diameter at his head position.

The unique features of this screen are the high gain factor, the controlled screen exit pupil, and the geometrical configuration.

2. Eyepiece Type of Virtual Image Displays

a. Contact Flight Simulator, Device 14-L-2 (Figure 3-16)

This device was developed for the U.S. Naval Special Devices Center by the Farrand Optical Company under Contract N5ori-82 and was delivered at the close of World War II. Its primary purpose was to give pilots contact flight training.

The trainer is described in a patent by H. P. Wicklund (15), assigned to the U.S. Navy, and in a Farrand operation and maintenance manual (16). The trainer consists of a movable chassis with cockpit, periscope, and related components; an aero-dynamic computer unit; and a servo amplifying system. The three sections are mounted on a chassis frame which acts as a crab (Figure 3-16). The unit simulated the view from an F6F aircraft, utilizing a terrain relief map hung in an inverted position from the ceiling of the operating room. The terrain model was viewed through a periscope device attached to the cockpit. Manipulation of the trainer controls results in an illusion of contact flight over actual terrain at corresponding altitude and attitude of the aircraft.

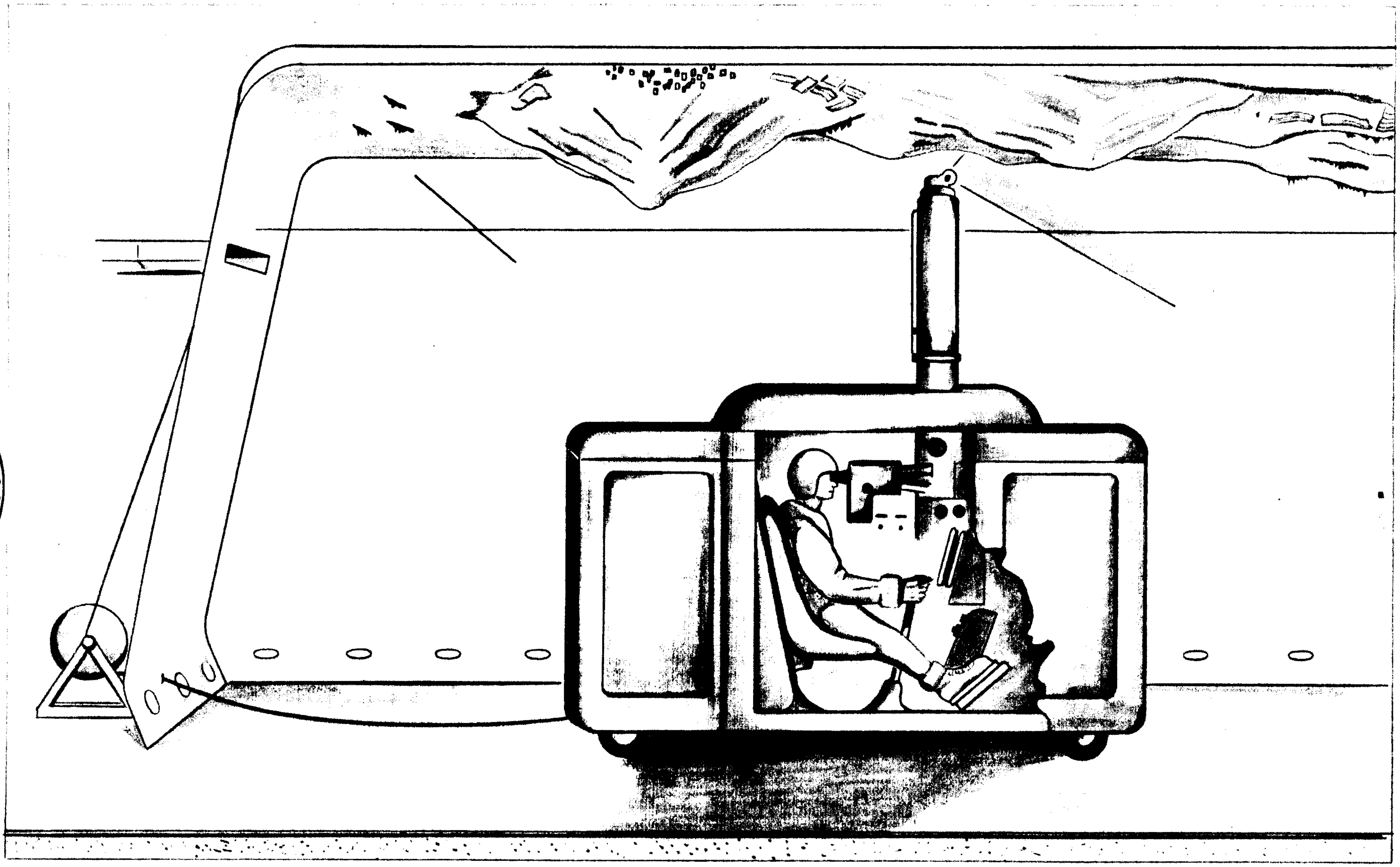


FIGURE 3-16 CONTACT FLIGHT SIMULATOR

A fixed position, binocular eyepiece type viewing system gives a wide field of view (76 degrees f/1) (3). The canopy frame, the operator's hands manipulating the controls, and the instrument panel are visible in stereo. The trainee cannot move his head since his eyes must remain on the fixed binoculars. The movable tube of the periscope is basically a simple telescope and contains a scanning head, an objective, a derotator prism, and an erector. Altitude is simulated by raising and lowering the periscope by drive shafts. Heading and changes in attitude are accomplished by manipulating the scanning prism, permitting the plane to fly at an angle not exceeding 30° above the horizontal, and to dive at an angle up to 15° beyond the vertical. Roll is achieved by means of the derotator prism located inside the periscope.

The chassis itself moves in X and Y translation (without rotation) on a scale ground track and is controlled by electrically driven caster wheels.

The realism was further enhanced by such refinements as simulated engine and machine gun noises, variable resistance to the movement of controls (the resistance increasing with increased air speed and/or control displacement from neutral position), and the inclusion of a shudder device back of the seat. This last effect caused the seat to vibrate, in a manner similar to the vibration experienced in a stalling airplane, whenever the pilot attempted maneuvers which would cause the aircraft to lose flying speed.

b. Tank Platoon Leader Trainer, Device 17-AR-1 (Figure 3-17, 3-18)

The H. A. Wagner Company conducted a feasiblity study in 1957 (17) for U.S. Naval Training Device Center to design a tank platoon leader trainer for operation under a simulated, natural environment. As a result of this feasibility study, it was recommended that a servoed optical system which derives its input from the motion of the head of the trainee be used in conjunction with an inverted periscope to view a model terrain at reduced scale.

The final equipment development and construction of a prototype unit are discussed in a preliminary proposal (18). This proposal describes a facility and installation for the training of tank platoon leaders under simulated battle conditions. A terrain model forms the external environment of an overhead gondola in a training room. A set of five interchangeable models is utilized to represent a variety of types of terrain: typical European, mountainous, arctic, desert, and jungle. Each terrain model is approximately 40 ft. x 60 ft. in size and represents, at a scale of 1:150, typical terrain features such as roads, hills, buildings, vegetation, etc. Infantry models and remotely controlled vehicle models are utilized to heighten the sense of realism.

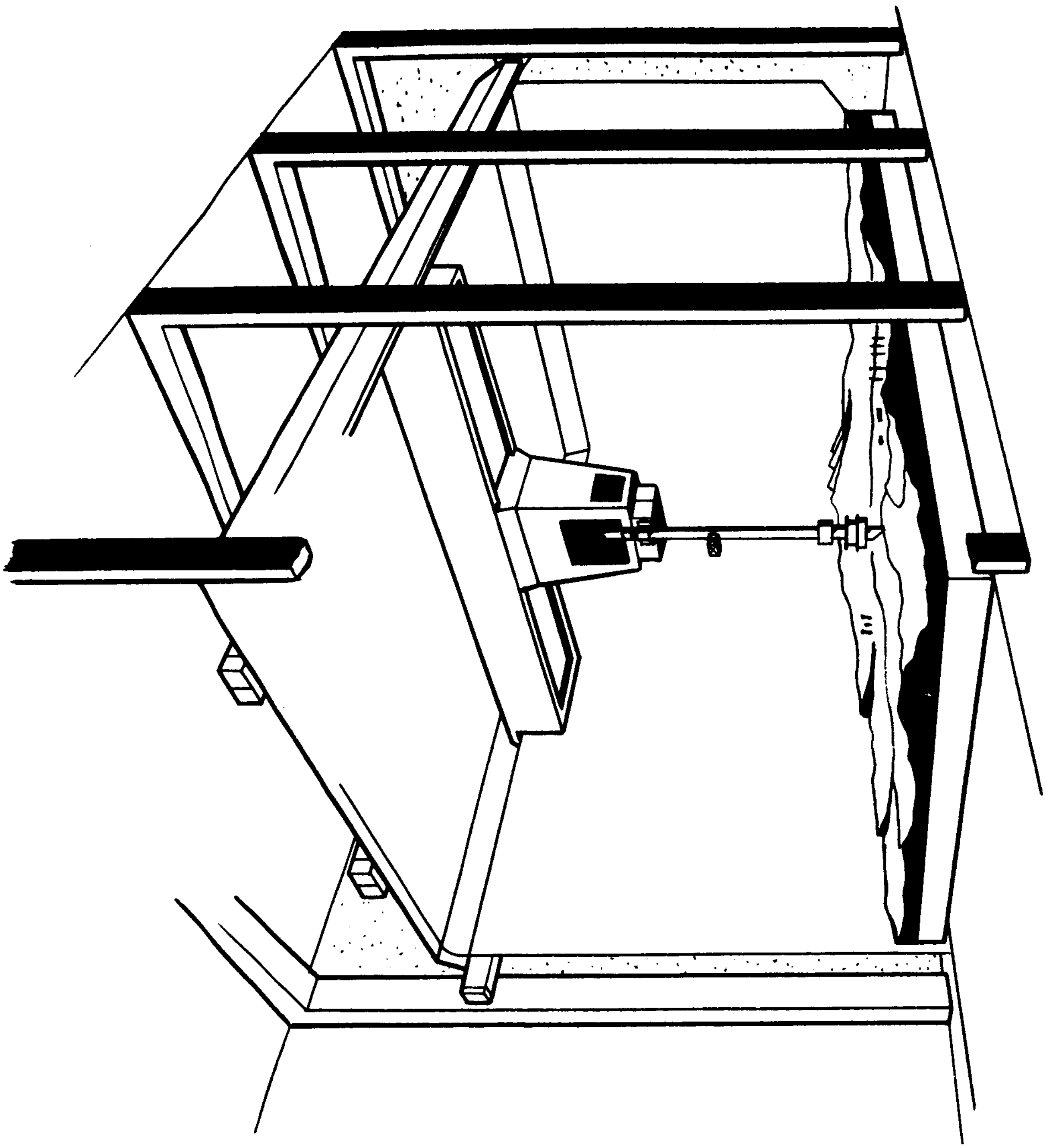


FIGURE 3-17 WAGNER TANK PLATOON LEADER TRAINER, DEVICE 17-AR-1

The installation is shown in Figure 3-17. The gondola comprises the trainee's simulated tank turret, the turret's supporting structure, and a structural support for a direct-viewing periscope. The turret duplicates the inside of a tank commander's station of the M48 tank. The turret is stationary with respect to the gondola, but the cupola, a functional replica of that found on the tank, is rotatable in azimuth, and the hatch opens and closes.

When a trainee is in his operating position, he can view the terrain only through the optical system provided. A multipath optical periscope system provides a realistic simulation of the viewing situation that exists when a tank platoon leader rides with his head out of that cupola for direct viewing of the terrain (Figure 3-18). From inside the cupola, the trainee views through the cupola periscope and viewing slots and through a range-finder. The internal arrangement and mechanisms of an M48 tank turret are reproduced in the gondola and the trainee performs all the necessary functions of the tank platoon leader in the normal manner. The translations of the gondola are controlled by the trainee's tank driver who is stationed on an overhead gallery where he cannot be seen by the trainee, but from where he can observe the terrain, the gondola's position, and the position of the periscope pickup prism.

The multipath periscope is a unit-power viewing system. A successive

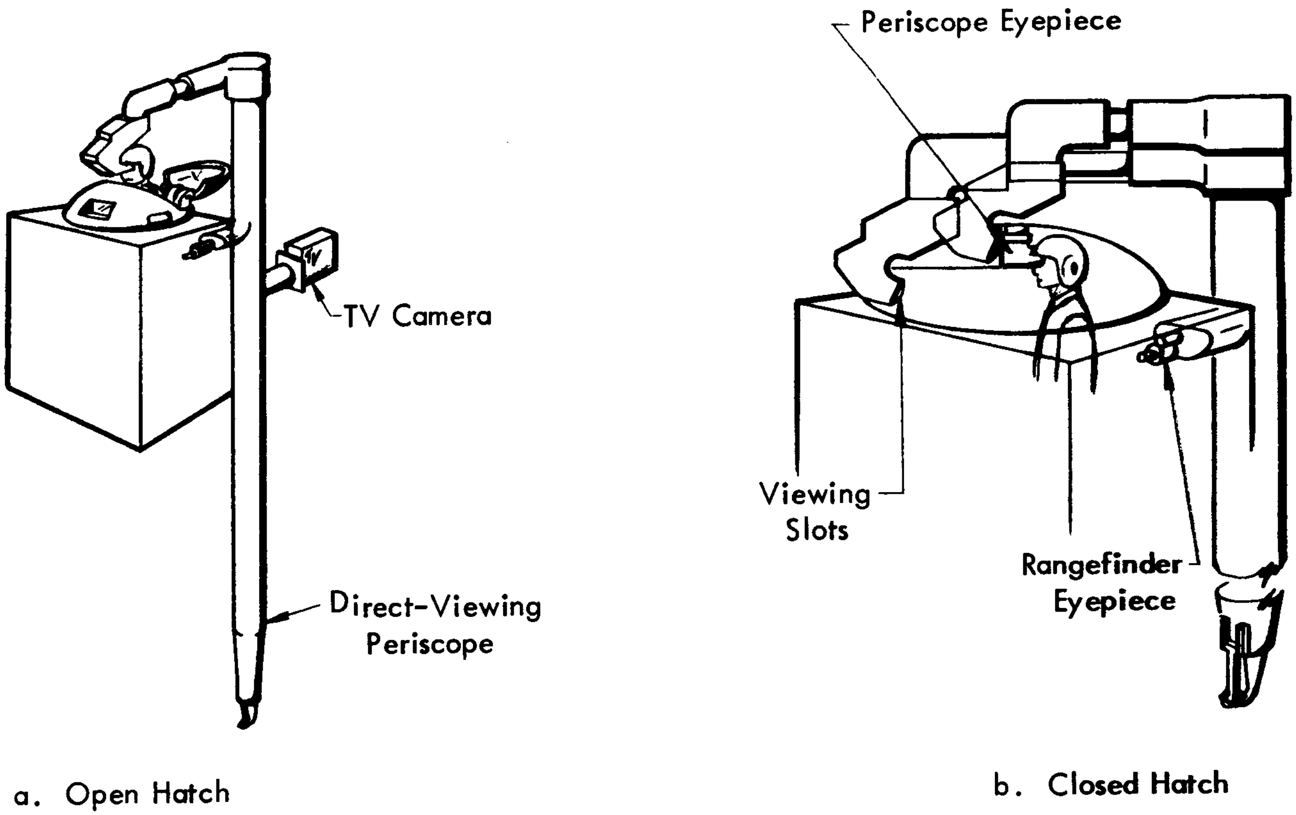


FIGURE 3-18 VIEWING ARRANGEMENT FOR TANK PLATOON LEADER TRAINER, DEVICE 17-AR-1

image-relaying system pipes the light from the model terrain surface to the trainee's eyes. It provides the same visual effect as if the observer's eye were actually placed at the instrument's exit pupil. A mechanical construction around the optical system provides five degrees of freedom of head motion.

The upper viewing head is used to deliver images to the five viewing slots in the cupola. A coincidence rangefinder is simulated by inserting a pair of small rhomboid prisms in front of the pickup prism. At such times the periscope and viewing slots will be inoperative.

The trainer is designed for an azimuth presentation of 360° and a vertical field angle of 80°.

A demonstration periscopic viewer was constructed for the feasibility study. It was provided with azimuth rotations of 140°, as well as up-down, fore and aft, and left to right movements of 12 inches. A high quality seromechanism moved the viewing head in response to the motions of the trainee's head, without the viewer ever touching the trainee's head or eyes. The trainee had unhindered, complete freedom of head motion.

A field of view of 85° was obtained with the monocular viewing periscope. The servo system of the viewer was shown to be capable of following all normal head motions without objectionable errors.

3. Other Than Virtual Image Simulator Systems

a. Link Visual System-Mark I (VAMP) (Figure 3-19)

The Link Variable-Power Anamorphic Motion Picture (VAMP) system was developed for an aircraft landing simulator for training in visual approaches. Motion picture film that has been exposed from the cockpit of an aircraft performing missions of take off, flyabout, landing, etc., is projected onto a curved screen in front of the observer by a special projector linked to the dynamic controls of the simulated aircraft. The resulting visual presentation is suitably altered in apparent perspective so as to provide an image having the correct appearance in relation to the pilot's viewpoint even though the projector may be displaced laterally and/or vertically from the pilot's eye position. An artist's concept of the display is shown in Figure 3-19. It should be noted that the use of motion picture film limits simulated altitude changes, and the associated field of view changes as well as changes in lateral translation and forward velocity. These deficiencies of motion picture image generation are completely discussed in Section V of this report where the use of film in future visual simulation systems is explored in detail.

The VAMP projector uses a Zoomar lens of variable focal length with an anamorphic lens of single axis magnification to provide a variable power

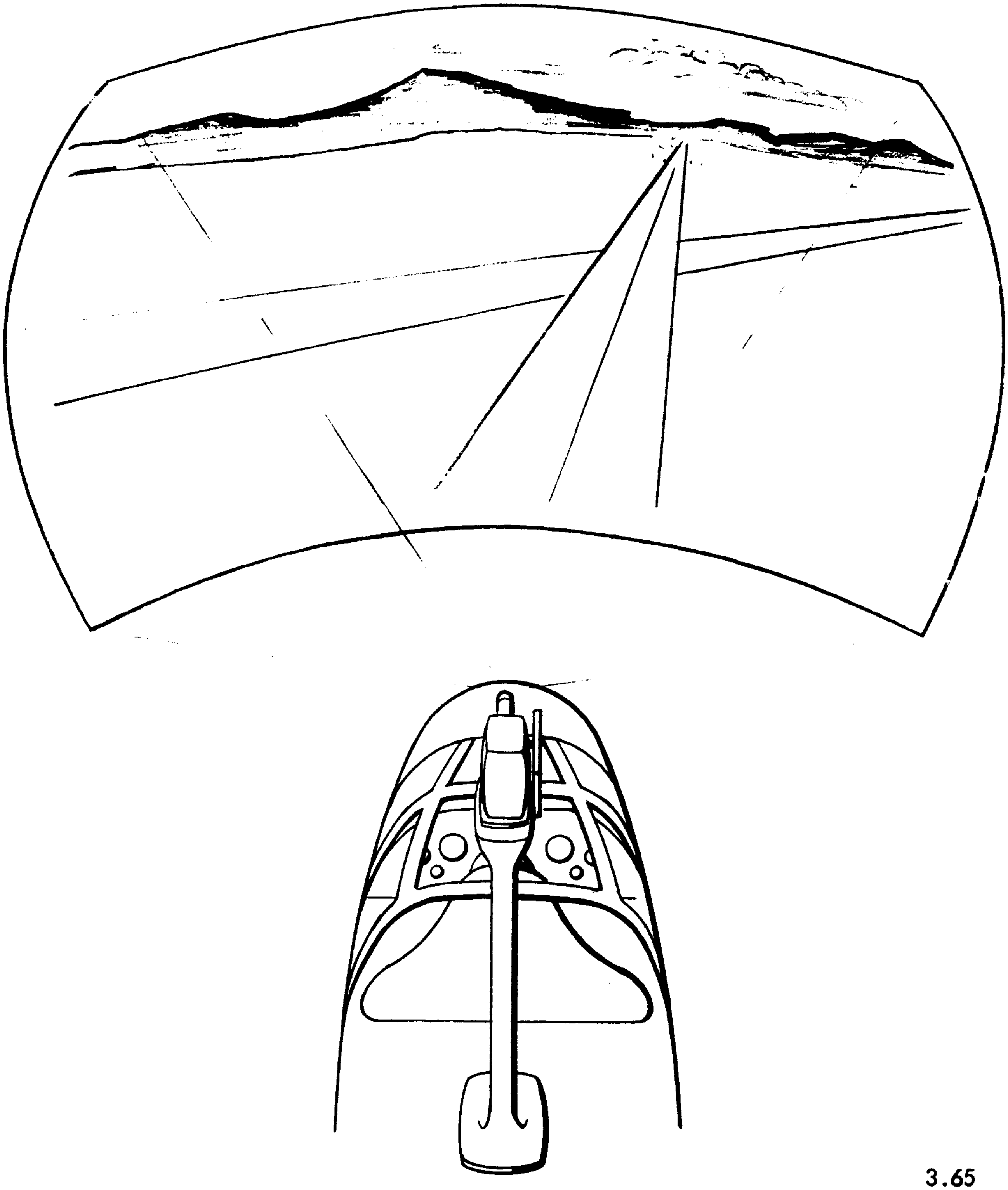


FIGURE 3-19 LINK MARK I VISUAL SYSTEM (VAMP)

anamorphic motion picture. The anamorphic elements alter the perspective of the viewed image within limitations, while the Zoomar lens varies the scale of the scene. Thus, a single motion picture of a real landing approach can be used in a flight trainer which gives three pertinent variables. The operator can control his altitude with the Zoomar lens. His lateral position, relative to the runway, and his angular position are controlled by the anamorphic lens. The simulator presents changes in velocity by increased picture frame rate. These three variables can be exercised only over a very limited range.

The realism of the projected view depends on four factors: the altitude of the observer above ground level; the angular shift in viewpoint resulting from the lateral displacement; relative vertical dimensions within the scene; and the horizontal and vertical fields of view. The system was reviewed in the Hutchinson report (5) to determine possible application to a driving simulator. Realism appeared adequate for an airplane approaching a landing strip but, for the requirements of a vehicle simulator, the realism is destroyed by vertical distortion. This distortion is inherent in the system because it cannot distinguish between horizontal and vertical components of real objects. Attempts by Hutchinson to analyze the vertical distortion in terms of viewpoint displacement simulation were not successful because of limited data.

A second anamorphic lens could be used to compensate for the height without introducing width distortion. Such a system has been proposed (12) but it is not known if it has been tried to date. (A brief review by Woodson (13) would seem to indicate that two anamorphic lenses are now being used in the VAMP optical system.) The practical problems of optical alignment of two cascaded anamorphic lenses with the Zoomar lens and the projector are difficult.

For its intended purpose this system offers good definition, high quality and full color.

b. Link Visual System - Mark II (COP) (Figure 3-20)

This system is often referred to as the Compensated Offset Projection (COP) display. It was designed primarily for use with a Bell H-13 helicopter simulator as a hovering trainer. A helicopter cockpit is suspended above the lower end of an inclined screen located in front of the pilot's position in the cockpit. A ground scene is projected onto the screen from an overhead projector, as shown in Figure 3-20. The display is controlled in response to simulated flight maneuvers to produce a realistic simulation of contact flight by visual reference.

The basic concepts involved in this invention are described in Hemstreet and Woodson's patent (14), assigned to General Precision, Inc. A student pilot sits in a flight trainer cockpit facing an inclined projection screen. The optical system of the projector, which includes an anamorphic lens element, functions in cooperation with the inclined screen to produce a realistic simulation

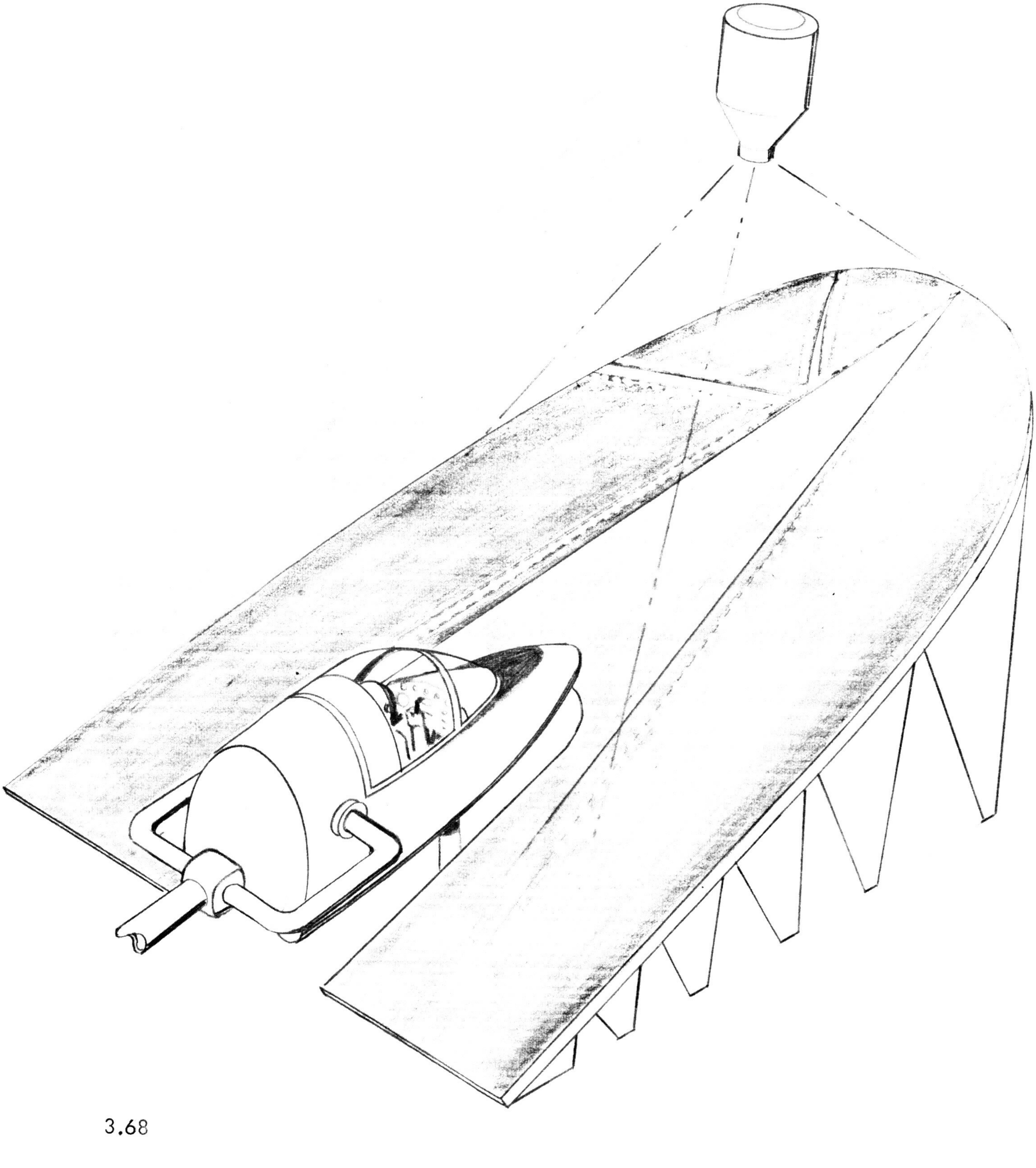


FIGURE 3-20 LINK VISUAL SYSTEM MARK II (COP)

of horizontal perspective in images projected onto the screen. In the preferred embodiment of the invention, controlled keystone distortion is created in the image by projecting an undistorted photographic transparency at an angle onto the inclined screen. The lower portion of the formed image, which is closest to the point of observation, is so magnified that it subtends a large angle at the eye than the upper or more remote portion of the image, creating the visual illusion of perspective. The system, however, does not provide an infinity display and although motion parallax increases in the right direction it is not proportional to simulated distance in the scale of the real world.

The illusion of vertical perspective may be added by employing a three dimensional transparent object in lieu of a simple two dimensional transparent film as the image source. An image will be projected onto the screen which will include shadowgraph features conveying a sense of a third dimension, or vertical perspective corresponding to the relative heights and shapes of the three dimensional transparent models. Such three dimensional transparencies may be used, for example, for simulating the maneuvers of hovering at a low altitude in a helicopter.

Molnar and Lybrand (1) describe the COP display which was built for the Bell H-13 helicopter display. Terrain information is stored on a transparency which is projected onto the inclined screen in front of the cockpit. The projector is located 25 feet forward of the cockpit, and 15 feet above the cockpit level. The projector consists of an incandescent lamp light source, a rotating and translating film transparency, a collimating lens, and a Zoomar lens. The light then goes through a field lens, a standard projector lens, an anamorphic lens attachment, and finally reflects off a mirror onto a flat screen.

The Zoomar lens provides altitude variation. Yaw is simulated by rotation of the film about the optical axis. Lateral viewpoint shift is obtained by displacement of the film strip center; fore and aft viewpoint shift is obtained by displacement of the frame center. Roll and pitch are simulated by cockpit rotation about the longitudinal and transverse axes, respectively.

Molnar and Lybrand report the greatest deficiency of this visual display is its inadequacy for presenting cues normally utilized by the helicopter pilot for perceiving changes in altitude and motion perspective. Hutchinson (5), in evaluating the display for an automobile driving simulator, said the limited field of view and the restricted viewing distance make this method unsuitable for such use.

As far as is known only a symbolic representation of terrain features, stored on a transparency, has been utilized in this display. However, conventional motion pictures of normal landing approaches are planned for future devices.

4. Optical Projection Displays

a. Helicopter Flight Simulator, Device 2-FH-2 (Figure 3-21)

The Helicopter Flight Simulator, Device 2-FH-2, was constructed by the Bell Aircraft Company and the deFlorez Company in 1954 for the Navy. The device utilizes an intense point light source to project a rigid, 6 by 6 foot transparency onto a panoramic screen. The purpose of the device is to teach hovering flight near the ground and to teach auto-rotation in flight.

An artist's concept of the system is shown in Figure 3-21. The principal components of the device are the projector, the cockpit, and the computer. The projection system consists of an overlapping sky projection and terrain projection display. The hovering display presents a small heliport from an altitude of 55 feet; the auto-rotation transparency simulates the view from an altitude of 2500 feet. All of the freedoms of motion of the helicopter are simulated by the projection system. Motion of the transparency simulates five of the six motions inherent in a helicopter; the sixth motion (altitude variation) is simulated by the movement of the point source suspended in the center of the main projection assembly. The point source may approach within 1/8 inch of the projection transparency, which is made of rigid Plexiglass, 3/16 inch thick.

The screen, which envelops the pilot for 240°, is 15 feet in radius. The contour of the projection screen is designed so that the majority of the projected terrain falls on a conically shaped sector which is an ideal shape for depth

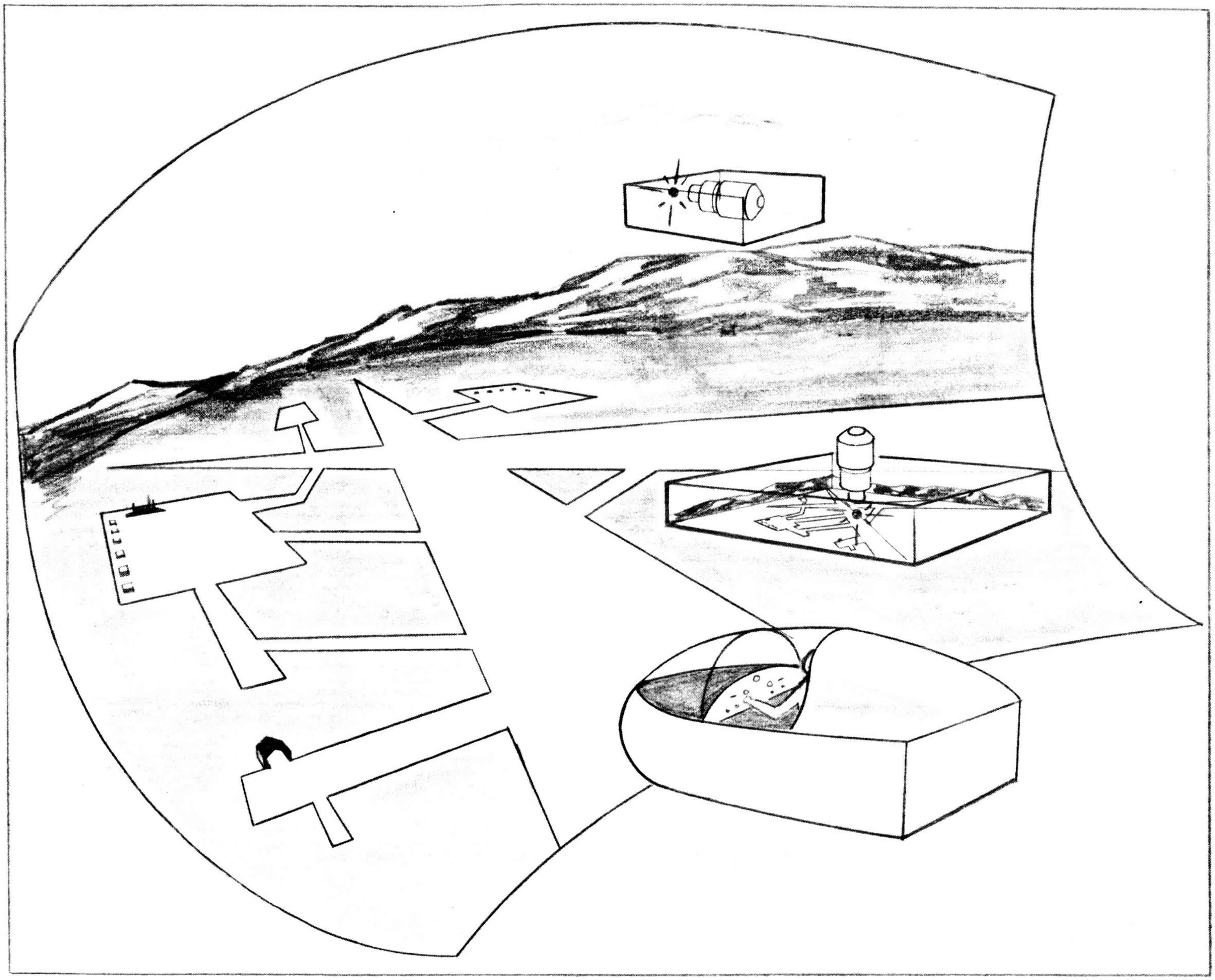


FIGURE 3-21 HELICOPTER FLIGHT SIMULATOR, DEVICE 2-FH-2

perception when retinal disparity projection techniques are not used. The pilot's cockpit is from an actual Bell helicopter from which the Plexiglass "bubble" has been removed.

The simulated flight is completely non-programmed and is limited in extent only by the "ends of the display world" as determined by the ground area provided on the transparency, and by the amount of horizontal and vertical motion provided in the device. The pilot-operator is free to maneuver his aircraft at will within the range of the device by manipulation of the helicopter controls provided. The outputs of electrical elements added to the controls of this helicopter provide necessary signals to the computer which controls projector motions.

In Device 2-FH-2, the computer is designed primarily to handle simulation of helicopter hovering. Because of compromises incorporated in the computer design for economic and other reasons, the device does not respond to control manipulations for other maneuvers exactly like an actual helicopter would. This gives rise to complaints from experienced pilots that "it doesn't fly like a helicopter". (19)

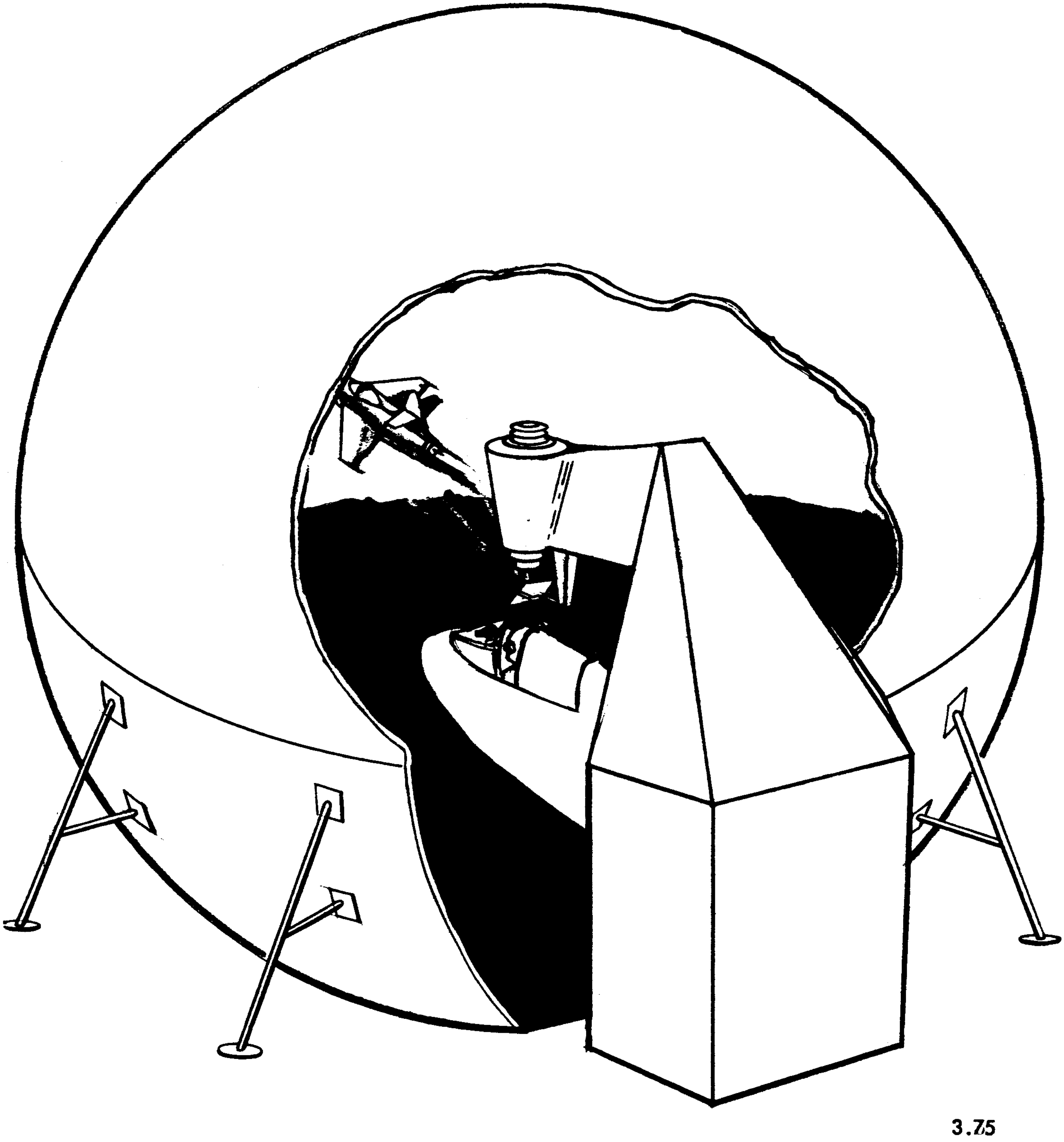
A report by Bulter and Havon (20) presents the results of an evaluation which indicates that training in the device shows no advantages over training in an actual helicopter. In fact, negative effects were noted. This was attributed to a lack of fidelity in the visual display and/or the compromises made in the generalized flight computer system. Motion sickness also affected a majority of the trainees and instructors using the device.

The visual display produced by a new light source and transparency for the 2-FH-2 were evaluated by pilots (19). These evaluations were then compared to determine the realtive merits of the original set and the new set of components. The new light source was closer to a point source than the old light source, and resulted in improved resolution from 2 lines/mm to 6 lines/mm at the model, while screen brightness at the horizon decreased by a factor of almost 2x to 0.131 foot-lamberts. The new transparency, prepared by a photographic technique, resulted in a more realistic display than that obtained with the wholly hand-decorated original transparency.

Development of the deFlorez Point Light Source Projection System was carried out under contract for the U.S. Naval Training Device Center. (The 2-FH-2 unit at NAVTRADEVCEN was inoperative at the time of the Farrand research team visit). Another unit is in operation in the Ryan Aeronautical Simulation Laboratory. Similar systems are currently being built for North American Aviation and Edwards Air Force Base.

b. <u>F-151 Fixed Gunnery Trainer</u> (Figure 3-22)

The Rheem F-151 Fixed Gunnery Trainer at Federal Aviation Agency, Atlantic City, New Jersey utilizes an optical system for pickup and projection of airborne and ground targets on a 10-foot radius spherical screen. Very small



3.75

FIGURE 3-22 RHEEM F-151 FIXED GUNNERY TRAINER three-dimensional models, illuminated by multiple lamps, are servoed on command from a simulated cockpit of an F-100 trainer, oriented so as to locate the trainee's eyepoint on the vertical axis of the sphere. The fixed projector, located on top of the cockpit, projects the target image to a movable reflecting mirror, located at the center of the sphere. The image is projected onto the screen at the appropriate azimuth and elevation (Figure 3-22).

A separate optical system uses a point light source to project a sky and earth horizon on the screen. The area of projection is 280° in azimuth by 120° in elevation.

The application is restricted to relatively simple target presentations, rather than to a terrain in relative motion with complex features.

The trainer originally employed a closed loop television pickup and projection system. A report by Gartner and Lybrand (21) presents the findings of the Psychological Research Associates (PRA) from their participation in the F-151 Fixed Gunnery Visual Presentation Evaluation. Many inadequacies were noted, among which the primary ones were lack of resolution, poor quality target models, lack of coordinated target maneuvering and absence of simulated target damage effects and line of fire indications (such as provided by tracers). PRA concluded that the trainer was best suited for simulating gunnery training situations.

In what appears to be a later study reported by Pfeiffer, et al (22), an analysis was made of the perceptual characteristics of the pilot's visual world while performing various flight tasks. These were compared with the perceptual characteristics made available by typical non-programmed visual displays attached to flight trainers. An experiment was then conducted in the F-100 simulator equipped with the original F-151 visual attachment to determine training effects. It was determined that, even among experienced subjects, the performance significantly improved, both with regard to the detection of in-flight emergencies and the maintenance of aerodynamic stability. However, some subjects complained that the horizon was difficult to see, contrast between the sky and ground being very poor.

The modified system gives better performance that the original system, but severe limitations still exist. The screen brightness is approximately three foot-lamberts. The contrast ratio is 5:1. It still is difficult, if not impossible, to produce a dark target on a light background.

One requirement for this display, as stated by FAA personnel, is to add a movable point source to represent the flashing red beacon of a distant aircraft.

5. Computation of Pictorial Elements Displays

a. University of Illinois Landing Display

This is a relatively uncomplicated device which utilizes projected pictorial elements for presenting a constantly changing outline image of a landing runway and horizon. Size and shape changes in the outline image are programmed to respond to simulator control movements. The display is used in conjunction with a trainer, such as the I-CA-2 SNJ Link Trainer, for human engineering systems studies.

This display, which was designed at the University of Illinois, is described by Molnar and Lybrand (I). A mathematical analysis was performed to determine perspective relationships of a runway profile, from the pilot's viewpoint. Using these results, a shutter was designed and constructed that nearly duplicated the relationships found. Two shutters were used to form the top and sides of the runway profile. They were placed in the lens system of a conventional projector and servoed to the simulator. The projection of light through the shutters formed a perspective picture corresponding to the position of the pilot within 10-degree limits of either side of the runway. A second projector provided the sky and green grass surrounding the runway. Presentation was by rear projection on a translucent screen.

b. Miscellaneous Displays

Rheem proposed a projected pictorial elements display using a reticle system for night landing training (I). Three independently controlled reticle systems are mounted in front of separate light sources and projected to form rows of light which simulate a runway from a pilot's viewpoint. The reticles are adjusted in response to flight control instruments by an electro-mechanical computer. Two of the reticles project both sides of the runway; a third reticle optical system furnishes the approach light.

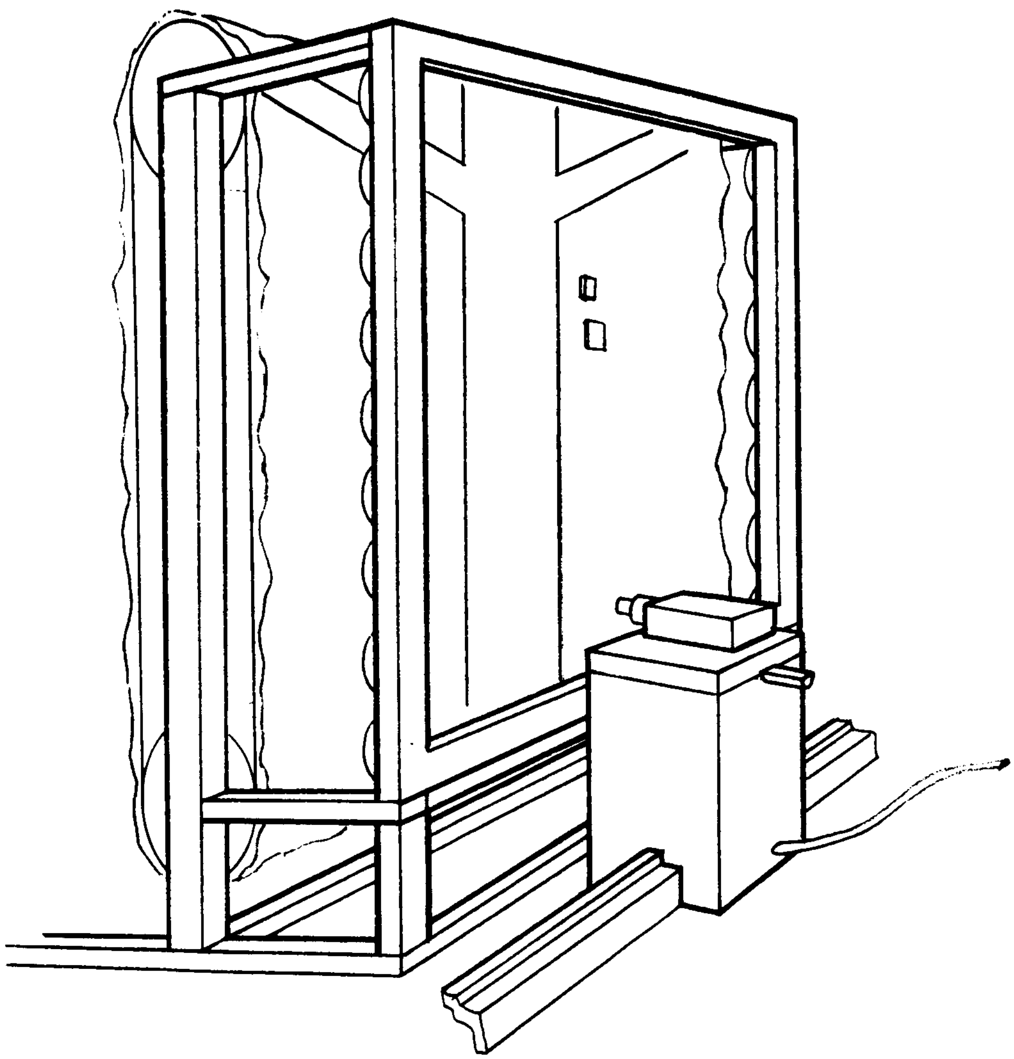
Naval Training Device Center experimented with a non-projected technique which utilizes a matrix of electroluminescent cells to reproduce the pictorial elements from previously calculated equations for solid objects and two-dimensional surfaces (3). A digital computer computed the display based on perspective equations and their intersection with the screen. The display maintained a full relationship to the observer based on the motion of the vehicle and its path with respect to a scene.

The 16 x 16 inch panels used in this display had a resolution comparable to 525 line television. Panel brightness was 1/2 foot lambert. The images displayed were limited to patterns whose shape and size can be expressed mathematically.

6. Closed Circuit Television Displays

a. Link Day/Night Visual Simulation System, SMK-23 (Figure 3-23)

Literature sources refer to the Link Day/Night Visual Simulator Attachment (2), the Mark IVa VisuaLink Day/Night Visual Attachment (13), the SMK-23 Day/Night Visual Landing Trainer (11), etc. which, by description, appear to be the same, or slightly modified, device. The primary purpose of



3.80

FIGURE 3-23 LINK DAY/NIGHT VISUAL SIMULATION SYSTEM, SMK 23 the system is to provide pilot training in the two most critical areas of flight, take-off and landing, particularly in the transfer from IFR to VFR at break-through.

An artist's concept of the system is shown in Figure 3.23. This visual display system utilizes a terrain model built on an endless belt principle. A 3D replica of an airport complex is mounted on a belt 27 feet long by 12 feet wide at a scale of 1:3000. Belt travel is bi-directional in a vertical plane, providing longitudinal motion.

A closed circuit color TV camera, scanning the pilot's field of view, is moved by five servos in response to signals obtained from the flight simulator. Horizontal camera travel and camera motion normal to the terrain map provide latitude and altitude information, respectively. A pitch mirror and a short focus pickup bead lens are rotated to provide pitch, roll, and yaw simulation. Complete fly-around capability is available.

Observer readout is on a 21 inch color TV monitor mounted in an optimum position or on a screen located in front of the cockpit. In the latter case, an Eidophor light valve projector with sequential filters provides a bright, full color picture.

Runway patterns are simulated for day and night use; an edge lighting principle is employed for runway and approach lights, and a mechanical switching arrangement generates approach flashers.

Among the visual effects which are possible with this system are those of fog, haze, and broken cloud cover. The cloud effects are electronically generated and can be supplemented by the use of synthetic clouds which are located in appropriate places over the terrain model. Wind effects can also be simulated.

Wise and Whittenburg (2) provide system specifications for the Day/Night Visual Simulator Attachment. These include a $\pm 25^{\circ}$ horizontal by $\pm 18^{\circ}$ vertical field of view, 7 foot lamberts highlight illumination for color, and 500 lines resolution.

Doty and Gill (11) discuss the SMK-23 in relation to some optical and television parameters and their interaction with overall design and performance.

The device has the highest scale ratio used on a terrain model to date; it has the smallest pickup lens, 2 millimeters in diameter, with an effective aperture of approximately f/54 and it has a 3 inch image orthicon tube developing a sequential color picture with all the attendant difficulties. The authors conclude that, while the SMK-23 has utilized the limits of the art in all phases, the design of the system is such as to be adaptive to modification when new state-of-the-art development materializes in related optical or electronic areas.

b. Link Visual System, Mark IV and IVA (Figure 3-24)

The Douglas Aircraft Company contracted with Link Aviation Incorporated, for the attachment of a display system of Douglas specifications to the DC-8 simulator. The device, called the Mark IV Visual System, is a closed circuit television system which scans a vertically mounted scale model of a runway and airport terrain, and then projects the image onto a screen in front of the cockpit simulator. The design concept of the system, which has been used by United Airlines and others, as well as Douglas, is shown in Figure 3.24.

The Mark IV system is described in the Molnar and Lybrand report (1). The vertical scale model, at a scale of 1:300, represents an area of terrain 21,000 feet long by 3000 feet wide, and depicts an airport, runways, and hangers. A television camera is directed at the model landscape to provide, through a projector, a visual reproduction on a screen of a scene which changes according to the trainee's manipulation of the cockpit controls. The camera is mounted on tracks which run parallel to the front of the model, and is driven by a drive mechanism which synchronizes movements of the camera to movements of the aircraft's

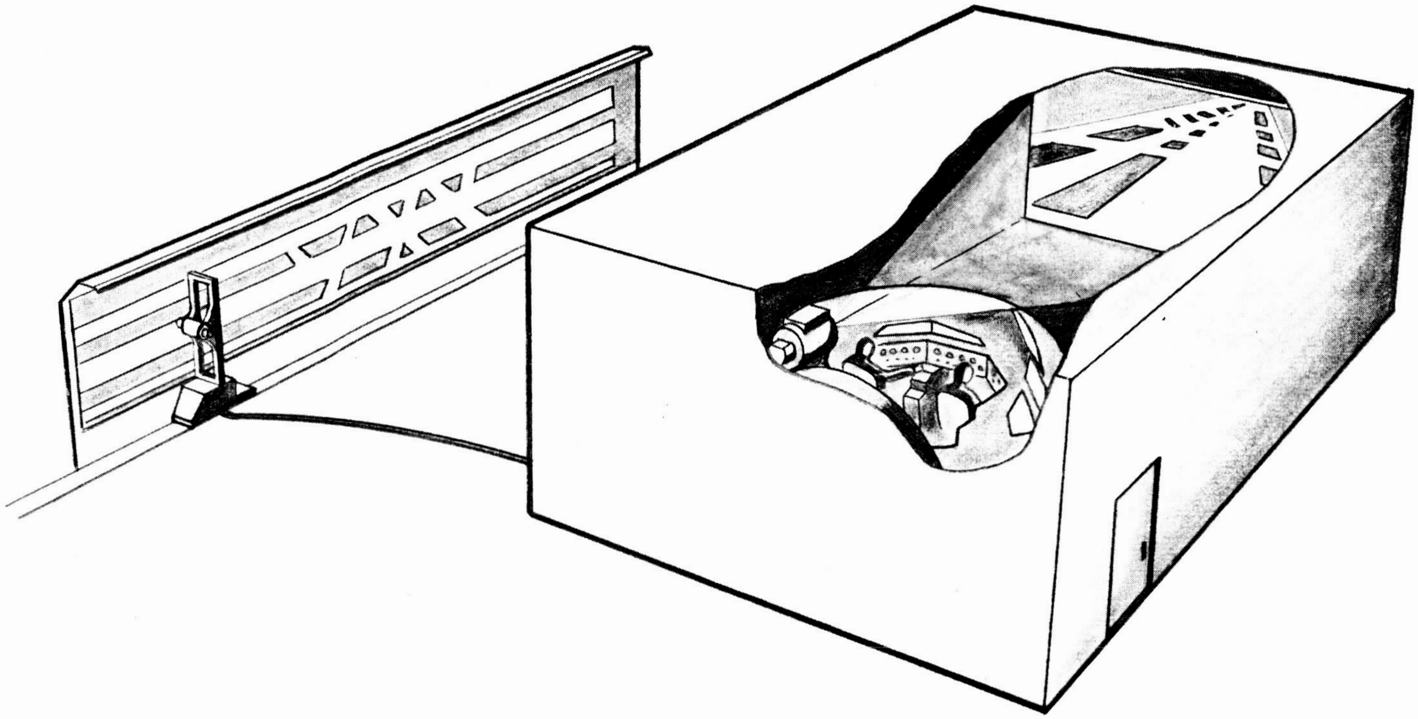


FIGURE 3-24 LINK VISUAL SYSTEM MARK IV AND IVA

controls.

The closed circuit projector is mounted in a fixed position directly over the trainee's head. The image is projected approximately 15 feet in front of the trainee on a 12 X 15 foot screen. The scene presented to the pilot subtends a horizontal field angle of 60°.

Controlled illumination simulates variations in daylight or night conditions. Aircraft landing lights for night landings are simulated by attached lights on the television camera.

A similar design concept is described in Klemperer's patent (23), assigned to Douglas Aircraft Company, for a visual simulator for flight training.

Clay reports that early television displays of this type were limited by low light output on the screen (4). To correct this, a light valve modification was considered by the company. Model size, continues Clay, more or less prohibits its use in a contact flight trainer. Other scales were reportedly tried, and it was found that the problems of mechanical stability and smoothness of change require a heavy and large setup.

Wise and Whittenburg (2) report additional disadvantages: poor imagery due to lack of depth of field of the camera lens, lack of perspective due to two-dimensional presentation, image quality limited by current TV techniques, and inadequate resolution due to model size. In order to eliminate such limitations, Link designed and built the Link Visual System, Mark IV A. This device provides a realistic visual environment for specific use in developing student pilot capability in take-off and landing maneuvers.

In general, the design concept for the Mark IV A system is the same as that employed in the Mark IV system, but the components have been designed with a greater degree of sophistication. An airport model is scanned with a television camera and the scene projected to a screen in front of a cockpit. The model is a vertically mounted representation of an airport complex, with 3D models affixed to a 2D terrain background. The use of 3D models enhances the realism in landing and taxiing. A 600:1 scale factor permits a total scaled area of 18,600 x 3,000 feet to be represented by a map 31 feet x 5 feet in size. Fluorescent lamps provide illumination for the model to simulate varying conditions of daylight, dusk and nighttime.

Command signals for the servo motor driven camera carriage gear assemblages are obtained from the dynamic flight simulator. Longitude, latitude, and altitude simulation are accomplished in this manner. Pitch, roll, and heading simulation are provided by rotation of optical elements in the camera head. The television camera is the GPL PA-505, or equivalent, which scans 525 lines per frame at 30 frames per second. Horizontal resolution of the TV system is 500 lines.

A Schmidt type projection system uses a GPL PB-611 A projector or equivalent. The screen projected field of view subtends approximately 45° horizontally at the pilot's eyepoint, or is equal to the TV camera field of view at the entrance pupil of the lens. The screen is located 12 feet ahead of the pilot.

There appears to be an apparent contradiction between the implied, improved resolution due to model size in the Mark IV A system, and the larger scale factor, resulting in smaller map dimensions. A more logical assumption would be that the Mark IV A system is being compared to another Link system, such as the Link Day/Night Visual Simulator Attachment, which utilizes a 3D replica of an airport complex mounted on a servo driven belt. The scale factor as here employed is 3000:1. In other words, models on the Mark IV A terrain board are five times larger than those used with the Day/Night Visual Simulator Attachment. The capacity for improved resolution is readily apparent.

c. Visual Simulator Attachment for F-104 Flight Simulator (Figure 3.25)

A visual simulator built by Canadian Aviation Electronics Ltd., Montreal, Canada, is described in two papers by P.M. Carey (24, 25).

The simulator was designed as an attachment for the F-104 flight simulator, developed for the NATO air forces. A non-programmed view projected on a screen in front of a pilot depicts what he would see from the aircraft in actual flight, giving him visual training in landings, take-offs, and tactical exercises.

The basic design concept used by CAE is shown in Figure 3.25. The visual system is built up around an analog model of the ground. An actual aerial photographic slide transparency of an area over which the simulated flight takes place stores the basic information containing the ground terrain. The slide is projected onto a "model" screen, - a 60-degree segment of a circle of 12 ft. radius - the image on the screen being a direct analog of the terrain to a certain scale. The screen is at an angle from the perpendicular to a scanning TV camera lens, which transforms the terrain image into a perspective image on the photocathode of the TV camera tube. The plane of the photocathode is inclined at an angle to the ground plane, this angle contributing to the amount of perspective distortion. The video signal which now contains the perspective distortion is cabled to a TV projector behind the cockpit. The perspective display is reproduced on a screen about 9 feet ahead of the windshield.

Simulated motions of the aircraft are managed by controlled movements of the TV camera (roll, pitch and attitude) and the terrain slide (aircraft heading). Servo information defining these parameters is generated by the flight computer and forms the input control signals to the visual system.

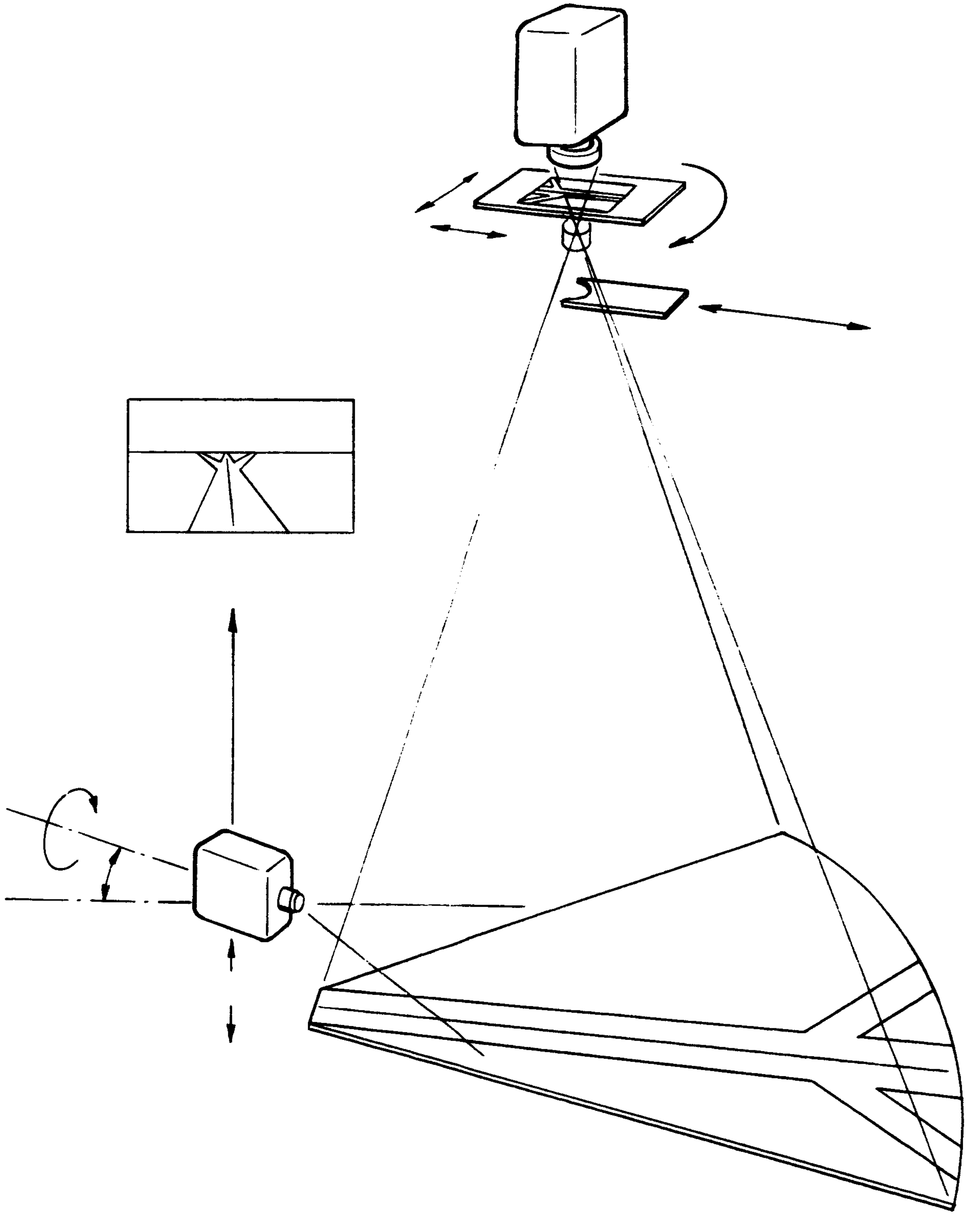


FIGURE 3-25 OPTICAL SYSTEM SCHEMATIC, VISUAL SIMULATOR ATTACHMENT

Aerial perspective is simulated by moving a diffusion plate in the light path of the projector, thus diffusing part of the terrain image. This, when viewed on the display, produces a realistic effect of the diffusion produced by the ground haze.

The TV camera lens operates at about f/12-f/14. The focal length of the lens is approximately 10 mm and the depth of focus extends from about 3 in. to 12 ft. within the resolution limitations of the vidicon. The TV projector uses Schmidt optics and a 5 inch Kinescope tube giving about 5 foot-lamberts brightness. Linear magnification of the TV image from vidicon face to pilot's display is 250 X. The perspective scaling is such that the pilot's display subtends the same angle at the pilot's eye as the real scene would from a real aircraft, which is required to be at least 60 degrees.

One assumption made in using this technique is that the earth is "plane". This means that buildings are not displayed in true perspective. This error only shows up when the aircraft is low enough to see the side of a building. Under this condition, according to Carey (24), the buildings are far enough away from the runway that the error is not noticeable. He states that other advantages, mainly the freedom of aircraft movements and slide-changing facilities, outweigh the small disadvantage.

d. Miscellaneous TV Displays

Many other visual simulator devices have been built or are in the developmental/proposal stage which are similar in design concept to the TV displays which have been discussed above. Systems currently in use which utilize a terrain model mounted on an endless belt, with the camera probe scanning the surface of the model, include: Dalto Low Visibility Simulator Attachment, Mark III Series (2); Fairchild Stratos Corporation's Trainer Attachment, Visual Simulator SMK 22/F37A-T (26); and Visual Flight Simulator (V.F.S.) (27), built by General Precision Systems Ltd., Aylesbury, Bucks., England. The first-named, sometimes referred to as Doman Approach Landing and Takeoff Simulator (DALTO) (5), was inspected by the Farrand research team at Federal Aviation Agency, Atlantic City, New Jersey. Observer read-out presentation is on a flat screen approximately 15 feet in front of a trainer cockpit. The display lacks sophistication compared to later model simulators. Resolution is low, and screen contrast is very poor.

Some devices make use of curved projection screens for brighter displays and larger fields of view. The Carrier Landing Trainer, Device 12-BK-5 and 12-BK-5a (28, 29) started by the Engineering and Research

Corporation and later completed by the National Scientific Laboratory, was built as a trainer for instructing student pilots in landing an SNJ basic trainer on an aircraft carrier deck. This was the first time that a television system was used to pick up the information generated by a scale model (4). It also illustrates the electronic mixing of display components. Two TV projectors produce a seascape image of 110°, overlapping slightly near the center line, on a spherical screen around the cockpit. Another camera is used to electronically insert the picture of the carrier into the seascape.

Several proposed systems using this approach are described by Wise and Whittenburg (2). The Goodyear Aircraft Corporation has proposed three versions of a Visual Simulation System which utilize ellipsoidal projection screens for directing the light reflected from the screen to the observer. The screens used in these systems are constructed of fiberglass with a special reflective semispecular material on the reflective surface, providing high gain characteristics. Two of the displays are black and white presentations, providing landing and take-off scenes to a trainee over a fairly wide field of view. The third system uses dual-camera projector equipment to project two color pictures on the semi-specular screen, giving a pilot and co-pilot individual pictures with true perspective. Each observer views his own color picture with a brightness of 40 foot lamberts on the screen. The field of view is 130 degrees horizontal by 80 degrees vertically.

Another Goodyear design concept, the Flight-Simulator Visual Display System, utilizes a servoed 35 mm continuous film projector to project an ocean-water scene onto a screen surface that is an extension of a horizontal terrain model. A mechanized TV camera views the 3D terrain model, converts the scene to electrical signals, and feeds these signals to a TV projection system for black and white presentation on a semispecular curved screen.

In a private communication, Goodyear described an automobile driving simulator test model that was recently completed under a contract with the U.S. Department of Health, Education and Welfare. The automobile driving simulator operates in real time. The visual scene is generated by a servo-controlled optical probe moving over a three-dimensional relief model . A closed circuit television system provides the relay link between the generation system and the display. It operates with 675 scan lines and has a system bandwidth of 10 megacycles. The scene is projected onto a large curved screen positioned a few feet in front of a standard size automobile. The 9 ft. by 12 ft. screen is a rigid structure of exceptionally light weight. The semi-specular characteristics of the screen offer a gain of 22 with an effective exit pupil of 2 ft. A test and evaluation program is presently being conducted by

GAC Human Factors scientists, to determine its adequacy for driving behaviour research.

7. Synthetic Image Generation Displays (Figure 3-26)

a. Link Night Landing Display

This device, which is used in research by the Flight Control Laboratory at Aeronautical Systems Division, Wright-Patterson Air Force Base, Ohio, has been described by Doty, et al (11), Wise, et al (2), and Clay (4). It uses the electronic abstract variation of the synthetic image generation technique in a completely non-programmed, all-electronic visual display system, the purpose of which is to train pilots in proper approach and landing techniques under nighttime conditions. The system concept is described in a patent by J.R. Mailhot (30), assigned to General Precision, Inc.

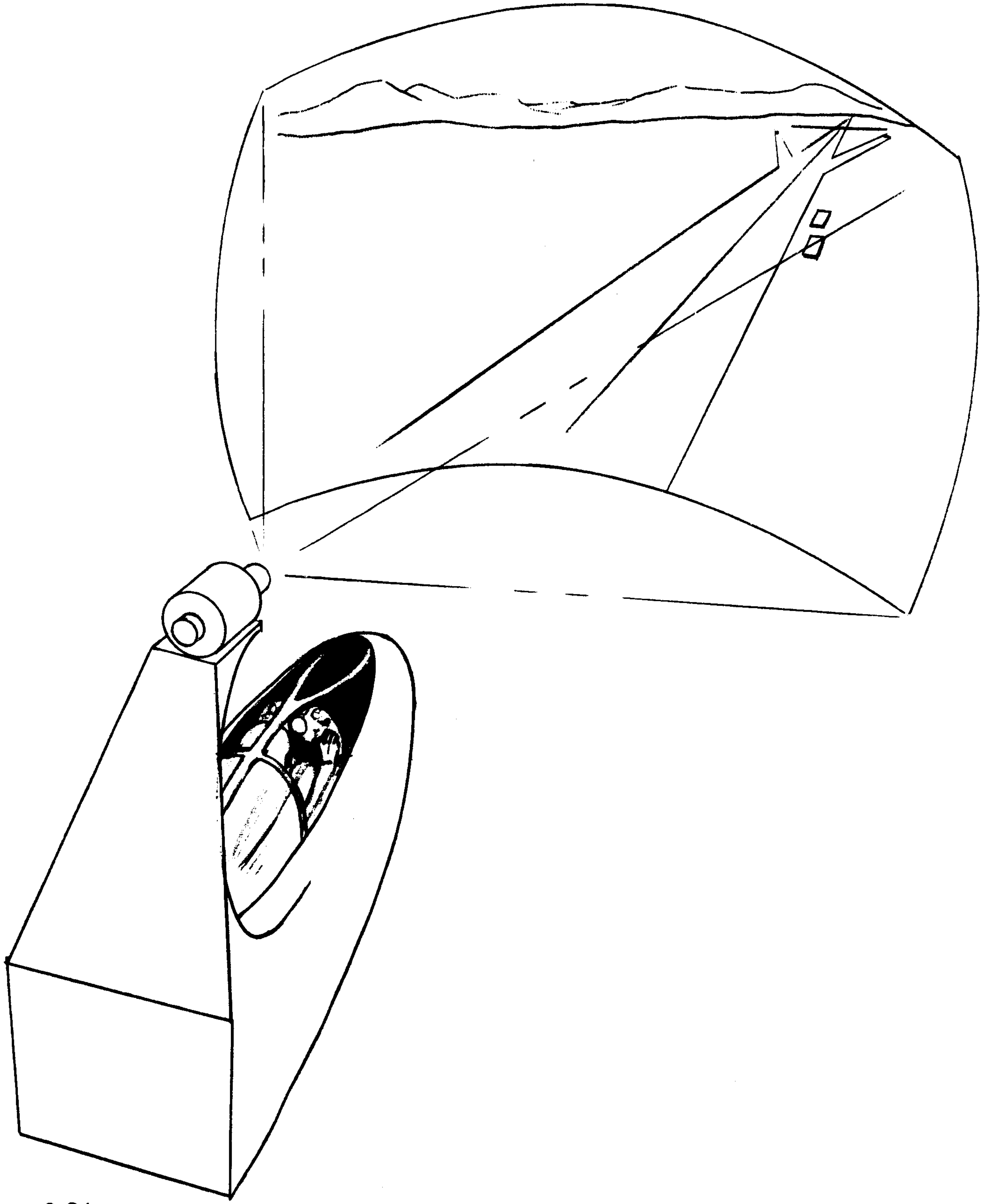
A conventional TV monitor is used in conjunction with a number of analog and digital computing elements to produce an airport lighting pattern. The position of each runway light and approach light in a basic rectangular pattern is stored as a pair of values in a resistor matrix. The changes in size and shape of the basic pattern of lights which result from changes in the relative position of the simulated aircraft with respect to the runway are computed and applied to the basic pattern before it is displayed. Angular changes in pitch and yaw are simulated by moving the whole pattern left and right and up and down on the cathode ray tube.

Roll is simulated by rotating the yokes which rotate the picture.

Observer read-out is presented at the proper scale on a standard 27-inch television monitor located just forward of the windshield of a trainer cockpit. The presentation can also be projected onto a screen by using a Schmidt projection system, if the requirement is established (Figure 3-26). The presentation is in black and white, although, as reported by Wise, et al, studies have been made by Link to determine the feasibility of incorporating a color display using a Lawrence signal gun color tube. Positive results were obtained.

In this system, fog and haze are realistically simulated by continuous variation of light intensity as a function of distance. Dynamic effects such as strobe lights are introduced by additional matrices and switching circuits. Because this device does not employ physical models or an optical pickup, it is relatively easy to achieve large maximum ranges and touchdown at low levels. The video signals used are simply computer pulses not requiring the large amplifications used in television. As a result, the runway and approach lights are sharp, clean spots of light, and the background remains black.

This system offers a choice of three different representative airport lighting patterns which are simulated by simply exchanging some of the printed circuit computer cards. Doty, et al state that it is highly probable



3.96

FIGURE 3-26 LINK NIGHT LANDING DISPLAY

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that formalized representation of terrain could be included without incurring unacceptable memory capacity requirements. They cite the ANIP program which showed that representations of farmland could be achieved readily.

In an earlier report, Clay, et al say that practically no daytime contact flight applications are possible since computation is restricted to specific kinds of configurations. However, they add, Link investigated the possibility of combining the approach with certain analog circuits. Potential applications were seen for situations where simple contact analogs would be applicable (helicopters, submarines) and/or where target and aiming practice depend on few salient features of the overall visual situation.

C. IMAGE GENERATION END

There exist eight basic methods of generating an image for input to the display end of a visual simulator. Whether the simulated scene applies to aircraft flight or to spaceflight the response time in the generation equipment is a function of the vehicle dynamic response. In any case the overall response is the sum of the vehicle dynamic response and the pilot's response. In almost every visual simulator this overall response is well within one second of time. The so-called real time system requirement narrows the choice of a suitable image generation system to one of the eight fundamental generating systems. In addition to real time response the image generator should in most cases provide six degrees of freedom or in other words the visual display must furnish an unprogrammed flight capability. This additional stipulation narrows the choice amongst the eight fundamental generating means currently available even further. Another consideration that may additionally narrow the selection of a suitable generating means lies in the mapping requirements that must be met between the image generating output and the input to the visual display system. This portion of the report will attempt to outline not only the various image generating means but also their most suitable application. The eight fundamental generating means may be classed as follows:

1. Film
2. Point Light Source
3. Model Plus Optical System
4. Epidiascopic Model Projection
5. Model Plus TV
6. Film or Film Projection Plus TV
7. Computation of Pictorial Elements Technique
8. Mosaic Techniques Plus TV

These techniques are not listed in any order of preference. However, all systems employing TV techniques are placed last in the list since the literature on these systems is voluminous and as a result, examination of various approaches employing TV must of necessity be lengthy. The paragraphs that follow will describe each of the systems and their limitations enumerated above.

1. Film Techniques (Figures 3-27 and 3-28)

Two fundamental techniques utilizing film have been explored in the past. These techniques may be classified as static and dynamic modes. In the dynamic or non-programmed mode where the film is used as a storage means, an optical probe coupled to a movie camera is flown during an actual simulator run over a model. The film is then processed, transported to a motion picture projector, and then projected on a display screen feeding the visual simulator. Although this technique results in true perspective, the time lag resulting from film development, drying and transportation to the projector is much too long for most vehicles in use today. The fastest available black and white film takes at least two seconds for development and detracts from the overall scene because the color cue is lacking. Any available color film is out of the question because of the complex and lengthy development required. In any case the dynamic mode film technique requires a full scale model and optical system equivalent to that used by the closed circuit T.V. systems. Since TV systems have an infinitesimally small real time response they are to be preferred at this time albeit their resolution is substantially less than black and white film.

The static film technique mode utilizes a movie camera which is flown over actual terrain making an ideal record for the particular flight. If this scene is projected onto a screen or into the input end of a virtual image system the result is a full color high resolution visual simulation. However, the simulated flight is tied to the actual path flown by the recording aircraft. There have been various attempts made to alter the programmed scene as a function of the simulator flight controls. All of these systems change the apparent perspective of the visual presentation over limited ranges through the use of a variable power lens and anamorphic attachments (7, 8). In detail, the restrictions created by the programmed nature of the film comprise perspective, altitude and speed. For example, even if the film-taking aircraft is equipped with a camera whose frame rate is extremely high there is a speed variation imposed on the final presentation which is bounded by a minimum of 20 frames per second (flicker fusion frequency) and the maximum velocity of intermittent film transport as well as maximum storage capabilities of projectors. Alteration of the perspective point in accordance with lateral translation is also a limitation although this can usually be overcome by other techniques (Section VII of this report).

The altitude variation presents a more serious problem since any altitude change requires more or less detail to be visible through the constant field of view afforded by the display system to the pilot. If a single frame of the movie film represents the full field of view instantaneously available to the pilot then an increase in altitude would require additional picture area to maintain the same instantaneous field of view and since none is available, the field of view would dimish. Arguments in favor of this technique include full color capability, good resolution and high luminence. Systems which have used the movie film approach include Bell Aircraft Company's Bellarama (4, 5), the Link Mark I Visual System (VAMP), and the Link Mark II Visual System.

The Farrand Optical Company utilizes film in a system named the Mission Effects Projector which is capable of providing views of the Earth or Moon from the subsatellite point out to the horizon in full color and with proper perspective. In addition, lateral or off-course travel of up to 5° measured from the center of the Earth or Moon can be simulated. There is no limitation on the variation of speed since the color film is of the continuous film strip variety and no framing limitations exists. Altitude variations are not limited by zooming lenses alone and the ratios achievable are infinite. This simulation therefore is not of the "canned" or programmed type.

Although the film strips supply two dimensional views, the projection system imparts a three-dimensional, spherical effect to the scene. The optical system recreates from a flat film strip the sphericity and perspective of the spherical globe as a function of the variation in altitude and the angle of "look" up from the nadir. The principle of providing the required distortion is illustrated in figure 3-27 where a simple negative element is used to distort a rectangular grid into an apparent sphere.

The projection is focussed on a screen which is located at one of the inputs of the virtual image visual display system. The size of the screen together with other optical parameters of the visual display system define the instantaneous field of view provided to the observer. Even though the instantanteous field of view is, for example, $80^{\circ} \times 110^{\circ}$, views from horizon to horizon at the lower altitudes are provided by the scanning system in the Mission Effects Projector which translates the projected scene on the screen in accordance with vehicle angular motions. The scanning system and the Mission Effects Projector are illustrated in Figure 3-28.

Orbital rates are simulated by driving the film along its longitudinal axis while lateral translations are accomplished by driving the film cassettes normal to the longitudinal axis of the film. The distortion required to simulate the sphericity of the Earth or Moon and the resulting "perspective or keystone" distortion when scanning towards the horizon is provided by optical elements located near the film plane, in one of the relay lenses and in the projection lens. It will be noted that the Mission Effects Projector consists of two film inputs with each input containing one or more cassettes. Each cassette contains a continuous film strip of orbital views repeated at different scales. Each projection leg immediately following the cassettes contains a varifocal lens assembly. When one of the cassettes is being used for projection, variations in altitude through a given range are accomplished by driving the varifocal lens through its range. When the limit of this varifocal lens and film scale is being approached, the second cassette positions the succeeding film strip (of the next scale to be used) to coincide with the subsatellite point on the film strip in use. At the same time the alternate varifocal lens is driven to either limit of its range depending on whether the vehicle is ascending or descending. At a time before the limits of the film strip and varifocal lens in use are reached the quick dissolve film illumination mirrors are driven to direct the alternate views into the projection system.

It should be noted from the illustration that the quick dissolve mirrors are not at or near a focal plane so that the switching procedure does not introduce any discontinuity. The drawing adequately describes the scanning system used to achieve the effect of vehicle motion. Also evident is the day-night terminator assembly which permits the simulation of the terminator and the dark side of the Earth or Moon. The upper portion of the illustration reveals a second illumination and varifocal lens assembly. This system projects moving solid cloud cover into the scene. The film strip assembly used to accomplish this has not been shown, in order to simplify the illustration. Since cloud cover is used to define the horizon of the Earth, a servo driven zoom lens creates a variable size image of a horizon mask. This horizon mask serves another purpose. Hidden behind the diaphragm, colored transparent annular rings are positioned so that when the mask is opened slightly on computer command the colors of a sunrise or sunset will be projected through the system and superimposed on the cloud cover at the horizon. Mission Effects Projectors are included on the Edwards Space Flight Simulator, the Apollo Mission Simulators, and the LEM Visual Simulators.

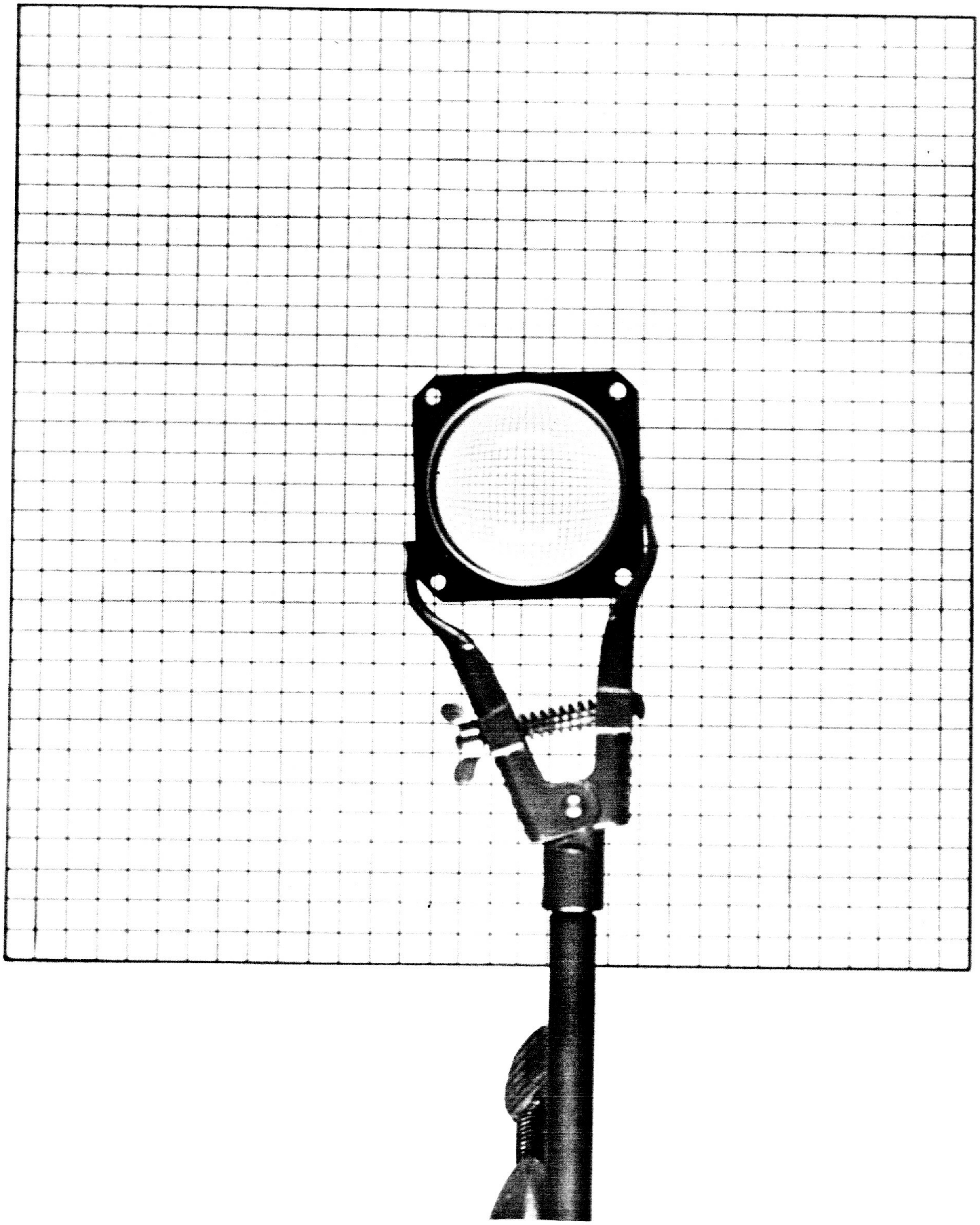


FIGURE 3-27 DISTORTION LENS

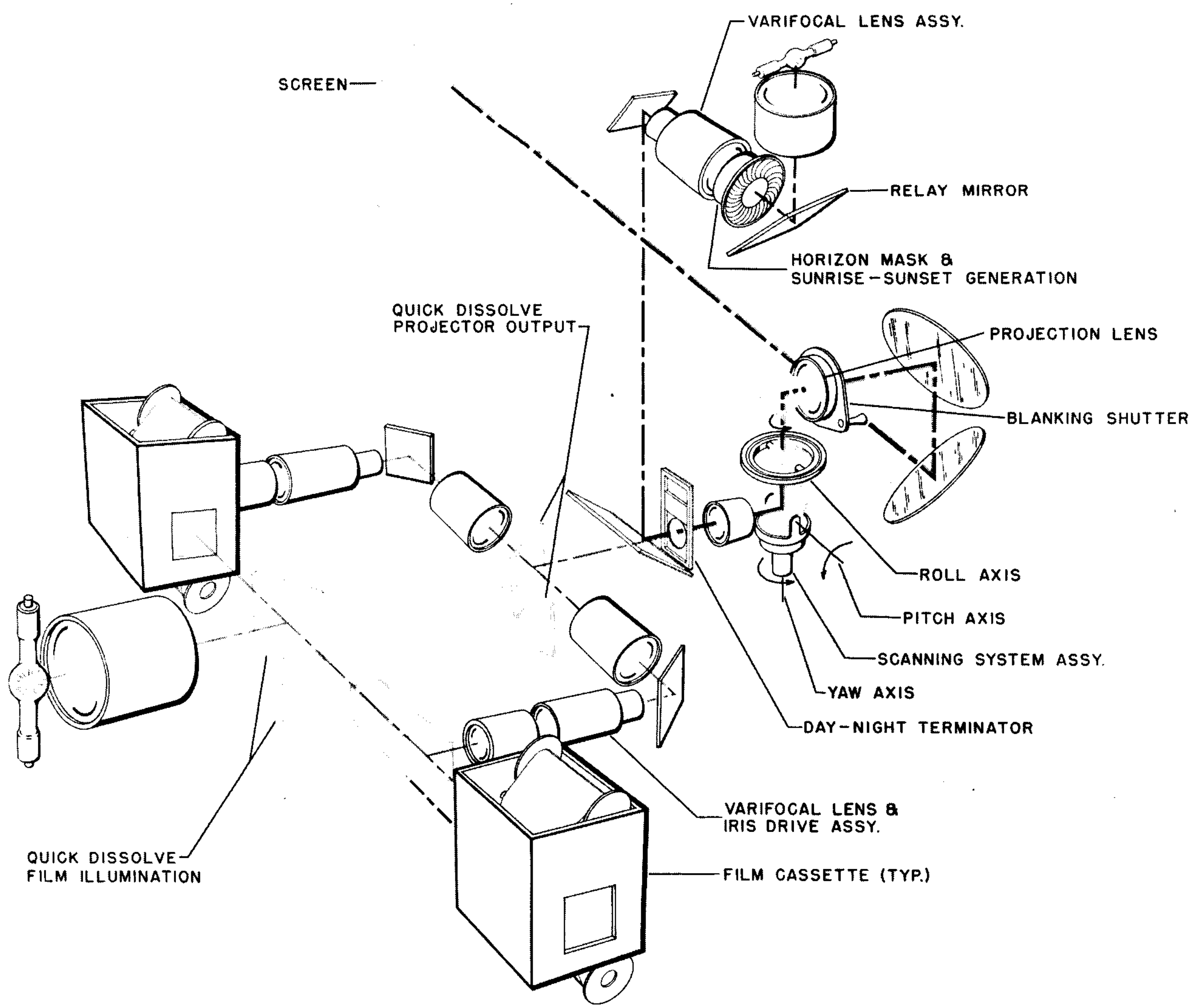


FIGURE 3-28 MISSION EFFECTS PROJECTOR

2. Point Light Source

The point light source technique of image generation as applied to the Helicopter Flight Simulator, Device 2-FH-2 has been explained in the previous section (see figure 3-21). This system images a transparency on a screen by means of an intense point source of light. Edge rays emanating at diametrically opposite edges of the source pass through an image point in the transparent model and this point is imaged on the screen by the diverging rays. The smaller the angle subtended at the image point by the diameter of the source, the higher the resolution at the screen. It is obvious then, that on the one hand we require a large source for brightness of the projected image on the screen while on the other hand an infinitely small source is required for image sharpness. These are two conflicting requirements which must be compromised to achieve an acceptable display in terms of brightness and resolution. The same analysis holds when one requires magnification or minification of the projected scene since the light source must be made either to approach the model (magnification) or to recede from the model (minification). This is a fundamental limitation since the development of higher brightness in point light sources has reached the point of diminishing returns with respect to development effort. In view of the fact that even the older, larger sources with greater total flux output provided marginal illumination it appears that the point light source technique is limited in scope unless there is a breakthrough in the development of point light sources which will increase the total flux output by several orders of magnitude without an increase of source diameter. This image generation technique however, does provide a degree of realism that is superior to most screen presentations because of the realistic perspective that is achieved, the range of magnification that is available, the realistic aspect of terrain and buildings attainable with transparent three-dimensional models and because of the color that is available. In addition to the disadvantages previously mentioned, one must also consider the rather limited flying area that is feasible with such a system because of the required scale and the limited volumetric clearance above the observer's head. These last limitations presently restrict the use of point light source image generators to flight simulation from helicopters or other VTOL craft as well as hover and landing simulators for Lunar missions.

With the advent of the relatively new virtual image display system configurations it may be possible to inject the generated image directly into the input of an infinity display system. Such a device would add to the realism of current point source visual display systems since the aspect point would no longer need to be placed close to the pilot's eye position but rather could be located directly on the optical axis of the display system at the input end by interposing a rear projection screen between the generator and the input focal surface. Scene brightness would still be present as the most significant disadvantage of such a system.

3. Model Plus Optical System (Figures 3-29, 3-30)

In this approach to visual simulation the pilot observes a model scene directly through an optical system such as a periscopic eyepiece instrument or a large exit pupil infinity display system. The realism of such a device depends directly on the realism of the model. The optical system does not, generally speaking, degrade the presentation. In addition, full color is available to the observer. Systems of the periscopic eyepiece type are generally suited to visual simulators for vehicles which contain the pilot in an enclosed environment such as tanks, submarines, armored vehicles, etc. Since translational and rotational motions are usually simulated by actuating the model, it is necessary for this type of simulator to drive either the model or some form of scanning head in the periscope. Since the observer's entrance pupils are in effect translated to the entrance pupil of the instrument, the scale of the model must be designed in accordance with his minimum simulated altitude whether this be an aircraft or a land vehicle. On this basis, scale becomes a problem because the clearance required by a scanning head tends to establish a rather large minimal height for the scale altitude of the observer's eye position. The model then becomes large if the simulated flight must belong or if the driving simulation extends for long periods. Illumination of the model may also be troublesome, since the amount of transmitted light through the usually complex optical system is low. An additional disadvantage with such systems is that the observer or pilot is tied to the eyepiece of the simulator. Hence his freedom of movement is severely restricted and he must remove his head from the eyepiece to observe any instrumentation that may be required. A singular attempt to overcome this restriction has been developed and is known as the Tank Platoon Leader Trainer Device 17-AR-1 (Ref. 9). This system imposes a head set on the observer which servoes the exit pupil of the sight in accordance with the observer's head movements. Response time of the servo system is never adequate to successfully follow all possible and natural eye movements which usually occur in addition to head movements.

Other simulators of the periscope eyepiece type include the Farrand Contact Flight Simulator Device 14-L-2 and the Oxford Corp. Carrier Landing Flight Simulator.

An alternate approach to direct model viewing has been made available with the development of large exit pupil long eye relief infinity image systems of the types fabricated by this contractor and listed in Table I. In devices of this type the pilot or observer is no longer restricted by an eyepiece type of device, however, a large exit pupil display end cannot practically employ a model of terrain in cases where variations in altitude must take place. The entrance pupil of such a system would be gigantic in size and the usual scaling problem of the model applies in this case. In other words, the model size and illumination requirement approaches the real world. One notable exception exists and this involves a model of the celestial sphere. In this case all projected images are point sources and they are retained at infinity focus. Hence there is no variation in magnification required. This type of image generation technique, developed by the Farrand Optical Company, allows all stars to be depicted as true point sources and by properly mapping their location on the input focal surface, interstellar angles are preserved over the very wide fields of view. The focal surface for the star field generation is spherical so that a complete sphere is used to simulate the heavens. On the sphere there are included approximately 1,000 stars located to an accuracy of better than 1 milliradian. The total number of stars includes 57 navigational stars and several of the "red" stars. All stars are simulated by highly reflective bearing balls imbedded in a black matte surface. The red stars are gold plated to simulate the proper spectral output. This so-called celestial sphere is suspended in an 8-ball type of gimballing system. The suspension system never permits any of the gimbal structure to be seen by the optical system. The Celestial Sphere is painted a matte black so that only the reflecting balls are visible when the sphere is illuminated by a light source. Figure 3-29 illustrates three completed Celestial Spheres. Although the star field appears on the surface of the sphere, the observer is effectively located at its center, looking out. This is accomplished by means of an optical inversion due to the reimaging mirror of the display system. In this manner, as the stars move across the field of view inter-stellar angles are preserved. Stellar magnitudes are simulated by variable size balls, of which, even the largest of these ball diameters projects a true point source star, even under magnification.

A true point source star is achieved as follows: Referring to figure 3-30, a point source of light is located at a large distance L from the reflective ball. The reflective ball forms an image of the illuminating source at a distance $\frac{R}{2}$ from its center thus the virtual image of the point light source is further minified by the ratio of $\frac{R/2}{L}$.

In accomplishing this minification, it is evident from the illustration that the virtual image is now visible through an angle θ. In other words, all of the balls illuminated by the single point light source will be visible from any position within the exit pupil out to the edges of the field of view without any visible brightness loss.

The celestial sphere is driven by torque motors which permit the achievement of driving rates as low as a fraction of Earth's rate without any perceptible jitter. Adding to this realism there has been developed an occulting system working in conjunction with the illuminating source of the celestial sphere. This system is shown schematically in the lower right hand portion of figure 3-30. Two occulting assemblies are illustrated. These consist of variable size opaque discs that are translated in X and Y in the collimated bundle collected from the illuminating source which is used to light the stars on the celestial sphere. These opaque discs are made to simulate the apparent diameter of a planetary body or target vehicle and as such they occult the illumination of "stars" in that portion of the celestial sphere.

4. Epidiascopic Model Projection

The Epidiascopic principle of projection is a straight forward projection system that utilizes an opaque model in the focal plane of a projection lens. The required degrees of freedom in rotation and translation are usually achieved by scanning the model with a mirror

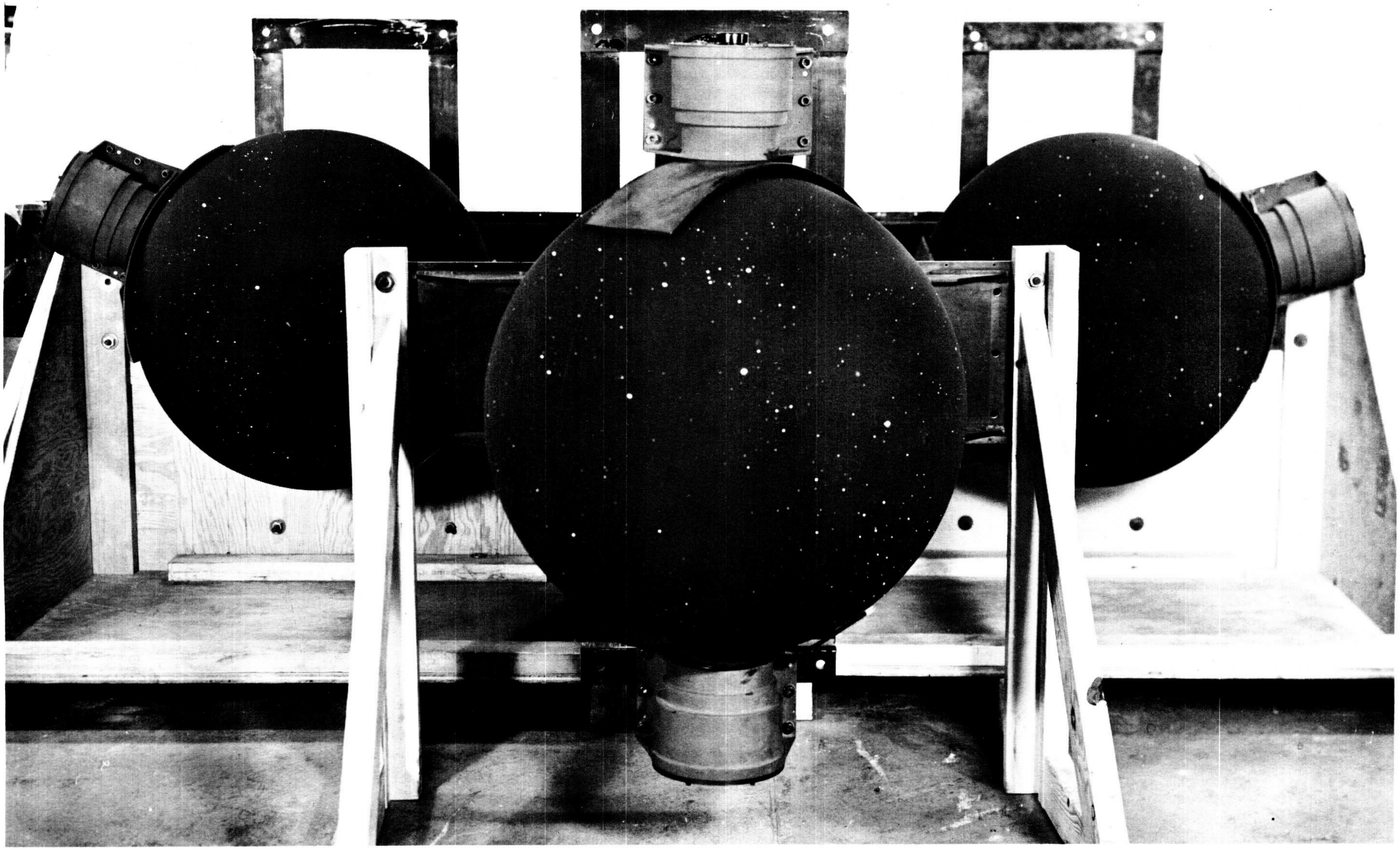


FIGURE 3-29 CELESTIAL SPHERES

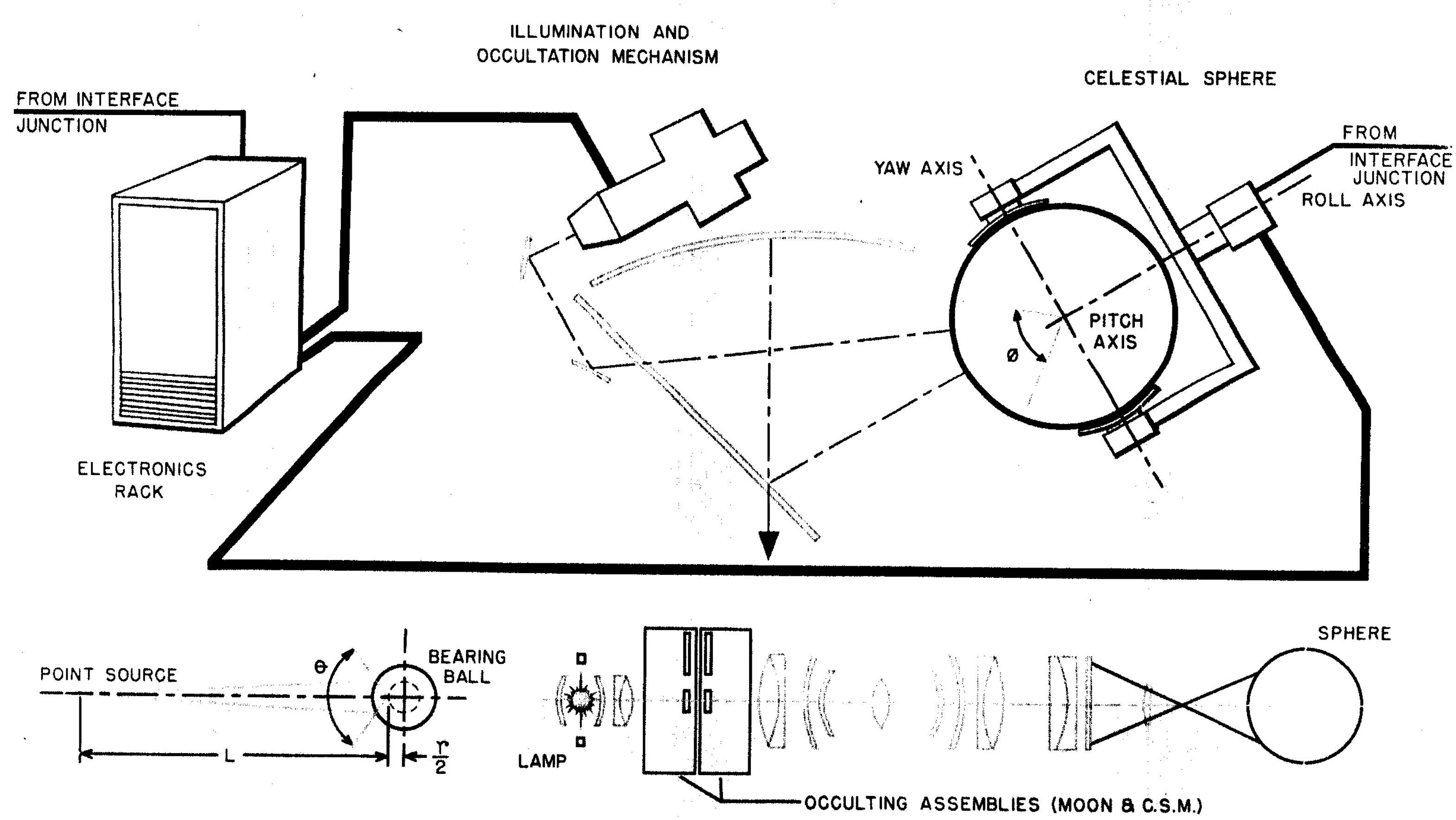


FIGURE 3-30 CELESTIAL SPHERE SYSTEM

or prism type of scanning head. In some cases where the model is relatively small, such as an individual aircraft or a ship, the model itself is moved in the focal plane. Epidiascopic systems function by reflected light and therefore the luminence of the final image at the screen is usually very low. The efficiency of such a system is so low that any attempts to increase the final scene brightness demand so much illumination on the model that heat absorption is a real problem. Resolution is good and color is fairly well reproduced if the proper reflective paints are used. In order to use a 3-dimensional model the optical pick-up must have good depth of field which in turn limits the f/no. and therefore fails to make maximum use of the illumination reflected from the model. The additional requirement for scanning where the model plane is tilted with respect to the optical axis of the pickup imposes an even more severe requirement for depth of field in order to project an image that is maintained in focus across the field of view satisfactorily, although recent Farrand Optical Company probe systems have overcome this limitation. (Section 6 of this report). Even if all of these limitations can be overcome there still remains a serious limitation involving altitude variations. When the range of altitude varies beyond the capability of the variable magnification optical system it is necessary to substitute or to switch models of a different scale into the field of view in order to maintain the continuity of the visual scene. The necessity for providing a variety of models of different scales makes the simulator somewhat cumbersome because of the size and switching means that must be provided. In general then, epidiascopic projection systems using 3-dimensional models are inefficient systems from the illumination or brightness point of view although they provide acceptable resolution, perspective and color reproduction. They are also limited in simulated maneuverability because of the difficulty in achieving desired magnification ratios. Examples of such systems constructed in the past include Rheem's Visual Attachment For Aircraft Flight Simulator (I) and the Austin Company's Torpedo and Rocket Attach Trainer Device 143B.

D. Electronic Image Generation Techniques

Under Part C of Section III there are 8 basic techniques of image generation that were listed by class. The first four (4) have been described as techniques that use no electronic circuitry in the image generation function. The remaining four categories employ some electronic means of generation including the pick up end and the display end of a generator. Because of the permutations and combinations that are possible between the signal acquisition end of an electronic image generation system and the display end of such a system it has been decided that all possibilities for achieving these separate functions (signal acquisition and signal display) will be examined in detail in logical sequence and that recommendations for the optimum combinations will be made at the end of this section. The four basic electronic image generating means that will be covered by the following paragraphs represent the following items:

- Model Plus TV
- Film or Film Projection Plus TV
- Computation of Pictorial Elements Technique
- Mosaic Techniques Plus TV

The discussion on electronic image generation must of necessity make reference to several technical papers. In order to provide ready access to these references, they have been included in this volume of the report at the end of this section.

1. Quality of Electronic Image Generation:

1.1 Subjective Factors

In the first group of considerations there should be listed those properties which one intuitively expects to be associated with any critical observer or observation device. These are the factors which contribute to "fidelity" and which should be capable of being measured on a set of objective scales. Such factors would include, for example,

A high degree of Sharpness

Lack of Noise

Lack of Flicker

True representation of color

True representation of tonal scale

Proper brightness

Not all of these criteria can be met perfectly in any simulation, and in a simulator based on television the restrictions are often quite severe. Nonetheless, an attempt must be made to evaluate and rate these factors in an objective manner if systems are to be compared sensibly and if tradeoffs among the factors are to be considered intelligently. Objective rating systems for images are covered in detail in several of the following sections of this report.

The second group of characteristics are psychophysical factors (W-1, B-1) which may be cleverly exploited in human observers in order to reduce equipment complexity or cost, or to improve apparent performance by taking advantage of certain unique properties of the human sensory system. Several of these properties are:

Fine picture detail is not seen in color . (Refer. F-5)

Fine detail is not seen in moving subjects. (Refer. S-9)

Smooth motion is observed even if only intermittent pictures are shown, provided there is no flicker.

The eye is greatly sensitive to brightness and contrast changes, while a very poor judge of brightness itself. (Ref. A-1)

Of these, the first is used as the basis for commercial color television, and permits full color to be transmitted at no increase in bandwidth over that needed monochrome TV. The third is the basis for the motion picture and television industries.

The first group of characteristics defines what "is really there" while the second pertains to what can be omitted from the presentation without being missed.

If a coherent analytical approach is to be made to the problems of defining a simulator TV system, a set of measures and techniques must be contrived by which the properties in the first group above can be defined and evaluated. As they are stated these properties are interdependent. However, Schade (References S-7, S-8) has shown that three independent objective parameters are sufficient to specify the characteristics which are usually meant when we refer to "Image Quality". Much of the section that follows is based on his work.

The second group, or the psychophysical characteristics will not be further discussed in this section. These are mentioned in passing in a later section on "computation of pictorial elements", and the subject is further elaborated on in the recommendations portion of this section.

1.2 Image Quality (S-7, S-8)

1.2.1 General

The problem of specifying image quality and the selection of units for this measurement should be considered as a universal one, in which optical and photographic elements are considered in addition to the electrical components applicable to television. Certainly the objective criteria must give results in general agreement with subjective impressions, and there should be ready explanations for any radical differences.

It has long been recognized that there is a limit to the degree of fineness of detail that can be observed in an optical image produced by any system, and that this limit, called the resolving power limit, is not the same for all systems. For a long time the quality of an optical system was expressed in terms of this measured or estimated "resolution limit". It was concurrently recognized, however, that sometimes an optical system that could image very fine detail would not produce as generally satisfactory an image as one that reached its limit when the detail was somewhat coarser. (Ref. S-7, S-8) The limit method of rating optical systems was for this reason never considered very satisfactory. In spite of this it was not until after about 1946 that more satisfactory methods of measuring and expressing the quality of systems and images were developed. These improvements came largely as a result of the appearance of new tools, techniques, and demands brought about by television. They have led to many highly technical and mathematical discussions of lenses and images in terms that are new and strange to those who are concerned with the problems of optical system application. It is one of the aims of this discussion to convey the sense of these new approaches to optical system and image evaluation without involving the mathematical complications which tend to make the subject unintelligible to most users of optical systems.

The quality of a device or system transmitting information of any kind (code, sound, or picture, etc.) can be specified in objective units by three fundamental characteristics:

1) The transfer or linearity characteristic

2) The fluctuation or "noise" level

3) The sine-wave response characteristic, including phase distortion when applicable.

Subjective impressions which would seem to correspond to these characteristics in optical systems are

1) Gradation and tonal range

2) Graininess

3) Sharpness.

These impressions are not direct equivalents, however, because they represent combinations of the three objective characteristics.

For example, the subjective judgment of tone, range, and gradation in an image is influenced by sharpness and graininess because the eye's ability to judge a gradual change of brightness or differences in brightness in nonadjacent areas is very poor, hardly better than two to one. The eye is capable, however, of detecting brightness differences in a step transition between adjacent areas as little as one-half of one per cent when the transition is "sharp", meaning normally that the "frequency" response in the image is high and the fluctuation level (graininess) is low.

The impression of graininess depends likewise on two objective characteristics: The signal-to-deviation ratio and the sine-wave response characteristic. The signal-to-deviation ratio specifies the rms value of the magnitude of optical random deviations (or electrical "noise") from a normal "signal" level. Optical deviations in an image area are deviations in luminance distributed at random in the image frame and occurring at random time intervals in any one small area of a "live" image in which they produce the appearance of a moving granular structure. The visibility and appearance of the fluctuating grain structure depend not only on the intensity, i.e., the rms value of the fluctuating grain area but also on the overall sine-wave response characteristic of the system following the point of "noise" insertion.

A judgment of sharpness is influenced by graininess and by the absolute amplitude (contrast) of the brightness step representing an edge. The optical sine-wave response characteristic is a relative measure of the Fourier components determining shape and length of transitions while the transfer characteristic determines amplitudes, contrast and other effects such as waveform distortion or rectification when the transfer characteristic is nonlinear. This separation is logical because it is well known that the transfer characteristic of an element or system is generally not controlled by the same parameters which determine the sine-wave response of the system.

This short discussion illustrates the important fact that a visual comparison of quality in two images does not permit a clean-cut separation in terms of the three objective parameters: transfer characteristic, sine-wave response, and deviation level.

An objective specification of image quality is, in principle, a precise description of the light flux distribution in the image relative to the light flux distribution in the original object or scene. A luminous object can be considered as a three-dimensional arrangement of an infinite number of point sources of light, varying in intensity as a function of the subject material. An image-forming device or system attempts to reproduce this light point distribution as a two-dimensional projection.

No real image-forming device can reproduce a point-source of light (such as a star) exactly as a mathematical point. The actual point-image (the image produced from a point-source of light by a real system) has finite dimensions and its geometry (i.e., its size and shape) and intensity distribution determine the definition in the image. (Ref.S-7, S-8) It is immaterial whether the point-images in a frame area are formed simultaneously or in sequence, provided the entire frame area is reproduced within a suitable time. The accuracy of reproduction can, therefore, be analyzed by examining the characteristics of an aggregate of point-images, or of a single point-image in successive stages of an imaging process, such as a photographic or television system.

1.2.2 Transfer Characteristic

The general relation of light or "signal" intensity in the image as a function of the corresponding intensity in the object is described by a transfer characteristic. Depending on the nature of the system element, the quantities related by the transfer characteristic are intensities of optical and/or electrical "signals". The transfer characteristic of a lens, for example, relates the light intensities in the image and object; the sensitometric curve of photographic film is a transfer characteristic relating the silver density in the developed film to the film exposure (light intensity x time). The transfer characteristics of television camera tubes show the magnitude of electrical signal currents as a function of light exposure and so on.

The transfer characteristic of a system is readily constructed from characteristics of its components and is usually shown in log-log coordinates.

It is readily appreciated that the transfer characteristic specifies the total contrast range which can be obtained in the image as well as any particular ratio of light intensities (contrast) in an object when it is reproduced or "transferred" by an imaging device or system. In fact, it specifies the general accuracy of reproduction over the entire intensity or tone scale. A more detailed discussion of transfer characteristics of television and motion-picture processing is given in ref.

1.2.3 Noise or Fluctuation Characteristic

When the test areas are reduced to the order of a point-image it is observed that changes in position may result in intensity readings which deviate randomly from each other requiring, therefore, a larger number of "sample" readings to arrive at an average value which will be found to agree with the reading taken from a large test area. Random deviations from the average are observed in photographic processes and in television systems. They are caused by noise or a random particle structure in the image which disturbs the uniformity of signal levels and makes it difficult to recognize small intensity differences in the order of the deviations themselves. It is, therefore, important to determine the relative magnitude of the desired signals and the undesirable deviations. The signal-to-deviation ratio (R) (electrically: signal-to-noise ratio) is the second basic characteristic needed for specifying image quality. The ratio (R) is proportional to the square root of the test area and changes with the intensity or signal level in the image. The signal-to-deviation ratio (R) is, therefore, specified by a characteristic curve showing the value (R) as a function of intensity and is measured with a test area equivalent to that of the point-image in the final image. (For a detailed discussion see Ref.. S-7, S-8.)

1.2.4 Sine-Wave Response Characteristic

The accuracy in the reproduction of detail is determined, in principle, by the diameter and intensity distribution of the point-image. When reproduced, every point in a point-image is expanded into an image of finite size. A second image of the original point is, therefore, increased in size and its intensity distribution is usually different from that of the first point-image. It is evident that a simple statement of the diameter of the point-image is meaningless as a specification unless the intensity distribution is specified accurately.

Practical point-images are not sharply defined but have a bright "nucleus" surrounded by a haze disc of gradually decreasing intensity. Beyond the diameter where the intensity of the haze decreases to less than 1 per cent of that of the bright center it cannot be seen any longer, but the total amount of light flux at this and even much lower intensities may represent a considerable fraction of the flux in the point-image. Assume as a practical example that both the nucleus and the haze in the point-image of a lens have a "cosine-squared" intensity at the center but a diameter 10 times larger than the nucleus which has 99 per cent intensity. The haze will hardly be visible beyond the nucleus but the relative light flux values have a ratio $R = \frac{.99 \times 1^2}{.01 \times 10^2} = 1$. Thus the haze contains one-half of the total light flux! This example shows that a specification of intensity must have an accuracy far better than one per cent to describe the flux distribution in the point-image.

The sharpness of an edge is directly dependent on the light flux distribution. A sharp transition between two light levels (see right side of Fig. No.3-31) is formed by a continuous surface of light points of equal intensity up to the edge where the intensity changes abruptly to a new value. In the image each point source is widened to a point-image. It is easily shown that the curve of the intensity from the overlapping point-images can be generated by convolution of a step with an "aperture" having a transmittance equal to the intensity distribution of the point-image. The transition curve is generated by moving the aperture over the edge and plotting the total flux passing

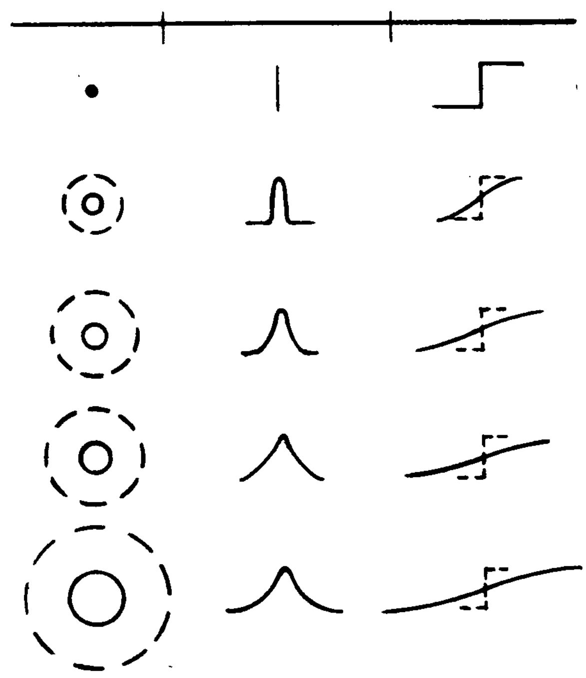


FIGURE 3-31
Point-Images and Edge Transitions

through the aperture as a function of displacement. It is now obvious that the length of the transition curve is determined by the diameter of the haze disc (the total diameter of the "aperture") and that the shape of the transition is not proportional to the intensity but to the flux distribution in the aperture. A specification and measurement of the "aperture effect" of the point-image is, therefore, much more accurate than a specification of the point-image itself.

The method of scanning with the point-image (considered as a scanning aperture) can, of course, be applied to synthesize any type of intensity distribution along the coordinates of the image frame area. It is well known that any intensity curve, no matter how complex, can be decomposed by Fourier analysis into a series of sine-wave components having certain amplitudes and phase relations. A complete specification of the aperture effect of the point-image can, therefore, be given by determining the relative response of this image to sine-wave patterns having constant amplitudes. <u>The sine-wave response characteristic</u> is the third basic characteristic required for specifying image quality. The properties of a point-image or scanning aperture can be tested and/or specified accurately by a response characteristic to optical sine-waves ranging in wavelength from infinity to zero.

Accurate sine-wave test patterns can be obtained from variable-density recordings of electrical constant-amplitude sine-wave frequencies on the sound track of motion-picture film. It is customary to express the wavelength in these patterns in reciprocal units: the line number N per unit length. The line number N is defined in television terminology as the number of half-waves or "lines" (dark and light) in a unit length which is generally taken to be the picture height. The line number per unit length has the dimension: length $^{-1}$. When the geometrical properties of the point-image are known, its response to sine-wave or square-wave flux patterns is readily computed by convolving the flux pattern with the point-image, considering it as a scanning aperture. The point-image and the resolving aperture or sampling aperture of the image-forming device are therefore identical.

The response characteristics of practical lenses, television tubes, etc. can be measured accurately by photoelectric methods. This can be done either by scanning test patterns with the point-image of the component or by using a device such as a microphotometer to scan the test pattern image formed by the device.

1.2.5. The Measure of Equivalence, N_e

One of the main purposes of the foregoing analysis is to develop an objective criterion for the definition of sharpness of television systems. It has been seen, however, that there is no single number which can be used to describe the sine wave response of a component or system.

This generally requires a curve, or a set of points, and depends on the flux distribution as well as aperture geometry.

The following discussion will attempt to justify the use of a single number as a reasonable and rational approximation which will result in meaningful results under most conditions.

The response characteristics of photographic and television systems may differ considerably in the relative response between low and high line numbers. In the case of optical lenses the response may decrease rather rapidly at low line numbers because of aberrations, although the theoretical resolving power may still be measurable in some cases.

The impressions of relative sharpness and definition in an image can be considered as visual evaluation of the complex waveforms from a large number of arbitrary cross sections of the intensity distribution in an image frame. In an ideally sharp image the sum of the Fourier components of these cross sections fills an infinity sine-wave spectrum with constant amplitudes. Superposition of all components in random phase relation results in a most general test pattern, which is optically a random grain structure. Any cross section of this structure taken by a microphotometer with infinitesimal aperture is a complex wave containing a constant-amplitude sine-wave spectrum up to a very high line number, as illustrated by Figure 3-32.

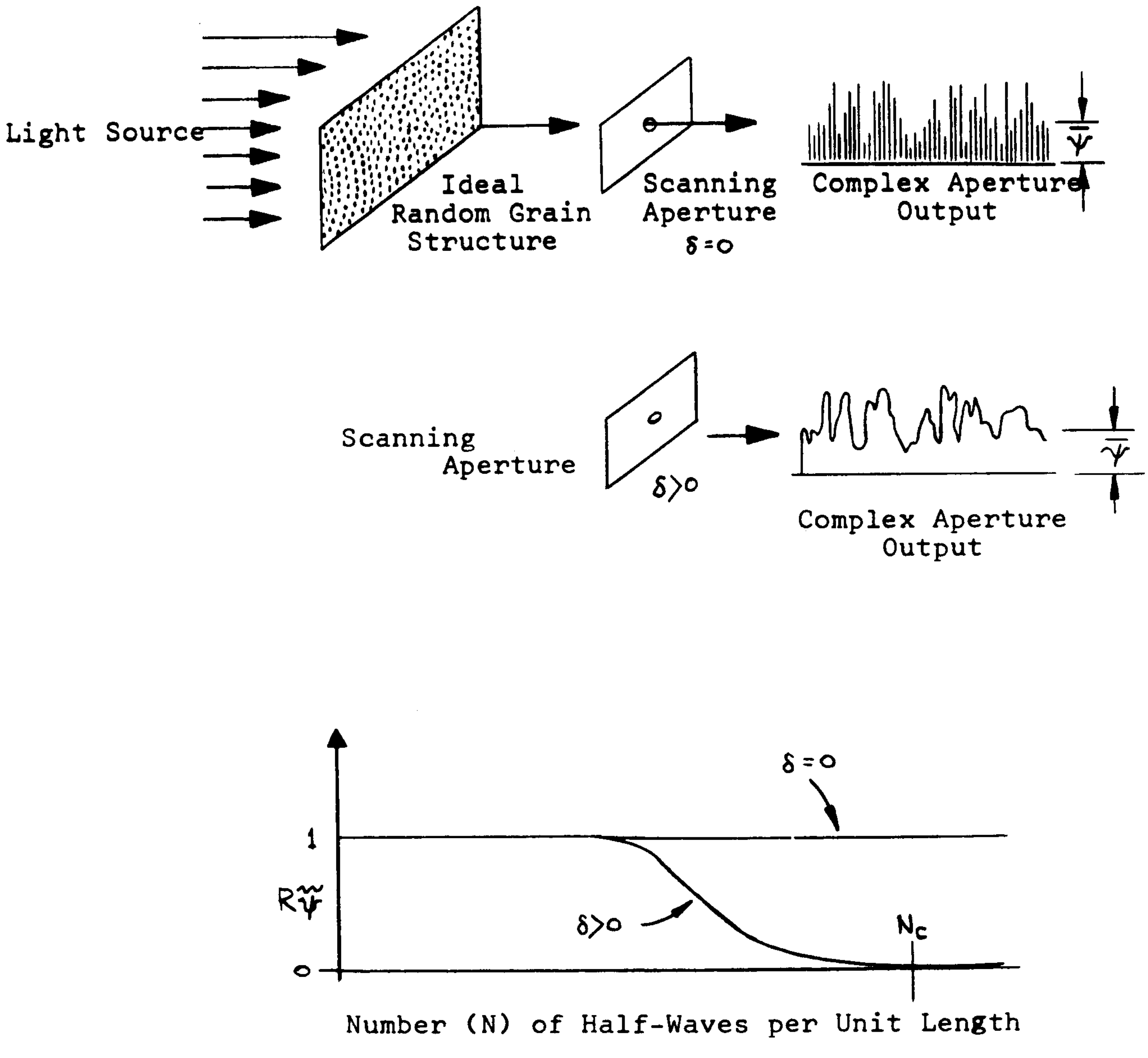


FIGURE 3-32

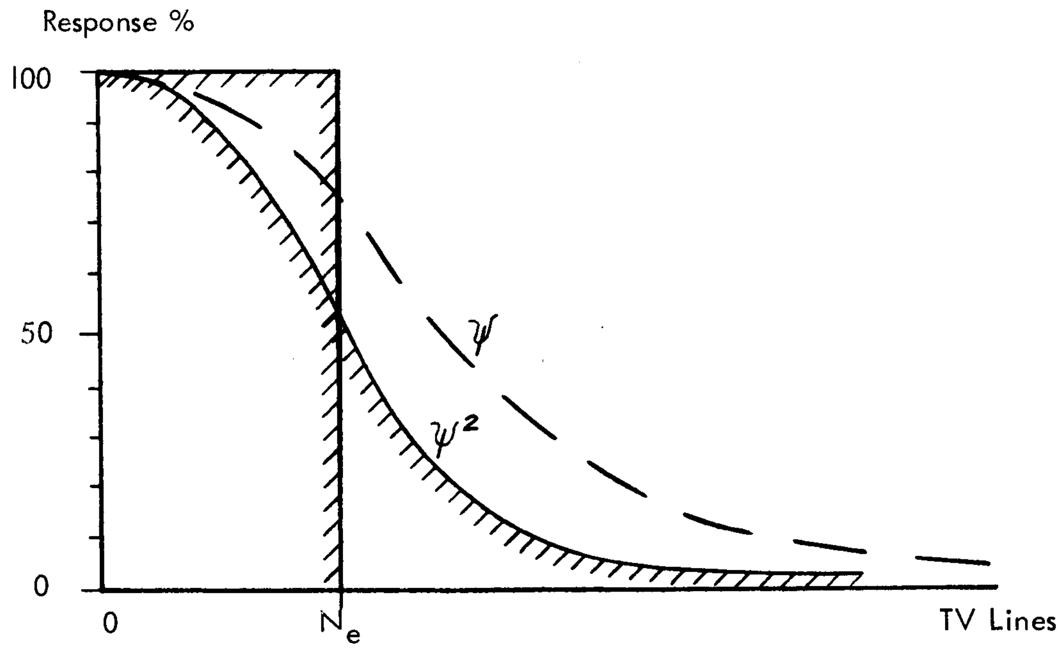
Fourier components of random grain structure before and after an aperture process.

An imaging device with a finite scanning or sampling aperture integrates "high frequency" components, again illustrated by Figure 3 - 32, and a hormonic analysis of the output furnishes the sine-wave response characteristic of the device. The complex wave contains a modulation component (χ) which can be measured in total by an rms current meter. The mean-squared value of the modulation is a measure of the total sine-wave energy which, when normalized, may be obtained as the area under the curve of squared sine-wave response factors. This area can be represented as a rectangle (Fig. 3-33) formed from the response characteristic of Fig.3-33 by a hypothetical aperture with constant response from N = 0 to some line number N_e, at which print the response drops abruptly to zero.

The line number N_e may thus be interpreted as an "equivalent optical passband" of constant amplitude containing the same total sine-wave energy as the actual passband of the aperture.

A general rule, which is in error by 5% or less when applied to most photographic processes, has been derived by Schade. (Ref. S-7, S-8). This states that $1/N_e = (1/N_{e1}{}^2 + 1/N_{e2}{}^2 \ldots\ldots + 1/N_{en}{}^2)^{\frac{1}{2}}$ where N_e applies to the overall system and the N_{ei} ($i = 1,2,\ldots n$) apply to the individual components.

Curves of detail response have been obtained for the human eye. Since the human sensory system is complex, nonlinear, and variable



Sine Wave Response and the Significance of N_e

FIGURE 3-33

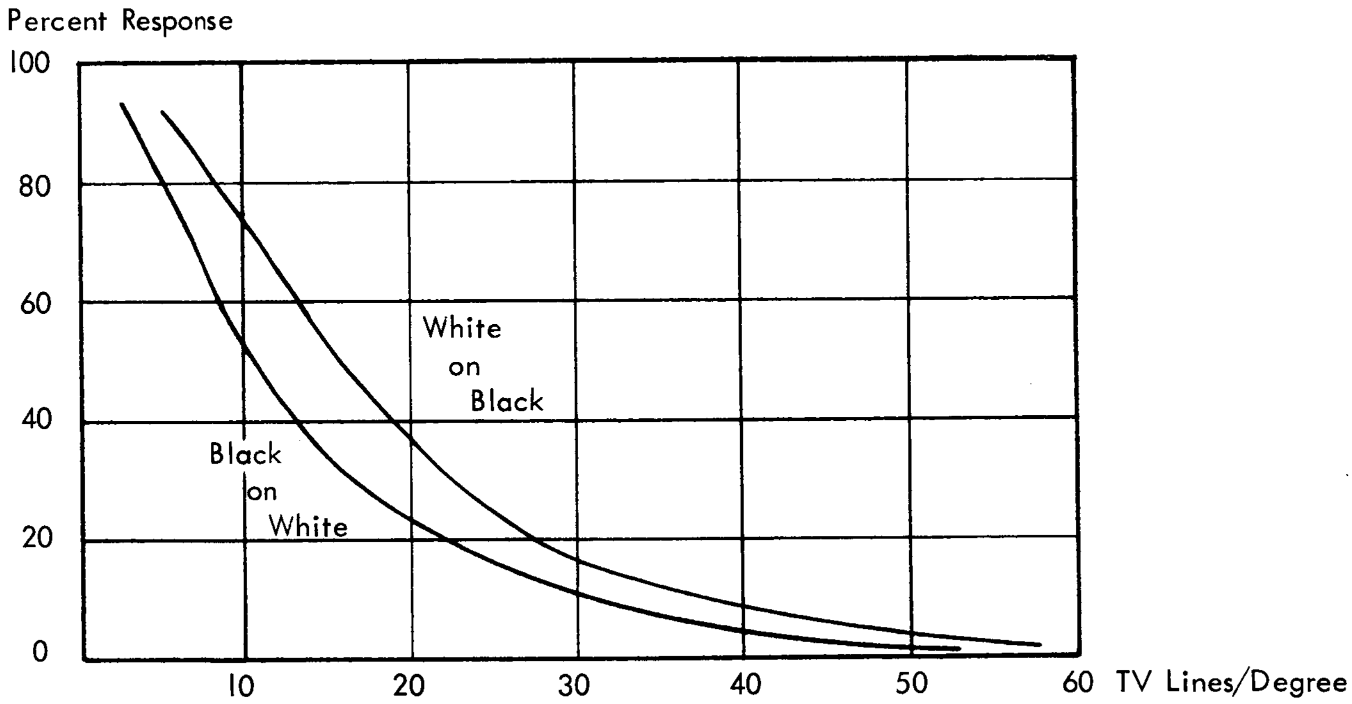
among individuals, what is obtained is not a single curve but an area within which typical curves lie. The results, for a particular average brightness and different arrangements, are shown in Figure 3-34. It can be seen that for the human eye, values of N_e will typically lie close to 10 TV lines per degree, even though the ultimate resolution capability may be several times this value.

2. Signal Acquisition Using Image Tubes:

2.1 General

Probably the most simple and straightforward way of obtaining a television signal is to have a camera view an illuminated model. In order to acquire a signal from a model, three items of equipment are needed – the model, an illumination system and the camera. These are usually supplemented by such other basic components as a model motion system, a camera motion system, and lighting control and occultation systems. The mechanisms required to provide the appropriate motions and illumination are not discussed here, since they depend greatly on the requirements of specific situations. The component which is subject to the most general and theoretical limitations is the pickup device, or camera.

Several camera tube or image conversion techniques will be explored in this section, both in a theoretical way, and in light of the present state-of-the-art as regards performance. A brief comparison



Detail Response of the Human Eye (After Schade)
(Kinescope Patterns at 7 ft-lamberts average brightness)

FIGURE 3-34

of image tube types is included at the end of this section before non-image tube techniques are considered in the following two sections.

2.1.2 Theoretical Considerations

The ideal sensor would not introduce any limitations in the process of generating a video signal and would be simple, compact and easy to operate. The resolution, contrast and sensitivity of this device would be limited only by the statistical fluctuations in the number of photons coming from the scene.

The basic relationships between brightness, contrast and resolution in an ideal video sensor are given by the following equation.

$$BC^2 \alpha^2 = \frac{5.3\ k^2}{D^2 t\ \theta}$$

B - scene brightness (foot-lamberts)

C - percent contrast ($C = \frac{\Delta B}{B} \times 100$)

α - minimum resolvable angle (minutes)

k - threshold signal-to-noise ratio

D - diameter of collecting lens aperture (in.)

t - storage time (1/30 sec. for commercial T.V.)

θ - quantum yield of the primary photo process

This relationship was reported by Weimer (Ref. W-8) and was obtained by considering the accuracy with which one can count the total number of photons hitting an elemental area of the photo-cathode in a time "t". For a scene under steady illumination the right side of this equation may be replaced by a constant (K_1).

$$BC^2\alpha^2 = k_1$$

$$\alpha = \frac{\sqrt{k_1/B}}{C}$$

It may be seen from this equation that objects with fine detail and low contrast will require more light to be sensed. The maximum resolution of a video sensor increases as the square root of the scene illumination and directly as the contrast. It is possible to increase the sensor resolution capability only by increasing the storage time or by using materials that have higher quantum yields. The capabilities of the ideal sensor are approached today by the high sensitivity video sensors at low light levels, but they depart from the ideal at higher light levels because of electron optical and structural target limitations.

This same equation can be used to calculate the signal-to-noise ratio of an ideal pickup tube.

$$BC^2\alpha^2 = k_1k^2$$

where

k_1 = constant

k = treshold signal-to-noise ratio R

B = ratio of the peak-to-peak signal-to-rms noise

l = limiting resolution in T.V. lines is reciprocal of α

Thus

$$BC^2 \frac{1}{l^2} = k_1 R^2$$

$$R = \frac{C}{l} \sqrt{\frac{B}{K_1}}$$

The relationships between the signal-to-noise ratio, resolution and brightness can be seen from this equation for an ideal tube. An increase in brightness or a decrease in resolution will increase the signal-to-noise ratio for the sensor.

The principles of operation of some of the more widely used video sensors are discussed below.

2.2 Camera Tube Types

There are basically two types of camera tubes in current use, these two types covering the vast majority of all television applications both in simulation and elsewhere. These are the VIDICON and the IMAGE ORTHICON. In addition to these, several other types and variants enjoy some popularity. Six tube types will be discussed in this section.

2.2.1 Image Orthicon (Ref. F-5)

While this is far from the simplest of the image forming camera tubes, it is the oldest type to find almost universal use. This is so largely because of its great sensitivity combined with high resolution. For a description of its operation, an image orthicon camera tube can be divided into three parts - the image, scanning, and multiplier sections (Figure 3-35).

Image Section

The scene to be televised is focused by the camera optics onto the photocathode which is the first element of this section. The photocathode emits electrons in proportion to the light falling on it. These emitted electrons are accelerated through a potential of several hundred volts to a target located behind a conductive mesh. As the accelerated electrons land on the insulating target, secondary emission causes several electrons to be ejected for each incident electron. The secondary electrons are collected by the target mesh leaving a pattern of positive charge on the target surface. This charge pattern is a good representation of the original scene.

Scanning Section

A low velocity electron beam is caused to scan the "target" of the image section. The positively charged portions of the target (corresponding to areas of high brightness) are neutralized by electrons from the scanning beam. The beam is thus made deficient in electrons when it passes those areas corresponding to picture highlights. Actually, just before the bulk of the beam strikes the target, it is reversed and returned in the same direction from which it comes. The return beam is focused onto an electron multiplier which surrounds the gun structure at

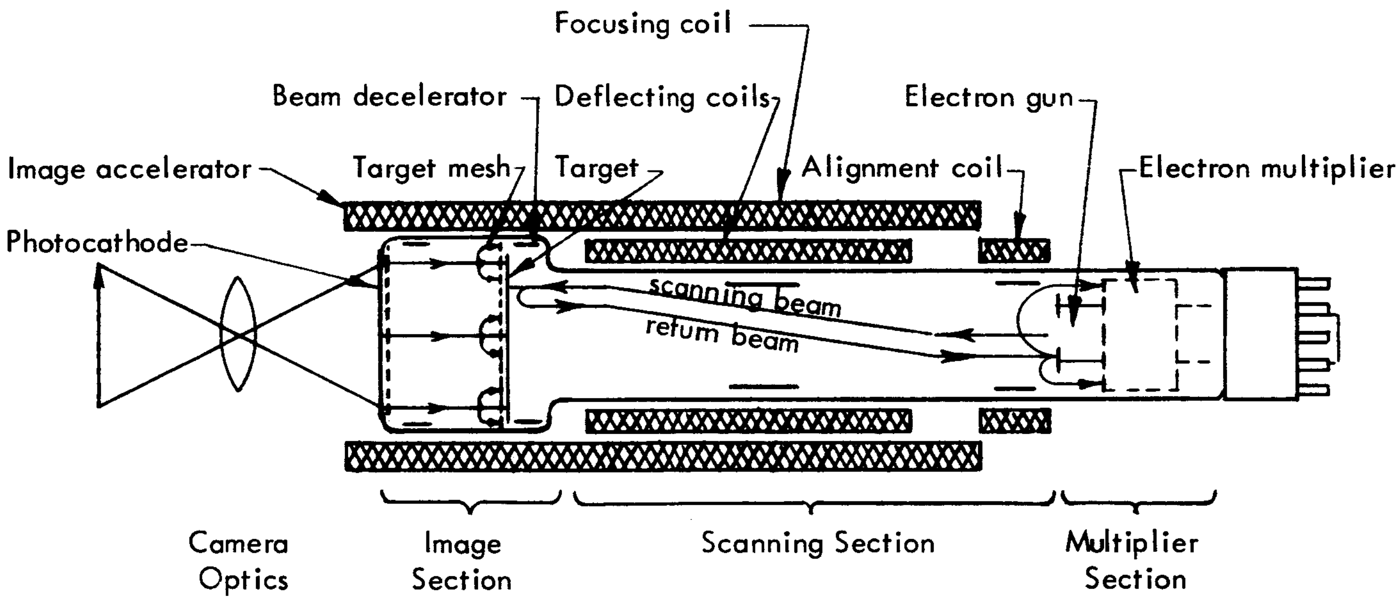


Image Orthicon Camera Tube

FIGURE 3-35

the rear of the tube.

Multiplier Section

The returning beam impinges on an electrostatically focused electron multiplier. This is an arrangement in which secondary emission of electrons is used to increase the signal strength. A current gain of 500 to 1000 times is typically achieved in this section. It is the built-in gain here and in the image section which provides the image orthicon with its high sensitivity. The image orthicon and its variants certainly have much higher sensitivity than any other commonly used imaging device. With high sensitivity image orthicons it is possible to obtain acceptable television pickup at night with only starlight for illumination.

At extremely low light levels the Image Orthicon resolution is limited by the available light, as outlined earlier in this section. In the operation range of 10^{-5} foot-candles and greater faceplate illumination, however, resolution is determined by factors internal to the tube itself.

One limitation is the finite grid size of the mesh ahead of the image orthicon target. These meshes are currently made with about 1000 apertures per linear inch, and the most that may be expected in the foreseeable future might be double this. A second limitation is due to cathode irregularities. This limitation usually comes into significance before that of the target mesh, because the mesh is normally out of focus. Since the scanning beam has a low velocity in the region where it interacts with the charged target electrode, it is important that the velocities of all the electrons be equal if the scanned image is not to be corrupted by extraneous disturbances. Researchers at RCA (Ref. No. C-3) have succeeded in reducing these fluctuations by careful processing of the tube cathodes. Tubes with experimental smooth cathodes have exhibited resolutions of up to 1500 lines, and are expected ultimately to yield 2500 lines.

The prices that must be paid for the extreme sensitivity of the image orthicon are in the areas of size, weight, complexity, signal-to-noise ratio and cost. In simulation systems these factors often outweigh the sensitivity advantage of the image orthicon.

2.2.2. Intensifier Image Orthicon

As a means of providing more gain prior to the target, an additional image section can be added to the image orthicon. Electrons from the photocathode of the intensifier section are accelerated onto a phosphor screen as in a conventional image intensifier. The other side of the intensifier screen glass is coated with photocathode material which matches the fluorescent response of the screen in spectral response.

Accelerated electrons hitting the phosphor produce fluorescence which in turn produces photo-emission from the photocathode. Electrons emitted from this photocathode are accelerated toward the image orthicon target and are stored there. The scanning and multiplier sections of this tube are similar to those of the image orthicon.

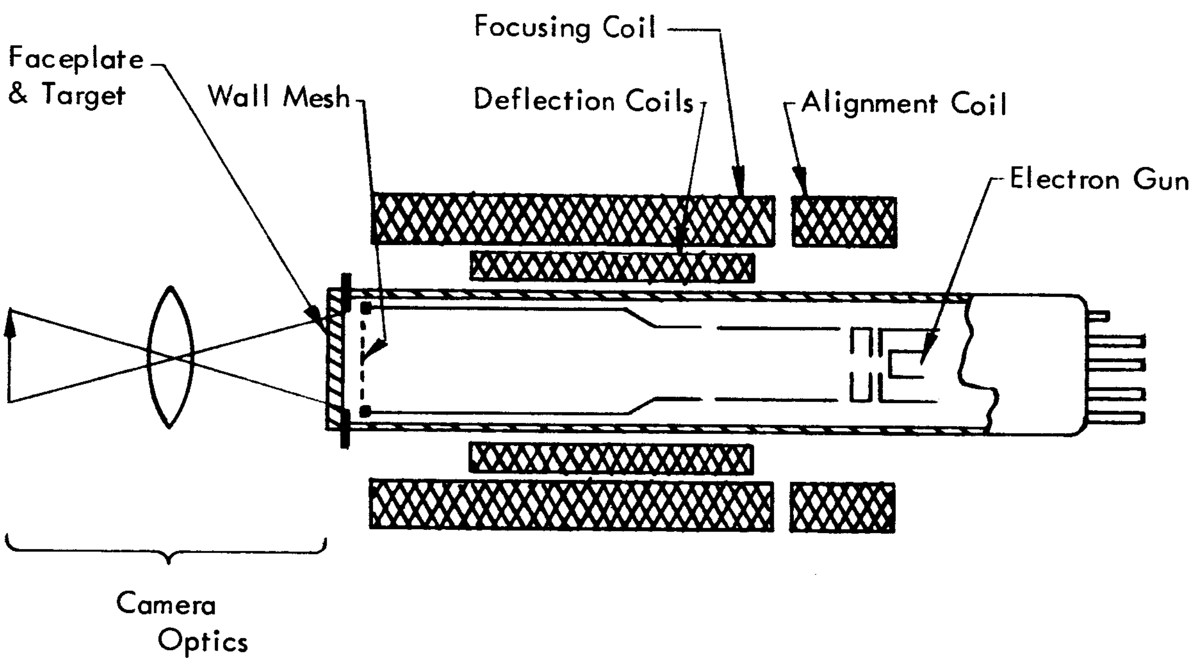
The additional gain obtained from the intensifier section is enough to raise the stored signal level to the point where the fundamental noise from the primary photocathode can exceed the beam noise. Such a video signal obtained at very low light levels is inherently noisy and limited in resolution although the intensifier image orthicon approaches the sensitivity performance of the ideal tube.

2.2.3. Vidicon (Reference F5)

The vidicon is a more recent development than the image orthicon. At a sacrifice in sensitivity, it affords a more compact, rugged and less expensive structure having a wider dynamic range, simpler operation, and generally higher resolution than does the image orthicon.

The vidicon (Fig.3-36) uses a photosensitive semiconducting target, usually made by depositing a thin layer of amprphous selenium or antimony trisulfide onto a glass plate which has previously been coated with a transparent conducting layer. Because the target has no structure, there is no limitation such as that imposed by the mesh in the image orthicon.

In operation the vidicon target acts as a charged capacitor. One



Vidicon Camera Tube

FIGURE 3-36

side is at ground potential by virtue of the transparent conducting layer. The other is at the electron gun cathode potential since it is raster-scanned by an electron beam from the cathode. The target is exposed to light focused on it by the optical system. Wherever the target is illuminated, the effective capacitor at that point is short-circuited by the photoconductive action of the semiconductor. Next time the electron beam reaches this point charge will be absorbed from the beam to make up the deficiency. This flow of charge constitutes a current, which passes through the load resistor to ground. The vidicon output voltage is developed across this load resistor.

Because of the lack of structure in the semiconductor the vidicon target can be made smaller than the orthicon target for comparable resolution. This means that the entire tube as well as the deflection components can be reduced in size, provided that the scanning electron beam can be made comparably small. While the electron optical problems become less with smaller deflection areas, the point of diminishing returns is beginning to be approached at about the one-inch size currently in widest use. This is where electron beam noise due to the low electron density in the beam, and lateral leakage of the photoconductor become the limiting factors.

At present high resolution low-lag, one-inch vidicons, such as the types 7735B and 8507, are capable of limiting resolutions of 900 to 1000 TV lines, with N_e values of about 300 TV lines.

It appears unlikely that these figures will be improved greatly in the foreseeable future, or that they will ever be improved by more than a factor or two.

The advantages of the vidicon are: high signal-to-noise ratio, small size, sensor and system simplicity, and low cost. The disadvantages are low sensitivity, tendency for lag, or smearing of moving images. This lag is caused by two phenomena, photoconductive lag and capacitive lag. Photoconductive lag becomes especially objectionable at low light levels with the usual photoconductors.

Versions of the vidicon are also available in 1-1/2 and 2-inch sizes. While these tubes are capable of greater resolution, they have less sensitivity and are more subject to faceplate blemishes and imperfections than are the smaller sizes.

2.2.4 Plumbicon (Ref. H-6)

The plumbicon is a recently developed variant of the vidicon. There are two main differences, both concerned with the makeup of the photoconductor.

1) The plumbicon photoconductor is made of lead oxide (P_b0) which incidentally gives the tube its name.

2) The plumbicon target is actually made of three layers compared with a single layer for the vidicon.

First layer of the target is a conducting layer of S_nO_2, which is a strongly N-type semiconductor. Next is deposited a layer of intrinsic (undoped) P_bO, which forms most of the overall thickness of the photoconductor. Lastly, a layer of P_bO which is doped to make it P-type is deposited. It is this sandwich construction which gives the plumbicon its useful properties of low dark current combined with high sensitivity.

When the tube is in operation the photoconductive target sandwich constitutes a reversed biased diode. The dark current is the leakage current of this reverse biased diode, rather than the bulk resistivity of a photoconductor as with conventional vidicons. The high sensitivity arises from the intrinsic layer sandwiched between the N- and P- type layers which form the diode electrodes. Conduction electron-hole pairs generated by light incident on the sandwich appear in the relatively high field-strength intrinsic region. Since this region occupies most of the sandwich thickness, there is high efficiency of collection and high sensitivity. Had the target been made with simply a P- layer and an N- layer in close proximity to one another, the high field region would exist only at the junction, and a large portion of the light-generated charge would be ineffective.

Thus the plumbicon has the following desirable properties:

Small size

Simple construction

Low, dark current

Stable, simple operation

High sensitivity

High speed of response

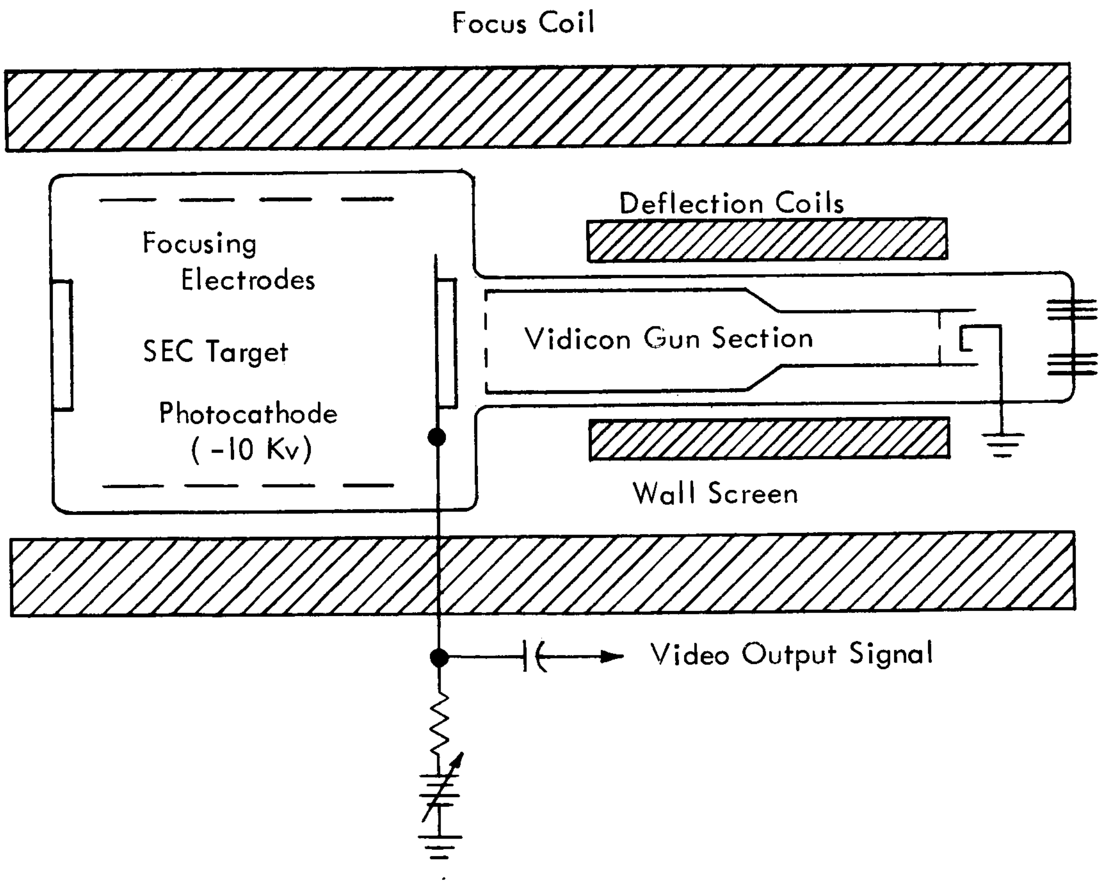
Good resolution

Low lag

2.2.5 SEC Vidicon (Ref. G-2)

Another variant of the basic vidicon concept is the SEC, or secondary electron conduction vidicon. This tube is similar in construction to a combination of image intensifier and vidicon in cascade. Because of the intensifier action, it has much higher sensitivity than the vidicon.

An illustration showing the basic configuration of the SEC vidicon is shown in Fig. 3-37. Light from the scene to be televised is focused on the photocathode. The photoelectrons emitted by the cathode are whisked by the high electric field (approximately 10 kv) to a focus on the SEC target. This target consists of an aluminum



Secondary Electron Conductivity (SEC) Vidicon

FIGURE 3-37

signal plate backed by a thicker coating of KC_l. Electrons incident on the target easily penetrate the thin aluminum backplate and dissipate most of their energy in the KC_l layer, liberating many low-energy secondary electrons in the process.

The signal plate is returned to a positive potential with respect to the scanning beam cathode. Since the scanning beam is swept across the KC_l side of the target, maintaining it at cathode potential, there is initially an electric field across the KC_l target. The low-energy electrons liberated in the KC_l target are swept toward the positive aluminum plate, causing the KC_l layer to charge to more positive values.

When the KC_l layer reaches the potential of the signal plate, another effect becomes important. Transmitted electrons emerging from the far side of the KC_l target are collected by the wall screen, so the KC_l layer continues to charge to even more positive values. Eventually the charging process is terminated when the scanning beam comes by and returns the potential of the scanned area to ground. As in the conventional vidicon, it is the capacitive discharge at this time which produces a video signal voltage across the load resistor.

The high gain taken directly at the image stage provides high sensitivity and low noise. The large capacity for integration due to the combination of charging effects results in a wide dynamic range and good integration capabilities. Because the target produces signal by the accumulation of a large effective charge of free electrons on a low capacity target, the beam is able to discharge the target almost completely in a single frame time. This results in virtual elimination of discharge lag and image smear.

Thus the SEC vidicon has several advantages which promise to make it a very important sensor.

2.2.6 Isocon Scanning

A relatively little used method for operating image tubes is available, known as Isocon scanning. The technique has been used with vidicons as well as with image orthicons (Ref. C-6, C-7, W-5).

Isocon scanning makes use of the fact that when an image tube target is scanned with an electron beam, two effects take place at sensitive target surface.

The usual primary effect is a reflection or return of the beam toward the cathode after removal of sufficient electrons from the beam to neutralize the target surface charge differential. In addition to the reflection, however, there is some scattering of the electrons which reach the target. In other words, the target does not appear merely as a specular reflector but has scattering properties as well. It is the scattering property which is used in Isocon scanning.

In the image isocon, an isocon version of the image orthicon tube, the scattered electrons are separated from the reflected electrons and fed to an electron multiplier from which the output is obtained.

One serious disadvantage of the image orthicon is that noise in the image is more pronounced at the lower light levels, because the signal is taken as the difference between the incident and return beams. With isocon scanning the reverse is true. Scattering takes place only where the signal is present, hence the scattered electron beam has minimum density and minimum noise at low signal levels.

Isocon scanning in the vidicon is similar. In normal vidicon operation the signal is taken as that portion of the electron beam required to replace charge dissipated at the target by photoconduction. In the isocon method of vidicon operation it is scattered electrons from the incident electron beam which are used. If the scattering coefficient of the target is greater than unity, this mode of operation yields a greater signal current than does the normal vidicon mode. Moreover, since in the return beam the scattered electrons appear in space, and not as a conduction current, they can be routed to an electron multiplier for essentially noise-free amplification. This provides the isocon-scanned vidicon two important advantages - high resolution and low noise. The sensitivity is not as good as that of the image orthicon, however.

Although Isocon Scanning can yield modulation approaching 100%, the critical adjustments required for its operation have thus far precluded its use outside of the laboratory.

2.2.7 Image Dissector

This tube type was one of the earliest developed for use in television and still enjoys popularity in some specialized applications. It is discussed here for its unusual features, not available in other image tubes. These include relatively straightforward analysis and prediction of characteristics, high resolution, and lack of storage. Unfortunately, this last feature also results in low sensitivity.

The image dissector (Fig.3-38) possesses a photocathode which emits electrons as light from a focused image falls on it. These electrons are released into an electric field which sweeps them in a direction roughly perpendicular to the plane of the cathode. Electric and/or magnetic control fields are applied to the space behind the photocathode in addition to the high voltage electric field. By these means the entire "picture" of electrons can be "waved" in space and scanned. A small aperture leading to an electron multiplier is located at a fixed point a

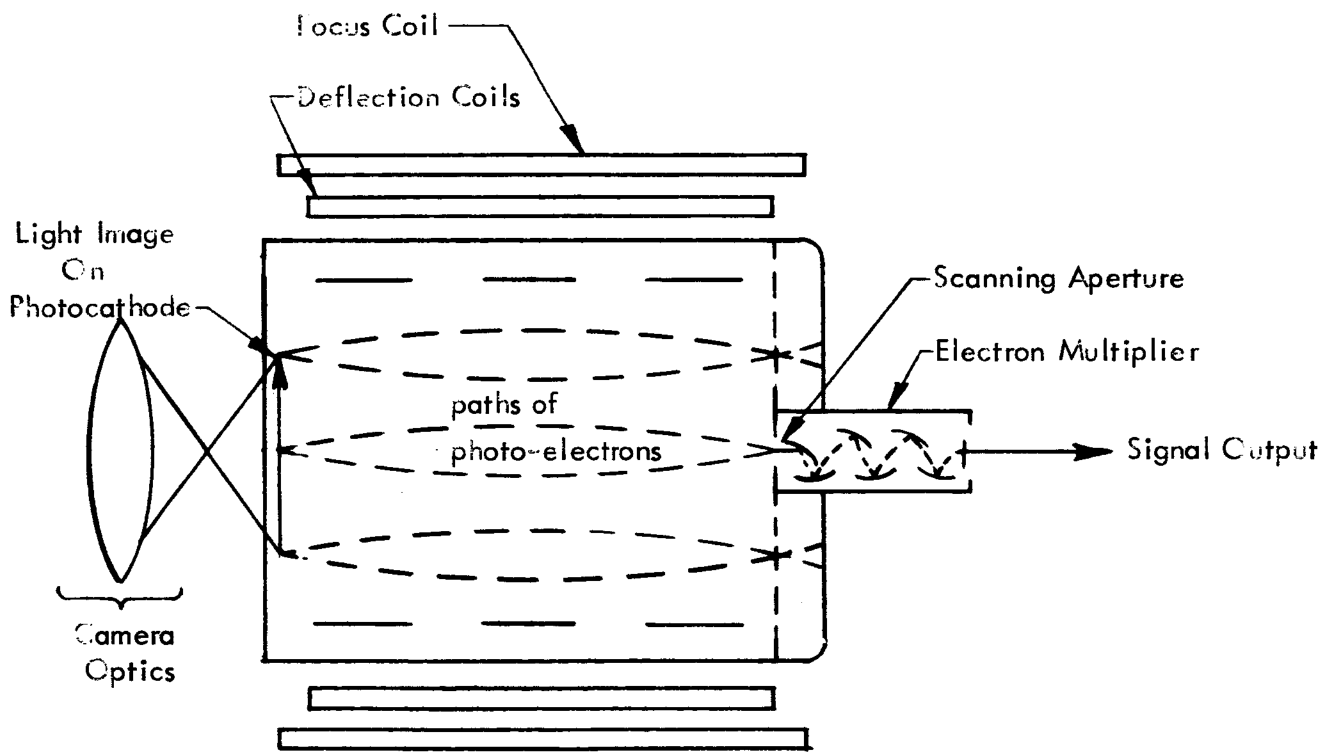


Image Dissector Camera Tube

FIGURE 3-38

suitable distance behind the photocathode. Thus the picture is caused to scan past the aperture, which is analogous to the scanning of the picture by an electron beam in camera systems previously discussed.

It can be seen that the above-described method of image scanning has the following properties:

There is no storage involved. The signal appearing at the electron multiplier output is an instantaneous function of the input at the time and position being scanned, and the picture can have no lag no matter what the picture slewing rates might be.

The scanning aperture may be made virtually as small as desired, with no real limitations.

In exchange for these advantages, one must pay dearly in practical terms. Because of the lack of storage the signal output current at any illumination level is considerably less than the output of one of the storage type tubes at the same level. This situation is further aggravated as the aperture size is decreased in an effort to achieve higher resolution. As the resolution is increased linearly in proportion to the decrease in aperture diameter the available output current decreases as the square of the diameter, since it is an area function. To make matters still worse, as the scanning aperture is decreased to improve resolution the amount of "dwell time" at any one picture element is also decreased, while the video bandwidth needed to accommodate the added information is increased. These factors operate toward decreasing the available signal and increasing the system noise, where both parameters are in marginal regions to begin with. The only cure for this situation is to increase the illumination, but this too soon reaches the limits of practicability.

Two techniques have been proposed for circumventing the problem of poor signal-to-noise performance (in reality low signal) which results from lack of storage in the image dissector.

One is a brute-force method applicable to flying-spot scanners only (Ref. P-4). This would require illuminating the subject matter with a flying spot scanner in synchronism with the scan of the image dissector. This insures that the source material is highly illuminated at the spot where the illumination is needed, while the image dissector would provide the high resolution.

The other proposed attack on the lack of sensitivity might be regarded as a concession. If the dissector can be provided with an effective storage, (Ref. E-1) or time dispersion of received photoelectrons corresponding to an input event, a statistical advantage is achieved which results in improved signal-to-noise ratio. The price paid for this advantage is a reduction in response time and a certain amount of storage. The advantage of high resolution, however, remains unaffected.

2.3 Comparison of Camera Tube Types

Table 3-2 is a summary of the sensitivity and resolution characteristics of a few selected image tubes. This comparison chart indicates that in general the Vidicon types lead the field in terms of resolution and signal-to-noise ratio, while the image orthicons have the advantage in terms of sensitivity. (The image dissector is discussed separately below). Even the small vidicons have greater resolution than most Image Orthicons, while the large vidicons (1-1/2 and 2-inch) have limiting resolutions well in excess of 1000 lines. There is presently under development an image orthicon which is expected to have a resolution of 1500 lines at 50% response, (Ref. C-3), but this work has not yet progressed to the point where a tube can be considered available for use in a television system.

The SEC vidicon, which requires a power supply of 10 kv or more for its operation, has the resolution of a vidicon with sensitivity approaching that of an Image orthicon. It must be observed that the size of the SEC vidicon (18-inch length, 3-inch diameter) makes it mechanically more similar to an orthicon than

TABLE 3-2

COMPARISON OF IMAGE TUBES

Tube Type Number	Faceplate Highlight Illumination [d]	Limiting Resolution	Response at 400 TV Lines	Equivalent Response N_e	Raster Size	Typical S/N	Nominal Tube Size	Comments
Units	Ft-Candles	TV Lines	%		Inches	Ratio	Inches	
Image Orthicons:								
5820A	5×10^{-4}	**625**	**50**	-	.84X1.12	40:1 [a]	3	**Studio Type.**
7389A	9×10^{-2}	**800**	**60**	-		90:1 [a]	4-1/2	**4-1/2 Inch Orthicon.**
7967	10^{-6}	**300**	-	-	.84X1.12	-	3	**High Sensitivity Type** **G.E. Type Similar to Westg. WX-4861.**
Vidicons:								
7735B	.1 - 1.0	900	50	300 [c]	.375X.5	300:1 [b]	1	Low-Lag, High Sensitivity & Resolution.
8507	.1 - 1.0	1000	45	280 [c]	.375X.5	300:1 [b]	1	Field Mesh Version of 7735B.
8051	6.	1200	60	270	.6 X .8	-	1-1/2	High Resolution Type.
8521	.1 - 1.0	1500	65	325 [c]	.6 X .8	-	1-1/2	" " "
ML-2128G	15	600	-	-	.375X.5	-	1	Fiber Optic Faceplate.
ML-2058G	15	2000	65 [c]	500 [c]	1 X 1	300:1 [b]	2	High Resolution Type.
ML-7351 A	.3 - .7	-	-	-	.375X.5	300:1 [b]	1	High Sensitivity Type.
7845	.1 - 1.	1000	-	-	.375X.5	-	1	FPS Vidicon-Electrostatic Deflection.
TH 9830PA	.05 - 1.	1200	80	500 [c]	.6 X .8	-	1-1/2	High Resolution, Post Acceleration.
SEC Vidicons:								
WX30150	10^{-4}-10^{-5}	1000	60% / 200 Lines	-	.375X.5	-	1	
Plumbicon:								
55875	.5	>>600	> 40	230 [c]	.5 X .66	200:1	1	
Image Dissectors		To 3000						Sensitivity lower than for any Vidicon or Orthicon, specific Parameters depend on Tube Design.

NOTES: a) at 4.5 Mc Bandwidth b) at 5. Mc Bandwidth c) estimated from manufacturer's data d) typical value for stated limiting resolution to a vidicon. (The table does not indicate physical sizes of the various image tubes nor the power supplies needed for their operation.)

The low lag and high speed of response advantages of the plumbicon do not show up in the tabulation, which is based on the parameters of illumination, signal-to-noise ratio, and resolution. There appears to be no inherent reason why Plumbicons cannot be constructed with characteristics are at least as good as for other types of vidicons, however the type listed is the only one commercially available at present. The Plumbicon is made by Amperex, but other companies have expressed interest in the principle involved. RCA, for instance, is at this writing about to come out with a "Selenicon" in which the photoconductor will be based on the element selenium rather than lead as in the Plumbicon.

Image dissectors are usually made to order for specific applications. The ultimate resolution is determined by aperture size, and the aperture in turn is directly related to the sensitivity. Since the Image Dissector is not a storage device, its sensitivity for a given resolution is much less than for any of the other image tubes listed, all of which do employ storage.

The bandwidth required to realize the best resolution obtainable with the larger vidicons in real-time flicker-free television systems exceeds the 30 mc or so that is considered a practical upper limit. This does not mean that such types cannot be employed profitably. They can be used to obtain improved contrast and modulation response with existing high resolution television systems.

When high resolution scans are used with standard size tubes, the number of image elements is increased and the effective dwell time on a single picture element is therefore reduced. For a given level of illumination, the light flux available per picture element decreases as the number of lines scanned (and hence number of image elements considered) increases. When resolution is increased by using a larger tube, the light flux per image element does not decrease. Thus it would appear that the way in which resolution should be increased is by making the image tube bigger. This is a delusion for two reasons. First, in a larger tube the same total light flux must be spread over a larger area. For a given amount of light flux the illumination on a larger tube will be less than on a smaller tube, leaving the two situations equivalent. The second disadvantage is that of manipulating a larger probe. The volume and mass increase as the cube of the tube size, while resolution (measured linearly, in lines per picture, etc.) increases only linearly with tube size.

Thus it is evident that the arguments are not all one-sided. The one certain fact is that with conventional television systems, presently available sensors are capable of generating information at a rate faster than that which can be handled conveniently by other system components.

2.4 Camera Optics

2.4.1 General

T.V. cameras used with model systems in the simulation art are normally referred to as probes. Probe designs in the past have been directed towards the problem of simulating aircraft flight with special attention paid to the landing phase. These probes were not required to cover exceptionally wide fields of view, so that the real problems encountered were concerned with illumination, depth of field or focus across the field, and closeness of approach to the model, since scale is an important parameter in achieving a model of reasonable size. In probe designs the scale of the model is determined by the minimum distance of approach of the pilot's eye position to the ground. The entrance pupil of the probe is analogous to the eyes of the pilot. In other words the pupil of the probe may be referred to as the "look point". If this minimum distance of approach in the real world scale is related to the model scale it is important that the model scale be large enough to permit the required closeness of approach of the entrance pupil. If the simulator scene must serve pilots seated side by side the scale may be determined by the size of the single entrance pupil required instead of the closeness of approach that must be simulated. For this side by side probe the scale distance between pilot eye positions must be completely inscribed within a single pupil in order to provide a correct "look point" for both pilots. The properly scaled closeness of approach then is limited by the scale distance between the pilots and the required pupil size in this case. If two separate pupils are to be employed for other reasons then these pupils must be effectively superimposed or separated by the proper scale distance in order to provide the proper "look point" for both pilots.

Some of the more current requirements in aircraft and spaceflight simulators demand reasonably sized multiple fields of view displayed about a "look point" in a manner such that a single camera optical system would have to cover a field of view of approximately 200° in a horizontal reference plane. On first thought one might be tempted to design a system utilizing a single objective to cover this ultra wide field and then masking and combining portions of the field in the focal plane so that the required fields of view in the appropriate directions could be picked up by a single image tube. This approach becomes unattractive however, if one considers two resulting problems. Firstly, the resolution of the best available closed circuit television system borders on 1000 lines. Considering a 100° field of view system this would result in approximately 12 arc minutes of resolution. For a 200° system, the resolution available would drop to approximately 24 arc minutes. Since the usual limit of resolution quoted for a human observer is 1 arc minute it is apparent that a 24 arc minute system could hardly be termed satisfactory. The second problem resulting from single ultra wide field objective systems concerns the distortion usually accompanying such designs. For example, in order to map a 220° hyper-hemisphere onto a flat focal plane as required by the photocathode of the pick-up tube it is obvious that distortion must be accepted. This distortion amounts to a variation in magnification across the field of view in rotationally symmetric fashion and as such it is unsymmetric across a portion of the total field. To try to electronically compensate for this is not only difficult but also results in a variable resolution across the field.

In spaceflight simulators where a continuous field is usually not required a single pick-up tube can be made to cover the extremely wide field required by employing mirrors of other means in a focal plane to pull off the desired fields of view. However, this becomes awkward and extremely difficult to implement in a practical manner especially because of the unsymmetric distortion across the individual portions of the field. It would be much more desirable to view these separate fields through separate optical systems and then feed separate pick-up tubes with the required information. In this way one could apportion 1000 lines to each 65° field resulting in a much more favorable view of the external field. At the same time, since the fields are relatively narrow, the individual optical systems would also provide distortion free images on the photocathodes of the pick-up tubes thereby eliminating the objectionable feature of the single wide field optical system.

This multiple camera approach does have one obvious disadvantage, namely the difficulty of providing a single "look point" for all cameras. The "look point" or viewing point must be the same for each of the camera systems otherwise as the observer switches his gaze from one window image to another he would be under the impression of translating himself a distance in the real world equivalent to the scale of the system multiplied by the separation between the "look points" or entrance pupils. This "look point" is in actuality the entrance pupil for the optical system.

It should be noted true simulation of vehicle dynamics would normally require that the center of rotation of the probe head be located, scalewise, a distance from the entrance pupil equivalent to the distance between the observer's head position (for exit pupil at the eye) and the center of rotation of the spacecraft.

All probes heretofore have required a relatively small entrance pupil in order to achieve a large depth of field. This approach results in two severe problems. The first involves illumination and the second involves optical resolution and contrast limitations. Needless to say the approach is merely a compromise as far as maintaining reasonable focus across the instantaneous field of view is concerned even though these probes are usually equipped with a focus control to accommodate for slant range. Using such a small aperture the illumination conditions are so severe that one must be concerned with the temperature rise of the model itself. However, even in cases where the illumination is not severely limited one must employ good judgement in designing the aperture versus illumination condition in order that 1) the pinhole aperture does not effectively starve the resolving capability of the pick-up tube and 2) that the diffraction pattern limitation does not contribute appreciably to image contrast reduction.

2.4.2. Probe Design

The Farrand Optical Company has recently developed a Landing and Ascent probe for the LEM visual simulator which overcomes all of the limitations discussed in the prior paragraphs. This operates at a geometric speed of f/5 and a photometric speed of T/10. This relatively "fast" design is possible because the probe is focussed not only for slant range but also across the full field for all obliquities of the object plane.

3. Signal Acquisition without Image Tubes

3.1 General

Although the most common method presently in use for pickup of television picture information is by means of image tubes, this has not always been the case. The earliest proposed TV system which actually worked, for example, used a mechanical scanning device, the Nipkow Disc. More recently flying-spot scanners and mosaic systems have been used for converting picture information into electrical signals.

In addition to the above schemes, the advent of the LASER has opened up new possibilities for image signal acquisition.

Still another substitute for the image tube is a rather radical approach which holds tremendous promise for future development. This is the direct computation of image elements from a combination of stored and real-time data. Since computations can be done with any required accuracy, and since the outputs can be buffered in any appropriate manner, signals can be produced with any desired degree of fidelity and resolution, and can be truly noise-free. A further advantage of this scheme is that the need for models, illumination and manipulation systems are completely eliminated. Problems of scaling and mechanical interferences are similarly disposed of.

Of course, the difficulties eliminated by the computational methods are replaced by the problems of programming and defining the subject matter in terms which are adaptable to existing computer technology and capability.

The various approaches mentioned will be examined in turn in this section.

3.2 Flying spot scanners

These devices fall logically into three sub-classes. They are:

Film Transparency Scanners

Scanners of physical models

Line scanners with mechanical motion.

The basic concept underlying all flying spot scanners is that a spot of light is caused to traverse the material being scanned. The light collecte after modification by the scanned subject material is collected by one or mor photomultipliers to provide the output signal.

The recent advent of the LASER has provided a light source which is particularly adapted to use in flying-spot scanners, since it has high brightness and small effective source size. This section concludes with a brief discussion of LASERS in flying spot scanners.

3.2.1 Film Transparency Scanners

In the conventional film transparency flying spot scanner, the first requirement is to achieve a high intensity high resolution raster on a CRT. This raster is imaged onto the transparency to be scanned, and the transmitted light is collected and focused onto the cathode of a photomultiplier. Changes in scaling and orientation can be introduced by performing the appropriate motions on either transparency, the CRT raster, or both.

Electronic distortion of the flying spot raster can be used to produce effects which are very useful in simulation work. Some of these are employed by the Dalto Corporation in their Scanalog image generator. (Ref. T-l) Here the scanning raster is given trapezoidal distortion so that when the distorted display containing the distortion-generated video is viewed, a sense of perspective is introduced. The resultant display is very effective except for the noise which appears in the regions of sparse line distribution.

Rotation is accomplished by rotating the CRT about the point at infinity, while scale changes are made by altering the size of the raster.

The Dalto system is also supplied with an auxiliary feature to simulate the "strobe" lights of airport runway approaches. This consists of a beamsplitter which diverts a portion of the scanning raster through a second transparency which is opaque except for the strobe light positions. Light passing through this transparency is further processed to provide a running sequence of bright spots at the display. These give a very realistic simulation of the flashing runway approach lighting at night.

3.2.2 Scanners of Physical models

No scanner of this type is known to have been developed for a visual simulator application, although there are several inherent advantages to such a system. The flying spot would be projected onto an actual three-dimensional model of the terrain to be simulated and the reflected light would be recovered by means of a photomultiplier. This results in an output which includes the occultation and aspect information available through the use of three-dimensional models. By placing the scanning raster at the simulated source of light and the photomultiplier collecting aperture at the simulated viewing position, shadows can be simulated in proper perspective.

Two obvious difficulties with such a system are the pickup of scattered light from non-target surfaces during the scan, and collection of all the light available at the photomultiplier. The light lost in scattered reflection is far greater than that in transmission through a screen or slide.

3.2.3 LASER Light Sources

Best performance in a flying spot scanning system is achieved when the spot is made as small and as bright as possible. The recent advent of the LASER has resulted in a giant step in both these directions. The wavelength of the LASER emission is unimportant in a flying spot scanner, so long as it falls near an efficient conversion point on the sensitivity curve of the photomultiplier detector.

If the LASER is to be used as a source of illumination in a flying spot scanner, suitable means must be available to deflect and scan the beam. These can be electrical, mechanical or combination methods in conjunction with the appropriate optics.

Purely electrical techniques for scanning laser beams have been investigated by the Perkin-Elmer Corporation and are reported on in AD612725. (Ref. P-3). These and other scanning systems are discussed below and in the section on displays.

3.2.4 Non-CRT Scanners

Mechanical scanning techniques are possible for the field scanning rates of television systems, about 60 fields per second. For line scans, which range upwards from 16 kc, purely mechanical methods must be almost completely rejected.

The most promising approaches for horizontal (line scan) deflection would seem to be those based on either magnetostrictive or piezoelectric principles, or on the electro-optic effect. The latter, the variation in the refractive index of an electro-optically active crystal under the influence of an electric field, has been investigated by Perkin-Elmer for Rome Air Development Center. (Ref. P-3). By the use of large crystals, and multiple passes through single prisms or through several prisms in cascade, it is predicted that a resolution of about 1000 elements per scan can probably be achieved.

As noted above, the difficult part of non-CRT flying-spot scanning is the accomplishment of the fast line-scan motion. A recent development which accomplishes this, even though it uses a CRT, is worth mentioning at this point.

Work has been carried on for the past several years at the DuMont Laboratories of Fairchild Corporation, in which a circular scan on a CRT is converted into a line scan by means of a fiber-optic adapter or transition section. (Ref. R-5) Thus the result of scanning a circle on the CRT (which has the advantage of having no retrace as it repeats its pattern) is the production of a line scan which has zero retrace time and is moreover π times as long as the diameter of the CRT. In a practical sense, this approximately triples the available resolution of the CRT scan.

Since this system can provide only a linear, or one-dimensional scan, another effect must be used for scanning along the other axis. In the DuMont work, which is not designed to result in a flying spot scanner, this is done by introducing a mechanical motion for the second axis. It is also possible to use mirrors or direct electro-optical means such as discussed above.

3.3 Mosaic Techniques

3.3.1 General

The resolution of a television system is limited by the poorest performing element in the chain consisting of the pickup device, transmission and/or processing components, and output or display device. In order to improve the information handling capacity of a system, it may be synthesized from several subsystems each of which has more modest resolution or information handling capabilities. Such an arrangement, consisting of more than one image sensor or more than one display is referred to as a mosaic system.

Mosaic techniques are not new. Some of the very first proposals for television systems were predicated on the concept of decomposing the picture into individual elements, each of which would have its own sensor, transmission channel, and display. (Ref. S-10, pp. 15 - 17). More recently, such systems have been built, and are in fact in daily use. Consider, for instance, the "spectacular" signs and moving news billboards such as are found in Times Square and elsewhere.

Resolution in these displays is necessarily coarse, because of the limited number of elements used. For a high resolution system (10^6 or more picture elements), a scheme which employed one sensor, transmission channel, and display element for each picture element would be prohibitively expensive, and probably could not even be built.

Mosaic systems for improving the resolution of television must rely not on element-by-element picture synthesis, but on a combination of television subsystems so constituted and coordinated that the array has capabilities in excess of those of conventional high resolution single-channel television systems. The problem is complicated by the difficulties encountered at edges, where the sub-scenes are joined. If resolution is lost here, the net result might be poorer performance obtained at the expense of added complexity.

Three mosaic approaches are discussed in the following sections. The first two, fly's eye and fish eye systems (Ref. C-4), have been proposed and recommended for further study. The third has actually been built.

3.3.2 Fish Eye Pickup System

In a study performed for the U.S. Naval Training Device Center, the Radio Corporation of America (Ref. C-4), recognizing the fundamental limitations of conventional pickup devices, proposed two rather radical departures from existing techniques in order to improve resolution of simulator presentations. The first of these is called the "Fish Eye Image Acquisition System" and is described here. The second, called the "Fly's Eye" approach, is detailed in the next section.

The fish-eye system employs a relatively small number of wide band channels in parallel. The number suggested in the referenced study is five. Since the system is intended to scan mechanically through 360 degrees in azimuth, the five pickups are oriented at equal azimuthal intervals of 72 degrees. Five optical pickup heads are formed into a single "scanning lens assembly" and each head is responsible only for a vertical line scan, 90 degrees in extent.

The five focal surfaces are removed by means of fiber optic tapes to five specially constructed vidicons. These tubes have high resolution, wide bandwidth capability, and extremely short storage time. Azimuthal scanning is accomplished by rotation of the entire assembly. (The vidicons need not be rotated physically, since a de-rotation prism can be provided in the optical path). Scanning in elevation is done electronically by a single line scan across the face of each vidicon.

Assuming that the technical problems involved in implementing this system can be solved, the basic advantage of the fish eye arrangement is a five-fold increase in the effective bandwidth, resolution, and informanon-handling capability. The price to be paid for this improvement is mechanical complexity and the difficulty of edge registration at the five seams.

3.3.3 Fly's Eye Pickup System (Ref. C-4)

This system is an attempt to reduce the individual channel bandwidth so that simpler pickup transducers can be used than are required for the fish eye approach. In this case, one channel is used for each element in elevation, for a total of 3025 channels. Again, the entire array is rotated in azimuth to provide 360 degree coverage.

The pickup scanning assembly consists of an array of very small lenses. Each lens gathers light from a unique incremental band of elevation. The lens focuses light into the end of an optical fiber transmission medium. After passage through a derotation prism, the light paths present their images to an array of phototransistors. It is these 3025 phototransistors (one for each channel of elevation) which act as the pickup transducer. Since the phototransistor output is very weak, the system also requires 3025 amplifiers, with the added requirement that all transistors and amplifiers must be approximately matched and balanced with respect to each other. If the effective bandwidth of each channel is only a modest 200 KHz, the effective bandwidth of the system is over 600 MHz.

Such a system offers only limited advantages in return for an enormous increase in complexity over conventional television systems.

3.3.4 3-Channel Wide Angle System

The U.S. Naval Training Device Center has contracted with General Precision Laboratories to produce a wide field high resolution television link for simulator use. This system employs three high resolution television chains which are physically and optically combined to cover the required field.

The three television rasters are rotated and placed side by side, so that scanning of each takes place vertically with a 3 x 4 aspect ratio. A single pickup lens matches the combination to the wide optical field in the real world. The display is presented on three standard CRT's mounted close to each other.

Edge registration and synchronization are expected to be problems. To provide the best chance of success against these, the sweep systems are run in common from a single piece of driving equipment.

Results actually obtained with this system have not yet been published.

3.4 Computation of Pictorial Elements

3.4.1 General

There are several limitations which restrict the performance of conventional television systems used in simulators. Some of these, such as model and lighting size and motion limitations are a part of the overall simulation problem. Others, such as resolution, noise, and the effect of large dynamic scale requirements are more directly imputable to the television system alone.

Traditionally these problems have been approached in a piece-meal fashion. For instance, resolution can be improved by the use of mosaic techniques. Large dynamic range of scale can be accomplished by the use of several models for different portions of the scale range as required. These are all patchwork solutions, however, which solve particular problems but do not provide a "universal" simulation approach.

Recently, computational approaches to the television problem have resulted in techniques applicable to a wide range of simulations without the restrictions of physical model systems. Computation of the image elements can be carried out in digital, analog, or hybrid form.

In any picture computation scheme, the various components of perspective, illumination, scaling, reflectance, and occulting obstructions must be introduced. When fine detail or complex situations must be simulated, the computations can become highly involved. It has not been until the present decade that machines of sufficient speed and capacity have become available to generate visual scene information by direct computation. Two different approaches to digital image generation will be discussed in the sections which follow. One is based on a scheme proposed by the Pennsylvania Research Associates (PRA), and is an extension of work they have performed in the field of radar landmass simulation. The second is a system made by the General Electric Corporation for NASA (Ref. G-4).

An introduction to picture computation is provided by a brief review of analog computation. Analog methods are the simplest to devise and to program. Unfortunately, they are also most limited in terms of performance capability.

3.4.2 Analog Computation of Pictures

Probably the most simple sort of analog image which can be generated is a Lissajous Figure. By the use of these patterns, produced by the application of harmonic signal waveforms to the horizontal and vertical deflection systems of a display, a great variety of shapes with spherical symmetries can be simulated.

In 1962 Buddenhagen and Wolpin of Bell Aerosystems (Ref. B-2) designed an image generator using this principle. The simulated object was an orbiting space station having a torroidal form. The simulation was produced by having a rapidly scanned circle move in an elliptical path. After making certain corrections and refinements for intensity, the display obtained was quite realistic.

Such simple analog image generators certainly have limitations, and the resulting patterns cannot be displayed on every output device with as much simplicity as they can be generated, but the concept can be varied and expanded upon.

...ore recently the group at Bell have produced a highly sophisticated piece of image generating equipment in connection with the GEOS program. This is an analog-generated simulation of the AGENA vehicle, to be used in the Gemini training program. Results of this program are reported in the paper "Image-Related Scanning Systems for Visual Simulation". (Ref. W-7)

In space scenes, the data are usually concentrated in certain scene elements, such as planets, stars, space vehicles and targets, etc., with great expanses of the field void of data. In order to capitalize on this fact, consideration should be given to the possibility of generating a scene with the resolution distributed not uniformly, but in accordance with the existing data distribution. In this way scan time will not be wasted on portions of visual field having no interest to the viewer, and can instead be concentrated by placing greater detail in those areas which are of greatest interest.

In the generation of the Agena vehicle video a scan structure was set up to cover the entire vehicle surface with scanning lines. Video intensity modulation is used to mark those surfaces which the observer can see, and to blank out those which are either not illuminated or are occulted by portions of the vehicle or by something else. Computations take into account the perspective corrections, angle of illumination, vehicle orientation in space, and window axis. All computations are done in analog form, and corrections are made to keep brightness constant as the spot velocity varies. Other subtleties enter into the computations as well. The dynamic range of the distance simulation in this case is 285 to 1.

The earth scene generator portion of the GEOS system is basically a flying-spot scanner but it also employs an image-related scan technique.

The portion of the scene which is to be filled with the earth image is scanned with a "raster" of non-uniformly spaced lines. The lines are sparsely spread near the horizon (where resolution is poorest) and are concentrated near the nadir (where resolution should be greatest). The beam is also defocused at and near the horizon both to blend the lines together and to complete the low-resolution illusion. Brightness is controlled in both cases to maintain constant apparent brightness in spite of spot velocity variation.

As the scanning pattern is generated at the display, the appropriate pattern is traced out on the flying-spot CRT and applied to a transparency representing the reflectivity function of the earth. This is a color transparency, and the output display is generated in two colors, A color system using blue and yellow-orange (P-11 and P-20 phosphors) to define the color axis is used. This permits reproduction of most of the colors seen from orbit, and the combination of the two complementaries produces white.

Image-related scanning, while not so versatile nor so efficient as direct digital computation, does provide certain advantages over a fixed raster scan. Valuable raster space is not wasted on areas in which there is certain to be no useful information. For scenes in which it is certain that information will exist over most of the displayed area (such as lunar or earth approach at low altitudes and with full illumination) this advantage disappears. Image-related scanning also has the disadvantage of not being readily combined with other scanning systems.

3.4.3 PRA Approaches

It is obvious with a little thought that any terrain representation scheme based on a brute-force storage and computation of all possible image elements of size small enough to provide a high resolution display will be too unwieldy to work. The PRA approach proposes that mathematical models from which the terrain can be calculated be stored. These may be in several scales, not all of which need be available for all regions. By suitable coding, a cleverly worked out set of algorithms for making use of the stored data, and a hierarchy of memory and computation stages, the total computation and information storage problem is reduced to manageable proportions. In addition, the redundant features of the natural terrain are exploited to further reduce the rate of information flow.

This type of technique apparently has been successfully applied to radar landmass simulation, which, admittedly, is a much simpler problem than that of visual simulation. Major components of both systems would be similar. These would comprise:

a. A vehicle computer; a general-purpose machine which flies the vehicle under control of the pilot, and subject to the dynamical constraints imposed by nature and by the vehicle being flown. (Required for any simulator)

b. A Terrain Computer, a general purpose machine which stores and accesses as needed the pertinent terrain features.

c. A Display System and Computer. This device converts processed data from the above two machines into a form suitable for display. Here a special purpose design would probably prove most efficient. This section would have to be designed especially for the simulator system.

Equipment estimated for a lunar "terrain" simulator is estimated by PRA at the following:

Vehicle Computer - As for any simulator

Terrain Computer - General purpose digital computer with 32k of 48 bit memory and 10 μsec cycle time. Eight tape transports.

Terrain function generator - 600 circuits special-purpose hybrid computer

Display Computer - 300 circuits if analog.

This would result in a simulation capable of covering an area of 7,000,000 square miles with a ground resolution of 50 feet. Resolution to selected target sites could be considerably better. Other features would be:

Speed - 0 - 27,000 mph

Altitude - unlimited (large dynamic range)

Heading Rate - 0 to 10 radian/sec.

Control over illumination

Occultation

Rendezvous

No limitations caused by supports

Can land within lunar crater

In the Pennsylvania Research Association approach, contour maps are stored on magnetic tape in the form of polygonal representations. The map of the terrain and cultural features is stored in digital form, with numbers representing location, height, and type of terrain and structures. Redundancy in the data and repetitiveness in the scan pattern are taken advantage of by passing the data through several memories in succession, each memory acting as a transformation, or digital filtering, from greater to lesser data but lesser to greater speed of access. Ultimately, the processed digital data are used to set function generators, which reconstruct the terrain height and reflectivity profiles and to operate on them with the simulated illumination. Certain important properties of contour lines, such as their nesting relationship, are used to afford a convenient method of accessing data on the positions of contour polygons and their sides. Easily implemented algorithms have been developed for continuous interpolation of height and reflectivity as the map is scanned with the speed of light, while "flying" with the speed of the vehicle. Digital portions of the equipment are used to select data for setting and controlling the analog portions of the equipment while analog portions perform calculations to generate controls for the digital portions. For example, whenever a contour line is crossed by the sweep as it traverses the digital map of the terrain, the sign of an analog signal changes, causing activation of a digital circuit which selects data on the next contour and feeds it in turn to the analog circuitry.

This hybrid model, based on a close marriage of analog and digital computing techniques, can have general utility and flexibility, rather than being a simulator for a specific vehicle and mission.

A more recent technique being developed by PRA involves a different type of function representation. Instead of storing contours in the form of connected line segments or polygons, the regions are represented by polynomials in two variables, whose coefficients are stored. The entire area is made up of these regions, and the polynomials are arranged so that there is appropriate continuity in height, slope, etc. in going from region to region. Both continuity and representation efficiency are achieved by storing not coefficients but values of the polynomials and their derivatives at region corners, each set of values serving for part of each of four regions.

The choice of region size, degree of polynomial, and the number of bits stored per coefficient or value are optimized to give the best balance between roundoff error and polynomial approximation error, taking into account the specific accuracy and other requirements of the model. This is discussed in greater detail in Section VIII of the appendix.

According to PRA, this technique was tried out experimentally on "random" terrain in two areas: a portion of the Pocono Mountains in Pennsylvania, and on a portion of Maine, including both coastal and mountain areas. The results indicated that an area varying in height over a range of 10,000 feet could be stored to a root-mean-square accuracy of under 20 feet in height, with only 60 bits per square nautical mile as compared to 600 bits per square mile in the contour method and up to 10,000 bits per square mile if only the many individual heights were tabulated. The polynomial approach also lends itself to simple mechanization of function reconstruction.

3.4.4 General Electric Approach

The General Electric image element computation system was designed as a part of a space flight simulator for NASA. The visual attachment involved, in addition to the special-purpose digital computer, three color TV display units and the optical systems for viewing these displays.

On the basis of inputs giving the attitude and position of the vehicle with respect to the simulated terrain and sky, the computer generates three perspective views of the idealized environment. The three views are then displayed through three wide angle out-the-window optical displays.

The idealized environment consists of an unbounded plane surface, called the ground plane and a field of stars. The ground plane is textured with cyclical orthogonal patterns, variable within certain constraints, plus a "landing area" which has a distinct texture and color. The star field is similarly composed of a cyclic pattern of "constellations" which is variable within limits. As an alternative to the ground plane, a bounded textured surface, called the "rendezvous surface" can be selected.

The surface patterns are stored in the computer. Dynamic inputs inform the computer of the attitude and position of the vehicle in its environment. The computer performs a perspective transformation of the environment onto the planes of the three ports of the vehicle. These three perspective pictures appear on the television displays. The optical system allows these pictures to be viewed with the proper angular relationships, collimated so that the environment appears focused at infinity.

Some of the parameters that can be set by the user are station (or viewing) point position, picture sight line, angular coverage, texture pattern, texture color and texture scale.

Display roll is not introduced into the computations, but it is implemented by electronically rolling the raster in the display units as required.

To avoid the disturbing moire patterns which might result from beats between computations and scans, fine detail is gradually faded out of the picture in response to information from the digital computer.

3.4.5 Conclusions

The techniques of image element computation, as described above, seem to offer the best possibilities for future television system improvement. Not only are the problems of probes, models, illumination and mechanical motion systems eliminated but dynamics can be simulated which are beyond the capabilities of physical motion systems. This group of techniques, whether accomplished in analog or in digital fashion, certainly appears to be the television technology best suited to future simulation efforts.

Unfortunately, advances in display technology have not kept pace with the great strides made in the computational field. At present, and probably for the next several years, (decade?) it would seem that only simple simulations will be practical if the computational techniques are to be used for achieving high resolution. If the goal is one of achieving the excellent dynamic capabilities available by computation, with resolution less than the best available with present image tube pickups, then the solution is at hand now.

The matter of displays is considered further in a later section of this report.

4. Image Display Systems

4.1 General

There are a great many possible ways for achieving the display of television signals. Sometimes the system designer may have a great many of these from which to select. More often, optical considerations and the use to which the display will be put will restrict the choice to one or two types.

Most displays can be considered in one of three broad categories. These are:

Light generated by a CRT

Light generated by an external source, modulated and scanned separately

Light generated selectively (without scanning) on a surface.

In the following sections a slight revision of this grouping is used to permit a greater orientation toward the use rather than the source of the display.

4.2 Displays using CRTs

4.2.1 General

The most common form of television display device in current use is the kinescope, or cathode ray tube (CRT). This tube, the "picture tube" of home television receivers, employs an electron beam which can be made to scan rapidly over a phosphor surface and to produce illumination selectively as it scans.

Cathode ray tube displays can be viewed either directly or through an optical system, or can be projected onto a secondary screen for viewing. Projection systems can employ refractive optics (direct projection) or a combination of reflective and refractive optics, the most common form of which is the Schmidt system. These will be discussed in the following sections, after a brief essay on the basic design parameters which determine the brightness and resolution of CRTs. Color CRTs are covered in a later section of this report.

4.2.2 Basic Properties of CRTs

In any type of display there are three basic and interrelated factors which are of great importance to the user or observer.

These are:

Highlight brightness and linearity

Resolution, or modulation transfer function

Contrast ratio

Other factors such as field of view, or total picture extent, field shape, viewing angle, etc. cannot be ignored but the listed parameters are direct functions of the CRT and have some basic limitations. It is the purpose of this section to explore these limitations and their interrelations.

The highlight brightness of a CRT is determined by the electrical energy applied per unit area. (Ref. L-5)

$$B = f(E)$$

where $E = \frac{VI \times t}{A}$

and E = electrical energy

V = accelerating potential

I = beam current

t = exposure time

A = area

It can be seen from the above equation that an increase in accelerating voltage, beam current or exposure time (i.e., slower writing speed) will increase the light output of a CRT. A limit on light output is reached when excessive electrical energy is applied to an area causing burning and permanent damage to the phosphor screen. Temperature rise of a phosphor screen normally results in a decrease in its energy conversion efficiency. Coating the rear surface of the screen with aluminum improves contrast and helps to reduce the hot spot temperature by conducting the heat away from the area exposed to the high electrical energy.

An important measure of CRT performance is resolution. The CRT's resolution capability is usually stated as the minimum spot size or line width that the tube can produce. The spot or line on the screen is formed by the tube's electron beam which has an approximately Gaussian current distribution. The basic electron beam size limitations are due to diffraction, space charge within the beam and thermal emission energies (Ref. M-5). The electron beam consists of a bundle of electrons emitted by the cathode of a tube, the image of which is focused on the screen by either an electromagnetic or an electrostatic field lens.

The electron beam size is usually smaller than the area on the screen from which the light is emitted. This is primarily due to the electron and light scattering properties of the phosphor and to reflections from the glass surfaces. These phenomena are especially important in high resolution tubes. Special fine grain phosphors deposited in very thin layers are used in high resolution CRT's to improve resolution. High resolution screens are less efficient in converting electron energy to radiant energy because the energy conversion is reduced as finer particles are used. The spot size increases as the beam current of the CRT is increased to obtain more brightness, while electron guns operated at higher accelerating potentials will yield a smaller spot size.

Focusing and deflection circuitry play an important role in the final resolution capability of a CRT display. The <u>contrast,</u> defined as the ratio of maximum and minimum brightness values in a picture (Ref. F-5) is greatly reduced if the screen is illuminated by ambient or its own scattered light.

The effect of front illumination on the contrast of a display is given by the equation:

$$C \approx \frac{B_{max} + kTE_o}{B_{min} + kTE_o + .05\, e_o}$$

where

B_{max} = display's peak brightness

B_{min} = display's minimum brightness

k = reflection factor of screen material

T = transmission factor of filters placed over screen

E_o = front illumination

$.05\, E_o$ = reflection from filter or glass

In a dark room, where $E_o = O$,

$$C = \frac{B_{max}}{B_{min}}$$

Although this equation does not include the variations in contrast with front illumination angle of incidence nor the excitation of the phosphor by the incident light, it gives an overall idea of the role ambient light plays in determining overall display quality.

The brightness of home TV receiver tubes usually will vary from 30 to 100 foot-lamberts (Ref. F-5) and the line width might be as wide as .020". Special purpose tubes are available in sizes from 1" to 27" with different types of phosphor screens, higher brightness, and higher resolutions.

4.2.3 Directly Viewed Kinescope

The CRT can provide high resolution and high brightness over a screen ranging in size up to about 27 inches in diameter.

Prior sections of this report have examined various methods of displaying visual scenes. It has been determined b actual experience that virtual image or infinity image displays are the most realistic and the most psychologically satisfying displays. On the other hand, if one elects to look at a CRT directly he is merely looking at a "picture" so that any fore and aft head motion either increases or decreases the apparent magnification, while lateral or vertical head motions change the apparent direction of the visual scene. These two drawbacks alone legislate against direct view of TV screens since there is absolutely no realism attached to this method. Limitations such as difficulty in achieving wide fields because an observer cannot visually accommodate for the closeness of approach required in order to simulate a wide field of view with large screen CRT's as well as limitations that involve multiple inputs again legislate against the direct view approach. From the technical viewpoint the use of large screen CRT's requires dynamic focus in order to maintain high resolution over the entire screen area. This electronic requirement is costly in terms of power and temperature problems as well as in dollar costs.

4.2.4 Infinity Matched Kinescope

In an infinity imaging system based on reflective spherical optics, the input focal surface is spherical. To provide the best match of a kinescope to this surface requires a spherical CRT faceplate and screen. This has been achieved, in angular sizes up to 110 degrees and in tube diameters as great as 27 inches. Greater angles would require considerably more complex processing of the tube faceplate, and tube diameters greater than 27 inches might be impossible to fabricate without specially built equipment. The present range of available sizes has been suitable for several different spaceflight simulators.

Difficulties which have appeared in the manufacture of these tubes stem solely from the fact that they are a "new breed" and require close tolerances of many electrical, optical and mechanical parameters. One incidental advantage appears, in that the strong curvature of the screen causes the focal length of the electron beam to be nearly constant over the entire scanned surface. Thus the dynamic focus correction requirement for maintaining proper focus over the entire tube surface is relaxed, together with its attendant power drain and circuit complexity. Resolution of 2000 lines (limitive) has been achieved in a 13-1/2 inch radius of curvature 110 degree tube produced for the LEM EVDE simulator.

4.2.5 Direct Projection

Images produced at the CRT surface can be projected onto a screen by the simple insertion of a lens between the CRT faceplate and the projection screen. This process is somewhat inefficient because of the poor light-gathering ability of well-corrected refractive optics. Lens openings of f:2--f:4 are typical, and openings faster than f:1.5 are almost never found.

With projection systems there is also the problem of producing very intense high resolution images on a small surface in order to be compatible with reasonable sized optics. The requirements of high resolution and small size tend to be mutually incompatible in spite of the fact that the small image size reduces the electron-optical problems.

4.2.6 Schmidt Projection Systems

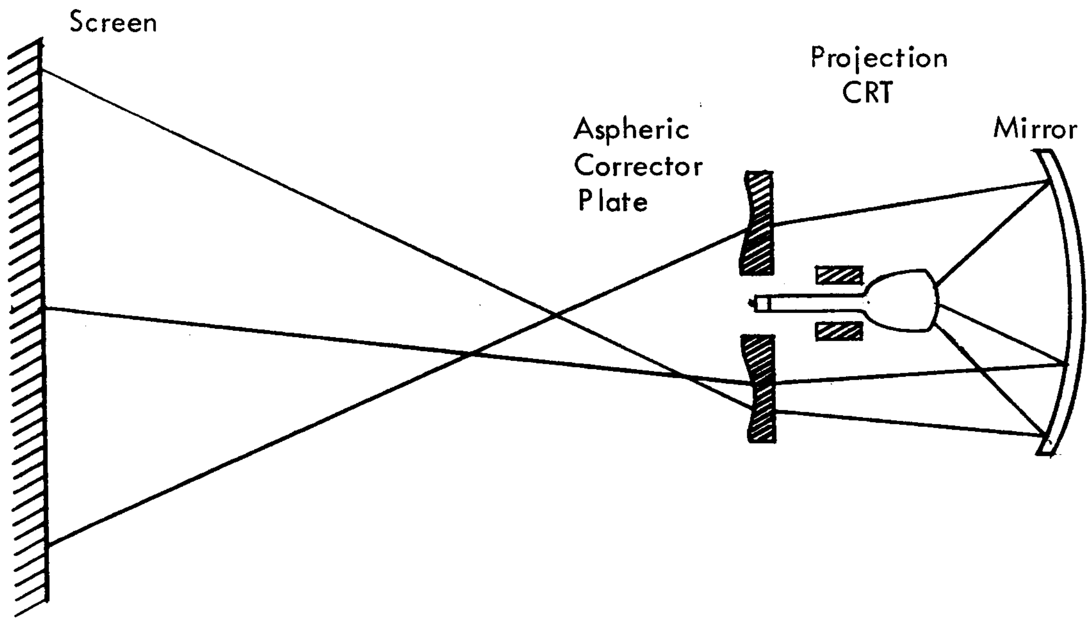
The poor light-gathering ability of refractive optics can be overcome by the use of fast reflective systems. The Schmidt system (Fig. 3-39) is probably the most widely used of these. It consists of a spherical mirror with an aspheric refracting corrector plate between the mirror and the screen. Good efficiencies are obtained with high brightness for screen displays.

Some of the advantages which Schmidt systems enjoy relative to refractive projection systems are: (Ref. A-1)

1. The system can be made relatively fast (low f: number) with fairly wide corrected fields.

2. The system design is straightforward because it uses relatively few optical components.

3. The Schmidt system permits the use of a convex CRT face,



Schmidt Projection System

FIGURE 3-39

which simplifies the design of both projection CRT and optical system.

Of course, any screen projection display suffers from certain disadvantages in terms of focus accomodation and realism. This is discussed further in section IV of this report.

A novel development in Schmidt system design should be mentioned at this point. In the search for ever higher brightness and light output, designers have been stressing projection CRT design to the point where the tube life is often limited because of heating due to the high power dissipated in the phosphor and faceplate at high brightness levels.

It has been known that if the phosphor surface could be cooled, higher power and brightness levels could be obtained. This has been accomplished in a CRT developed by the Raytheon Corporation.

A projection CRT electron gun and faceplate are mounted in an evacuated enclosure together with the Schmidt reflecting mirror, as shown in Figure 3-47.(The corrector plate is mounted external to the tube.) This arrangement was intended to permit the phosphor surface to be cooled, and thus to increase the available light output. In addition to the accessability for cooling, however, there are several beneficial side effects.

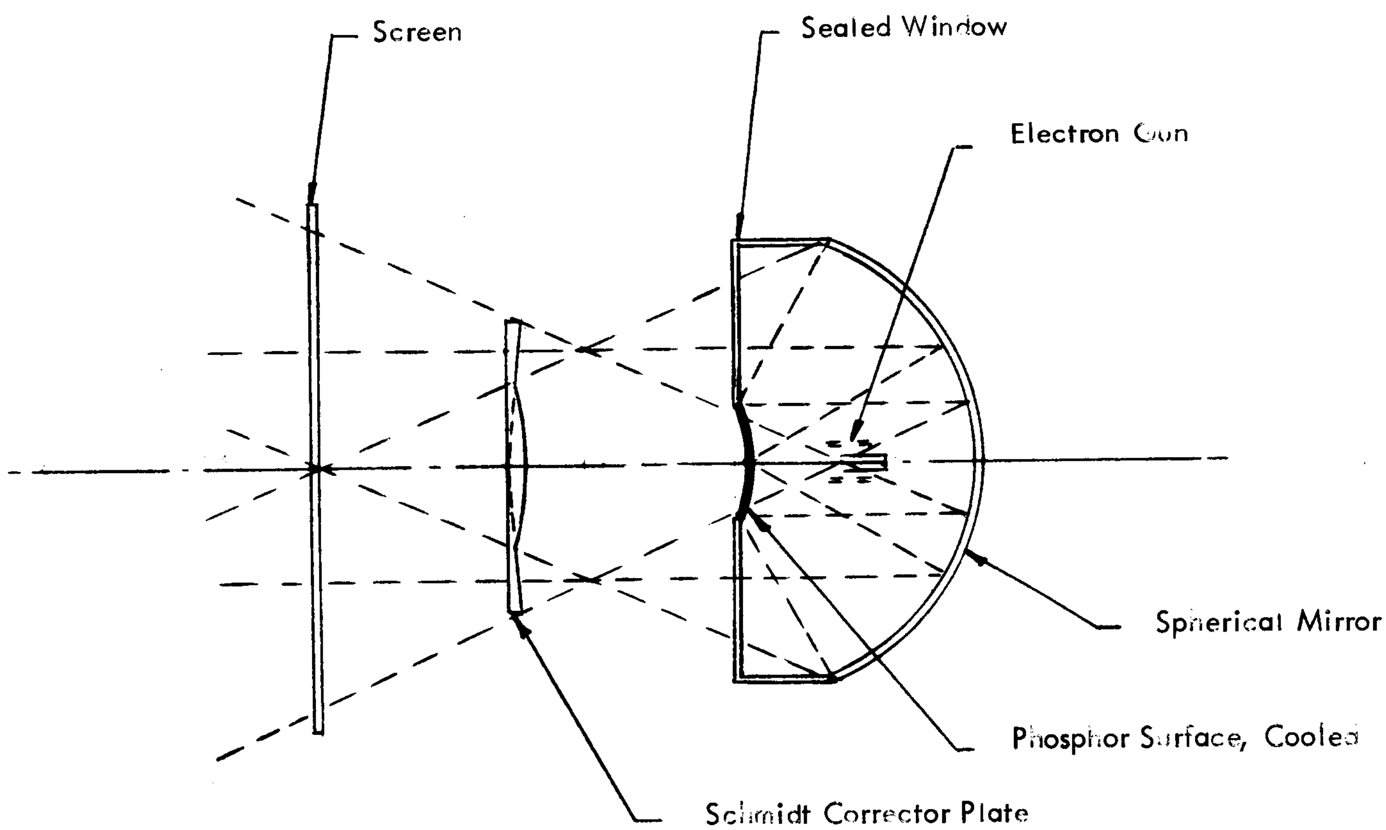


FIGURE 3-47 INTEGRATED SCHMIDT CRT AND MIRROR

It is well known that the inner surface of a CRT phosphor (the side struck by the electron beam) is far brighter than is the outer, or conventionally viewed surface. Thus a serendipitous advantage accrues immediately in terms of increased light output and efficiency.

Mirrors in Schmidt systems often accumulate dust particles because of the precipitation action of the high strength electric fields needed to work the projection CRTs. In the sealed-off combination system, the mirror is always in the vacuum chamber, and so cannot become dusty or dirty, nor can the coating deteriorate. Once the tube is completed, the CRT and mirror are aligned permanently. This adjustment cannot be disturbed accidentally thereafter.

A tube being produced by Raytheon under a development contract (NObsr-92564) is due to be delivered late in 1965. It will have an overall diameter of 24 inches, and light output of 800 to 1000 lumens. Resolution is to be compatible with "high resolution" 945 line television systems.

4.3 Color Displays

4.4 General

The addition of color to the television system provides an added dimension of realism in most simulations. There are many ways in which color displays can be produced, and several will be discussed in this section.

Probably the most basic technique for generating color television images is by the use of three separate channels of black and white which are passed through the appropriate color filters and added. This can be done with any of the TV systems described above, the optical arrangements being basically the same for all. For screen displays, the actual mixture can take place at the screen, while for this others this will generally be done by combining beamsplitters in the viewing path.

In a field-sequential color system (discussed below) a mechanical filter sequencing arrangement can be used to produce full color pictures from a single CRT. All systems in which the color information is changed at a rate more rapid than the field rate require the use of special color display tubes if a single tube is to be used for the output.

The balance of this section will treat very briefly some of the tubes and techniques used to produce color pictures using a single tube. Color displays can also be produced by the Eidophor, TPR and certain mosaic techniques. These are covered in the other appropriate sections.

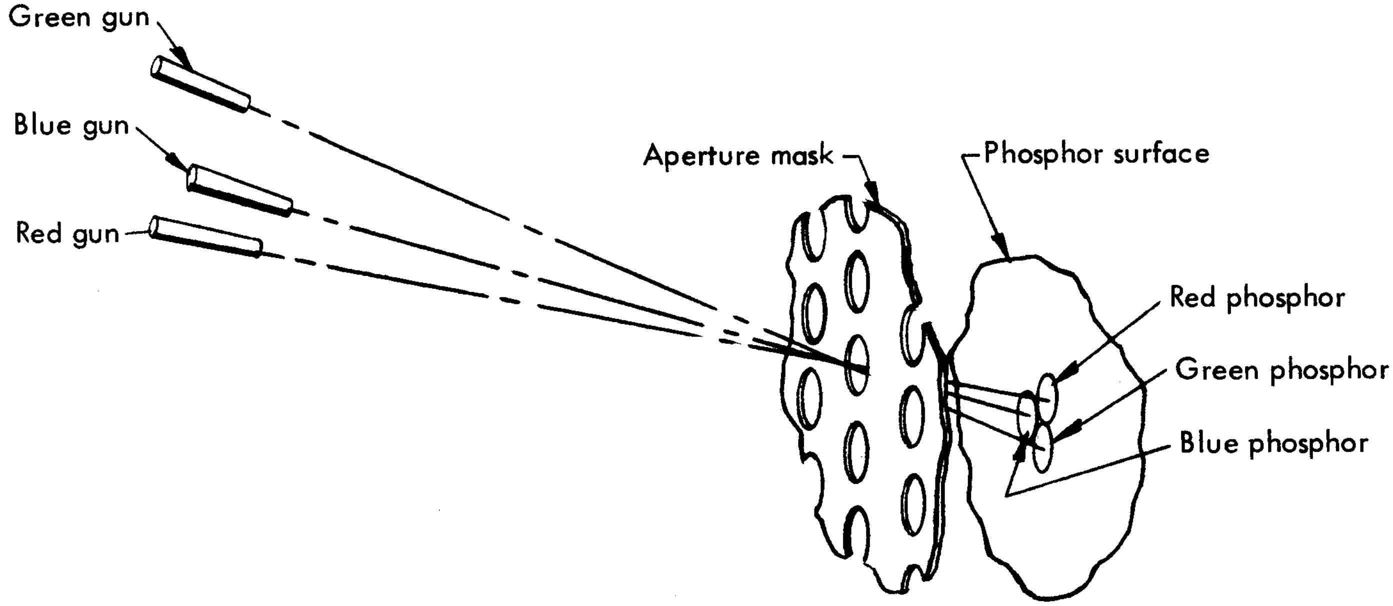
4.4.1 Color Wheel

In conventional rectangular raster scanning, the television picture is traced out in regular fashion from top to bottom. If three complete repetitions of the raster are permitted for each color frame, then a mechanical color wheel or other device bearing filters of the three required colors can be used to lend the appropriate color to each field of the frame. The only requirement is that the appropriate color filter be made to appear in front of the scanning light spot at all times. This is not a difficult feat, since the spot is moving from top to bottom of the picture at a relatively slow rate. Thus the filters can be placed on the sectors of a simple "color wheel" driven by a motor synchronized to the vertical frame rate.

4.4.2 Shadow-mask Tube

This is the output device in common use for home television. It has the advantage of being in wide use, a history of relatively successful production and has provided a practical solution to the color display problem. Several drawbacks appear, however, when its use in wide angle displays is considered.

In the shadow-mask tube, three separate electron guns located in three physically separated places are focused onto the same spot. The resultant beams are made to pass through a "shadow mask" or "aperture mask" before they impinge on the phosphor surface. This is illustrated in Fig. 3-40. The geometry is so arranged that every spot on the phosphor surface is accessible to one and only one of the three electron beams. Thus, if the spots associated with the red gun



Shadow-Mask Color Kinescope

FIGURE 3-40

are covered with red phosphor, etc., and if all the apertures are uniform and sufficiently small, any small region of the phosphor surface (large enough to contain at least several spots of each color) can be made to phosphoresce in any desired color, depending on the combined excitation of the three beams.

Of course, the theoretical maximum transmission of the shadow mask is 1/3, for perfect alignment. This cuts down brightness at the display surface, and in the most advanced shadow mask tubes brightnesses of only about 60 foot-lamberts can be achieved.

Shadow-mask tubes are currently made in only a few sizes, and these have required long and costly development programs. Any future development work would probably not be greatly simplified by this experience. Further, if the screen curvature is to be changed greatly from its present nearly flat shape, it is possible that production might become impossible.

4.4.3 Other Color Display Tubes

There have been many proposals and some developments for color kinescope design in addition to the shadow-mask tube. A few of these are described here.

Beam Indexing Tubes (Ref. F-5)

These include the "Apple" and "Goodman" types. In all beam index tubes the phosphors are arranged in vertical stripes which are scanned horizontally by the electron beam. Additional vertical stripes are introduced which produce no visible output when struck by electrons from the scanning beam. Instead, these added stripes produce an output which serves to inform the system where the writing beam is, so that the intensity can be properly modified as it crosses the color stripes.

In the Apple tube the indexing is done with a separate beam and the index stripes are made of M_gO which is a good emitter of secondary electrons. Thus the presence of secondaries (which are collected by an anode coating) indicates that the beam is passing a reference or index stripe.

Beam index tubes depending on secondary emission are limited in speed of response by the relatively slow velocity of the secondary electrons. In a tube proposed by D. Goodman, the secondary emission system is replaced by one in which X-rays are generated and detected by Scincillators and photomultipliers to index the beam. The principle of such a tube has been successfully demonstrated, but the electronics needed to operate it are, needless to say, quite complex.

Other beam indexing schemes are possible, but the difficulty of depositing the phosphors in accurate registration is common to all. One advantage these tubes possess is that the screen is nearly completely covered with phosphor, permitting relatively high brightness efficiency to be obtained.

The Chromatron, or Lawrence Tube

This is one of a variety of single-gun color tubes which employ switching at the screen for color selection.

The screen structure includes a flat plate which bears phosphors in the form of strips oriented horizontally. The screen supports a grille frame. The grille itself consists of a set of wires parallel to the phosphor stripes. Alternate wires are connected together, so that there are two interlaced coplanar grilles. These are energized by voltages derived from the color signals, and serve to focus the electron beam onto the appropriate color stripes.

No real-time beam indexing is required and switching is simplified since all grille wires are connected to one of the two driving sources. Color registry is built into the tube during manufacture by proper alignment of the grille wires relative to the phosphor strips.

Bannana Tube

In this configuration, the tube has only three color stripes. Each extends the entire length of the picture in the direction of scan. The second component of scan is obtained by mechanical motion. A low amplitude electronic scan is performed in a direction perpendicular to the line scan for the purpose of indexing to the proper color stripe.

This tube has not attained a great deal of popularity probably because of the mechanical motions required. The electronics, however, are relatively simple.

Summary

In all color kinescopes the colors are generated by individual phosphor-coated areas. The electron beam or beams traverse these patches and are intensified at appropriate times, causing the appropriate colors to be produced.

It is immediately apparent that for a given electron beam diameter resolution is limited to less than that of an equivalent black and white presentation for all color tube types. This must be true, since for each possible position of the color display there can be three different possible positions of the beam in a comparable black and white display.

In addition there are inefficiencies resulting from improper matching between beam size and available phosphor element size, and inefficiencies in the arrangement of phosphor elements themselves. Improper matching can also be a serious source of color dilution. If the beam is larger than the patch of color phosphor on which it is to impinge, adjacent color areas will be partially illuminated with the result that the color is diluted and fully saturated colors cannot be produced. This results in a "washed out" picture.

The efficiencies of color phosphors are in general much lower than that of the universally used P-4 white phosphor. This is another factor which contributes to the lower brightness of color tubes as opposed to black and white.

Attempts have been made to overcome some of these difficulties by other means, such as by employing phosphors which respond in different colors to electrons of different energies. To date, none of these approaches has yielded any results which can be considered useful.

4.5 Non-CRT Displays

4.6 General

This section will deal with an assortment of display techniques which do not logically fit together as a group, but the techniques of which are important in a survey of display systems. They range from the modern TPR systems through the well-tested Eidophor to the historically interesting Scophony systems.

4.6.1 Eidophor - type Systems (Fig. 3-46)

Television projection by the "control layer system" is used in the Eidophor, developed by Gretag Limited, (a subsidiary of Ciba Ltd.) jointly with Philips of the Netherlands. Basically, the phosphor screen of a cathode ray tube is replaced in the Eidophor by a uniformly thin layer of oil on a spherical mirror. Light from an

*Registered Trade Mark

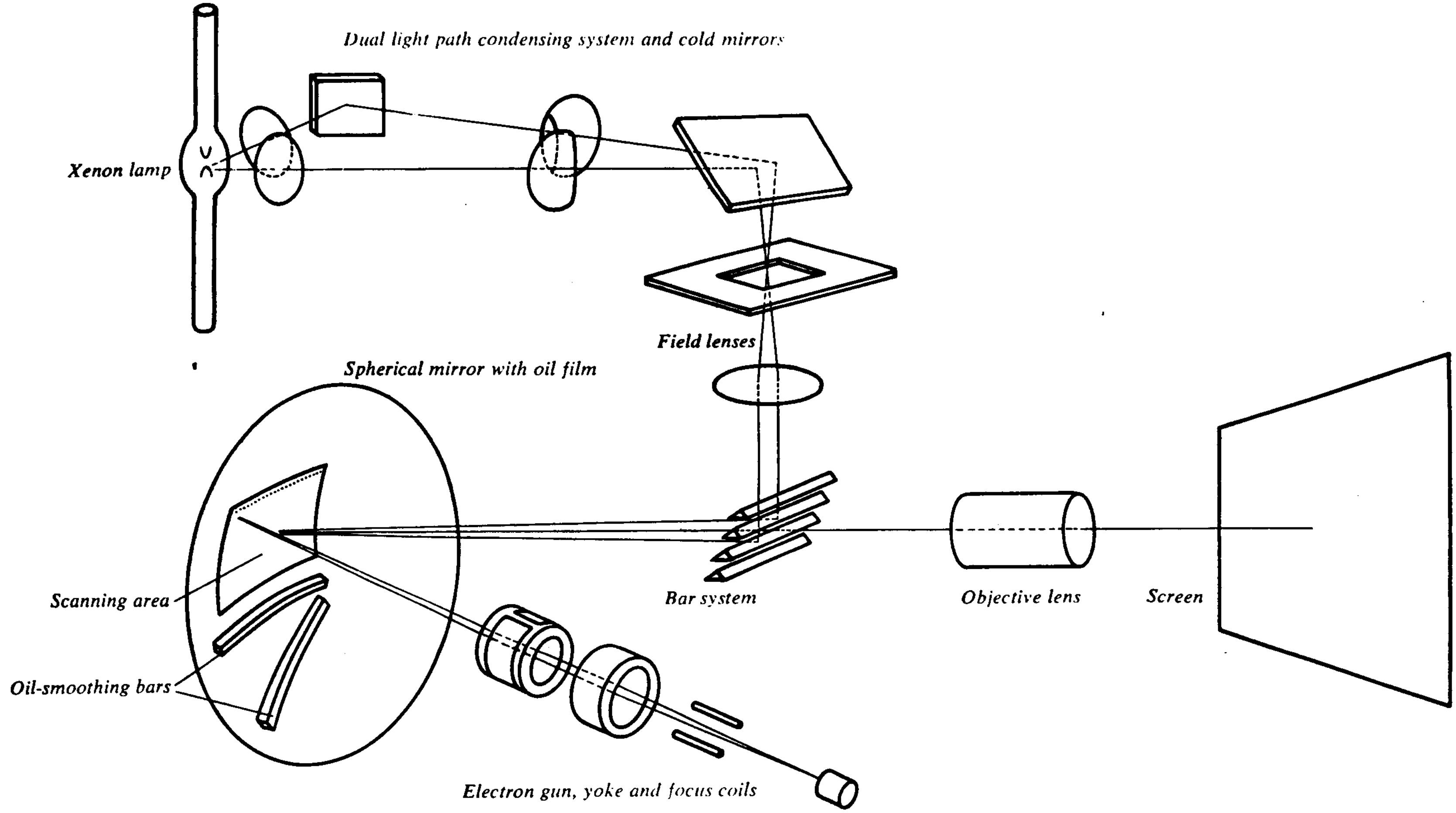


Figure 3-46

The Eidophor System

intense Xenon arc lamp is also directed against the oil coated mirror. Perturbations of the oil layer caused by the electron gun are projected by the mirror through suitable optics to a viewing screen or screens. The process has been likened to the principle of projecting light through a photographic plate, except that the image, in this device is reflected from the "film" instead of being transmitted through it. In the Eidophor (Figure 3-46) light from the xenon arc is reflected by a slotted mirror onto the oil layer. So long as the oil is smooth (black level video signal) all the light is reflected back to the light source leaving the screen dark.

When the electron gun writes its "electronic" TV picture onto the oil layer, however, the light from the xenon arc passes through the resulting "wrinkles" and is refracted so that it passes through the slots in the mirror and is focused on the screen by the objective lens.

4.6.2 Separate Modulation & Deflection Components:

Probably the most important reason for interest in these components as related to television displays is the recent advent of the LASER. Although advances remain to be made, in several areas before this tool can be put to practical use, the LASER represents a source of extremely high brightness and small effective size. These are the basic requirements for a light source to be used with a high resolution scanning display system.

Components for such a television system are the subject of a study by Perkin-Elmer, results of which are reported in (P-3). Further details of this type of system are contained in Section 3.2.3 of this report under the title of LASER Light Sources used as pickup devices.

In a display, the light source must be modulated in intensity as the beam is scanned. This is also discussed in Ref. P-3, in which several scanning techniques are analyzed. Conclusions drawn from the Perkin-Elmer report are that (a) electrooptic effect deflection components and a Pockel cell modulator should ultimately be capable of providing modulation consistent with 1000 TV line resolution.

4.6.3 Photochromics

Certain materials have the property that their transmission and absorption in one region of the electro-magnetic spectrum are affected by illumination with energy from a different spectral region. Materials such as these are known as photochromics, and they have an obvious potential in display systems.

In a report by Bjelland of the National Cash Register Company (Ref. B-3) work is reported on a photochromic display which uses ultraviolet light for control. The photochromic is used as a light valve for the production of an image by projection.

To date no photochromics exist which have suitable characteristics for a high resolution real-time television display. They are, however, being investigated for other uses such as for information storage and display and may ultimately prove useful in television as well.

4.6.4 Scophony System (Ref. A-1, F-5)

This arrangement for achieving projection television displays came into being just before World War II. Although the system is quite outdated now, some of its basic features may be useful in certain display applications.

The light modulator is the really novel feature of the Scophony system. This modulator consists of a liquid cell in which is mounted a piezoelectric crystal. A high frequency signal applied to the crystal creates ultrasonic waves in the liquid. These produce striations in the liquid and cause it to act like a diffraction grating. The pattern can be read out with Schlieren or other optical techniques.

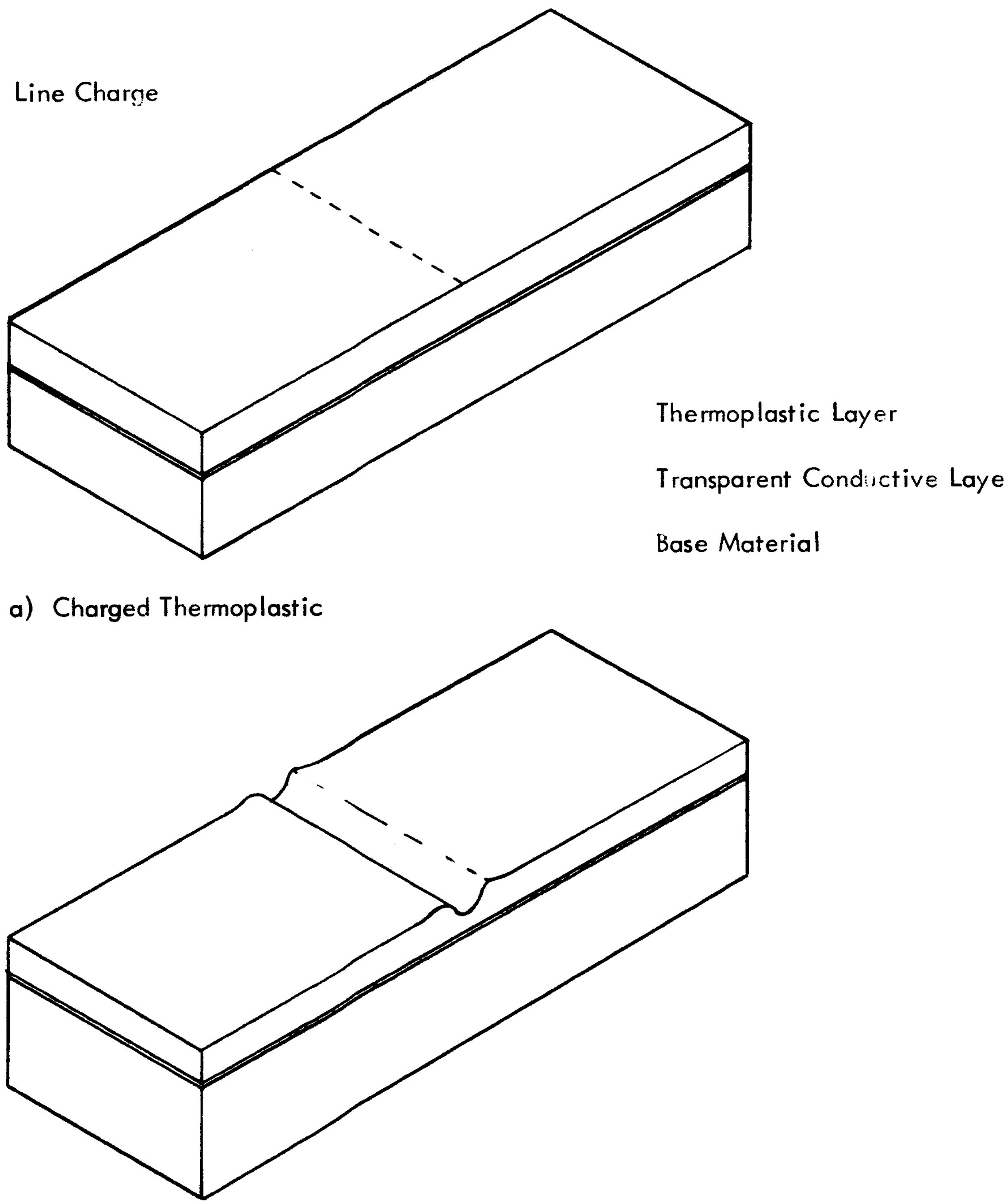
A complete line of modulation information is stored in the crystal. This line must be stopped either by mechanical scanning or by separate on-off modulation of the source lamp. The mechanical method was used in the original Scophony system. In this case scanning took place at uniform angular speed while the wave propagated in the liquid cell at constant cell at constant linear speed. The scanning angles must be kept low if good tracking is to be obtained. Frame scanning was accomplished by means of a second rotating mirror system.

While this system may have seemed eminently practical in 1939, the advent of improved cathode ray tubes and other display devices has probably doomed it now to being an interesting historical curiosity.

4.6.5 Thermoplastic Recording

1) Introduction

Thermoplastic recording was developed several years ago by Dr. W. E. Glenn of the General Electric Company as an extension of their investigation into an Eidiphor-type system employing an oil film. The recording of information on a thermoplastic medium is accomplished by the conversion of a charge pattern on the medium (Figure 3-41) to a surface deformation (Figure 3-41). Electrical forces between the surface charge and the conducting layer mechanically stress the thermoplastic material. When the thermoplastic is heated to its fluid point, any abrupt changes in charge density cause a deformation of the thermoplastic due to different forces in adjacent areas. After cooling, the deformation is a permanent record of the written information unless it is erased by additional heating.



Response of Thermoplastic Medium to a Line Charge

FIGURE 3-41

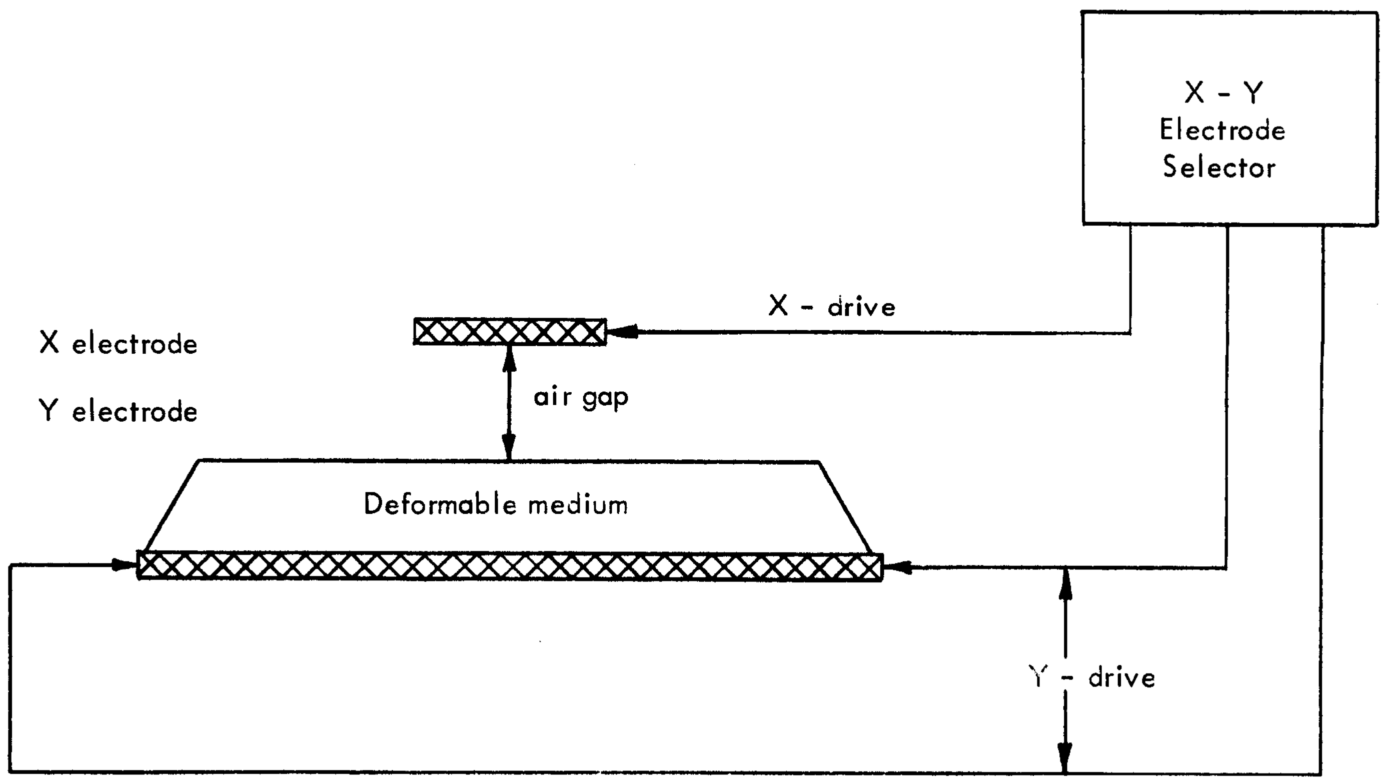
2) Image Production

Several methods for obtaining the charged image have been evolved over approximately a decade of investigation. The most straightforward of these is by direct writing using an electron beam.

Another technique involves using for the thermoplastic layer not an insulator, but a photoconductor applied over a conductive base. In this approach the sensitive surface is giving prime charge by a corona discharge. The light image focused on it causes the photoconductor to leak some of the surface charge away. When the image is later "developed" by heating, the charged areas are attracted to the base material, causing a local thinning of the photoplastic. Heat is applied for only 10 to 100 msec., after which time the image is "frozen" into the plastic material as it cools.

A third technique is an "in-air" method developed by General Electric (Ref. G-3). This makes possible an X-Y matrix controlled display. Matrix control is illustrated in Figure 3-42. A Townsend discharge is produced at the intersection point selected by the X and Y matrix control inputs. Thus charge can be placed on the deformable medium at a selected location or it can be prevented from being placed there.

Resolution of the in-air matrix display is limited by the fineness of the elements and by the size of the matrix that can be



Block Diagram of In-Air Thermoplastic Recording System

FIGURE 3-42

fabricated. This has been demonstrated to be at least 32 by 32 lines per inch in a preliminary model. Resolution of thermoplastic recordings made by electron beam techniques is several hundred lines per mm (500 TV lines) and for the photoplastics the figure is still better (720 TV lines).

3) Image Display

There are two fundamental improvements to be gained from thermoplastic and photoplastic recording techniques. One is the high resolution attainable with these techniques. The second is the ease of obtaining high light outputs. Since the medium can be used as a light valve rather than acting as a source of luminant energy, the entire picture can be illuminated at once, rather than being scanned point by point as, for example, in a cathode ray tube.

Another bonus, which will be recognized shortly, is that the medium does not absorb energy in order to remove light from the image. This means that the film heating limitations which apply to conventional photographic films are not nearly so stringent in TPR display systems.

In those applications where a permanent or delayed representation of the display is wanted, the TPR medium can be used and not immediately erased. This feature is not easily obtainable in other display systems.

The image in a thermoplastic recording is represented not in terms of gradations of gray, but as an array of depressions and slopes on the surface of a medium. These slopes can be read out in at least three different ways. These are 1) by using a Schlieren optical system, 2) by using the phenomenon of Total Internal Reflection, and 3) electrically.

In a Schlieren optical system, illustrated in Figure 3-43, the image of an obscuring bar pattern formed by slits is imaged onto a second set of bars. In practice a single set of bars with suitable optics can perform both functions. When the material to be read (or projected) is inserted into the optical path between the two sets of bars, those parts of the subject which have slopes will cause the light to be deviated from its normal path which would terminate on the obstructing bar. Thus the light from these areas misses the stopping bar and forms a portion of the picture. In this way, not only can an image be generated, but the energy which is not used for the display is dissipated in the same bar it would normally strike.

The TIRP, or Total Internal Reflection Prism system, also detects slopes, but by means of an entirely different principle. In the case of a light ray attempting to emerge from a dense medium into a rarer one, there is a "critical angle" beyond which the ray will not succeed in emerging, but will instead be reflected back

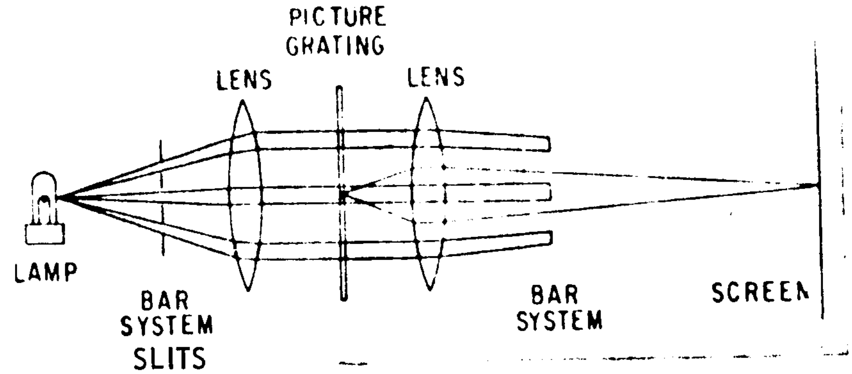


FIGURE 3 - 43

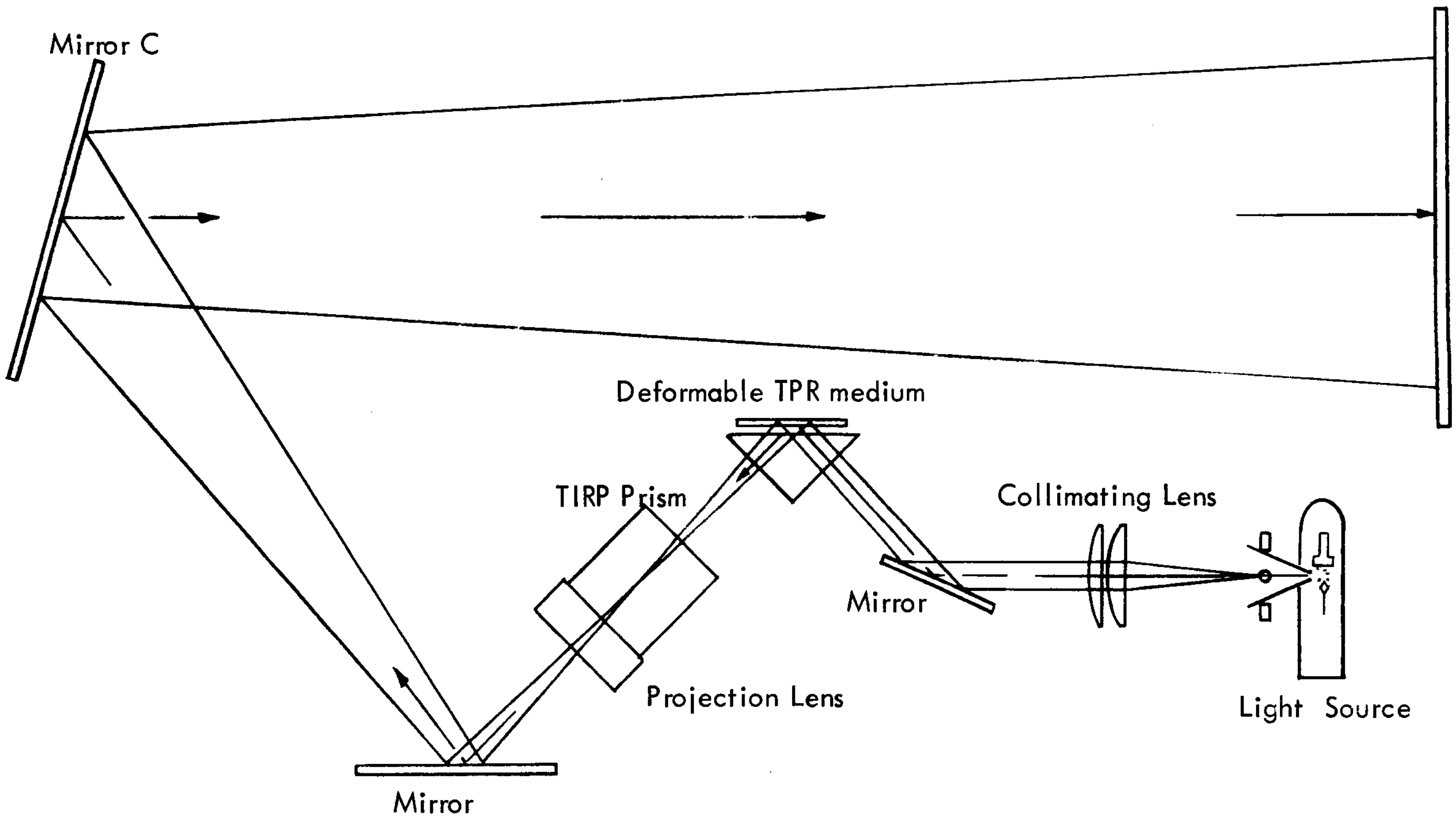
Schlieren Optical System

into the original medium. In the TIRP readout scheme, illustrated in Figure 3-44, the TPR or deformable medium is placed behind the total internally reflecting surface of a prism. The void is filled with oil, so that there is no optical distinction between the TPR material and the prism material. At the rear side of the film, however, the ripples on the TPR film surface cause the angle to vary locally above and below the critical value. Thus a portion of the energy is totally reflected and the balance passes out through the rear of the film-prism combination.

TPR material can also be read out electrically. This has application mostly when the film is used as a high resolution storage medium, and where a direct visual display is not desired. Electron beam and other types of readout are discussed extensively in Ref. W6 Ad-293 201.

4) Recording

Since the TPR medium retains its information until it is relaxed by heating, this technique also performs the function of storage or memory. This may not have direct application in simulation, but it is an inherent feature of the TPR system. A slight disadvantage may accrue in simulation work because of the time delay between exposure and availability of the developed TPR material for viewing. This can be reduced to the order of tenths of a second in



TIRP Optics for TPR Display

FIGURE 3-44

the present systems.

4.7 Mosaic Displays

4.8 General

As was outlined in an earlier section, the resolution of a television system may be improved by synthesizing it from several subsystems. Such an arrangement is referred to as a mosaic television system. If the input or sensor of a television system is a mosaic array, the balance of the system must usually involve multiple operation of components as well. However, the converse is not true. If a single sensor is used, or if no sensor is used (such as with the element computation method of video generation) it is still possible to use a mosaic arrangement for the display. In certain cases this may be desirable for reasons other than those determined by the TV system.

Five types of mosaic systems are discussed in this section. The first two of these are proposed display schemes associated with particular image generation arrangements described in Section II of this report. The third is an arrangement used to provide Air Traffic Controllers with large amounts of RADAR data from multiple sources. The fourth is the display intended for use with the 3-channel wide-angle pickup system described above. The fifth technique discussed is the so-called "elemental mosaic" system, in which each element of the mosaic is used for the display of a single picture element.

Each element will be addressed individually, making this method quite compatible with an elemental computation alone.

4.8.1 Fish Eye Display

The proposed fish-eye television system (Ref. C-4) would use five line-scanning vidicons for image pickup. The proposed readout for this arrangement consists of a special array amounting to five Eidiphor type projectors operated in synchronism. A single source would illuminate all displays, simplifying the problem of illumination uniformity. No special efforts are proposed to deal with edge registration or other alignment difficulties. These would tend to be minimized since the display would be rotating continuously, but no claim is made that the problems would disappear. This display was proposed for use with and would be applicable to only the Fish-Eye pickup system.

4.8.2 Fly's Eye Display

This system was proposed as a display for the Fly's Eye mosaic pickup described in Section 3.3.3 above. The Fly's Eye Pickup scans 3025 lines in elevation on a continuous and repetitive basis.

The proposed display is by means of 3025 cathode ray tubes, one for each channel in the elevation coordinate. Each CRT channel need provide illumination only. It would have to be modulated in intensity but would not have be to scanned, the scanning motion being accomplished mechanically. The hardware items of this system are complex, and the electronics required would be difficult to fabricate and to keep in alignment. One of the problems would be that of maintaining proportional brightness and linearity of the brightness curve among all the CRTs. The eye is a good discriminator of small contrast differences in adjacent areas. This might create difficulties in a display containing 3025 cathode ray tubes used to form a single display. Extremely good linearity of transfer characteristic (or at least a good match among the nonlinearities) of the amplifier, cathode ray tube, and other components of each channel would be needed in such a system.

The Fly's Eye display approach has not been proposed for use with other than the Fly's Eye pickup system.

4.8.3 FAA - Radar Mosaic

The Raytheon Corporation has produced for the Federal Aviation Agency a mosaic TV display system intended to be used with airport traffic monitoring radars. This is a system in which an operator can have access in a single display to high resolution information available from several different radars.

Four separate television rasters (945 line high-resolution television channels) are matted together to form a "super raster" which forms the basic "big picture". The video signals associated with this super raster are keyed by means of a specially prepared transparency and flying spot scanner. In this way, as many as eight radar sets can share their coverage in contributing information to make up a video signal for the super raster.

The display itself is a separate 945 line high-resolution television channel, which can access any 25% rectangular section of the super raster. The output or display raster can be made to cover any 3 x 4 rectangular portion of the super raster, under control of the operator. Since the output has access to a raster four times as great as its own area at no loss in resolution, there is a fourfold improvement in the amount of presentable information and no decrease in the picture element information content.

This system is reported to have been successfully used for its basic purpose - the display of radar data. It was not intended for use with halftome television displays, and the fast switches used in the radar application might require considerable modification if the system were to be considered for use with halftone television material. Also, the advantage over a single high resolution television channel is only a factor of four. It is doubtful whether a television system of such complexity could be justified in exchange for the relatively small advantage in resolution.

4.8.4 Three-Channel Wide-Angle Display

GPL has produced a projection display for the U.S. Naval Training Device Center which is intended for use with the Three-Channel Television system whose pickup elements are described in a previous section of this report. (Ref. 3.3.4)

This system employs three type 5AZP4 projection CRTs operated at 35 kv, with three sets of refractive optics, to fill a large spherical screen. The screen has an angular size of 80 by 180 degrees, and is covered by three television rasters of 60 by 80 degrees each. The rasters have the conventional 3 by 4 aspect ratio, but are oriented so that scanning takes place vertically rather than horizontally. Thus the 180 degree direction, corresponding to an azimuthal coordinate, comprises three separate rasters combined with two seams.

The system is designed for an 875 line raster at frame and field rates of 60 and 30 per second respectively. Use of a 20 mc bandpass for all video components is expected to result in a vertical resolution of 1000 lines in the line-scan direction.

Since this system has not yet been set up in its final location, detailed data are not yet available on its performance.

4.8.5 Elemental and Matrix Mosaic Displays

It is not necessary that anything be scanned in order to produce a television display. While most television systems do employ scanning, a display can be formed by combining a suitable number of components in an array wherein each "resolution element" of the picture is formed separately. Such a display will be called here a "matrix display", or and "elemental display".

In most approaches to the achievement of matrix displays, the matrix elements are addressed by row and column indices. This is the case, for instance, in the "matrix display" discussed in reference G-3, and reviewed above under the subject of TPR Displays.

With coordinate addressing, the element is selected by combined selection (or half-selection) on two orthogonal axes, such as row and column. Thus only a single element may be addressed at a time. A simple system such as this imposes a severe restriction in that there is no provision for storage in the matrix. Of course, this can be overcome by using the addressing to enter a store, and having each store location control the illumination of a single picture element. The perfection of a simple store and display which will achieve these ends will result in a display which will have high brightness without storage since each picture element can be excited at all times, under the control of its own storage element.

Another approach which would seem to have good promise for use in matrix displays is the use of the electroluminescence phenomenon. Certain materials, such as zinc sulphide, have the property of emitting light under the stimulus of electrical excitation. These panels have been made in arrays with up to 300 elements per linear inch over a one-inch surface (Ref. E-2) and much larger surfaces with lower densities. Light output from these arrays is not great, with typical large-area values below 100 ft-lamberts. In general, panel life decreases with the light output demanded of it.

There is no reason in principle why other sources cannot be used as the elements of display. Some suggested light sources have been incandescent lamps, miniature solid-state lasers, gas discharge lamps in various configurations, and devices employing the cathode ray principle. While many of these may be applicable to certain types of matrix elemental displays (e.g., the incandescent lamps used in animated billboards) a much more stringent set of limitations must be imposed on elements considered for use in a television display.

In a television display large areas of the picture are formed by the combined excitation of many small elemental areas. Thus, if the large areas which are intended to represent a uniform surface are in reality formed of many small elements, it is important that these elements behave uniformly under excitation. In other words, they must possess either a linear transfer characteristic, or at least the same transfer characteristic from one to another. Since a display might consist of several millions of elements, this problem is not trivial.

The discussion of a high resolution elemental display thus leads to the conclusion that the elements which form it must emboy the following properties:

They must be small

They must have the same transfer characteristic

They must have high inherent brightness (unless the system can employ storage, in which case this requirement may be relaxed some what).

They must be easily and cheaply mass-produced.

They must be easily and cheaply interconnected.

Elements which are not sufficiently small for a given application should not be discarded immediately as inapplicable. Through the use of fiber optics it is possible to transfer sources of light from one place to another. By this means the light generating elements can be of a convenient size and shape, and can be conveniently arranged for interconnection with the selection of driving circuitry. Illumination can come from a point convenient to the succeeding optics or optical system, rather than being rigidly fixed by the television system.

5. Comparison of Displays

Many displays and display techniques which can be used with television systems have been discussed in the preceding paragraphs. Some of these may be directly applicable to state-of-the-art television systems, while others are of only limited significance in this regard. In the present section the salient features of several important displays and display techniques will be outlined. Emphasis will be placed on the relative advantages of those features deemed most important.

By far the commonest form of display device at present is the cathode ray tube. These tubes have been made in various forms, including many with special features such as multigun display, dark trace for use in high ambient light levels, display storage, etc. For use as a television output device, however, the important features are usually brightness and resolution.

Presently available tubes can produce up to several thousand foot lamberts of screen brightness, or several thousand lines of resolution, although accurate data often are not available from the tube manufacturers. Unfortunately, the brightness and resolution requirements are mutually conflicting, so both features cannot be optimized simultaneously. In the resolution range of 1500 to 2000 TV lines, the usual maximum brightness available is 40 to 50 foot-lamberts. When the brightness requirement is raised by a factor of ten, resolution typically falls to about half this value. These factors hold for "large" or direct-view tubes, such as the 21EWP4; tubes which are not designed for extremely high surface brightness. In these tubes the faceplate area is large, and cooling of the faceplate is usually by air convection.

In projection CRT's, where forced air cooling is usually possible, the faceplate is considerably smaller and is operated at much higher dissipation values. (At high temperatures phosphor efficiency falls off, and phosphor life is decreased). Thus the surface brightness of a projection CRT may be as great as 30,000 foot-lamberts (Ref. A-1), but not greatly in excess of this. When extremely high surface brightness is produced in a small raster, as in a projection CRT, contrast suffers and resolution decreases.

In projection CRT's employing curved faceplates, the electrical focusing problem is simplified somewhat because the electron beam length can be made approximately constant. The focusing of a flat or large radius CRT (such as the 21EWP4) usually requires dynamic focusing if the maximum resolution is to be obtained over the entire tube face.

Special cathode ray tubes have been designed and built for optical matching with infinity imaging systems. These have been developed to match both 16 inch and 13.5 inch radius of curvature systems. The widest-angle CRT design thus far realized has been the 110 degree tube designed for the LEM Simulator External Visual Display Equipment. This tube has a phosphor surface radius of curvature of 13.5 inches, included angle greater than 110 degrees, and operates at up to 35 kv.

Specifications for this tube include brightness: 300 foot-lamberts minimum, Resolution: 2000 TV lines center, 1500 TV lines edge, and Contrast ratio (large area) 200:1. The tube has an accurately figured spherical surface and the faceplate employs neutral density attenuation for reduction of "ghosts" and to aid in maintaining the high contrast ratio. A high efficiency antireflective coating on the faceplate is used to reduced "ghosts" and interference from ambient light.

This tube design may currently be considered "the state-of-the-art". It is unlikely that tubes of included angle much greater than 110^{o} will be developed, primarily because of the severe glass technology problems involved.

For narrow angle projection displays (up to 60 degrees), the Schmidt system may be considered. It has relatively high light output (up to 14,000 lumens) and is capable of good resolution, although this is limited by the projection kinescope used. Efficiencies of wide angle systems are low (for instance, 6% for a 60 degree projector) but can range up to about 30% for a more modest requirement of only 15 degrees of projection angle (Ref. A-1).

No color kinescope either presently available or contemplated can be expected to have the brightness or resolution possible with a black and white tube of comparable design. Also, it may be extremely difficult to design color CRT's to special configurations. These are facts of life for color CRT's, but do not apply to some of the other methods of achieving color television displays.

Probably the most fruitful area for high brightness displays involves the various light valve techniques which employ a source and a modulator as two distinct elements. The most highly developed system in this group is the commercially successful Eidophor, which can be used for either color or black and white projection.

TPR (Thermoplastic Recording) systems have been built which are reported to be capable of extremely high resolution, but these are not "real time" devices. In short-loop continuous record/project arrangements the delay time may be made short enough to make this limitation negligible.

Use of the LASER as a light source is still in the early experimental stages. Feasibility has been demonstrated, but much remains to be done in the development of ancillary control components before this approach can be considered as a serious contender for practical display use.

Ultra-high resolution displays cannot be considered as isolated components but must be thought of and discussed in conjunction with the information path to the display. In conventional television systems, where the scene is scanned completely 30 times per second, the flow of information becomes too unwieldy for handling by ordinary techniques when pictures consisting of more than a million elements are considered. This means that for higher resolutions, some alternative method of picture production will have to be considered. (Mosaics of several conventional TV rasters can provide some improvement, but the gains are small for the complexities involved).

The approaches based on elemental mosaic picture elements involve large numbers of components. If, however, these components can themselves be designed to be simple, have reasonable tolerances, and preferably to possess some kind of self-contained information storage feature, the problem could be considered in essence solved. Elements could be combined practically without limit, to build up high resolution displays capable of being fed from diverse sources of picture information. At present no such system exists. The closest approach may be the "matrix controlled TPR display" of GE (Ref. G-3). Certainly the employment of a light-valve type system with individually controlled picture element values should be a winning combination.

It is this kind of display, with elemental storage and brightness control, that will ultimately permit full exploitation of the Image Element Computation schemes discussed earlier. The storage may be by means of a modulator such as a rapidly reversible photochromic or an electrooptic effect crystal, or it may be a form of light emitter with storage capabilities. One thing is certain; without such a storage feature, high information transfer rates to the display device will prevent full realization of the highest resolution image generating systems.

6. Special Effects

In any television system used for training or simulation purposes it is often useful and sometimes necessary to have available a repertoire of what are called "special effects". These permit control over individual portions of the picture by means other than simple switches. Special effects include control of displayed picture information by video signals from the televised picture itself, or from a separate television video channel. Some examples of special effects are:

a. Superposition:

Signals are produced from two or more cameras, usually viewing separate scenes, and are combined by simple addition on a point-for-point basis. This is accomplished by addition of the electrical video signals from the appropriate cameras, usually in a simple resistive matrix. The only precautions necessary with superposition are those required to insure that there is no interaction among the various signal sources or between a source and the load.

b. Matting:

As with superposition, separate scenes are generated and combined. In the case of matting, however, one of the signals is dominant over the other. This is called the keying or inserted signal. In those areas of the picture where the keying signal has a value in excess of the predetermined level, the background signal is removed and the keying signal (or some other signal) is inserted. Thus a montage is formed consisting of portions of each signal, although no single picture area contains the information from more than one of the inputs.

c. Occultation:

In simulations where the television is but one component of several which are optically combined, it may be necessary to blank out the television presentation in those areas of the visual field where material is to be inserted by another optical channel. This occultation function can be performed by a keying system similar to that used for matting or insertion. The difference is that in this case no signal is inserted into the "hole" keyed out of the background TV signal.

d. Other Effects

There are a great many other special effects used in the television industry which are not needed in training simulation work. These include various wipes, fades and dissolves which are usually used when changing from one source of program material to another. In the case of the television display in a training simulator, this sort of freedom and these dramatic effects can be produced, but usually are not needed.

e. Conclusions

Mainly because of the advances made in the field of digital and fast analog computation, the present state-of-the-switching and control-art is quite well developed. The various keying and switching functions needed to implement the effects described above are capable of operating faster and more accurately than would be required by most camera chains. At least one wideband (30 mc, 40 nsec switching time) keyer is available commercially,*. Still

*Ball Bros. Research Corp.

faster units can be developed if there is sufficient need. It is unlikely that there will ever be any interest in television video channels of bandwidth greater than 100 mc, and present switching techniques can probably be extended this high if needed.

The subject of television keying and special effects is covered in considerable detail in prior studies (Ref. H-5).

7. Summary

7.1 General Comments

From the foregoing analysis of television systems by both input and output devices and structures, it can be seen that conventional television improvement has apparently reached the point of diminishing returns as far as picture resolution is concerned. Increased resolution in a given sensor can be purchased only at the expense of either increased bandwidth or decreased sensitivity; both of which result in increased noise. In an earlier study (Ref. B-2) it was pointed out that increased signal-to-noise ratio, or increased resolution at a given signal-to-noise ratio can be had only by increasing the size of the sensor. This means an increase in the total incoming light flux. Even if the light is available, the mechanical problems associated with moving a large probe multiply at a rate much greater than the linear dimension of the probe and pickup tube.

7.2 Systems Immediately Available

As noted above, no dramatic breakthrough appears in the offing for conventional television systems employing image tube sensors. Small improvements can be made in the areas of increased resolution, sensitivity, etc., but these will very likely come at the expense of having larger image tubes and hence larger probe assemblies.

Advances such as the SEC vidicon will provide an increase in the sensitivity of vidicon systems without loss of resolution. The increased probe size for cameras using the SEC Vidicon will not always be objectionable, but neither will the increase in sensitivity improve the resolution.

High resolution closed-circuit television systems are presently available from several sources. These include General Precision, DuMont, and Dage. For instance the GPL Precision 840 model, designed for use with the Lunar Excursion Module training simulator has a nominal resolution of 900 TV lines in either direction at the center of a 3 x 4 raster. This system employs 30 mc video components to match the 1200 line raster structure and 60 cycle field rate and still provide 900 line resolution. Aperture compensation in this system improves the resolution at the expense of some additional noise. If flicker-free television reproduction using the existing sensor (8507) is to be improved in resolution, the bandwidth will have to be even greater than 30 mc. Use of a different sensor will permit greater amplitude response at the present resolution level, which is also a significant improvement. This advantage, however, will be achieved only at the expense of using physically larger image tubes. Here again, one comes up against the problem of probe size and complexity, as well as the increase in light needed to cover the larger pickup tube surface.

Improved sensitivity can be obtained by using the SEC vidicon. This can probably be made in a size large enough to provide 900-1000 line resolution, and the increase in sensitivity will balance out the light decrease with increasing size. Thus a higher amplitude response at 900-1000 lines can probably be obtained. This would represent a real and noticeable improvement in the television system, both to the human observer and when measured by the "sine wave response" method. Limiting resolution cannot be improved much beyond present capabilities using existing concepts.

The use of mosaic techniques would seem to be a way out of the resolution-noise-bandwidth maze. In a practical sense, very real and formidable problems arise in matching several conventional raster scan television systems to form a single large imaging array. No matter what techniques are used to eliminate the "seams" between adjacent sections of the final picture, it appears that there is little chance for real success with this approach. Small errors in mapping, linearity, brightness, etc., cause discontinuities which are very evident even to the untrained human observer.

On the other hand, the use of sufficiently small elements for the mosaic (elements comparable in size with a picture resolution element) would eliminate these problems. It is unlikely that such elements will be developed for high resolution systems in the near future, in spite of the strenuous efforts being exerted in this direction for status boards, annunciator displays, and other coarse on-off information display systems.

7.3 Long-Term Prospects

As was seen in the previous section, the brute force extension of present television techniques cannot be expected to produce a dramatic improvement in either sensitivity or resolution on a "per T.V. channel" basis. Mosaic arrangements might be considered, but these tend to become complex at a rate far in excess of the improvements gained from the complexity, with no real promise of practicable systems appearing in the next few years.

In the search for an "order of magnitude" improvement in television techniques, the only technique which seems to offer unlimited possibilities is that of "computation of Image Elements." This art is now in its infancy, having been made possible in recent years by the advent of fast, large capacity computers. Two systems and approaches have been described which represent the first successful attempts in this direction. Much development needs to be done to gain the experience necessary for the perfection of both the hardware and software aspects of this approach. This path should ultimately lead to a system capable of producing realistic views of quality superior to conventional television. Three factors must dominate any discussion of this method, however. First, it seems to be the only way in which a significant breakthrough can be achieved. Second, the use of computation for the generation of picture information eliminates the need for models, model manipulators, lighting, cameras and their controls and their mechanisms, as well as the need for maintaining all these equipments. Third, with the elimination of models and illumination systems the problems of mechanical and optical limitations due to mechanical interferences disappears as well. These are replaced by the problems of large scale computers, and of program or "software" generation.

By the use of clever coding and storage algorithms and techniques, many of which now exist but still more of which are yet to be developed, the computation problems can be dept to manageable proportions. Several coding and computation "tricks" are discussed in Section III of the volume and in Volume II of this report. These bear directly on how the computations can be undertaken.

In conventional television systems, the bandwidth and method of transmission is sufficient to permit a complete change of picture information with every frame (usually 1/30 second.) It has long been known that this results in the consumption of bandwidth far in excess of that which can be absorbed by the human observer. Various schemes have been contrived to improve the information channel efficiency by clever coding and the exploitation of redundancy in the pictures.

In addition to the frame-to-frame and line-to-line redundancies usually considered, there is another important phenomenon which can be worked to advantage in the quest for bandwidth reduction. This is the phenomenon that the eye cannot discern fine detail immediately after a scene change. An investigation into this effect has been made by Seyler and Budrikis (Ref. S-9). In this study slides were presented to viewers by way of a television system in which the bandwidth could be controlled electronically. After a change of scene, the bandwidth was abruptly reduced and then increased exponentially to the original 5 Mc. The characteristic approximated the function $B(t) = B_m (B_s/B_m)^{t/T}$ for $0 \leqslant t \leqslant T$

where B_m = the minimum preset bandwidth just after transition

B_s = system bandwidth (5 Mc)

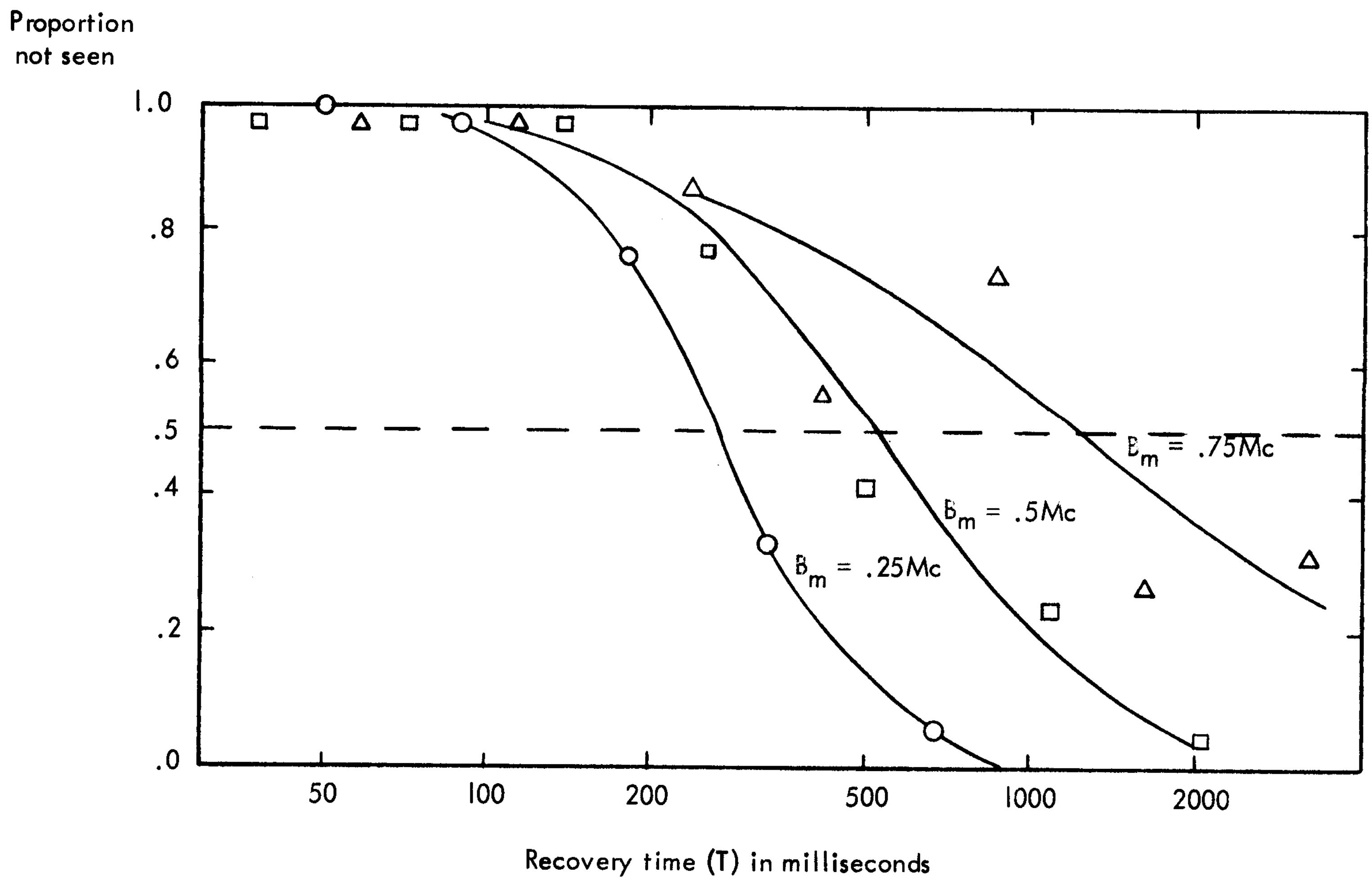
T = the recovery interval

t = time

Results are presented in terms of the number of times the observers noticed a "smearing" of the picture after transition, versus the time T of transition.

Minimum bandwidths from 0.25 to 1.0 Mc. were used, with transition times ranging from 30 to 3000 milliseconds. Response distribution curves for skilled observers were essentially as shown in Figure 3-45. It is seen that at the 50% confidence level more than one full second can be allocated for picture reconstruction where the bandwidth begins at 750 kc. This indicates that in a system using controlled resolution there is a great deal to be gained by making use of this phenomenon. The bandwidth can be reduced by a factor of seven for some thirty frame times in order to generate the main picture features. Later image generation time can be devoted to "filling in the details" and supplying high resolution components to the new scene.

It may well be that certain parts of the scene should intentionally remain "fuzzy" while others should be computed in as sharp detail as possible. This may be advantageous for several reasons. It may be that the trainee is to concentrate on a particular picture area and that the balance of the picture will appear out of focus if he does so. There may be extraneous elements in the scene which have fine picture detail but which are unimportant



Response to scene changes with bandwidth variation. (Skilled viewers, unexpected changes, viewing distance = 4 x picture height.)

FIGURE 3-45

to the mission at hand. Certain objects may be intentionally out of focus because of optical elements being simulated, such as a navigational telescope which finds a radar antenna in its field of view.

In brief, the computation method can exploit many known factors in order to produce high resolution pictures for simulations. There are certainly other factors, which will also contribute to easing the computational burden when they are determined and evaluated.

The image computation technique is the first television video generation scheme capable of producing images in which the resolution is not limited by the system, but by the scene and display alone. The usual restrictions of sensor and channel capacity no longer apply. The only real restrictions which will limit a television system based on computation are the computers, computational methods, and the displays.

The field of computation and computers is making rapid strides as the need for ever greater computing power is felt in all phases of business, industry, and government. Thus it is almost a certainty that the computer art will advance at a rapid rate independent of the needs of the simulation industry. The software, or programming art cannot be expected to move so rapidly without some additional stimulation from the users of simulation programs. This impetus is being provided at present by government programs with such organizations as General Electric and Pennsylvania Research Associates.

The area in which the greatest strides must be made in order to utilize the picture computation techniques, and which will have to be developed if there is to be any order of magnitude advance in the television art, is that of the display. Present displays, as has been pointed out in Section III are mostly oriented about the cathode ray tube. There is need for a high brightness high resolution storage display for use with computer outputs. Such a display must be capable of being addressed element by element, or in terms of groups of elements. A storage capability is necessary, since this would simplify the information interfacing between the image generator and the display, and would reduce the instantaneous brightness requirement of any one area of the picture. The display should also be capable of a reasonable number of halftones at each image point.

Such a display does not presently exist, but there exist several obvious approaches which promise achievement of the end result.

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SECTION IV

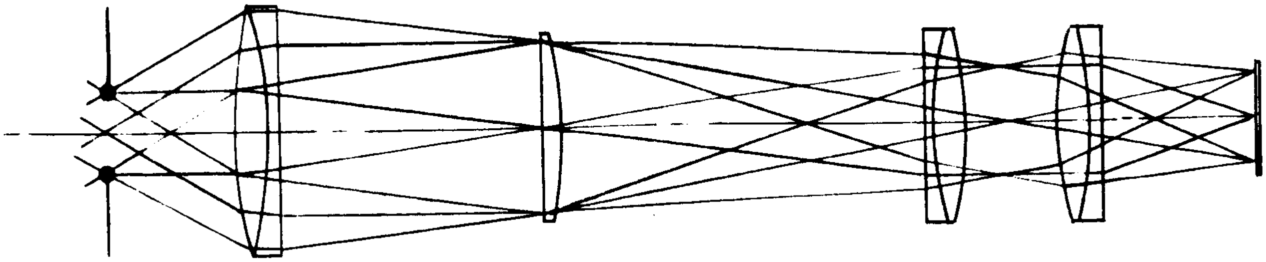
DEVELOPMENT OF THE DESIGN FOR THE VIRTUAL IMAGE DISPLAY SYSTEM DEFINED BY THE STUDY PROGRAM

A. Candidate Systems

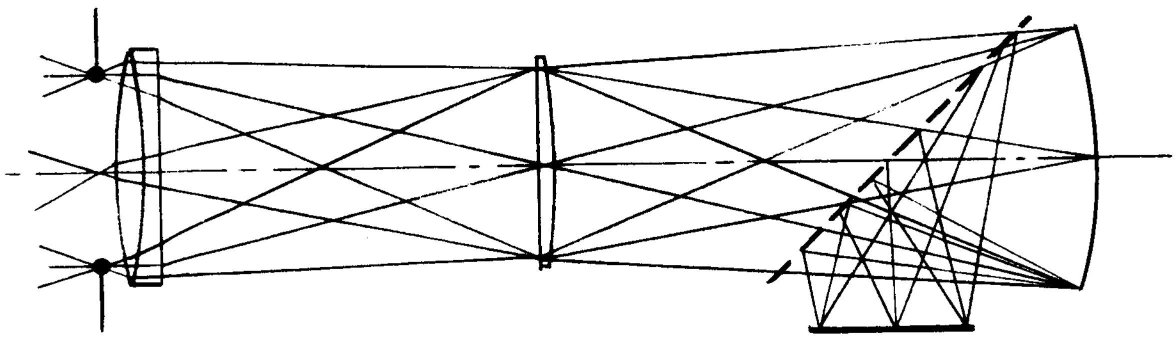
In general the desired goals of the study are an infinity display system having the following characteristics:

1) $80^{\circ} \times 110^{\circ}$ field of view
2) 12 inch diameter exit pupil
3) at least 24" between the exit pupil and the first optical element along the optical axis with a maximum clearance in all directions
4) at least two separate inputs with a desire for three. One of these inputs is to be a celestial sphere display and a second is to be a 21" color TV display having a useful diameter of 19.25" and a radius of curvature of 26.4 inches. The third input would be a normal 21" black and white TV tube which has a 19.6" useful diameter and a 29" radius of curvature phosphor surface.

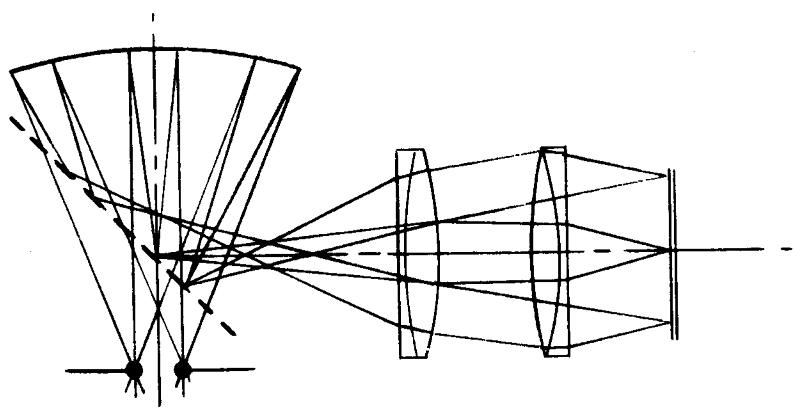
As indicated in Section III, page 3.4 of this report, the Farrand Infinity Display System is the equivalent of an erecting eyepiece in that it consists of an eyepiece system and an erecting system. Each of these independent parts may utilize either a reflecting or a refracting system. Thus there are four possible combinations that may be employed to achieve a desired set of characteristics:



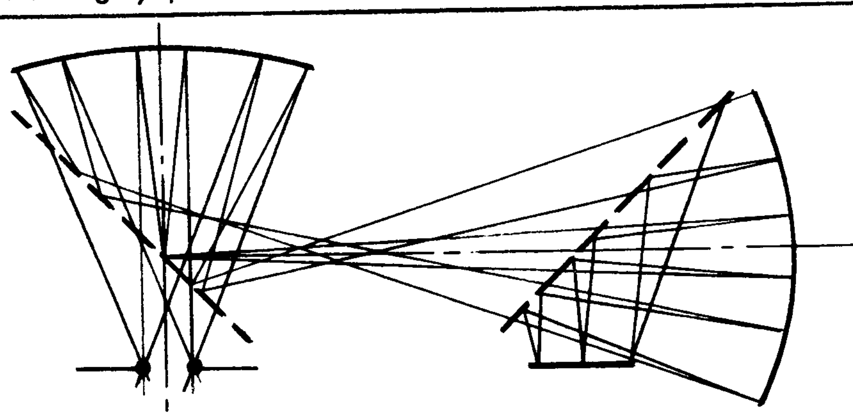
1) Refracting eyepiece and refracting relay



2) Refracting eyepiece and reflecting relay



3) Reflecting eyepiece and refracting relay



4) Reflecting eyepiece and reflecting relay

The first and second combinations employ a refracting eyepiece. Consideration of the required twelve inch diameter exit pupil, 24 inch eye relief and 110° field leads to a first lens diameter for a refracting eyepiece of over eighty inches. Reducing these values to the eventually recommended values of 8 inch diameter pupil, 24 inch stop distance and 100° field would still require the diameter of the first lens to be over sixty five inches with all subsequent lenses of larger diameter. These values are unrealistic in terms of size and cost even disregarding optical design performance considerations. For these reasons we have disqualified the use of a refracting eyepiece in the present evaluation.

Once we have established that a reflecting eyepiece is to be used the next choice is between combinations three and four where the relay system can be either reflecting or refracting. In addition, depending on the layout of the system this choice may include both refracting and reflecting relay systems for multiple input systems (see Mercury Simulator, Figure 3-2 A & B).

One input of the desired system is to be a celestial sphere. The success of the mirror relay in all previously built celestial sphere systems precludes the consideration of any but the mirror relay system. The mirror relay is ideal because in the geometry of these systems the Petzval sum of the Petzval contributions of the two mirrors usually work out to be approximately identical with the 13.5 inch radius of curvature of the celestial sphere. In addition, the mapping of the classical two mirror systems can be brought to almost exactly 13.5 sin θ. This achieves a presentation of the celestial sphere as though it is being viewed from its center of curvature. The match between the Petzval curvature of the display system and the radius of the display accounts for this ideal situation where the heavens appear as if they are viewed from the center of curvature of a sphere that has an infinite radius of curvature exactly analogous to the real case. We may conclude therefore, that in the case of a celestial sphere input the ideal relay system is a reflecting one.

The Color Television Input

The choice of the color television relay system is somewhat less straightforward. The faceplate of the 21" color TV tube on which the 110 degree field is supposed to be mapped is shown in figure 4 - 1.. While in the celestial sphere system the focal length and the radius of curvature of the object surface are identical thereby leading to an ideal mapping where the chordal height in the image plane is f sin θ, there exists no such relationship between the focal length, image surface radius ot curvature and mapping of the color TV input. If the chordal height is proportional to tan θ:

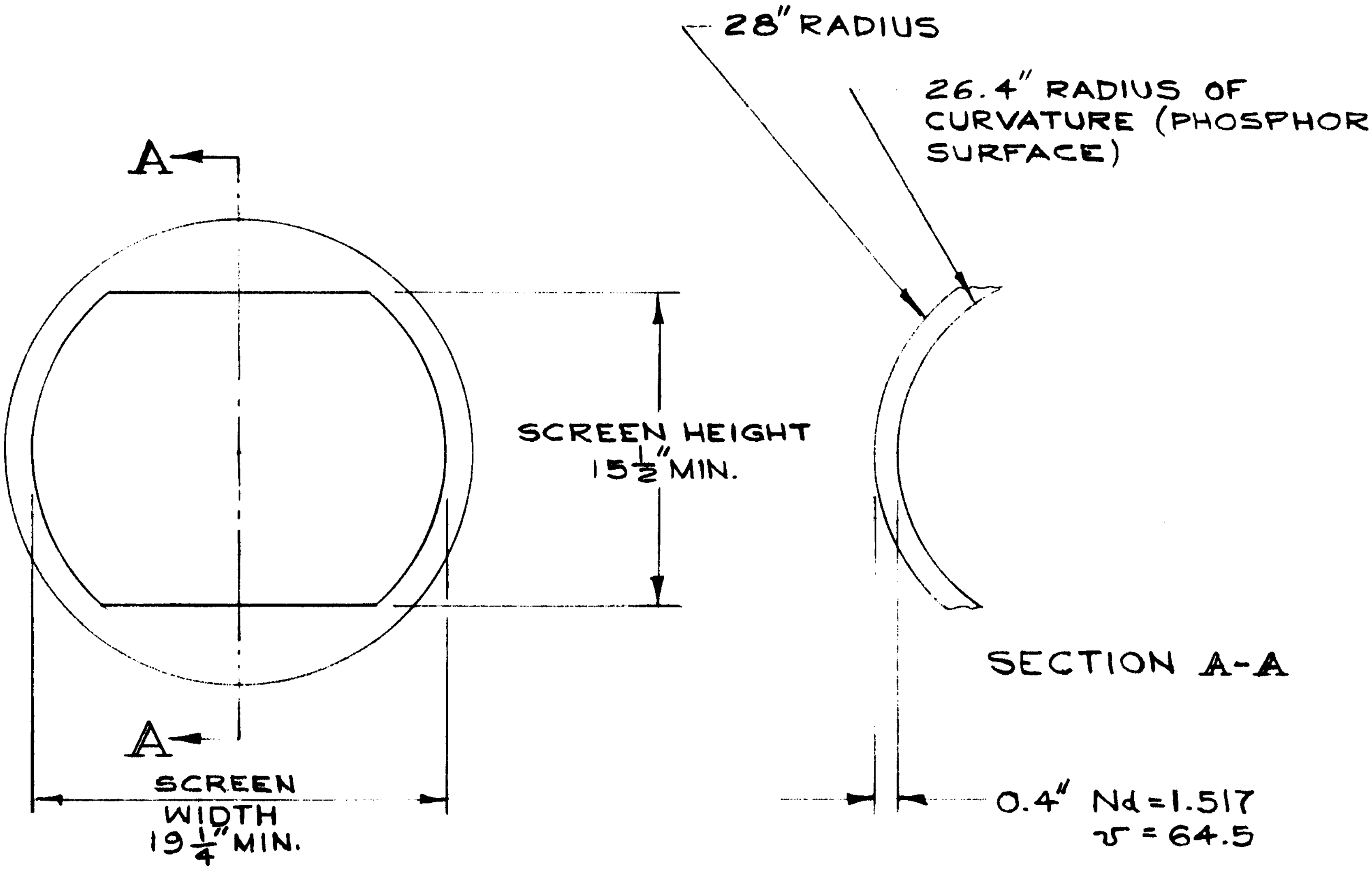


FIGURE 4-1 R.C.A 21" COLOR T.V. TUBE 21FBP22

$$F = \frac{19.6''}{2 \tan 55^\circ} = \frac{19.6''}{2.856} = 6.85''$$

or to θ in radians:

$$F = \frac{19.6''}{(2)\ (55^\circ \text{ in radians})} = \frac{19.6''}{1.92} = 10.2''$$

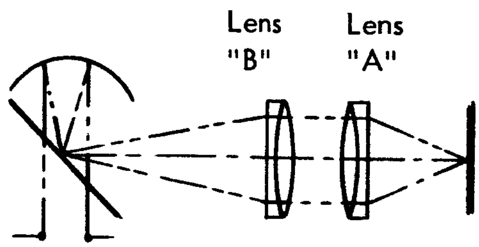
or to sin θ:

$$F = \frac{19.6''}{(2)\ (.819)} = \frac{19.6''}{1.638} = 11.95''$$

Obviously the focal length of the system is dependent to a very great extent on the mapping chosen for the system. If one considers the "resolving power" (number of lines) of the tube to be a constant along the surface of the tube, a constant number of lines per degree of angular field would correspond to a mapping between f (θ) and f (sin θ) where the actual mapping at the extreme edge of the field would be 7% below the f (θ) mapping. This corresponds to a focal length of approximately eleven inches.

The choice of whether to use a refracting or a reflecting relay system for the TV leg is very much affected by these considerations as well as several other interrelated factors.

The design and layout considerations for the eyepiece mirror which must serve both the celestial sphere input and the TV input, based on the pupil, field and eye relief requirements lead to a mirror with a focal length of approximately 28 inches. If we consider the refracting relay to be made up of two parts, collimating lens [A] and a reimaging system [B]:



and we further assume that system B has the same focal length as the eyepiece mirror. The EFL of "A" would be 11 inches and the Petzval Sum for the total system would be approximately

$$\frac{-1}{28} + \frac{0.67}{29} + \frac{0.67}{11} =$$

Mirror "B" "A"

$$\frac{-11}{(28)(11)} + \frac{(11)(.67)}{(28)(11)} + \frac{(28)(.67)}{(28)(11)} = \frac{-11}{(28)(11)} + \frac{26}{(28)(11)} = \frac{15}{(28)(11)}$$

leading to an object surface that is <u>Concave</u> and has a radius of curvature of 20"; this radius is far from the 26.4" <u>Convex</u> radius required.

If we were to arbitrarily double the focal lengths of the relay system leading to the same overall magnification and ignore all of the other negative considerations of such a step the Petzval Situation would be

$$\frac{-1}{28} + \frac{0.67}{56} + \frac{0.67}{22}$$

Mirror $\frac{-2\,(22)}{56\,(22)} + \frac{(0.67)\,(22)}{(56)\,(22)} + \frac{(0.67)\,(56)}{(56)\,(22)}$

$$\frac{-44}{(56)\ (22)} + \frac{14.74}{(56)\ (22)} + \frac{37.52}{(56)\ (22)} = \frac{1}{149}$$

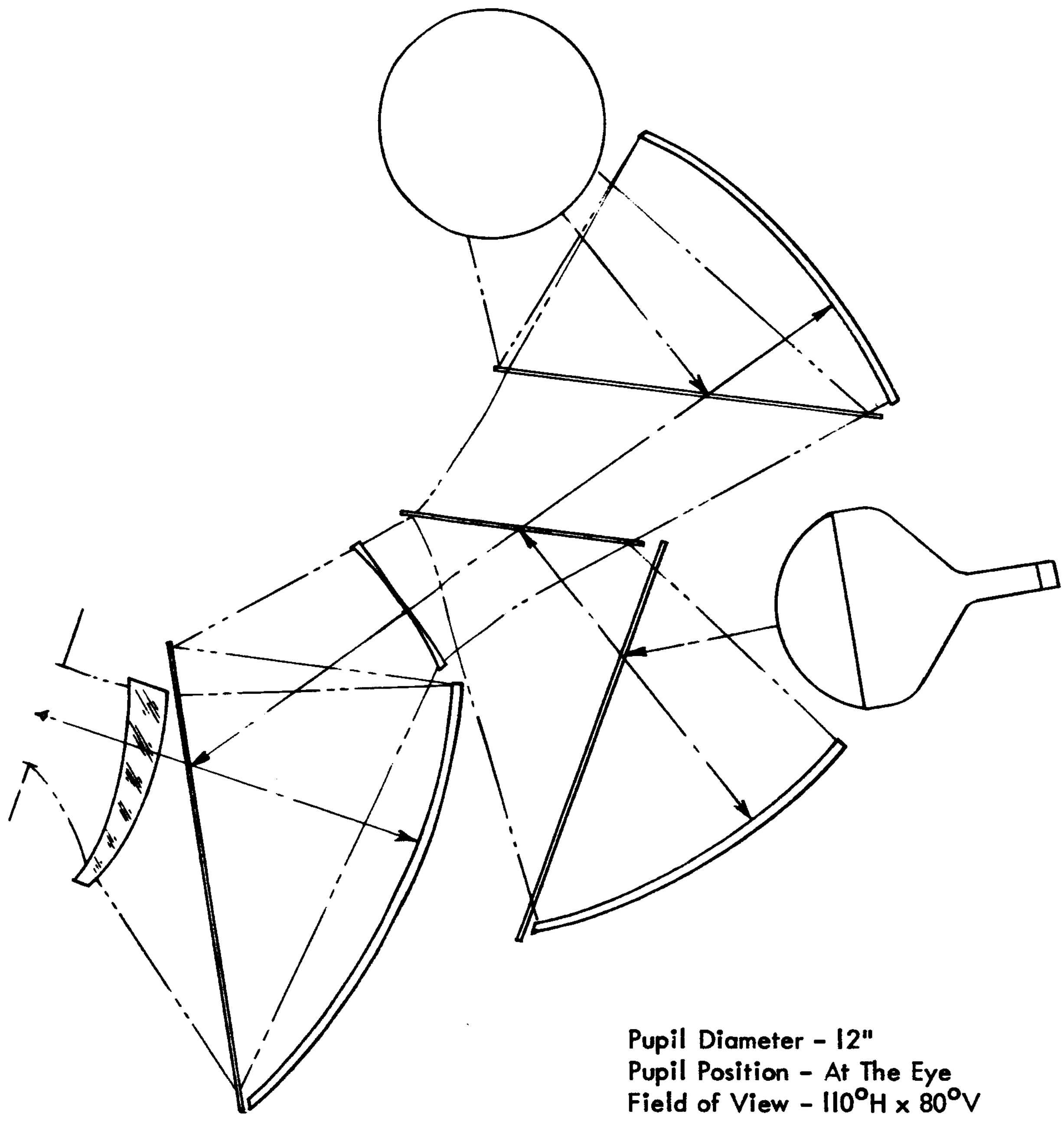
This leads to a system with a much longer radius of 149" but the radius is still undesirably concave.

Such considerations in addition to past experience with such systems lead us away from any further considerations of a refracting relay system for the new window and into a detail consideration of the classical reflecting relay system for the color TV input.

Study of the Classical System

A perusal of the layouts of prior systems designed and built by the Farrand Optical Company for Space Capsule window simulators show that while several of them have many of the characteristics desired for the task at hand, none of them fulfill all of the current requirements.

The system that most closely satisfies the current requirements is the Lunar Excursion Module front window figure 4 - 2. This system meets all of the requirements except requirement 4 of the characteristics listed on page 4.1 . A system patterned after this window was laid out and is shown in figure 4 - 3. From the drawing it is seen that a "compressor lens" is positioned along the optical axis and is located within 10 inches of the exit pupil. While this



Pupil Diameter - 12"
Pupil Position - At The Eye
Field of View - 110°H x 80°V

FIGURE 4 - 2 LEM Front Window

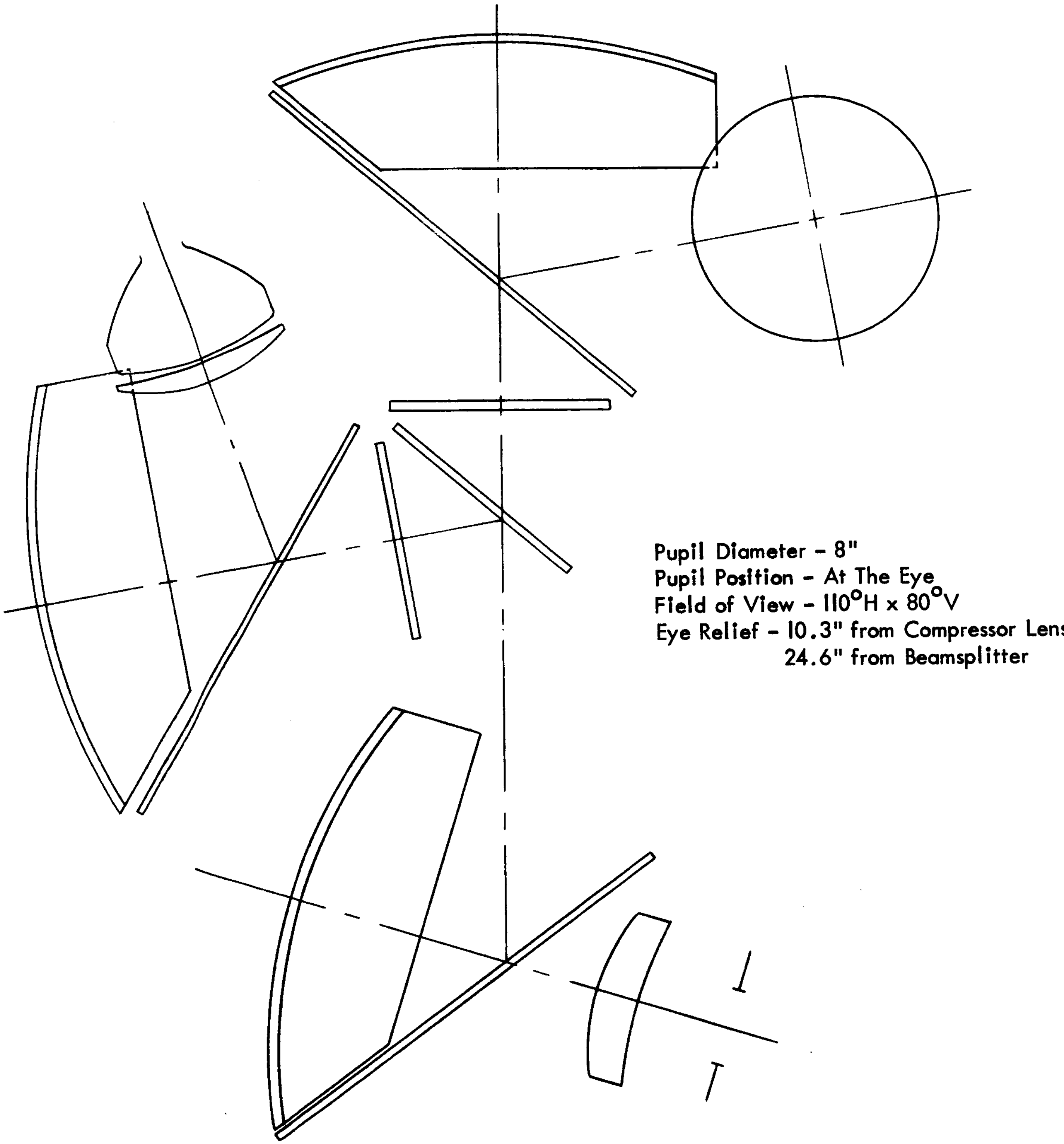


FIGURE 4-3 Proposed System with Compressor Lens

compressor lens snout is apparently compatible with presently known capsule window configurations, it was felt that its presence would considerably lessen the universality of the window simulator for future use since the window completely loses its "infinity display" characteristics if this lens is removed.

Without this compressor lens in the system it became obvious that some compromises would have to be made in the system characteristics in order to utilize the 21 inch color TV input.

The tradeoffs that have had to be made in the system come from the following interaction of effects when considering the television input system.

1) Vertical field

   a) Major effect on fitting in of eyepiece beamsplitter and clearance between exit pupil and eyepiece beamsplitter.

   b) Major effect on fitting in relay beamsplitter.

   c) Major effect in system in region of beamsplitter for combining inputs.

   d) Usually no effect on system focal length.

2) Horizontal field

   a) Major effect on eyepiece mirror maximum size.

b) Major effect on eyepiece beamsplitter maximum size.

c) Major effect on relay mirror maximum size.

d) Major effect on relay beamsplitter maximum size.

e) Major indirect effect on fitting in relay beamsplitter. This is really the dominant effect on the whole system in that once the mapping type is generally set this field sets the e.f.l. of the total system since the linear dimension of the format has been set by the tube format.

3) Vertical pupil

a) Major effect on fitting in of eyepiece beamsplitter.

b) Major effect on combining beamsplitter fitting.

c) Major effect on fitting in of relay beamsplitter.

4) Horizontal pupil

a) Major effect on eyepiece mirror size.

b) Major effect on eyepiece beamsplitter size.

c) Major effect on combining beamsplitter size.

d) Major effect on relay mirror size.

e) Major effect on relay beamsplitter size.

In summary, the horizontal field and tube size and mapping determine the e.f.l. of the system. Once the e.f.l. has been established, the vertical field and vertical pupil size determine the layout of the system.

A number of these combinations were considered and the following specifications were agreed to at a meeting between Farrand and MSC representatives held at MSC on 10 November 1965.

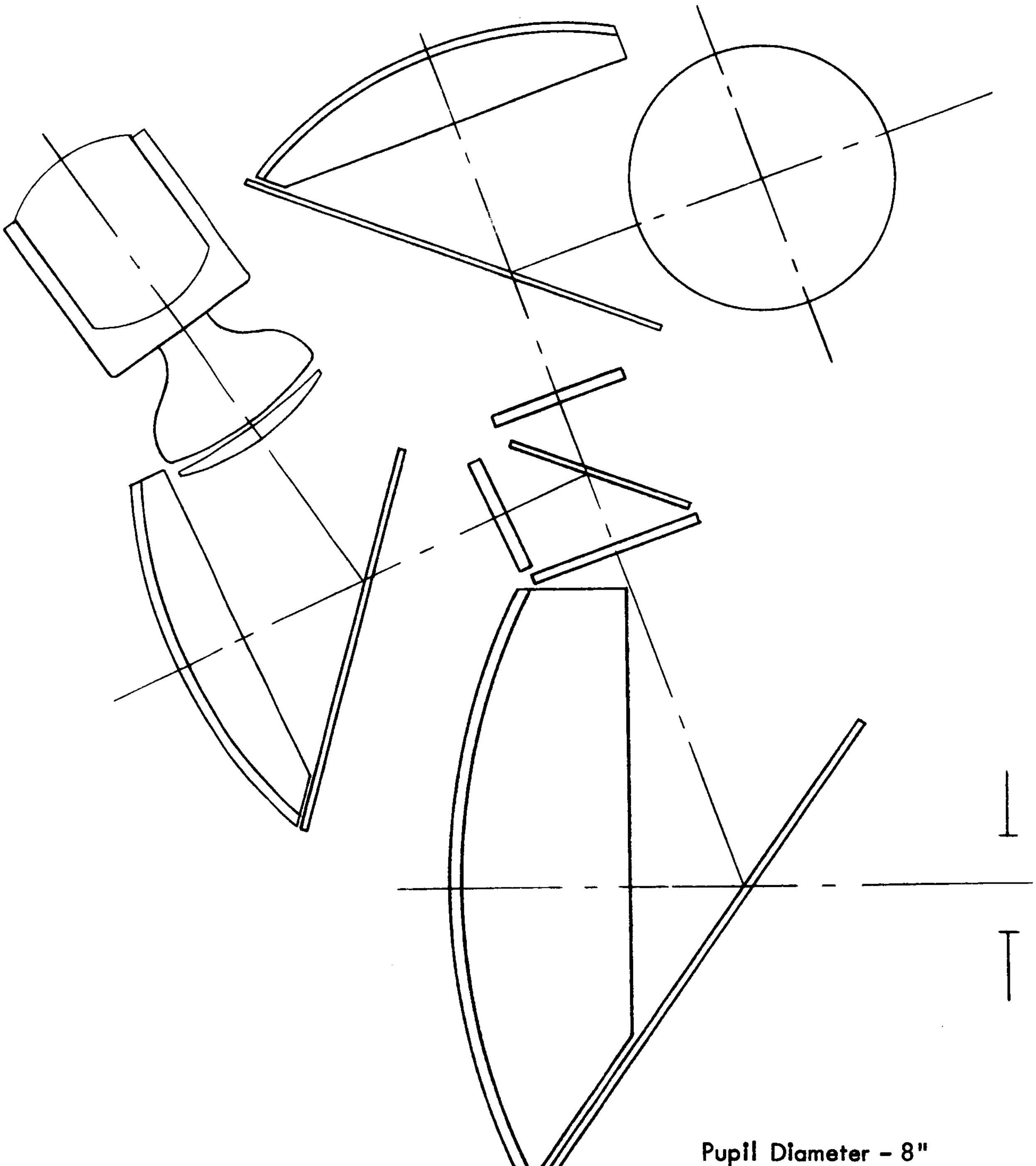
1) Vertical Field - 60°

2) Horizontal Field - 100°

3) Pupil Diameter - 8 inches with one inch clipped top and bottom for the extremes of the vertical field.

A layout of this system is shown in figure 4 - 4.

The Display system arrived at represents the optimum system approaching the required characteristics while utilizing existing components such as the 27 inch celestial sphere and the specified 21 inch color TV tube. Specifications for this system are given in the Statement of Work which comprises the next section of this report.



Pupil Diameter - 8"
Pupil Position - At The Eye
Field of View - 100°H x 60°V
Eye Relief - 25" from Beamsplitter

4.14

FIGURE 4 - 4 Proposed System

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STATEMENT OF WORK

DESIGN AND FABRICATION OF OPTICAL SIMULATOR FOR NASA, HOUSTON, VISUAL DISPLAY SYSTEM

I. Introduction

The purpose of this work statement is to outline the technical characteristics of the optical simulation system and associated peripheral equipment, and to identify the contractor tasks relevant to the design, fabrication, test and delivery of the equipment.

II. Equipment Description

A. General

The simulator to be designed and fabricated shall present to the trainee in a crew station a view which gives a realistic illusion of the external field as seen through a spacecraft window. It shall consist of two inputs (one television and one celestial sphere) and associated optical elements, together with structure, enclosures and mounts suitable to permit viewing of the separate or combined inputs from the specified pupil position.

Enclosures shall be provided to exclude all ambient light and dust. A light-and-dust-tight interface with the crew station shall be provided.

Mountings shall be provided to properly locate the equipment at the required attitude and height above the floor.

B. TV Input

The TV input shall contain both an RCA 21 FBP 22 color tube and a 1029-line black and white tube in a quickly-interchangeable mount such that either may be presented. The tubes shall be supplied as Government-Furnished Equipment. The tube interchange shall be performed manually.

The simulator shall contain such optics as are required to correct for CRT face curvature and to present to the trainee an aerial image of the CRT screen. It shall be designed to incorporate a focusing feature such as to provide the TV image at any apparent distance from the observer between 10 ft. and infinity. The magnification of the optical path shall be such that the usable horizontal portion of each CRT face fills the total visible horizontal field.

C. Celestial Sphere Input

The simulator shall have provision for accepting and displaying star fields from the surface of a celestial sphere. It shall contain such optics as are required to form a corrected aerial image of the star field at infinity. The magnification of the optical path shall be such as to provide a one-to-one angular correspondence between the celestial sphere and the observed image.

The celestial sphere shall include all stars of the fourth magnitude and some selected fifth magnitude stars. In addition all 57 navigational stars shall be included. The stars shall appear as approximate points of light, with intensity varying according to star magnitude.

The six reddish navigational stars shall be so colored.

The celestial sphere shall be suitably gimballed and provided with servo mechanisms which may be slaved to a computer to simulate spacecraft roll, pitch and yaw motions and attitudes.

D. Occulting Illuminator

The celestial sphere illuminator shall contain an occulting device such that occultation of stars by an intervening body may be simulated. Servo systems shall provide the motions necessary to simulate spacecraft roll, pitch, yaw and range variation between the body and the spacecraft.

III. Detail Characteristics

Detail characteristics shall be as follows:

a) Field of View

The field of view shall be 100 degrees horizontally by 60 degrees vertically.

b) Exit Pupil

The exit pupil shall be eight inches in diameter with a one inch wide segment removed from the top and bottom.

c) Eye Relief

The distance from the exit pupil to the axial point of the first optical element shall be a minimum of 24 inches, with a design goal of 30 inches.

Care shall be taken to give the maximum free space between any portion of the optical system and the exit pupil.

d) Celestial Sphere Diameter

The celestial sphere shall have a nominal diameter of 27 inches.

e) Number of Stars

The celestial sphere shall contain a minimum of 1,012 stars.

f) Occulting Mechanism

The occulting mechanism shall occult stars occluded by a body ranging in diameter between 5° and 155° anywhere in the window field of view.

g) Television Input

The television input shall utilize an RCA 21 FBP 22 television tube for the color TV input and a standard 21 inch black and white TV tube for the black and white TV input. An example of the black and white tube is the RCA 21 AUP4. Each tube format shall fill the complete 60 x 100 degree field of view of the display system.

IV. Performance of the System

A. Positional accuracy of the 57 navigational stars on the celestial sphere will be within 1 milliradian.

B. The error in apparent angular position of a star as seen from the center of the exit pupil as the celestial sphere is rotated shall be a maximum of one percent of the angle off-axis or 2 milliradians; whichever is greater.

C. The departure of the mapping of the two TV inputs from their nominal design shall be a maximum of one percent of the angle off-axis or two milliradians; whichever is greater.

D. The system shall be adjustable at the center of the field to infinity focus within 0.01 diopters. The focus shall not vary across the field by more than 0.07 diopters and nowhere shall light from any field point in the displayed images be convergent as seen from the exit pupil.

E. Either TV input shall be matched to the celestial sphere within 0.02 diopters over the central 60° field and within 0.04 diopters over the rest of the field. Nowhere shall the TV input appear to be farther away than the stars.

F. The servo drives for the celestial sphere shall achieve the following performance:

Acceleration capability - (all axes)	2 rad/sec^2 with positional error less than 15 arc min.
Velocity capability - (all axes)	3 rad/sec with positional error less than 15 arc min.
Slow speed capability - (all axes)	at 0.01°/sec jitter shall be less than 1 arc min.
Static accuracy -	3 arc min per axis

V. Contractor Tasks

The contractor shall perform the following tasks:

A. Design and fabricate one optical simulator, celestial sphere and occulting illumination system in accordance with the specifications of the Work Statement.

B. Demonstrate the equipment to the satisfaction of the specifications of the Work Statement prior to delivery of the equipment. In this connection, a detailed set of acceptance tests is to be formulated and submitted to NASA, for approval, thirty days prior to the scheduled demonstration.

C. Supervise installation of this equipment at NASA, Houston, Texas and to assist in the marriage of the optical simulator to the crew station.

D. Assist in the installation and demonstrate this equipment at NASA Manned Spacecraft Center, Houston and provide instruction to NASA personnel in its operation and maintenance.

E. Provide spare parts list for one year's service and maintenance of the equipment including any necessary special tools or test gear.

F. Submit a monthly program performance report. These reports to detail progress on each of the items contained in the cost proposal, and contain a financial statement with a breakdown of the elements of cost for each major item.

G. Submit monthly technical status reports.

H. Provide ten copies of a manual of operating and maintenance instructions of the equipment.

SECTION V

VISUAL SIMULATION TECHNIQUES FOR THE FUTURE

A. GENERAL:

The art of visual simulation has made tremendous strides within the last decade. The advances over the last five year period have been even more impressive. Out of all the activity in the simulation field as reported in this volume several trends have emerged. The most significant of these trends involve the emphasis that is being placed on wide field infinity image systems. Other trends, perhaps of equal importance, involve the image generation end of the visual simulator. For example, the requirements for accuracy and realism in celestial sphere presentations, high resolution and color imagery and the use of parallax to simulate differential distances in the display. These requirements imposed on the art of visual simulation primarily because of the exacting demands of space flight simulation have resulted in the most significant advances of the art to date. Although most current demands have been satisfied, additional demands continue to be made and one may justifiably ask the question "what additional improvements in the art of visual simulation are on the horizon"? This report has certainly defined the current trends in simulation development but it has also pointed to the approaches that will undoubtedly result in future improvements. Once again we will consider separately the future of visual simulation as applied both to the display end and to the image generation end.

B. DISPLAY END:

Insofar as image quality is concerned, the Farrand type of Infinity Image System* leaves very little to be desired. (Refer to "Visual Simulator Performance Objectives", Pg. 2.6.) The resolution and contrast rendition of this system are excellent; the resolution depending only on the input source while the contrast rendition of the all mirror system is unsurpassed. Additionally, since multiple inputs can be provided, distance parallax between separate inputs are readily simulated in exact accordance with simulated differential distances. This degree of realism can be accomplished only with a display system using multiple, separately driven inputs.

Field of view, based on such interrelated parameters as size of mirrors versus eye distance and the focal plane size of the inputs, may in some cases be limited in a practical sense to sizes of the order of 110° in the horizontal field. The vertical field on the other hand is usually limited by the interference of eyepiece beamsplitter and eyepiece mirror and in most cases one may say that

*Patent Applied For

the practical limitation of the vertical field is approximately 84°. However, depending upon the geometry of the observer's enclosure, multiple units of infinity image systems may be used to extend both the vertical and horizontal fields to the desired limits. For moving base simulators the masses of these systems must be considered in terms of the motion system power requirements and the desired dynamic response characteristics. Generally speaking however, the Farrand type of infinity image system can be designed to satisfy the field of view requirements of most current state-of-the-art simulators.

The exit pupil diameter of the infinity image system can also in most cases satisfy either the window diameter requirements of space flight simulators or the head motion requirements of aircraft simulators. The first drawback of the system is encountered when a visual simulator is required for a side-by-side aircraft where fields of view in excess of 110° must be supplied to both observers. In such cases, the common field of view or the overlap field, is limited in these pupil forming display systems by the closeness of the eyepiece mirrors to the observers. Based on current cockpit designs this minimum distance usually limits the overlap field to less than 30 to 40°. If we attempt to utilize a direct screen input to the eyepiece beamsplitter-mirror combination (neglecting resolution and contrast losses) to provide a non-pupil forming display which serves both observers and therefore provides maximum overlap fields to both, we find that the vertical field is severely limited by the geometry of the eyepiece beamsplitter-mirror combination (see appendix on optical theory). In the non-pupil forming systems, the horizontal field is also limited by the required curvature of the screen and by the resulting illumination loss.

In either case a second compromise is sometimes encountered which concerns the fitting of the eyepiece mirror-beamsplitter combination to provide the required field and eye relief distance to suit the capsule configuration. It is the intent of this study in fact to arrive at a solution to this last difficulty which emerges when a general purpose simulator must be made to fit a variety of capsule configurations. It is this generalized requirement that offers the most challenging task to the design of a Farrand infinity image display system. Although provision of such a wide field, large exit pupil diameter display system with exceptionally long eye relief (on the order of 25 inches) has been achieved in satisfying the requirements of this study contract (see figure 3-50), future infinity image display systems will undoubtedly make further demands in areas including:

1. Wider horizontal fields of view (in excess of 150°)

2. Wider vertical fields of view (in excess ot 100°)

3. Longer eye relief distances without resorting to scaling up of current designs.

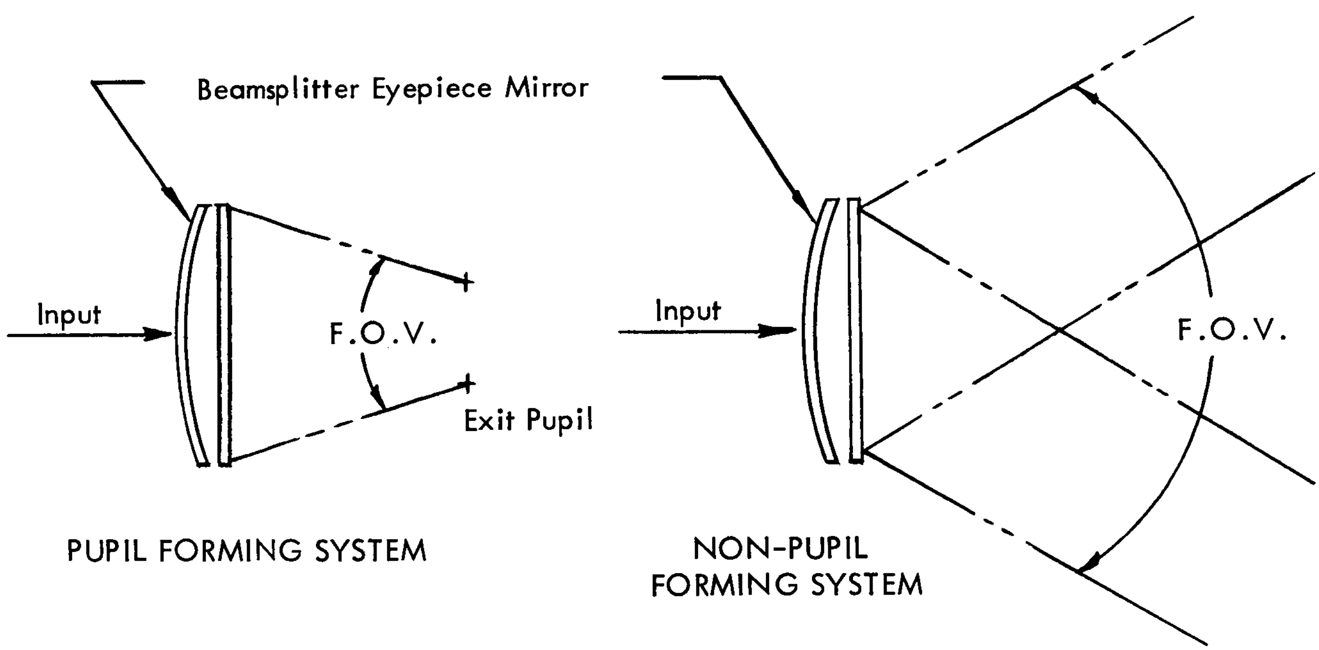
4. Achievement of all the foregoing requirements in a non-pupil forming system to serve side-by-side observers simultaneously for aircraft applications.

5. Decrease in overall weight and size of infinity image systems.

The Farrand Optical Co., Inc. has recently achieved a promising breakthrough in the design of infinity image display systems with a device termed the "pancake window" which promises to exceed all of the aforementioned requirements.* This device has a total axial depth only a fraction of an inch more than the sagitta of the eyepiece mirror. Its vertical field of view can be made to equal the horizontal field of view. It may be designed to be a pupil forming or non-pupil forming instrument; and it is capable of accepting multiple inputs. The "pancake window" utilized as either a pupil forming or non-pupil forming infinity image system as shown below provides a display which will not interfere with most possible cockpit configurations since no obstructions or inclined beamsplitters exist forward of

* Patent Applied For

the collimating eyepiece mirror. Furthermore, this new system will provide a vertical field equal to the wide horizontal field of view, unlike the infinity image systems designed heretofore where the inclined beamsplitter between the spherical eyepiece mirror and the observer seriously limits the vertical field of view. Although the development of the "pancake window" is still in the research stage, it offers a promising answer to the various requirements of future wide field display systems for simulators.



C. IMAGE GENERATION END:

Several of the most recent image generating techniques have been incorporated into hardware recently delivered by this contractor. Since most of the new techniques will be operational by mid 1966, personnel engaged in the art of visual simulation will soon be able to evaluate these new methods. All of these techniques employ real time generation methods to satisfy the dynamic response requirements of current and future simulators both for spaceflight and aircraft flight.

The following paragraphs are intended as a review of the most recent image generating techniques as well as techniques currently under development. A review of the section of this report titled "Visual Simulator Performance Objectives" starting on page 2.6 may help the reader establish a frame of reference in judging to what extent these techniques have approached the ideal objectives.

1. Celestial Sphere

This image generator of the star field developed by the Farrand Optical Co., Inc. in 1962 is the most realistic celestial simulator currently available. All stars from -1 to +5 magnitude subtend subliminal points to the observer's eyes, even under magnification. The device incorporates occulting mechanisms for simulating occultation of the heavens by planetary bodies and by man-made satellites or other space vehicles. The occulted area may be filled in by images of the planet or spacecraft if the display is utilizing multiple inputs. It is significant that the celestial sphere drives and suspension system are so designed that it has complete rotational freedom about all three axes and the gimbal suspension never becomes visible in the field of view. A full description of the Farrand celestial sphere system is given on page 3.111.

Where overall fields of view must exceed those presently attainable with a single display system, celestial spheres may be duplicated in the system and driven in synchronism as has been done for the Apollo, LEM and Gemini simulators. One recognized drawback at this time is the difficulty of providing occultation of the celestial sphere by objects of odd shapes, or shapes other than circular and objects whose shape or outline changes with aspect. It is in this area of occultation that improvement must be sought for future simulators when exact occultation of the celestial sphere by objects of other than circular, or of changing shapes is a requirement.

2. Mission Effects Projector (MEP)

Developed by the Farrand Optical Co., Inc. the MEP was designed to overcome drawbacks such as resolution and lack of color in presently available closed circuit television systems. This image generator, illustrated in figure 3-28 and described on page 3.101 of this report not only overcomes the aforementioned drawbacks of television systems but it does so in a much smaller volume than would be required by a television and model system of equivalent capability. In addition, since the model is in reality a full color film strip, the range of magnification for altitude variation is dependent only on the scale changes included on the film because of the multiple film cassette and optical switching system employed. The present MEP could simulate a flight from launch pad to lunar orbit without discontinuities or interruptions in the visual display. Direct optical projection techniques permit the insertion of such special effects as horizon, sunrise, sunset, terminator, nighttime illumination and moving cloud cover. Of great importance is the fact that, because perspective distortion is generation optically with the use of two dimensional film, the film may be translated to simulate flight in any direction and therefore the image generation using film is not programmed or "canned". It is the considered opinion of this contractor that the MEP provides the best solution to orbital flight simulation not only for the current crop of spaceflight simulators but also for future spaceflight simulators where accuracy, color and resolution are prime requirements.

3. Ground Effects Projector (GEP)*

Currently under development by the Farrand Optical Co., Inc. the GEP represents an extension of MEP principles to the unprogrammed simulation of aircraft flight. This device, like the MEP, utilizes two color film transparencies of the identical maneuvering area to provide a completely unprogrammed flight simulation with complete freedom in lateral translation within the confines of map width and scale. The two identical transparencies provide for scale change effects to achieve a continuous variation in altitude from touchdown to any desirable maximum altitude. The GEP will provide high resolution color imagery for input to an infinity display system. This image generator will also simulate any aircraft

*Patent Applied For

velocity from hover to supersonic velocity. The complete system will be capable of generating a horizon with haze, moving clouds and other aircraft inflight.

Preliminary investigations indicate that the GEP method will provide for increased accuracy in the corresponding radar map simulation beyond accuracies currently available in radar landmass simulators when this is required. The complete GEP system because of its resolution, color and accurate auxiliary map displays should furnish the answer to most requirements involving the engineering evaluation of weapons and surveillance systems in simulators.

4. Closed Circuit Television Systems

All closed circuit television systems regardless of whether their output is designed around a display CRT or a projection CRT fall short of resolution requirements for wide field of view simulators. They have been employed by this contractor, however, for insertion of rendezvous space vehicles in a much wider field of view so that their low resolution capability does not influence or detract from the overall scene. In this respect they may be said to offer a suitable solution to current rendezvous and docking problems for spaceflight. For orbital views or for celestial presentations or for aircraft simulation the resolution available with current television systems does fall far short of the desired values. As this report has pointed out there is very little hope for increased resolution of such systems within the next decade unless a significant breakthrough is achieved in the technology. Certainly the outlook for color television systems is less promising and therefore not too attractive from the visual simulation designers point of view.

When closed circuit television systems must be used, as for example when it is necessary to fly over terrain whose contour must be made to uncover targets or other vehicle features as one flies over it or when certain aspect changes may be important and cannot be reproduced on two dimensional film then the visual simulator designer must resort to closed circuit television systems. Neglecting for the moment the size and complexity of an actual scale model, the optical pickup for the television camera has, up to this time, presented some formidable problems in terms of focus, illumination and field of view. Formerly, optical probe designs strove to operate with as small an aperture as possible in order to achieve the maximum depth of field. Depth of field is of particular importance during landing and ascent since the obliquity of the optical line of sight is very high. This means that there is a large separation between the closest and farthest ground points encompassed by the field of view of the probe. The small entrance pupil normally utilized to obtain this depth of field limits the system in several ways. First the amount of illumination that must be brought to bear on the model in order to develop the maximum resolution and contrast with available cameras is excessive. Second, the small apertures introduce diffraction effects which may ultimately degrade the theoretical resolution of the system.

The Farrand Optical Co., Inc. in addition to providing extremely wide angle optical probes (110° field of view) has just advanced the current state-of-the-art by designing and building optical probes for a vidicon camera system which operate at F/5 or T/10 while achieving a true in-focus condition across the full field of view imaged on the photocathode of the vidicon.

This condition holds over the full operating range of the probe regardless of the obliquity of the optical axis of the probe with respect to the plane of the model.

Considering other television display techniques such as flying spot scanners of photographic transparencies and computation of pictorial elements for display on CRT's it must be concluded that at this time they do not offer the versatility enjoyed by a television camera and model approach. However, various combinations of these basic principles have been explored earlier in this report and as concluded previously it appears that the techniques of image element computation seem to offer the best possibilities for future television system improvement.

5. Thermoplastic and Photoplastic Recording Techniques For CRT Display

These methods of recording a scene for playback in the system have at this time some inherent disadvantages which have been previously discussed in this report. Although their resolution capabilities are excellent generally speaking, one of the major disadvantages involves a time delay between exposure and availability of the recorded scene for projection and viewing. If this lag can be reduced to milliseconds such systems may offer serious competition to current high resolution closed circuit television systems.

D. SUMMARY:

Based on this very short review of what appear to be the most promising developments in visual simulation displays and image generation techniques even a conservative appraisal of the future of visual simulation would lead to the conclusion that the ideal visual simulator patterned after requirements listed in section IV of this report is rapidly being approached. Developments over the last six years have been far more rapid than over the last few decades and this momentum appears to be increasing to the point where we may expect even more rapid strides to be made over the next six year period. It should be borne in mind however, that those techniques selected in this report as appearing to be most promising are selected strictly from a review of the current state-of-the-art and with trends changing so rapidly because of the increased activity in this field, some of the techniques selected may in fact be left behind or replaced by completely new approaches. In any case the state-of-the-art in visual simulation is bound to advance continuously and rapidly.

SECTION VI
GLOSSARY

Aberration. — Generally, any systematic deviation from an ideal path of the image-forming rays passing through an optical system, which causes the image to be imperfect. Specific aberrations are spherical aberration, coma, curvature of field, astigmatism, longitudinal chromatic aberration, lateral chromatic aberration, and distortion.

Aberration, chromatic. — The dispersion of nonmonochromatic light due to the unequal refraction of the different wavelengths of light in the incident beam.

Aberration, chromatic, lateral. — A variation in the images size of a lens for light of different colors or wavelengths.

Aberration, chromatic, longitudinal. — The distance between the foci for light of different colors measured along the optical axis.

Aberration, spherical. — A symmetrical optical defect of lenses and spherical mirrors in which light rays that come from a common axial point, but strike the lens at different distances from the optical axis, do not come to a common focus.

Absorptance. — The ratio between the flux absorbed by a body and the incident flux. This term, and its specifications, are applied to radiant flux and to luminous flux.

Accommodation. — A function of the human eye, whereby its total refracting power is varied in order to clearly see objects at different distances.

Accommodations, limits of. — The distances of the nearest and farthest points which can be focused clearly by the eyes of an observer. Usually varies from 4 to 5 inches to infinity.

Achromat. — A contraction of the term lens, achromatic.

Achromatic. — Having the quality of being free of chromatic aberration.

Achromatism. — The absence of chromatic aberration.

Acuity, visual. — The degree of sharpness of vision.

Acutance. — Edge sharpness and high edge contrast.

Adaptation brightness. Brightness level to which the eye has been exposed for a time, thereby producing a degree of adaptation.

Adaptation, dark. The ability of the human eye to adjust itself to low levels of illumination.

Adaptation, light. The ability of the human eye to adjust itself to a change in the intensity of light.

Afocal. An optical system whose foci are at infinity.

Aluminizing. The application of a film of aluminum to a surface, usually by evaporation.

Anamorphic. A term used to denote different magnification along mutually perpendicular radii. The term is also applied to an optical system that produces this condition.

Anastigmat. A lens in which the astigmatic difference is zero for at least one off-axis zone in the image plane.

Angle, critical. The angle of incidence in a denser medium, at an interface between the denser and less dense medium, at which all of the light is refracted along the interface, i.e., the angle of refraction is 90°. When the critical angle is exceeded, the light is totally reflected back into the denser medium. The critical angle varies with the indices of refraction of the two media.

Angle of incidence. The angle between a ray of light approaching the boundary of an optical medium and the normal to that boundary at the point of contact.

Angle of reflection. The angle between a reflected light ray and the normal to the reflecting surface at the point of contact.

Angstrom. A unit of measurement of the wavelength of light equal to 10^{-8} centimeters.

Aperture. An opening or hole through which light or matter may pass. In an optical system, it is equal to the diameter of the largest entering beam of light which can travel completely through the system.

Aperture, clear. Abbreviated CA. The opening in the mount of an optical system or any component thereof, that limits the extent of the bundle of rays incident on the specific surface.

Aperture, effective. Equivalent to the diameter of the largest bundle of rays that can be imaged by the optical system.

Aperture, free. A term sometimes used as a synonym for aperture, clear.

Aperture, numerical. Abbreviated NA. The sine of the half-angle of the widest bundle of rays capable of entering a lens, multiplied by the index of refraction of the medium containing that bundle of rays.

Aperture, relative. The diameter of the entrance pupil of a lens or optical system measured in terms of the equivalent focal length of that lens or system. It is written as a fraction in which f the equivalent focal length, is the numerator, and it is simbolized by f/ followed by a numerical value. For example, f/2 signifies that the diameter of the entrance pupil is equal to 1/2 the equivalent focal length.

Apochromat. An aplanatic lens which is corrected for spherical aberration for light of two colors and for longitudinal chromatic aberration for light of three colors.

Apparent contrast. The contrast of an object as it appears to a distant observer.

Apparent movement. Visual perception of motion when stationary stimuli are exposed in quick temporal and spatial succession.

Aspheric. Nonspherical. Aspheric surfaces are frequently, but not necessarily, surfaces of revolution.

Astigmatism. Abbreviated ASTIG. An aberration which causes an off-axis point to be imaged as a pair of lines at right angles to each other. A defect of the human eye, resulting from unsymmetric curves on the cornea.

Attenuation (atmospheric). Scattering of light by the atmosphere. Primary: scattering due to atmosphere along. Secondary: scattering due to particles (solid and liquid) present in atmosphere.

GLOSSARY

Axis, optical. The line formed by the coinciding principal axes of a series of optical elements comprising an optical system. It is the line passing through the centers of curvatures of the optical surfaces. The optical Centerline.

Axis, principal. A straight line connecting the centers of curvature of the refracting surfaces of a lens.

Beamsplitter. An optical device for dividing a light beam into two separated beams. A simple beamsplitter is a plane parallel plate, with one surface coated with a dielectric or metallic coating, which reflects a portion and transmits a portion of the incident beam.

Binocular. Vision with both eyes.

Binocular collimation. The adjustment of a binocular instrument so that the lines of sight of the two telescopes are parallel.

Binocular parallax. The inequality of separation, in each of the two eyes, of the retinal images of unequally distant objects..

Blackbody. A body which absorbs all the radiant energy which strikes it; a perfect radiator and a perfect absorber.

Brightness. The effect upon sensation by means of which an observer is able to distinguish differences in luminance.

Bundle, axial. A cone of rays that emanates from an object point which is located on the optical axis of the lens system.

Candle. Unit of light intensity. At a distance of one foot, one candle produces an illumination of one foot-candle (equivalent to one lumen per square foot) upon a surface normal to the beam.

Candle. A unit of luminous intensity.

Candlepower. A unit of measure of the illuminating power of any light source. The number of candles in the luminous intensity of a source of light.

Coat, hard. A term applied to the process, or to the result of the process, of producing (usually) dielectric coatings that are more durable under adverse conditions than those produced from other processes.

Coating, antireflection. Thin layers or films, also known as low reflecting films, that are ordinarily used for reducing the reflectance and increasing the transmittance of glass surfaces.

Coating, high-reflecting. A broad class of single or multilayer coatings that are applied to a surface for the purpose of increasing its reflectance over a specified range of wavelengths.

Coating, reducing, reflection. A thin film of transparent substances formed on glass-air surfaces.

Collimate. To render parallel.

Collimation. The process of aligning the optical axis of optical systems to the reference mechanical axes or surfaces of an instrument; or the adjustment of two or more optical axes with respect to each other. The process of making light rays parallel.

Collimator. An optical device which renders diverging or converging rays parallel.

Coma. An aberration of a lens which causes oblique pencils of light rays from an object point to be imaged as a comet-shaped blur.

Cones. Structures found in the retina of the eye which constitute specific receptors for chromatic and achromatic vision at high levels of illumination.

Confusion, least, circle of. A circle whose perimeter defines the area, for any point in the field of view, covered by the smallest image (usually of a point source formed by the lens.

Contrast. Difference in brightness between two portions of visual field, usually expressed in experimental procedure as:

$$C = \frac{B_{\text{background}} - B_{\text{test field}}}{B_{\text{background}}} \times 100\%$$

Also, change in the apparent brightness of color of a visual field as a result of recent stimulation of this field or a neighboring one; effect is to enhance opposing characteristics.

Contrast sensitivity. Ability to detect a difference in brightness expressed numerically as the reciprocal of brightness contrast discrimination fraction.

Convergence. Process of varying the torsion of the eyes, as the object observed approaches, to allow image to be formed at corresponding regions of the two retinas, i.e., the turning of the two eyes toward each other so that their respective lines of sight meet at a common point in space.

Cornea. The transparent structure forming the anterior part of the external layer of the eyeball.

Correction, color. The reduction of longitudinal, lateral, and secondary chromatic aberrations.

Critical fusion frequency. Fusion frequency of flicker, or the rate of presentation of successive light stimuli which is necessary just to produce complete fusion and to have the effect of continuous illumination (cff is measured in cycles per second.

GLOSSARY

Curvature of field.	That aberration resulting from the fact that the focal surface of an optical system is usually not a plane, but is curved.
Definitions.	The degree of clarity of reproduction of the object that depends upon a combination of resolving power and contrast.
Depth of focus.	of an optical instrument is the difference in focal position which can be tolerated without sensible degradation of the image quality.
Depth of field.	the tolerable difference in object position which will still result in the image being in focus.
Depth perception.	Direct appreciation of the distance of a given object or objects from the observer, or of the relative distance from front to back in the perception of solid objects.
Depth perception, real vs. apparent.	In "real" depth, the retinal disparity is produced by the different view each eye gets of a distant object; in "apparent" depth, this disparity is produced synthetically (as in stereogram of a stereoscope).
Diaphragm.	A fixed or adjustable aperture in an optical system.
Diaphragm, antireflection (or glare).	A Diaphragm for eliminating internal reflections and glare in the field of view of the instrument.
Diaphragm, iris.	A diaphragm whose circular aperture is smoothly and continuously adjustable, from its minimum to its maximum opening.
Dichroic.	Exhibiting the quality of dichroism.
Dichroism.	This term refers to the selective reflection and transmission of light as a function of wavelength regardless of its plane of vibration.

Difference threshold. — The least amount of change in stimulation necessary to produce an awareness of change in sensation. It is statistically determined, i.e., the difference between two stimuli which 50% of the time is perceptible and 50% of the time is not.

Diffraction. — The process by means of which the propagation of radiant waves or light waves are modified as the wave interacts with an object or obstacle.

Diffusion. — The scattering of light by reflection or transmission.

Diopter. — A unit of refractive power of a lens or prism. In a lens or lens system, it is numerically equal to the reciprocal of the focal length measure in meters.

Disorientation. — A temporary or pathological condition, in which the individual loses the usual perception of space or time relations between himself and the environment.

Distance, eye. — The distance from the vertex of the last optical surface of the visual optical system to the exit pupil. Also termed "eye relief".

Distance, hyperfocal. — The distance between the rear focal point of a lens and the image plane when the object is not at infinity.

Distance, interpupillary. — The distance between the two eye pupils, when the observer is viewing distance objects.

Distortion. — Also called radial distortion. An aberration of lens systems characterized by the imaging of an extra-axial straight line as a curved line, without necessarily affecting the definition.

Distortion, barrel. — A form of distortion, radial.

Distortion, pincushion. — A form of distortion, radial.

Doublet. A compound lens consisting of two elements. If there is an air space between the elements it is called an "air-spaced doublet." If the inner surfaces are cemented together, it is called a "cemented doublet."

Effect, stereoscopic. The sense of relief or solidity resulting when an object is viewed by both eyes. It is due to the fact that each eye views the object from a slightly different point of view.

Entrance pupil. In an optical system, that opening (real or virtual) which represents the common base of all the cones of rays entering the instrument.

Exit pupil. In an optical system, that opening (real or virtual) which represents the common base of all the cones of light emerging from the system.

Eyepiece. An optical system used to form an enlarged virtual image of the image formed by the objective, and to direct the light into the eye of the observer.

f/#. the relative aperture of an optical system. Equal to the ratio of the system effective focal length to its entrance pupil diameter.

$$f/\# = \frac{\text{E.F.L.}}{\text{diameter of entrance pupil}}$$

Fatigue. A scientifically inexact term referring to the various effects of physiological exhaustion, boredom, loss of motivation and whatever else may be present as an explanation of loss of efficiency following prolonged exertion.

Field, apparent. The size of the field of view in the image space of an optical instrument, as differentiated from the size of the field of view in the object space.

Field, curvature of. An aberration of a lens which causes the image of a plane to be focussed into a curved surface, instead of a plane.

Field, true.	The size of the field of view in the object space of an optical instrument as distinguished from the size of the field of view in the image space (see apparent field). More specifically, it is the maximum cone or fan of rays subtended at the entrance pupil that is transmitted by the instrument to form the usable image.
Fixation.	(Vision) The directing and focusing of the eye, or both eyes, upon a certain point in space in such a way that an image of this point falls upon the fovea or foveas.
Fixation point.	Point in the visual field at which the observer is looking directly. It is the point whose image falls on the center of the fovea.
Flicker.	(Vision) A rapid periodic change in a visual impression, due to a corresponding rapid cyclic change in the intensity or some other characteristic of the stimulus.
Fluorescence.	Luminescence that persists for less than about 10^{-8} second after excitation.
Flux, luminous.	The quantity that specifies the capacity of the radiant flux to produce the attribute of visual sensation known as brightness.
Foot-candle.	Unit of illumination, equal to the illumination falling on a sphere of one foot radius surrounding a uniform point source of one international candle. 1 ft-c = 1 lumen/ft^2.
Foot-candle.	A unit of illuminance equal to one lumen incident per square foot.
Fovea.	Central region of the retina and region of greatest sensitivity to form and color (also called fovea centralis).

GLOSSARY

Fusion.	(General) The combination of the effects of two or more stimuli in any given sense, so as to yield a single sensation. (Vision) The perception of steady illumination caused by rapid successive presentation of flashes of light at a certain rate.
High gain screen.	A screen in which the reflected or transmitted light beam is restricted to a much smaller bundle than was received by the screen, thereby resulting in a higher luminance.
Hyperfocal distance.	A calculated object distance governing the depth of field of an optical system.
Illuminance.	Luminous flux incident per unit area of a surface. Widely known as "illumination."
Illuminated.	A surface or object is said to be illuminated whenever luminous flux is incident upon it.
Image, erect.	An image, either real or virtual, that has the same spacial orientation as the object.
Image generator.	devices which create the images for display in the window displays.
Image, ghost.	Spurious multiple images of objects seen in optical instruments, caused by the reflections from optical surfaces. By coating the optical surfaces with low reflection films, the harmful effects of ghosts are greatly reduced.
Image, virtual.	If a bundle of rays having a given divergence has no real or physical point of intersection of the rays, then the point from which the rays appear to proceed is called the virtual image.
Infinity.	In the optical industry, a term used to denote a distance sufficiently great so that light rays emitted from a body at the distance are practically parallel. Infinity is indicated by the symbol ∞.

Interpupillary distance.	The distance between the centers of the pupils of the two eyes of an individual. It varies in individuals, from 58 - 74mm.
Irradiance.	Radiant flux incident per unit area.
Lambert.	Unit of brightness; it is the brightness of a perfectly diffusing surface giving out one lumen per square centimeter of surface area.
Lambert.	A unit of luminance, equal to $\frac{10^4}{\pi}$ candles per square meter.
Lambertian reflector.	A perfectly diffusing reflective surface. It exhibits the property that the intensity of the light emanating in a given direction from any small surface element is proportional to the cosine of the angle of the normal to the surface.
Lateral vision.	Perception of visual stimuli at the left and right outer edges of the visual field.
Length, focal.	In a lens, focal length is synonymous with equivalent focal length. In a mirror or single refracting surface, it is the distance measured from the focal point to the mirror or surface.
Length, focal, equivalent.	Abbreviated EFL. The distance from a principal point to its corresponding principal focal point.
Lens, achromatic.	A lens consisting of two or more elements, usually made of crown and flint glass, which has been corrected so that light of at least two selected wavelengths is focussed at a single axial point.
Lens, aplanatic.	A lens which has been corrected for spherical aberration.
Lens, condensing.	A lens or system of lenses of positive power used for condensing radiant energy from a source onto an object.

GLOSSARY

Lenticular screen. Either a rear or front projection screen composed of minute optical surfaces, which introduce a spread to the light beam which conforms approximately to the light distribution requirements of the application.

Light, white. Radiation having a spectral energy distribution that produces the same color sensation to the average human eye as average noon sunlight.

Limen. See Threshold.

Line of sight. The line joining the eye and the object being observed. The direction of the optical axis of a telescope.

Lumen. The unit of luminous flux.

Lumen. The flux emitted in unit solid angle (steradian) by a point source of one candle luminous intensity. A uniform point source of one candle intensity thus emits four lumens.

Luminance. The ratio of the luminous intensity emitted in a given direction by an infinitesimal area of the source, to the projection of that area of the source upon the plane perpendicular to the given direction.

Magnifying power. of a visual instrument may be defined as

$$MP = \frac{\text{size of retinal image obtained with instrument}}{\text{size of retinal image obtained with the unaided eye}}.$$

Mapping. The ability of the visual display system to accept angular relationships at the image generator end, and maintain these angular relationships at the output.

Marginal rays. Those rays which pass an optical element near its edge.

Meridional rays.	Those rays of an oblique bundle of light rays which lie in the plane determined by the optical axis and the chief ray of the bundle.
Meter.	A unit of metric measurement: 1000 millimeters equal one meter, 100 centimeters equal one meter, one meter is equal to 39.37 inches.
Micron.	(μ) A unit of length in the metric system equal to 0.001 millimeter.
Millidiopters.	A unit of metric measure equal to 0.001 diopters. The power of a lens in millidiopters is the reciprocal of its focal length in kilometers.
Millimicron (mμ).	A unit of length in the metric system equal to 0.001 micron.
Minimum distinguishable.	Least change in form that can be identified visually, i.e., the least lateral displacement in the end of two lines that will result in the experience of discontinuity. It is measured in terms of the angle subtended by the object, measured at the eye.
Minimum perceptible.	Smallest object that is visible. It is measured in terms of the angle subtended by the object measured at the eye.
Minimum separable.	Smallest space between two lines that can be discriminated as a gap. It is measured in terms of the angle subtended by the gap, measured at the eye.
Minimum visible.	Least area of a uniform brightness that can activate the eye. It is measured in terms of the angle subtended by the area, measured at the eye.

GLOSSARY

Mirror, mangin. — Essentially, a negative meniscus lens whose second or convex surface is silvered.

Monochromatic. — Composed of one color.

Monocular. — Pertaining to one eye.

Movement parallax. — The visual phenomenon of apparent difference in rate of movement of two objects actually moving at the same velocity but at different distances from the observer.

Movement parallax threshold. — The different angular velocity of two objects moving at equal speeds but at different distances from the observer which is just noticeable.

Near Point. — This is the point on the axis which is sharply focused on the retina when maximum accommodation is being exerted and the eye lens has its strongest refracting power. Although this distance varies in individuals, it is commonly taken to be 10 in. for the average eye.

Object space. — The space containing the object.

Oblique bundle. — A bundle of light rays not parallel to the optical axis.

Parallactic angle. — The angle between the two lines drawn from a single point on an object to the two eyes.

Parallax. — The condition which exists when two objects do not lie in the same plane; when the eye is shifted from side to side, the two objects appear to shift with respect to one another, especially with respect to the reticle of a telescope and the image of the field of view.

Paraxial. — Pertaining to the thin, threadlike region immediately surrounding the optical axis.

Peripheral field of vision. — Beyond the central field and included within the area of 120 degrees vertically by 160 degrees horizontally. This field will vary somewhat according to the features of the individual.

Periscope.	An optical instrument designed to displace the line of sight.
Photopic vision.	Vision as it occurs under illumination sufficient to permit the discrimination of colors. Sometimes called daylight vision.
Power, resolving.	A measure of the ability of a lens or optical system to form separate and distinct images of two objects close together.
Power, stereoscopic.	The gain in stereoscopic effect afforded by a magnifying binocular instrument, as compared with the ability of the unaided eyes.
Principal axis.	The line joining the centers of curvature of a lens, or joining the center of curvature and vertex of a mirror.
Prism, dove.	Also known as "rotating prism." It is used to invert the image in one plane without deviating or displacing the axis.
Pupil, entrance.	The image of the limiting aperture stop formed in the object space by all optical elements preceding the limiting aperture stop.
Pupil, exit.	The image of the limiting aperture stop in an optical system formed by all lenses following this stop.
Pupil, eye.	That opening formed by the iris of the eye. The diameter of the eye pupil varies with the intensity of light it receives, the iris increasing in diameter when illumination is low.
Radiance.	The radiant intensity per unit projected area of an extended source.
Refracting power.	The power of a lens to refract, or converge light. Dioptric power.

GLOSSARY

Refraction.	The bending of a ray of light upon its entering a different optical medium.
Resolution.	The degree to which detail is shown in an image.
Resolving power.	The power of a lens or optical system to form separate images of close object-points.
Reticle.	A pattern etched on glass or fine wires strung upon a diaphragm, placed in an optical system at a point where a real image is formed, for the purpose of locating the optical axis or of making measurements.
Rod.	Rod-like type of structure found in the retina of the eye which constitutes a specific receptor for achromatic visions at low levels of illumination.
Roof prism.	A prism containing a roof, or juncture of two reflecting surfaces at right angles, and whose line of juncture lies in the plane containing the incident chief ray. It inverts in two planes, and the roof itself deviates the light through 90 degrees.
Schmidt, pechan.	A prism composed of two air-spaced prism elements. This prism has the property of reverting without inverting an image, and can be used in convergent or divergent light as well as parallel light.
Scotopic vision.	Vision which occurs in faint light, or after dark adaptation. Sometimes called twilight or night vision. Hues and saturations cannot be distinguished.
Sight, line of (L.O.S.).	The line of vision; the optical axis of a telescope or other observation instrument. The straight line connecting the observer with the aiming point; the line along which the sights are set.

GLOSSARY

Sources, light, luminous efficiency of.	The ratio of the luminous flux emitted to the power consumed by the source.
Spectrum, visible.	The portion of the electromagnetic spectrum to which the retina is sensitive and by which we see. It extends from about 400 to about 750 millimicrons in wavelength of the radiation.
Speed, lens.	That property of a lens which affects the illuminance of the image.
Steradian.	Unit solid angle at unit distance.
Stereo acuity.	The ability to perceive binocularly the solidity and relative distance of objects. (Stereo acuity is defined arbitrarily as the degree of binocular perception of apparent depth induced by stereoscopic means; this is differentiated from the discrimination of real depth or the relative distances of objects viewed as they are actually oriented in space relative to each other.)
Stereopsis.	The perception of depth arising as a result of binocular vision.
Stereoscopic power.	The ability of an individual to perceive depth as a result of binocular vision.
Stimulus threshold.	That magnitude of stimulus at which a transition occurs from no sensation to sensation, measured by finding that magnitude of stimulus which is detected in 50% of the presentations.
Surround.	A term referring to both the color and intensity of the immediate environment of the object or image being viewed.
System, erecting.	A system of lenses or prisms, the function of which is to produce an erect image which would otherwise be inverted. An erecting system may consist of a lens or system of lenses to reimage the object or of one or more prisms.

GLOSSARY

Systems, optical, catadioptric. An optical system containing both lens (dioptric) and curved mirror (catoptric) optical components.

T/#. The ratio of an optical system f/no. to the square root of its transmittance (t), the latter being a number equal to or less than unity

$$T/\# = \frac{f/\#}{\sqrt{t}}$$

Telescope, panoramic. A telescope so designed that the image remains erect and the position of the eyepiece is unchanged as the line of sight is pointed in any horizontal direction.

Temperature, color. The temperature of a blackbody that emits light of the same color as the body in question. Color temperature is expressed in degrees Kelvin.

View, field of. In general, the maximum cone or fan of rays passed by an aperture and measured at a given vertex. In an instrument, field of view is synonymous with true field.

Vignetting. A term used to denote the loss of light through an optical element due to the entire bundle not passing through.

Vignetting effect. The effect produced when the edges of the field of view are insufficiently illuminated with respect to the central portion. An effect produced by photographers, where there is a gradual fading off into the background.

Visible spectrum. Radiant energy of a wavelength band to which the human eye is sensitive, producing the sensation of seeing. This band is usually taken to be from 380 to about 740 mμ in wavelength.

Visibility. The clarity with which an object can be seen. It is increased both by brightness difference within the visual task and by intensity of illumination on the task.

GLOSSARY

Visibility (atmospheric). — The distance at which an object may be detected in a variety of viewing circumstances.

Vision, distinct, distance of. — The near-point distance of the normal eye conventionally given the value of 10 inches or 25 centimeters. This value is used in calculating the designated magnification of a simple magnifier or eyepiece.

Vision, stereoscopic. — Vision in depth of three dimensions due to the spacing of the eyes. This spacing permits the eyes to see objects from slightly different points of view.

Visual acuity. — Ability of the eye to perceive form and detail in a plane perpendicular to the line of sight. (See retinal resolution)

Visual angle. — The angle subtended by an object of vision at the nodal point of the eye. The magnitude of this angle determines the size of the corresponding retinal image, irrespective of the size or distance of the object.

Visual Field. — The totality of visual stimuli which act upon the unmoving eye at a given moment.

Visual range. — Maximum distance at which an object can just be seen by an observer with normal vision.

White light. — Light, such as sunlight and daylight, which is composed of all different wavelengths of the spectrum.

SECTION VII

OPTICAL PRINCIPLES OF INFINITY IMAGE DISPLAY SYSTEMS

An infinity display system can provide an observer with a wide field of view, large exit pupil and controlled parallax from a number and variety of image generation devices.

Equally important is the generation of proper motion parallax between cockpit structure and the distant simulated scene that is possible only with an infinity display system.

One type of optical system used in infinity displays is the non pupil forming type as shown in Figure 7-1. A screen input is placed at the focal surface of a spherical mirror to present the images at infinity. Several problems arise from the geometry of such a system.

1. A large input device (i.e., screen) must be used for a wide field because the mirror focal length must be sufficiently long to permit the input to be located outside the direct field of view.
2. The vertical field is severely limited.
3. Differential parallax cannot be created since multiple inputs cannot be used.

These restrictions tend to limit this approach as a means of achieving display systems with ultra wide fields of view.

A more desirable approach is the multiple input, pupil forming type of display.

The exit pupil of an optical system is defined to be the image of the aperture

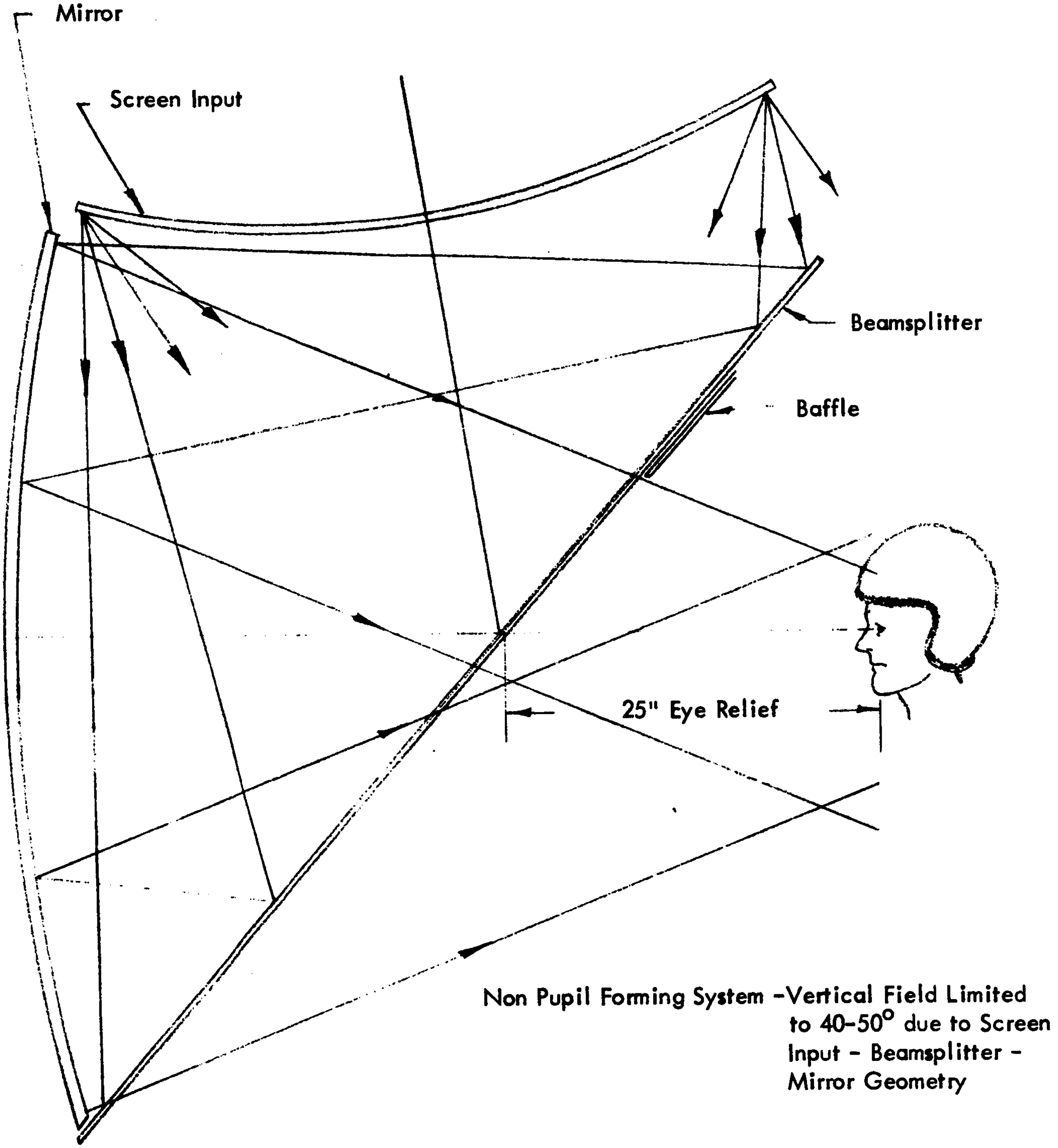
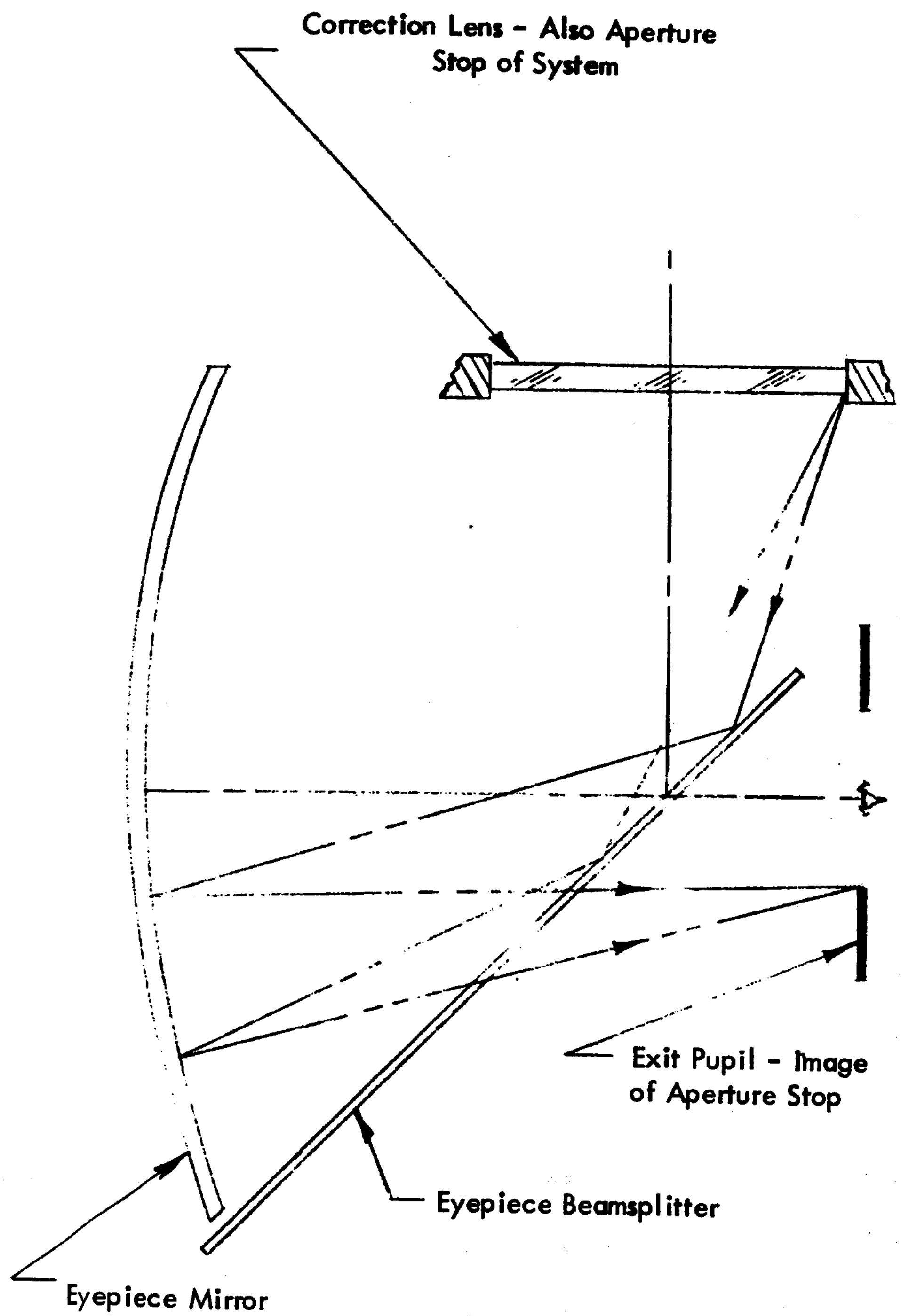

Mirror
Screen Input
Beamsplitter
Baffle
25" Eye Relief
Non Pupil Forming System -Vertical Field Limited to 40-50° due to Screen Input - Beamsplitter - Mirror Geometry

FIGURE 7-1

stop of the system as formed by the optics. A common form of Virtual Image Display system has the corrector lens as the aperture stop of the system, with the eyepiece mirror forming an image which is the exit pupil. Such a system is illustrated in figure 7-2. These pupil forming systems enjoy the advantage of wider fields of view as compared to the non-pupil forming system described in figure 7-1. The wider field of view is achieved because the aerial image seen by the eyepiece mirror can be deeply immersed in the eyepiece system without imposing any physical obstructions in the field of view of the observer, thus permitting a shorter mirror focal length.

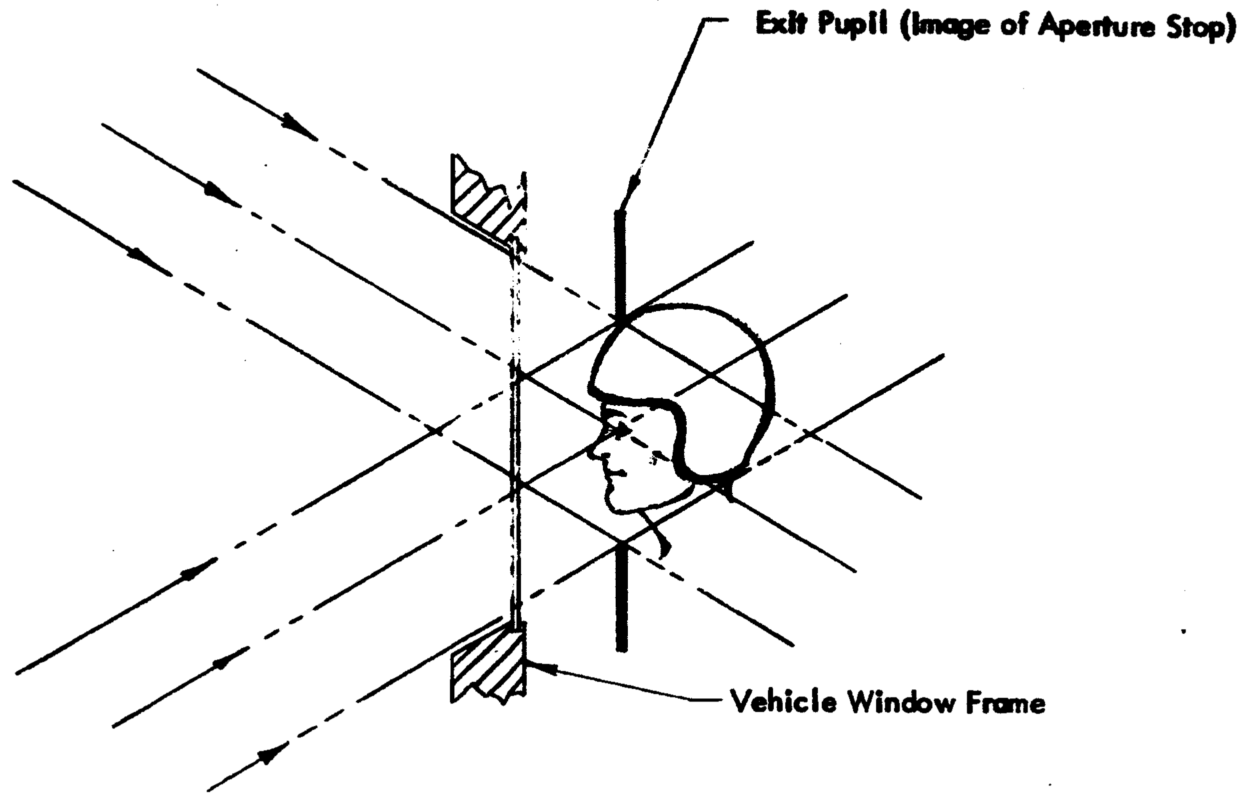
Figures 7-3 and 7-4 illustrate diagramatically how pupil forming display systems may generate pupils at either the normal eye position or at the observer's vehicle window. The choice of location of the pupil depends upon interrelated factors, such as the degree of freedom of the observer's head motion, the instantaneous field of view that must be provided, and space considerations in the capsule or cabin.

An observer who places his eye anywhere within the crosshatched volume shown in figure 7-5, will see the total field of view of the display system. When his eye is removed from this conical volume, a smaller angular field of view will be available to his eyes. This angular field is limited by the angle subtended at his eye by the diameter of the exit pupil as it would be in the real case of looking out a window. The observer however, may move

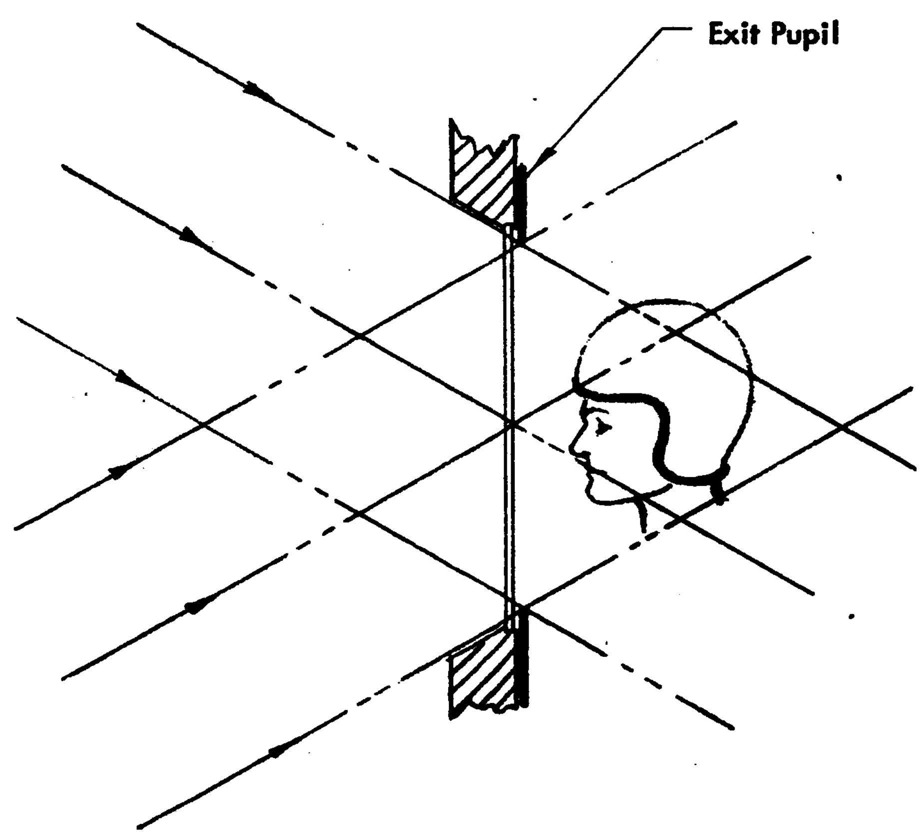


EXIT PUPIL FORMATION

FIGURE 7-2

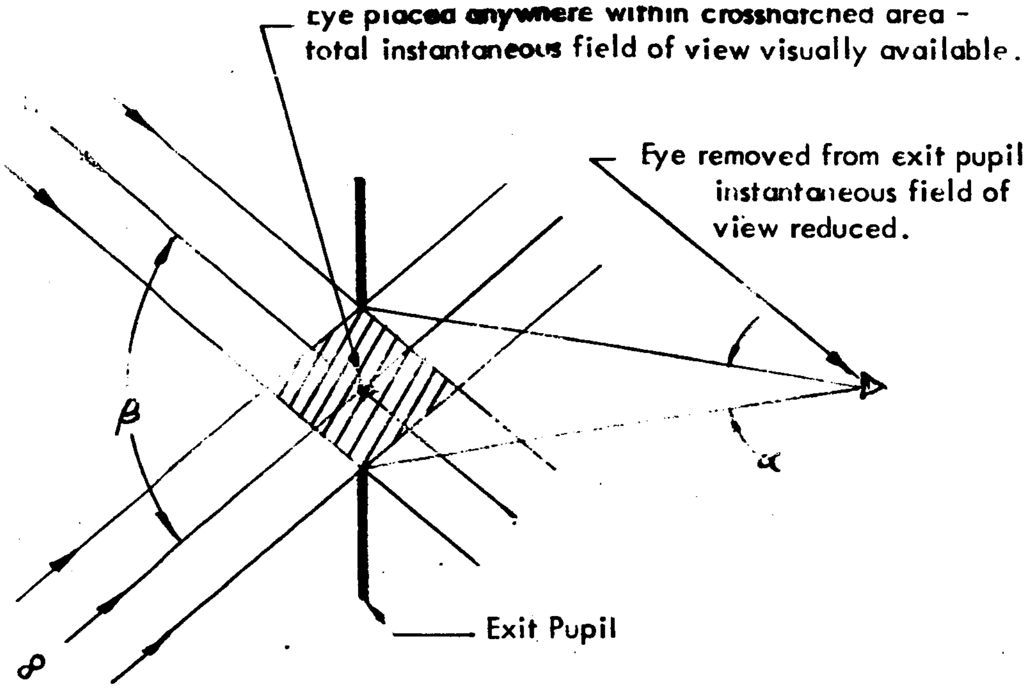


EXIT PUPIL FORMED AT EYE - FIGURE 7-3



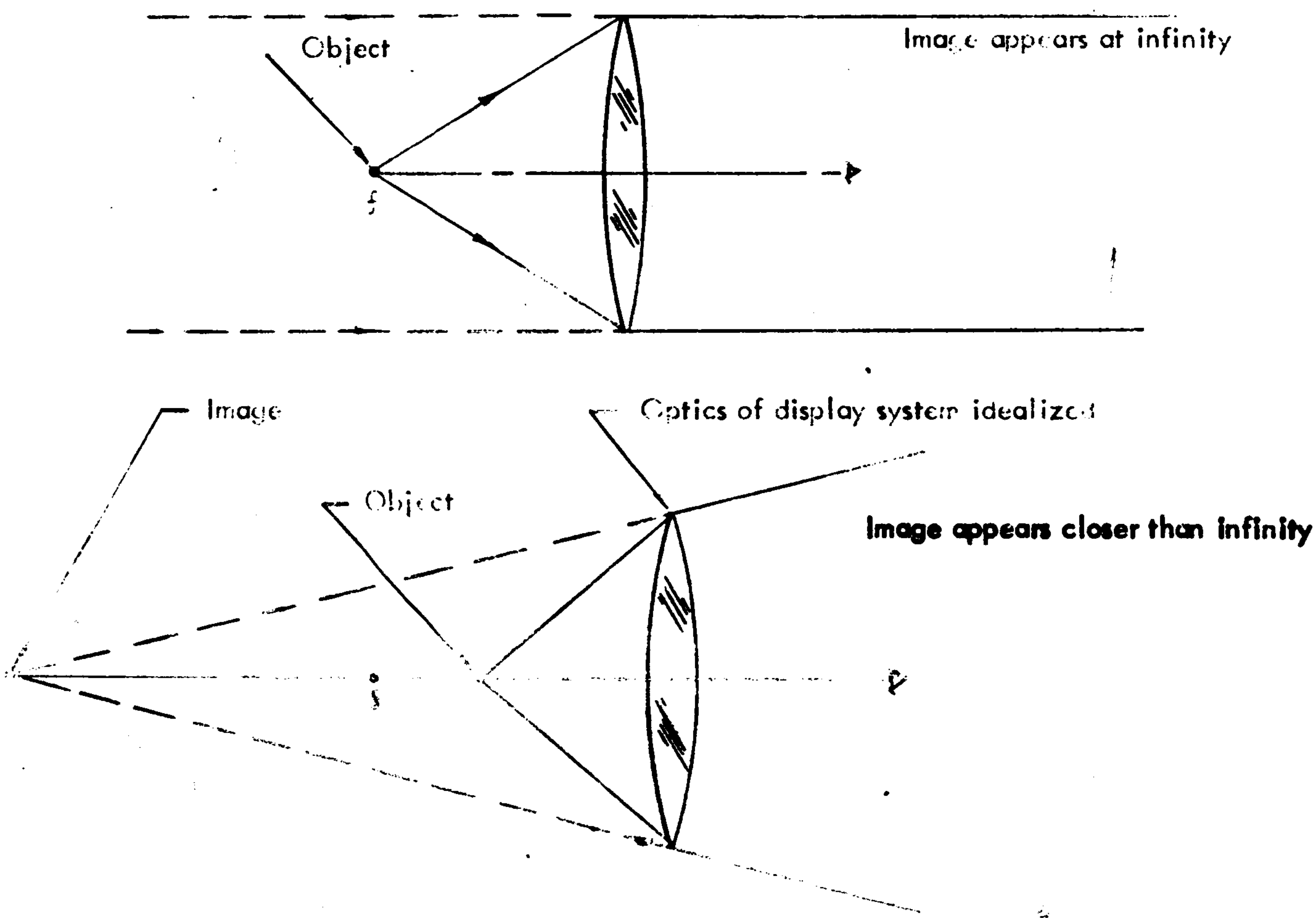
EXIT PUPIL AT WINDOW - FIGURE 7-4

FACI



FIELD OF VIEW OF VIRTUAL IMAGE DISPLAY

FIGURE 7-5



VARIATION OF APPARENT DISTANCES

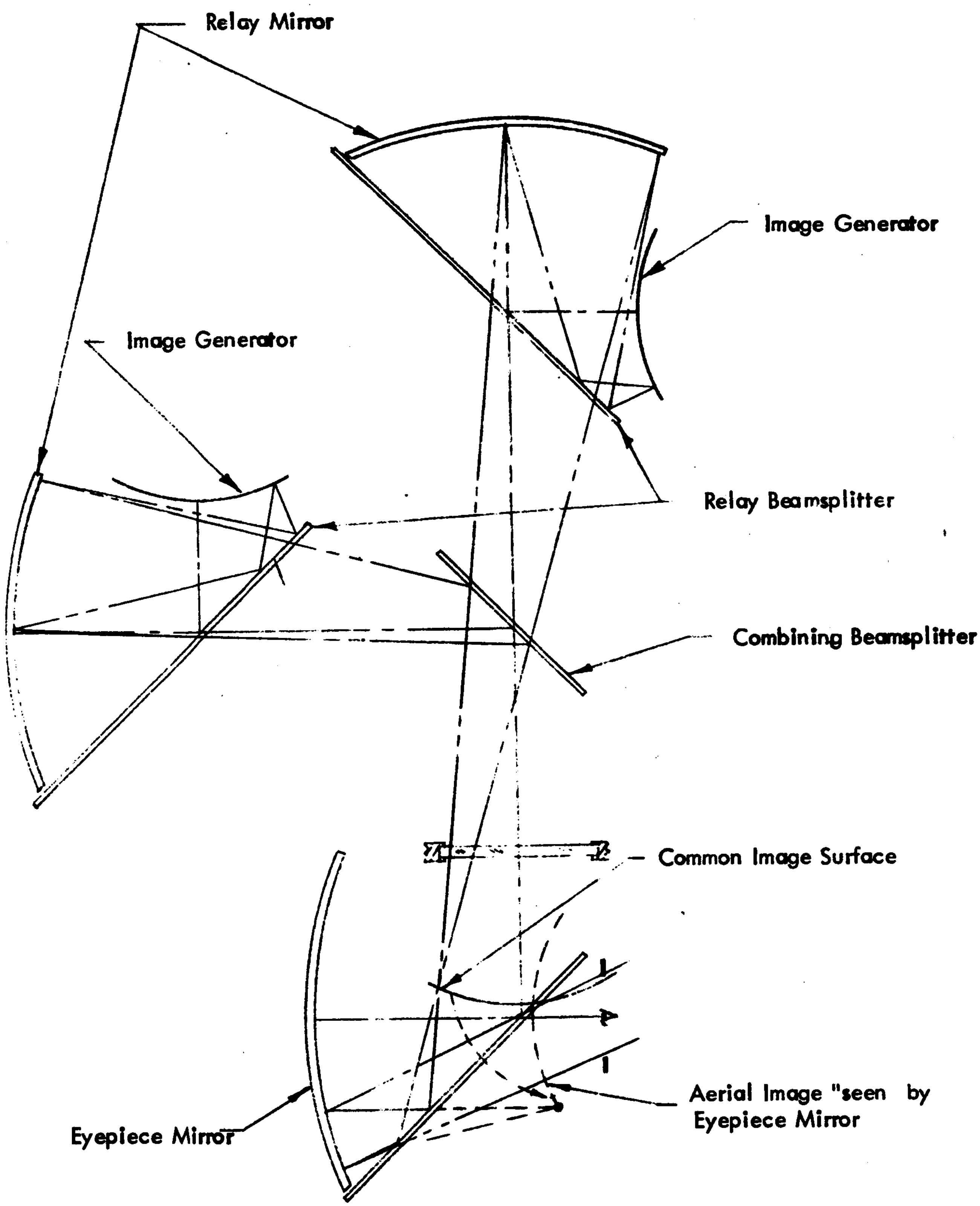
FIGURE 7-6

to view any angle within the total field of view illustrated as angle β in figure 7-5.

Another advantage of the multiple input system is the ability to control parallax between inputs. By idealizing the optics of a Virtual Image Display system into a simple thin lens (figure 7-6), it can be seen that any object located at the focal point of the lens will appear to the eye to be located at infinity. If the object is moved inside the infinity focal point of the lens, the image appears to be closer since the rays emanating from the object appear to converge to the object from the observer's viewpoint. This principle is used in multiple input infinity image systems to simulate apparent differences in object distance by moving the object planes relative to the normal infinity focal plane.

Figure 7-7 illustrates the typical make-up of a Virtual Image Display system. It shows how the images of the image generators, as formed by the relay mirrors, are superimposed by the use of a combining beamsplitter, forming a combined aerial image at the common image surface. The shape of this common image surface coincides with the curved infinity focal surface of the eyepiece mirror thus presenting a wide angle infinity display to an observer located at the exit pupil.

Thus far infinity image systems as applied only to a single observer have been considered. There are occasions where observers seated side by side



VIRTUAL IMAGE DISPLAY

FIGURE 7-7

must enjoy the same view. In these cases, it is important that certain principles be kept in mind. For example, in figure 7-8A the observer is afforded an infinity view through a single display system of a limited exit pupil size. In figure 7-8A it is shown that the exit pupil formed using an aerial image is limited in size primarily because of the F/number bundles associated with image and by the size of the collimating optics. To provide an exit pupil large enough to encompass both observers with such a system becomes impractical due to the size of the optical system. If one resorts to a screen type of input as shown in figure 7-8B where the pupil is essentially formed at the aperture of the collimating lens, it is seen that both observers may view the same scene with correct spatial directions. This system also has certain drawbacks involving the size of the optical elements in addition to previously mentioned drawbacks associated with non-pupil forming infinity displays. The most economical means of providing two observers with an external visual scene is illustrated in figure 7-8C where direct view of a screen is illustrated. However, this method violates the desirable principles of infinity display systems since spatial directions are inconsistent for both observers. One economical solution suggests the use of multiple infinity display systems. In this manner one may employ optical systems of reasonable size to provide both viewers with wide field infinity displays.

An attempt to use a single image generator with two separate collimating systems as shown in figure 7-8D demonstrates that corresponding spatial directions cannot be maintained.

If, however, complete systems are duplicated as in figure 7-8E, correct spatial relationships for both observers will be maintained.

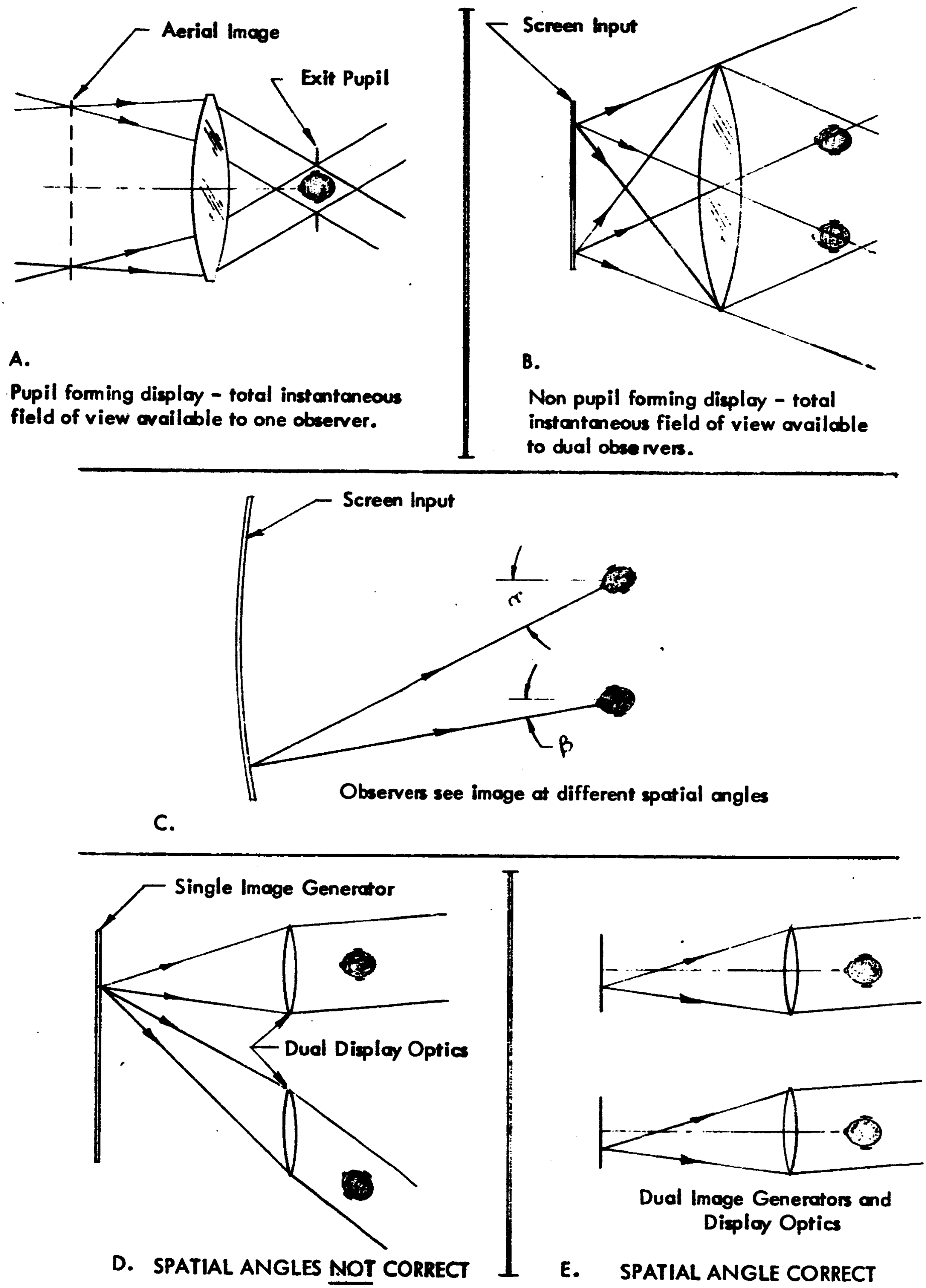


FIGURE 7-8
SIDE-BY-SIDE VIEWING ARRANGEMENTS