Back

NON-CGI
VISUAL IMAGE GENERATION

by

James L. Davis, Ph.D.

Consultant
Atlanta, Georgia 30342 U.S.A.

TEL: 1 (404) 333-1718
Email: jldavis@alum.mit.edu
or
drjldavis@bellsouth.net

TABLE OF CONTENTS

LIST OF FIGURES

NON- CGI VISUAL IMAGE GENERATION

1.0 Introduction

For those of us raised in this Age of Computers and jaded by continual exposure to CGI technology, it is difficult to imagine that other schemes exist for providing a flight simulator with an out-of-the-window visual presentation, much less that someone would buy one. Alternatives, however, do exist. Some existed previous to the birth of CGI but are still implemented and used today. Others are of more recent vintage. All share the characteristic of offering some advantage over CGI. Sometimes the advantage relates to performance; e.g., richer scene detail. Other times the advantage is simplicity and/or lower cost. The following sections define some alternate schemes and discuss their relative merits.

2.0 Model Board/Video Camera System

One of the earliest sources of visual imagery for simulation is the Model Board/Video Camera (M/C) System. Major components include:

1. A rigid model board representing a scaled version of actual or generic terrain and cultural features,

2. A video camera that observes the model board through an optical probe,

3. A movable gantry system capable of rapidly translating the camera along X, Y, and Z coordinates, and

4. A bank of flood lights facing the model board for providing high intensity lighting in a uniform manner.

Figure 2.1 shows one of two 15' by 47' terrain model boards used for the multicrew and fighter/bomber simulators located at the Air Force Flight Dynamics Laboratory. At the right of the picture is the gantry; visible are rails for facilitating smooth motion both horizontally and vertically. The probe and camera are currently resting near the bottom of vertical travel. The flood lights are out-of-sight beyond the right edge of the picture.

During a simulation exercise, the pilot trainee literally flys the probe across the model board. A control movement will move the gantry to a location that ensures the probe is located at a point comparable to the pilot's position. Pitch, yaw, and roll are adjusted using servo-controlled optics within the probe assembly. Light from the probe is coupled into a video camera that conveys the video signals to a processor capable of enhancing the imagery with haze, overcast ceilings, and sky above ceiling. The processed image then goes to a display mounted on the simulator cockpit.

The design of the optical probe plays a large part in the quality of the image presented to the pilot. A design common in this sort of system is the Scheimpflug-corrected optical probe. To appreciate this, consider Figure 2.2 which shows the relationship between probe and model board. The surface of the board is at an angle relative to the optical axis of the probe assembly. To compensate for this and thereby ensure good focus across the resulting image, the imaging plane of the video camera must also be tilted such that the plane of the model board, the imaging plane, and the "effective" median plane of the probe assembly intersect (see Figure 2.3). This condition is the Scheimpflug condition, so-called because Captain Theodore Scheimpflug of the Austrian Army is credited with pointing it out earlier this century. It is best satisfied over relatively flat terrain (e.g., airports) or over general terrain when viewed from sufficiently high altitude.

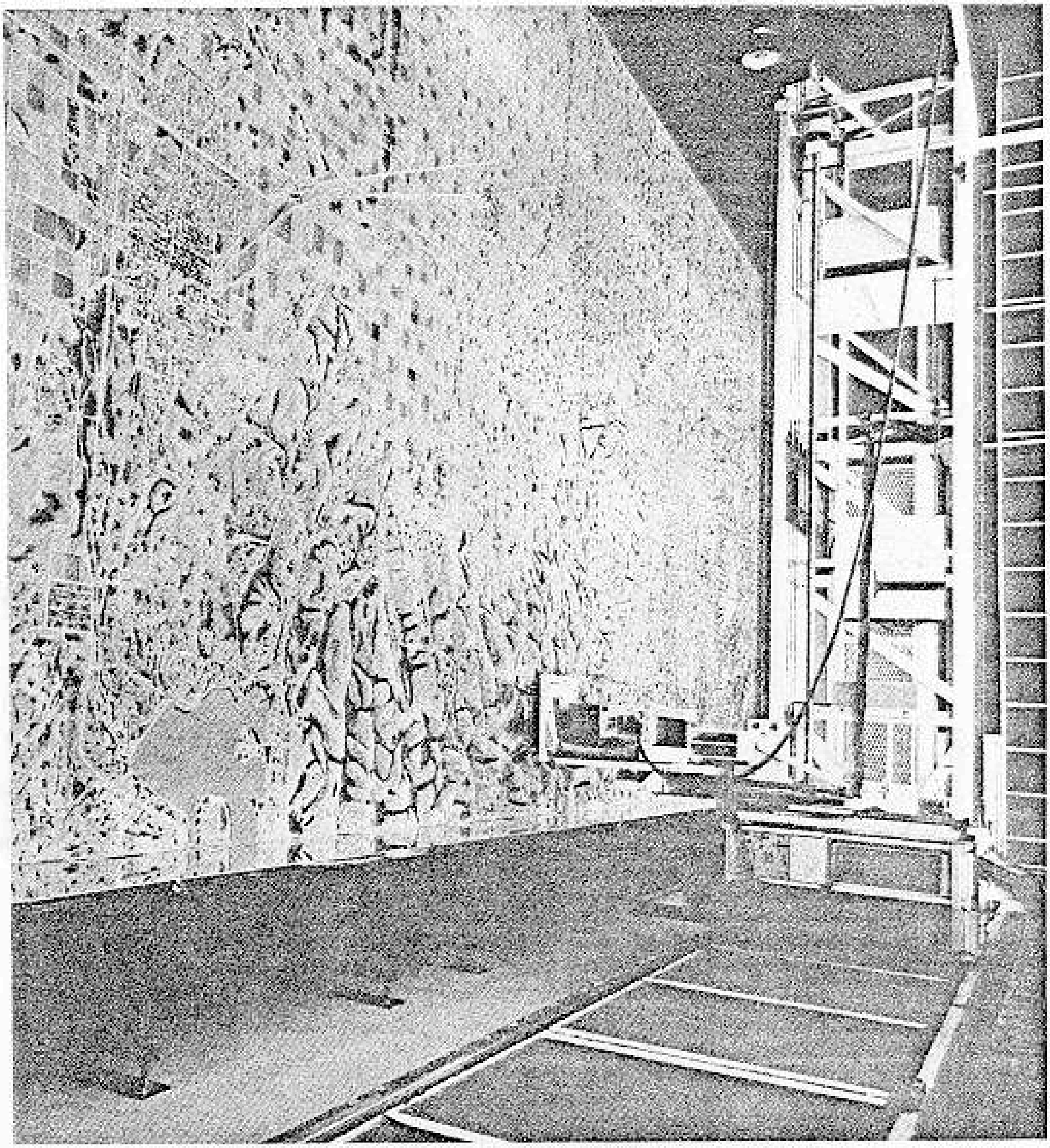

FIGURE 2.1 A 15' BY 47' TERRAIN MODEL BOARD WITH GANTRY AND PROBE

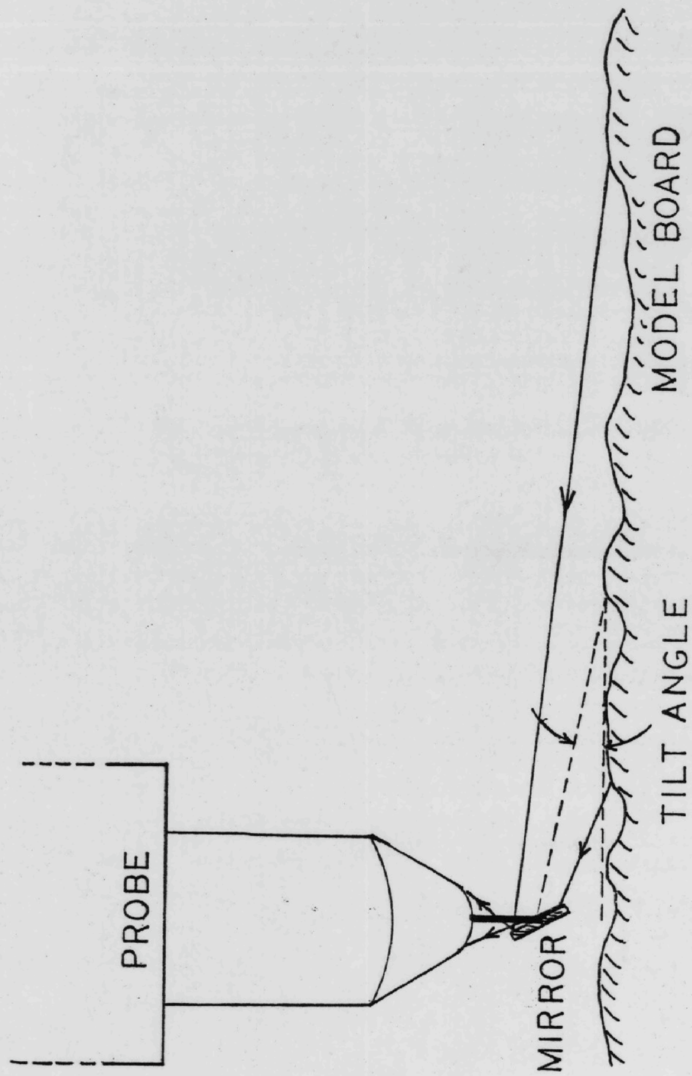

FIGURE 2.2 TILT ANGLE ARISING FROM PROBE/MODEL BOARD GEOMETRY

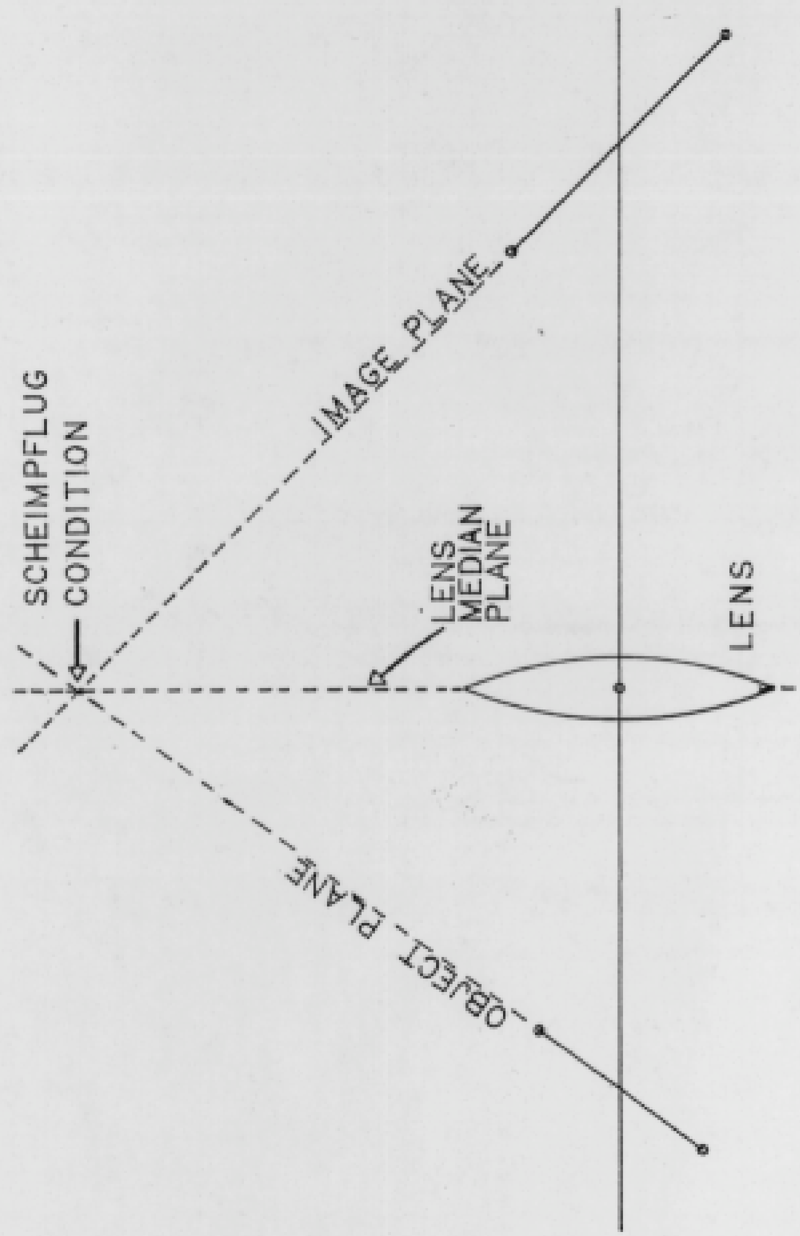

FIGURE 2.3 SCHEIMPFLUG CONDITION

At low altitudes, the Scheimpflug condition is not generally satisfied over the total Field of View (FOV) because of terrain relief and 3-D objects. Non-flatness causes defocus, as does a general breakdown of the Scheimpflug condition at large field angles. To attenuate the degradation, a small aperture (large f/#) is used for the probe to obtain increased depth of field at the price of brightness. To make up for light loss and ensure a good video image, a bank of high-intensity flood lights becomes mandatory.

Anyone familiar with model railroad fanaticism is one step ahead in appreciating the richness of scene detail available from a carefully constructed terrain model board. For example, the model boards at Air Force FDL mentioned earlier represent both urban and rural terrain features, and include an airport having Category 2 lighting effects. One board is scaled 1:1500 and represents an area of 3 by 11 nautical miles. The other large board is scaled 1:5000 and represents 11 by 36 nautical miles. A high-altitude model also exists for simulating flight at heights above 20,000 feet. At a scale of 1 inch per nautical mile, the 4' by 4' board represents an area of 48 nautical miles squared. Figure 2.4 shows a perspective view of a model board used at Ft. Rucker and built by Piper, Ltd. of Great Britain. The detail present in trees, the smoothly curving contours of hills and roads, and the overall quantity of 3-D objects is only just beginning to be approached in the realm of CGI, and then only by top-of-the-line, multi-million dollar systems incorporating cell or contour texture.

On the negative side, a M/C system has limitations in certain training applications. Though scene detail is high, the NTSC video camera limits resolution to at best 7 arc minutes per line pair, with near-field imagery being degraded to much less owing to limited depth of focus in the probe. This is especially true in the wider FOV probes (120° H x 60° V) which, because of their relative bulk, are also unable to approach the model board as closely as a normal probe (60° field angle) in either a horizontal or vertical direction. Another probe-related problem is the danger of the probe colliding with the model board and damaging itself or the board. Later systems use optical or mechanical proximity sensors on the probe assembly to prevent this; however, malfunctions do occur.

Other modelboard problems include:

1. An inability to portray moving targets or special effects (e.g., smoke, missile plumes, weapons effects),
2. Limited dynamic range of the video system, making night simulation unsatisfactory (Note: Lowering the illumination level also reduces signal/noise ratio),
3. Image motion causes an apparent loss of resolution due to "tailing"; third-field image lag can be as high as 25% in camera pickup tubes,
4. High-intensity lighting needed to support a high-resolution camera requires about 200 kW and air-conditioning capable of handling the heat dissipation,
5. A limited staging area over which to conduct the simulation exercise.

Providing wide FOV is also a problem. Normally, only a single camera/probe assembly is used for a single display window providing a forward FOV. Some installations go to the effort of building two identical model boards. Using separately-controlled camera/probe assemblies, two channels corresponding to a front and side window can be displayed. Another scheme, developed by Boeing-Vertol for an in-house engineering simulator, uses a single wide FOV probe and four monochrome TV cameras to sample the resulting image. The pilot is provided with three forward windows and a single chin window. Some geometric distortion exists at the FOV periphery; however, B-V has found that simulation tasks are not compromised.

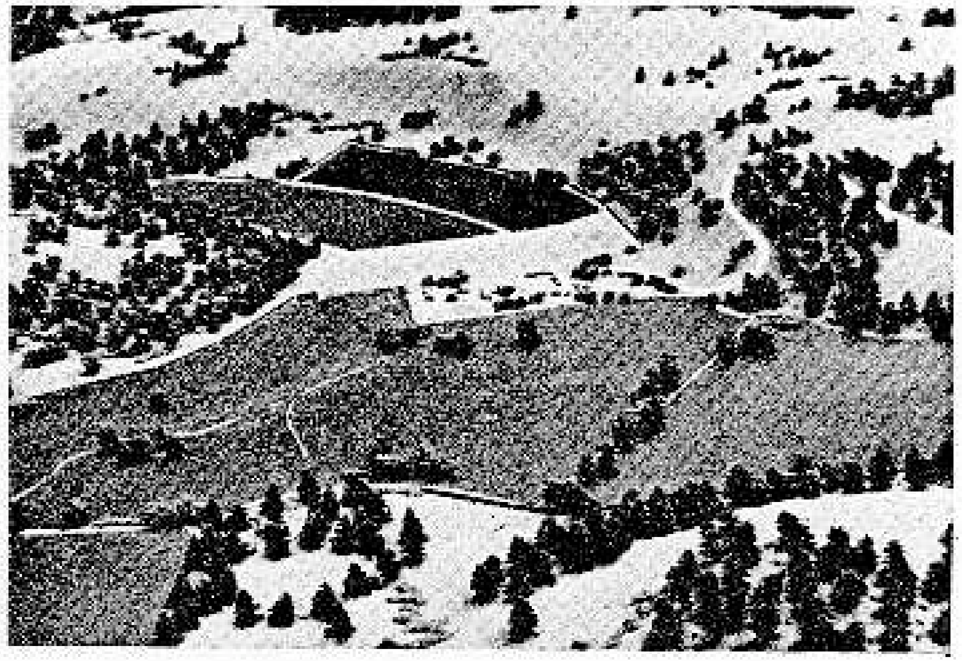

FIGURE 2.4 PERSPECTIVE VIEW OF MODEL BOARD

3.0 Laser Image Generation System

In an effort to overcome the limitations of the M/C systems (described in Section 1.0) while retaining the benefit of high information content at a reasonable price, Singer-Link and Singer-Librascope developed a system that eliminates the video camera and bank of flood lights. Replacing them are a laser system that scans the model board and a bank of photomultiplier tubes (PMT's) for detecting scattered light. A block diagram of the Laser Image Generator (LIG) is shown in Figure 3.1. The principal components are:

1. A laser table to generate red, green, and blue light components,
2. Transmission optics for the full color, collimated laser beam,
3. A laser scanning unit,
4. A Farrand 60° Scheimpflug corrected (tilt/focus) probe, modified to permit laser scanning,
5. A 24' by 64' terrain model board scaled at 1000:1,
6. Video signal processing capability.

Parts of item 2, plus items 3 and 4, are mounted on the gantry transport. And, as with many conventional M/C systems, cultural lighting is provided.

In operation, a collimated, white-light laser beam is created on the laser table by combining the outputs of a Krypton laser (red) and an Argon laser (green and blue). The composite beam is directed along the rail that carries the gantry. Once at the gantry, it is reflected upwards and relayed to the laser scanning unit. Horizontal line scan is accomplished using a 24-facet polygon mirror rotating at 76,000 rpm. Vertical frame scan is via a galvonometer-driven mirror vibrating at 60 Hz. This scanned beam is projected through the Scheimpflug probe and onto the model board in a region corresponding to the pilot's FOV. As with the camera, the gantry is responsible for positioning the probe at coordinates corresponding to the simulated eyepoint; the probe optics generate yaw, pitch, and roll corresponding to aircraft attitude. **Figure 3.2** shows the LIG system in operation. The left picture shows the probe relative to the terrain board. With a 1000:1 scale board, the LIG probe provides a minimum simulated eye height of 6.5 feet. The right picture shows the fan of laser light that results from scanning and projecting the beam through the probe.

Scattered, reflected light from the model board can be detected using a bank of PMT's and used to generate video signals. Because the PMT's are in groups of three, with each of the three corresponding to red, green, or blue, color-dependent video information is obtained that is analogous to the output of a traditional color video camera. These signals are passed to the video processor which inserts special effects such as sky, horizon, visibility, and weapons effects. The processed signals are then conveyed to the pilot using a raster display device at the cockpit.

In a M/C system, a common way of handling cultural lighting is to use appropriately scaled fiber optics which are affixed in the model board and illuminated from behind. In the LIG system, however, the lighting signals are detected using a special set of PMT's located behind the board rather than in front. In this way the cultural lighting can be processed independent of the other imagery. For night simulation, the result is the capability to have intense lighting against a totally dark background - a condition not achievable using a conventional M/C system.

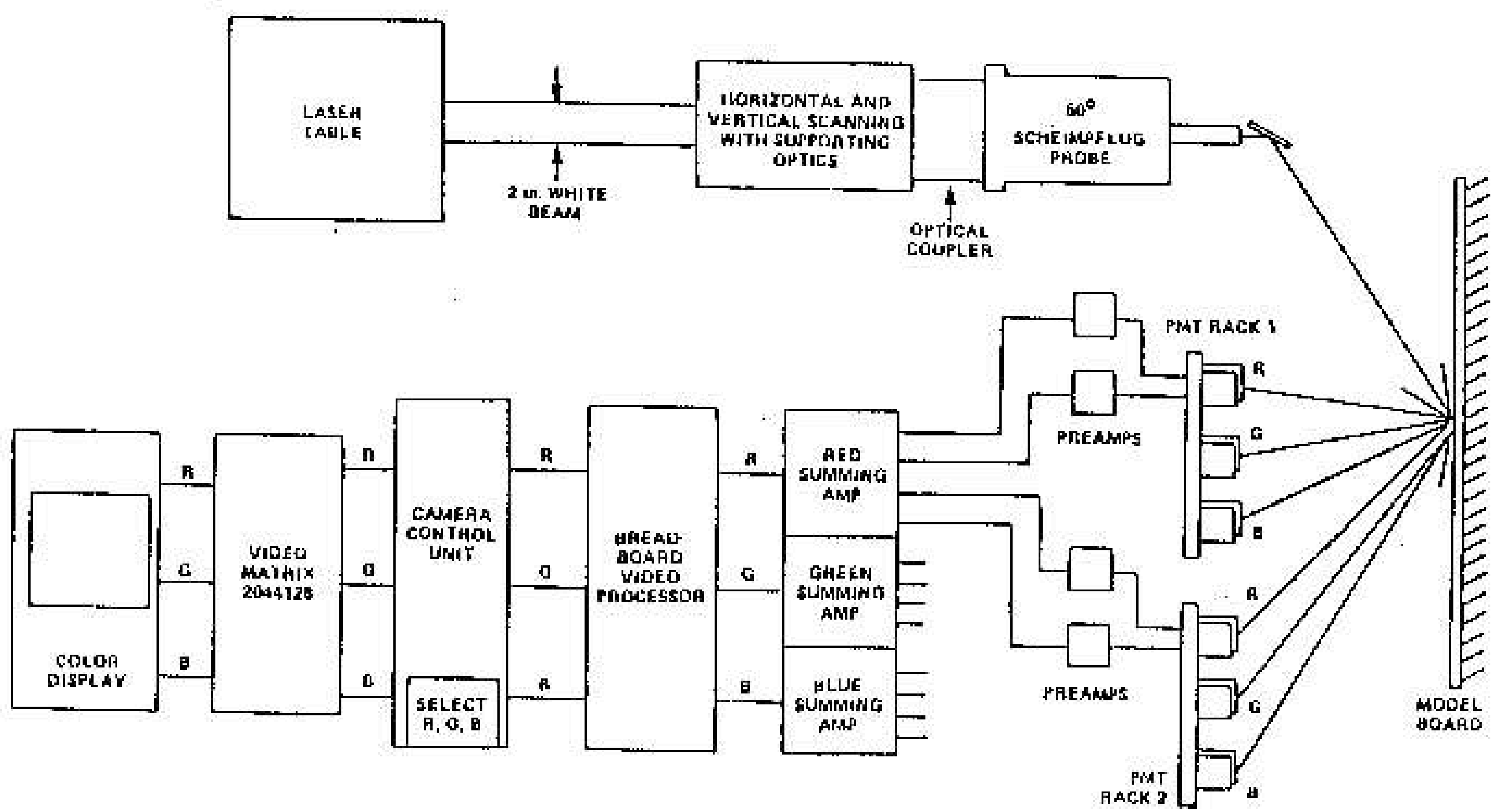

FIGURE 3.1 BLOCK DIAGRAM OF LIG

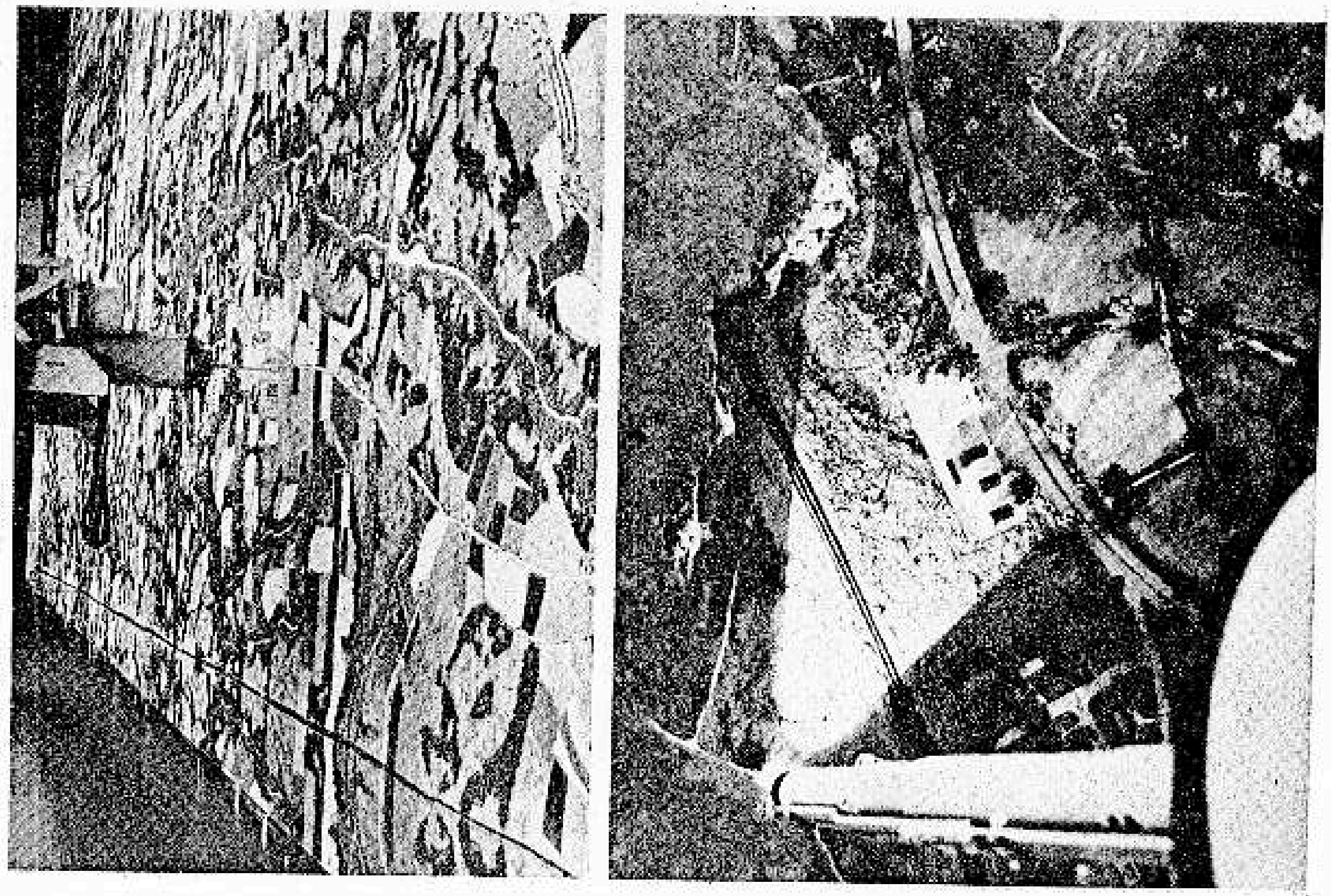

FIGURE 3.2 LIG SYSTEM IN OPERATION. (LEFT - PROBE RELATIVE TO BOARD. RIGHT - FAN OF SCANNED LASER LIGHT)

The first LIG production unit is for an Army AH-1S Cobra Helicopter Flight Weapons Simulator. It consists of two separate cockpit stations; i.e., one for the pilot and one for the copilot-gunner. The pilot's cockpit has two adjacent display windows, each of which can be driven by a separate LIG system. The copilot-gunner's station has a single display which either can repeat the pilot's front window, or can be independent if the pilot is not using both displays. The model boards supply a gaming area of 4.5 by 10.5 nm. Typical LIG display scenes showing a weapons delivery area and farm house are illustrated at the top and bottom (respectively) of Figure 3.3.

Concerning performance, FOV per channel is 36° by 48°. Using a BS/M virtual imaging system, brightness is 7 ft.L. with contrast exceeding 15:1. Static resolution is 6 arc-minutes per line pair, which is only incrementally better than the 7 arc-minutes available with a camera system. However, whereas camera lag degraded dynamic resolution in the M/C system, no such mechanism exists in the LIG (though it does in the CRT display). Thus, LIG dynamic resolution is equivalent to the static resolution. Since video S/N ratio exceeds 40 dB at 50% of rated laser power, reliability should be enhanced over that of the full power case. Geometry is better than 2.5% and convergence is better than 0.2% over the entire field.

Compared with the M/C system with its bank of flood lights, the LIG has 80% less energy consumption. This results from the LIG only requiring illumination in the immediate FOV of the pilot; the entire board need not be lit all the time. The LIG system, despite such advantages, does not avoid some of the limitations characteristic of model board systems. This includes limited FOV, no moving targets, no realistic weapons effects, and a limited staging area. Also of concern is the maintenance of 6 arc minute resolution over the entire FOV since no provision is made for dynamic focus.

4.0 Scanned Laser, Wide-Angle Visual System

Section 3.0 described an improvement on conventional model board systems through use of a Laser Image Generator rather than a video camera. A concept from Rediffusion Simulation, Ltd. takes this a step further by using two laser systems to simultaneously scan the model board and display the imagery to the pilot, thereby eliminating the conventional CRT's generally used. The goal is to achieve performance suitable for training low-level flight. Though a full prototype was never completed, a large part of the technology was proven and demonstrated under the auspices of development programs funded by PM TRADE, USAF, Ministry of Defense, and JR&D.

Figure 4.1 contains a schematic diagram of the Wide-Angle Visual System (WAVS). Red light from a Krypton laser and green/blue light from an Argon laser are combined to make a full color beam. It then passes through a focussing device and scanner before being projected onto the model board via a special wide-angle laser probe capable of scanning a 60° V x 180° H FOV. The preferred scale for an NOE model board is 1000:1; previous experience with boards indicates that very detailed models are achievable at this scale; e.g., pylons, wires, buildings, and vehicles can be modelled with sufficient realism to allow scrutiny from a simulated distance of 10-20 meters.

A bank of photo-multiplier tubes (PMTs) is used to detect reflected, scattered light from the laser probe. As with the LIG, the PMT's are in groups of three and individually filtered so R, G, and B can be differentiated. Video signals are passed to the three acousto-optic (A/O) light modulators that are part of the wide-angle laser projector. These A/O devices modulate R, G, B laser light produced from Krypton and Argon lasers. After the beams are re-combined, the full-color light passes to a scanner, similar to that of the probe and synchronized with it. The scanner projects an image corresponding to the simulated eyepoint on the front surface of a dome for viewing by the pilot. A sketch of the entire WAVS system is shown in Figure 4.2.

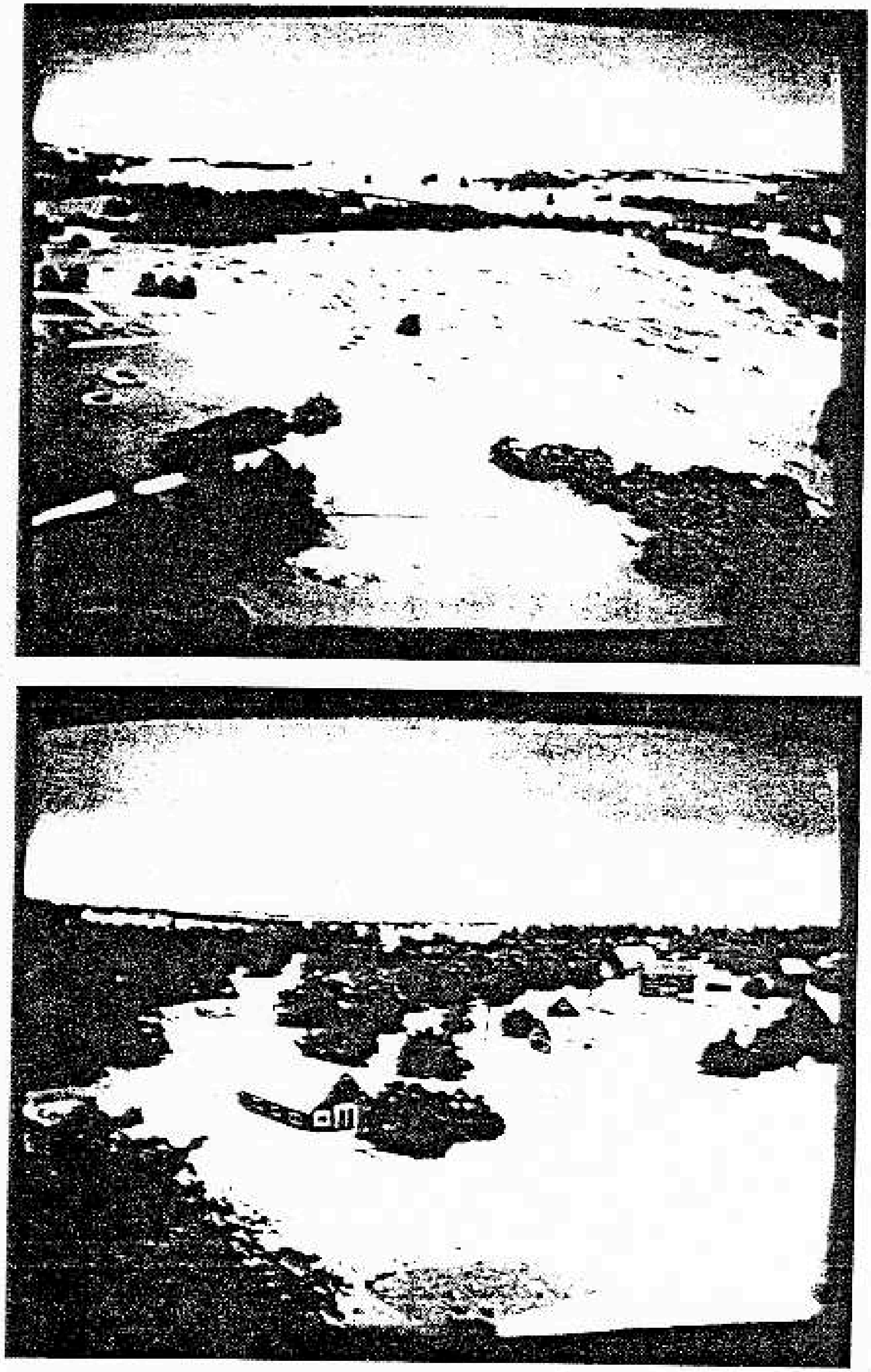

FIGURE 3.3 TYPICAL LIG DISPLAY SCENES
(TOP - WEAPONS DELIVERY AREA. BOTTOM - FARMHOUSE)

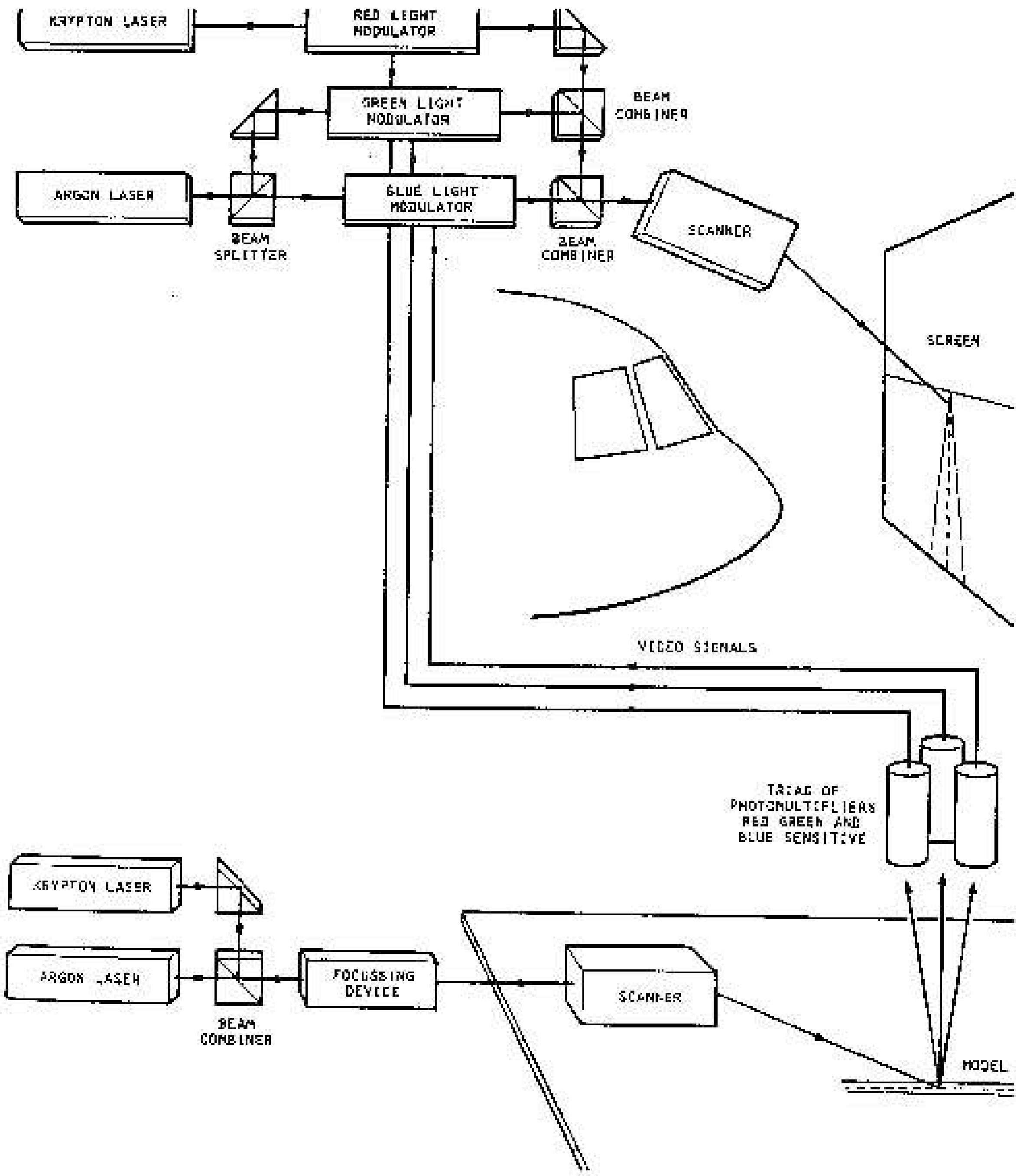

FIGURE 4.1 SCHEMATIC DIAGRAM OF WAVS

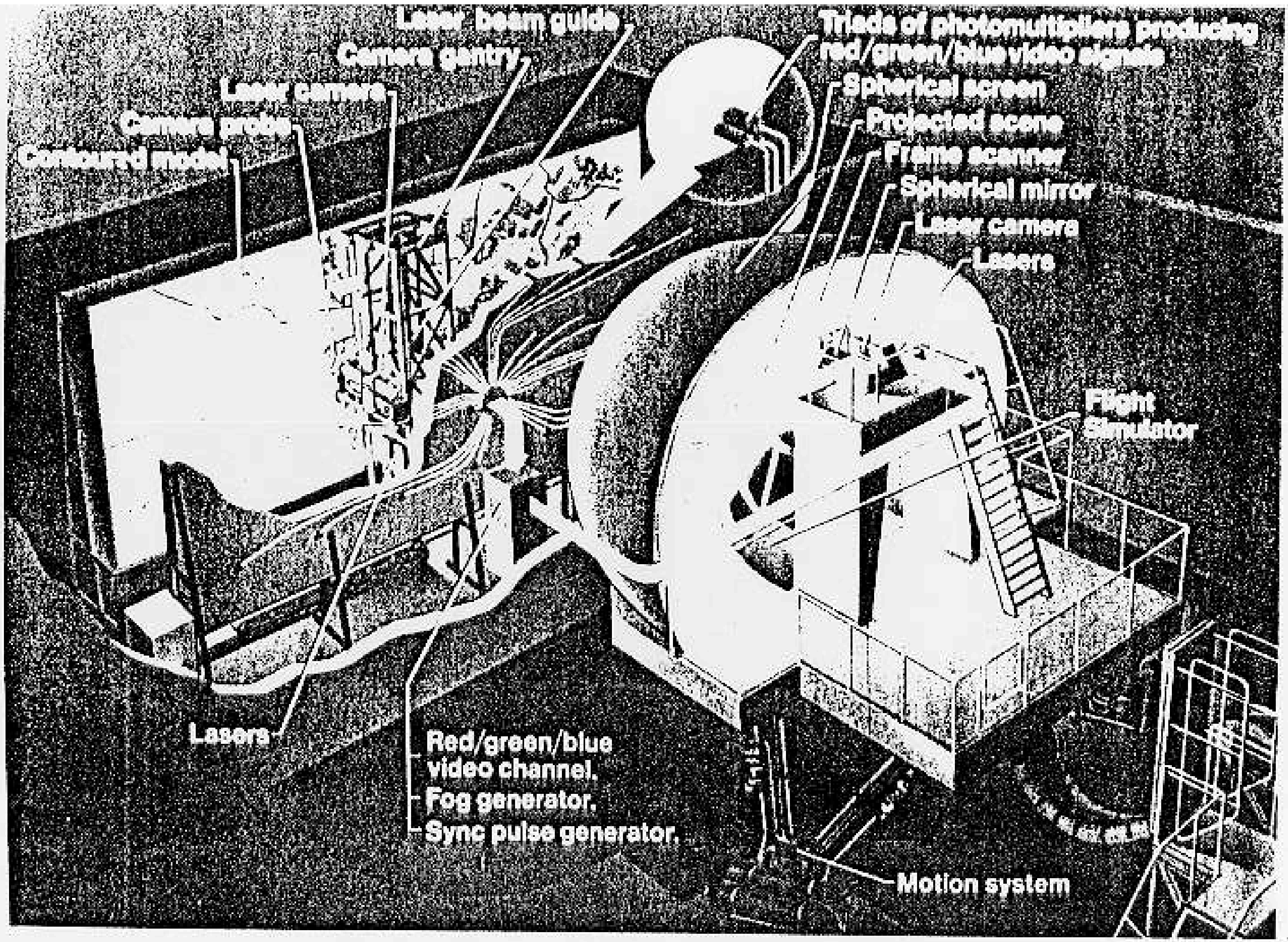

FIGURE 4.2 SKETCH OF SIMULATOR USING WAVS

Several interesting points are worth noting in this system. First, the focussing assembly contained in the model board scanning system makes it possible to refocus the laser spot during a line scan to keep all objects in focus, thus providing a depth of field much higher than that obtainable with camera systems or other laser systems not possessing dynamic focus. The focus mechanism is implemented using electro-optic cells that are able to switch the plane of polarization of the laser light. In conjunction with a birefringent lens (i.e., one which has different optical thickness for different polarization states), an E/O switch can produce two focus settings. Three E/O devices permit three bits worth of focus, or 8 different focus settings.

Line scanning is accomplished using a 12-faceted mirrored polygon operating at 79,200 rpm. The line-scanned output passes to the wide-angle laser probe consisting of three independent rotating optical systems (see Figure 4.3). Frame rate is set at 30 Hz by the 1800 rpm rate of the pupil prism; this allows a vertical line density corresponding to less than 4 arc-minutes per line pair. Switching the pupil prism by 90° permits both halves of a full rotation to be used for displaying imagery. The derotation prism ensures that the vertical raster lines do not tilt as the frame progresses. It should be noted that the scanner/probe of the wide-angle projector operates in a similar manner.

As with the previous two systems, a gantry containing the scanners and probe is used to position the simulated eyepoint in X, Y, and Z. In WAVS, however, the probe does not adjust pitch and roll—only yaw. Pitch and roll are controlled instead in the projection optics. The reasoning behind this is illustrated in Figure 4.4 and described as follows. For a wide-angle system in which the width-to-height ratio is large, the length of the horizon line is dependent on aircraft attitude. In low-level flight where concealment is important, a turn can cause nearby objects to disappear temporarily from sight. These "invisible" objects now pose a collision threat to the aircraft. By putting roll and pitch on the projector, the full horizon length is always visible because the entire FOV moves rather than just the image content. The resulting imagery is termed a "horizon stabilized picture" and prevents this type of information loss.

The target specification for WAVS is a follows:

- FOV 175° H x 60° V, continuous
- Raster 5,280 vertical lines/frame
- Refresh Rate 60 Hz field rate, 2:1 interlace
- Pixels 1200 pixels/line, or 6.25 x 106 pixels/frame
- Resolution Vertical: 3.5 arc-minutes per line pair.
  Horizontal: 4.0 arc-minutes per line pair
- Depth of Field 5 meters to infinity.
- Minimum Eye Height 1.8 meters (at 1000:1 scale)
- Nearest Horizontal 5 meters (at 1000:1 scale) Approach
- Brightness 5 ft.L.
- Contrast 50:1

There are problem areas with this system. Though dynamic focus ensures good depth of field, the added light loss associated with passing through additional optics implies that either video S/N suffers, or laser reliability is compromised by the need to operate closer to full power. FOV and resolution are exceptional, but require video bandwidth of 100 MHz; achievable but non-trivial. Finally, the usual problem of special effects and moving objects surfaces again. Rediffusion feels that these traits are best provided using CGI or a videodisc-based library, but maintaining quality and realism with an inset process is difficult.

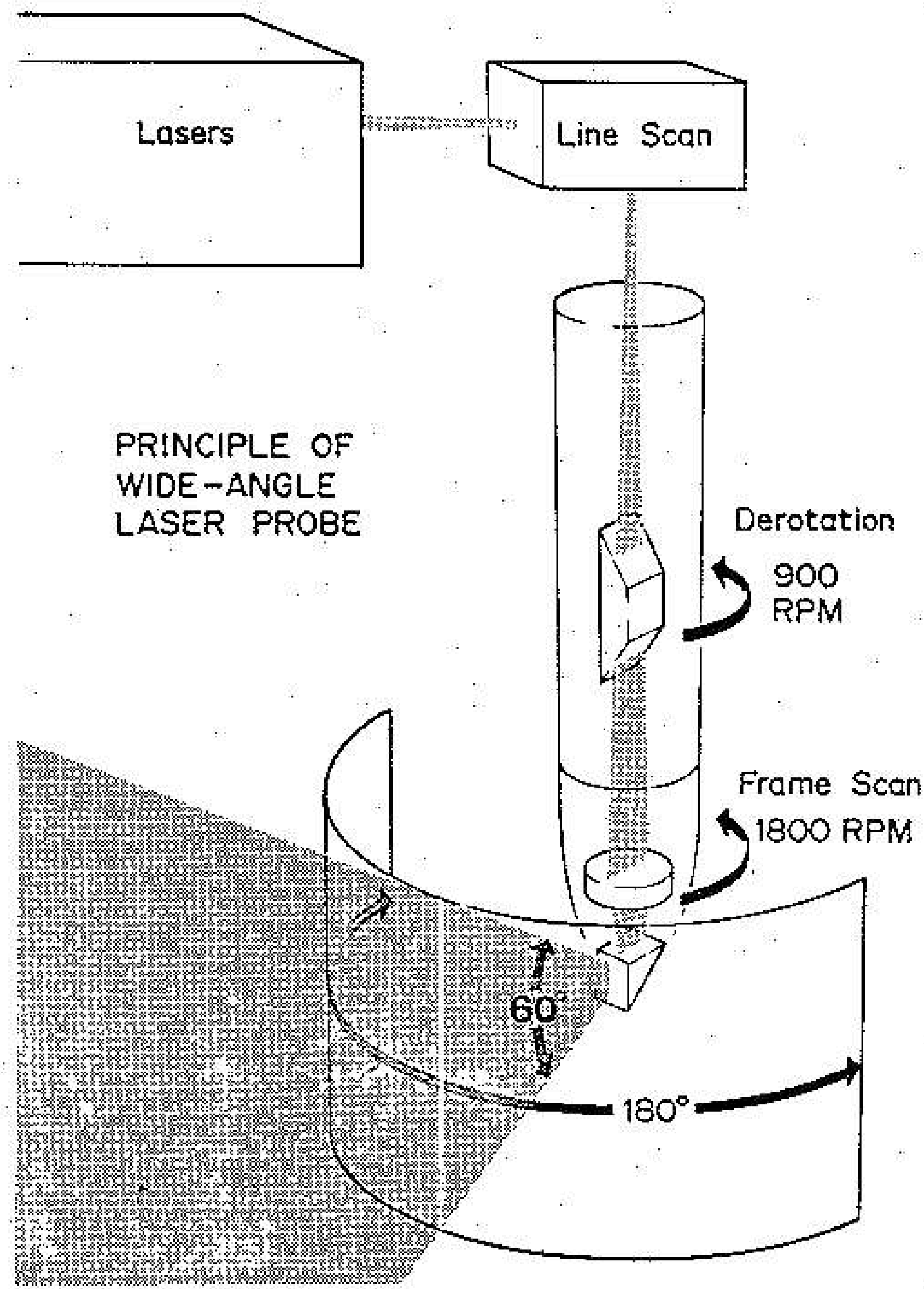

FIGURE 4.3 WIDE-ANGLE LASER PROBE

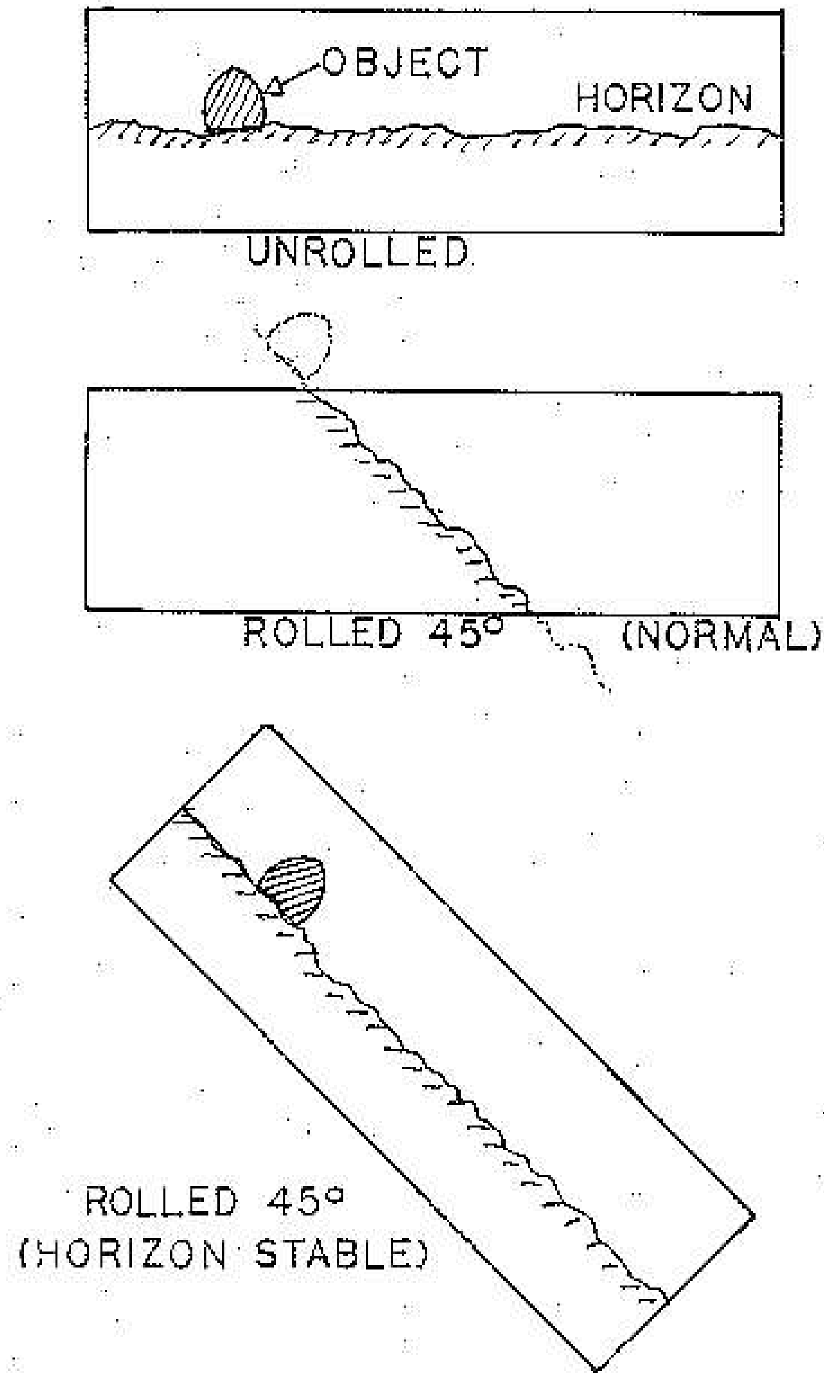

FIGURE 4.4 NORMAL AND "HORIZON STABILIZED" PICTURES

5.0 Air Combat Maneuvering (ACM) Systems

ACM involves aircraft maneuvering about, firing at, and being fired on by one or more hostile aircraft. As such, a great deal of ground information is not needed. All one generally requires is:

1. A full FOV corresponding to that available in the actual aircraft,
2. A horizon,
3. Some ground detail,
4. High resolution target(s), and
5. Visual feedback of weapons delivery.

During aerial combat, pilots are constantly jockeying for position. Thus, it is critical to a successful mission that a pilot have a full field of view for tracking the enemy aircraft wherever it may go. A horizon is important because the pilot orients himself with it and thereby avoids flying into the ground. Because a pilot often maneuvers while looking in a direction other than forward, the horizon should be visible over a full 360°. Terrain detail also helps the pilot to avoid the ground by providing closure cues. High resolution targets are necessary to ensure that both the position and orientation of hostile aircraft can be determined at ranges typical of an aerial engagement. For a large aircraft such as the F-15, this range can be 3-5 miles.

The conditions described thus far enable the pilot to fly a aircraft, acquire and identify targets, and maneuver relative to the targets. However, ACM training also involves the deployment of weapons. The pilot will need feedback concerning his learned ability to accurately fire guns and missiles, or successfully evade hostile fire. Keeping score and grading the pilot after the exercise is one means to accomplish this, but not nearly as effective as immediate visual feedback. Examples of visual feedback include tracer rounds, missile plumes, and explosions.

One non-CGI solution for the ACM training problem is to use a simulator cockpit inside a spherical projection screen (i.e., dome). A target projector, sky/earth projector, and special effects projector provide a high resolution target, horizon and ground details, and visual weapons effects, respectively. These projectors are mounted behind the cockpit on a gantry and can be rapidly slewed to simulate aircraft motion. An example of this technology is the twin-dome air combat simulator at British Aerosopace in Warton, England. Each of the 28' diameter domes is inflated and held by air pressure rather than being a rigid aluminum or fiberglass structure. The target and sky/earth projectors are mounted behind and above the cockpit on an unobtrusive gantry to afford the pilot as wide an uninterrupted FOV as possible. Two small projectors just behind the cockpit are used to simulate incoming and outgoing missiles, plus target hits.

The target projector in each dome is a Schmidt projector operating at 625 lines. Pointing direction can range over ±155° in azimuth and 145° (-40°/+105°) in elevation. It can slew at angular rates of 217 °/sec in azimuth and 300 °/sec in elevation. The target imagery is obtained from a gimbaled 1/44-scale plastic model of any one of several available aircraft. Figure 5.1 shows examples of 15 different targets used at British Aerospace. Two models of each aircraft are used; one is nose-mounted before one TV camera, and the other is tail-mounted before a second camera. This permits display of either approaching or departing target aircraft. These models rotate +95° in pitch and yaw at a maximum rate of 180 °/sec. Roll is unlimited in range, but limited in rate to 200 °/sec.

The sky/earth projectors are twin plastic globes one foot in diameter containing 50 watt quartz halogen lamps. Painted on the globes are translucent color pictures corresponding to sky, horizon, and ground detail. Figure 5.2 shows one of the units at British Aerospace; the target projector is just below it. Figure 5.3 shows schematically the two globes and their drive mechanisms. Each globe of the projector can rotate at 300 °/sec in pitch and roll and 180 °/sec in azimuth.

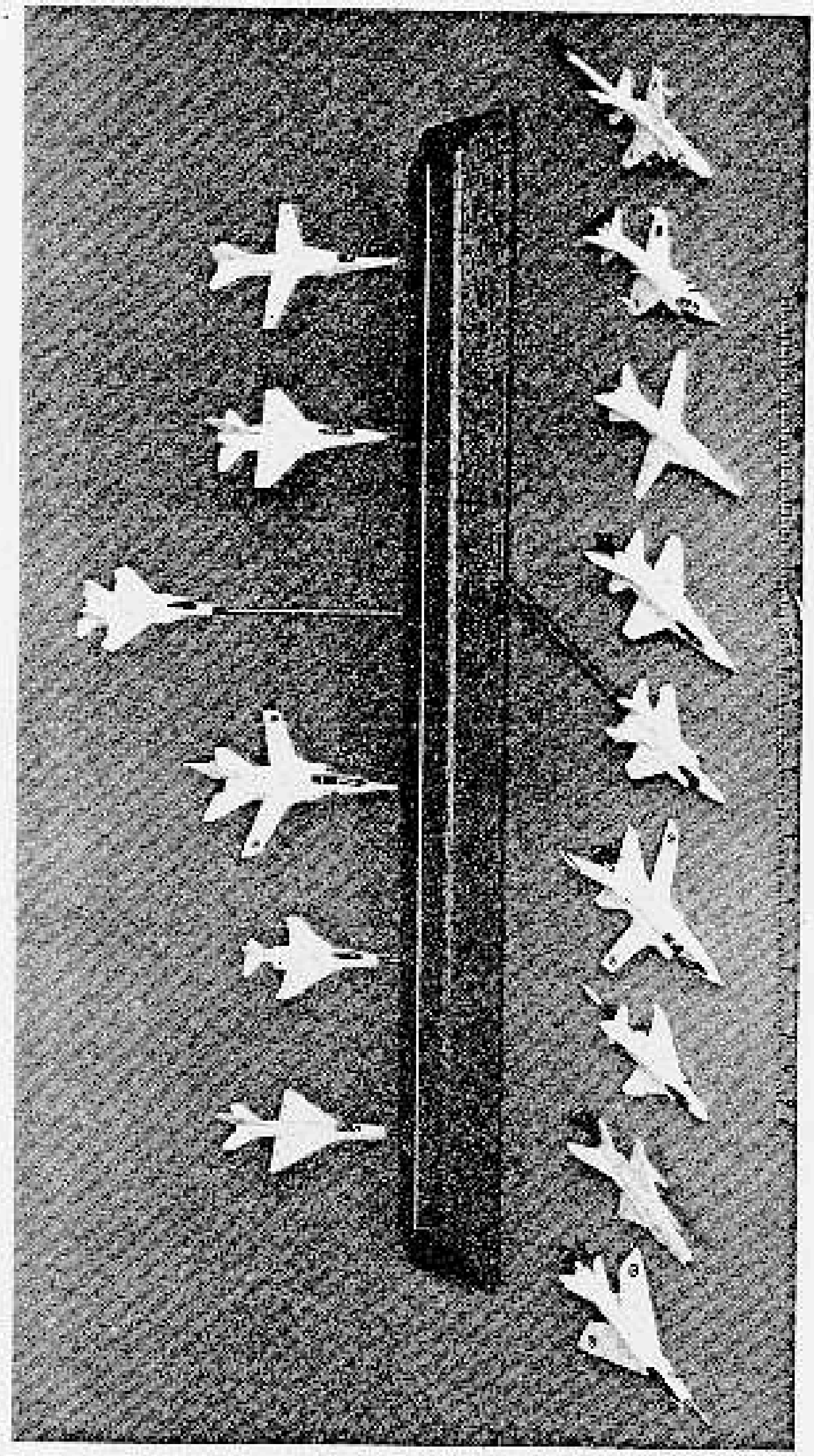

FIGURE 5.1 EXAMPLES OF SCALE-MODEL TARGET AIRCRAFT

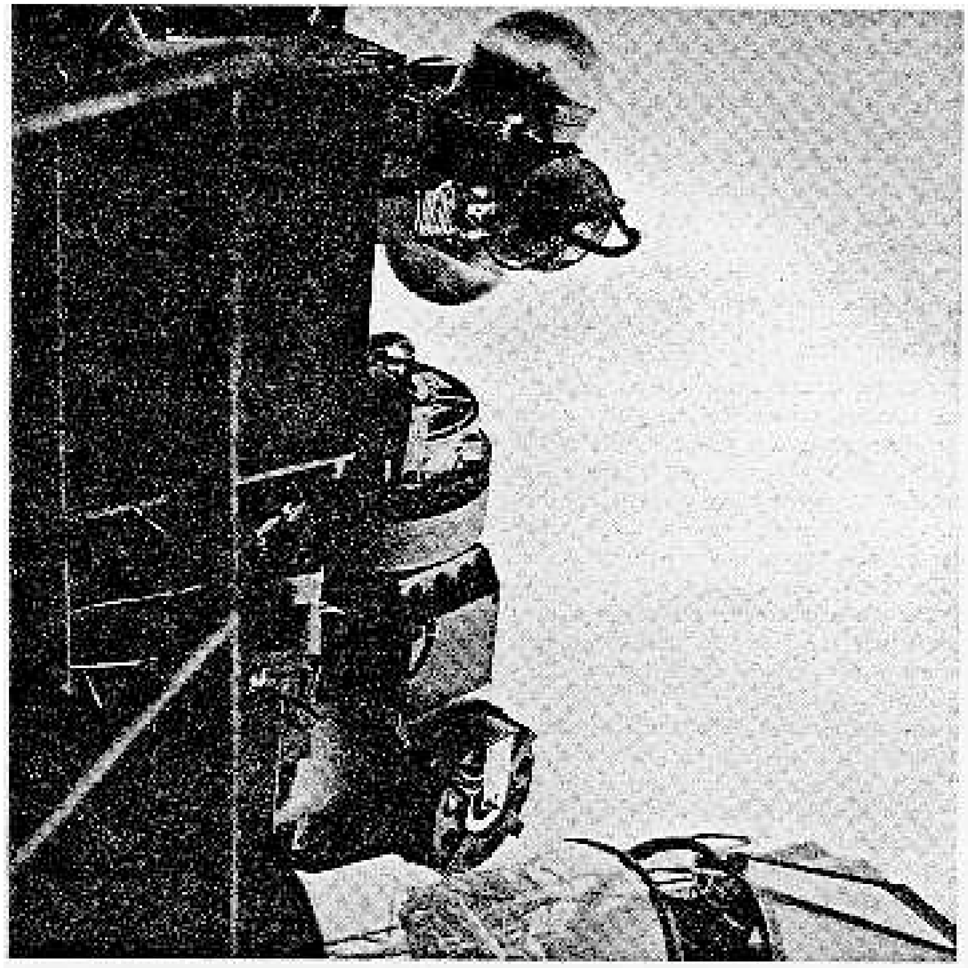

FIGURE 5.2 SKY/EARTH AND TARGET PROJECTORS

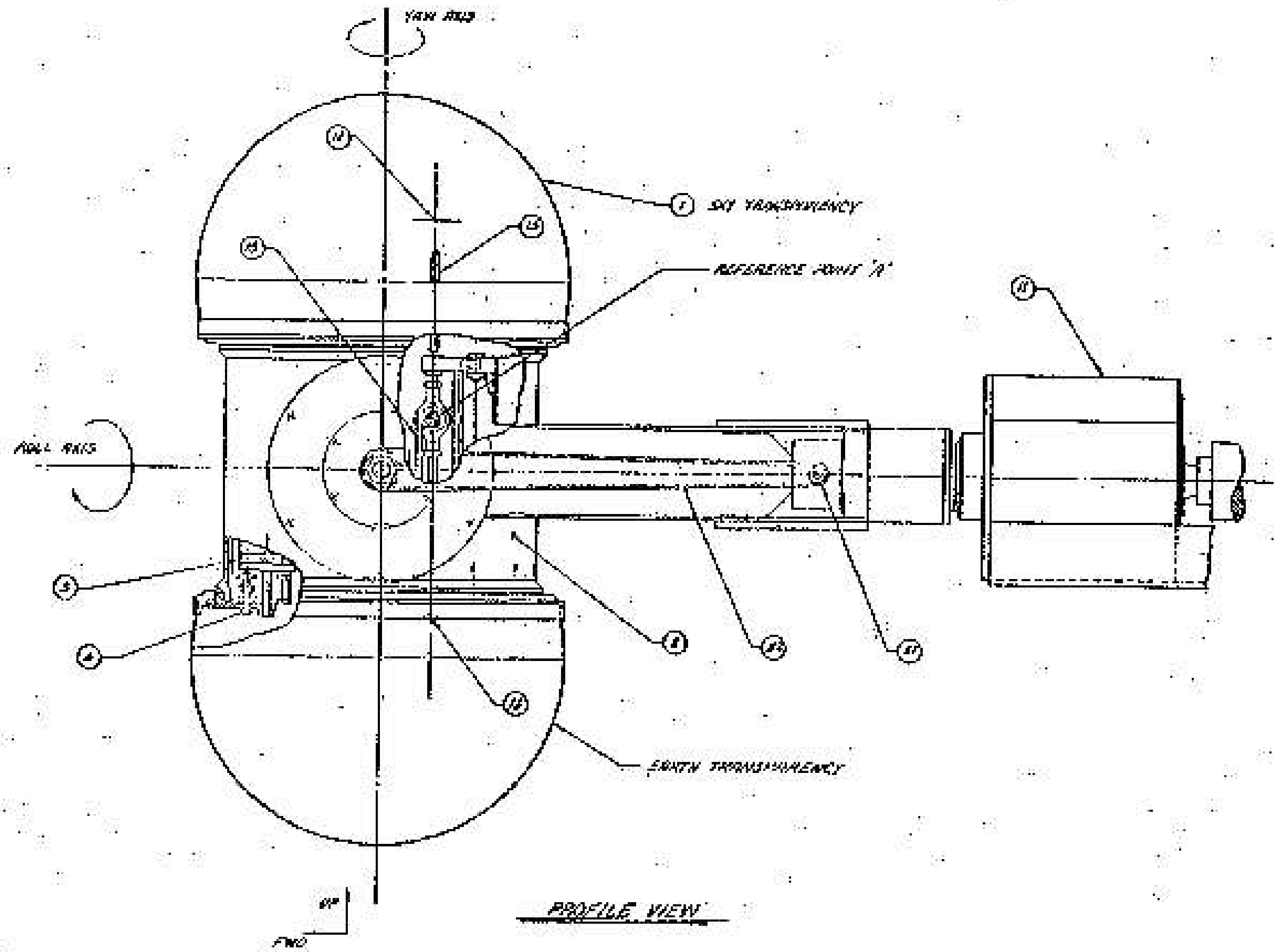

FIGURE 5.3 SCHEMATIC DRAWING OF SKY/EARTH PROJECTOR

The two special effects projectors can simulate two inbound missiles, two outbound missiles, or one each outbound and inbound missiles simultaneously. Outbound missiles appear red; inbound missiles appear blue. If the pilot fires a missile which successfully strikes the target aircraft, then a red ball momentarily obscures it to indicate a hit.

The air combat simulation described thus far is fairly simple and offers good cueing, and it is widely used as a result. However, it does have limitations. For example, consider the target projector. The one at British Aerospace is capable of resolving a target out to about 15,000 feet at best, owing to the 625 line TV camera and projector used. BA's approach to enhancing target visibility is to put a small TV in the cockpit of each dome to provide a close-up picture of the target aircraft model at all times. The pilot can quickly determine the target's actual position relative to the cockpit by momentarily flying head-down.

A more elegant approach which avoids the distraction of flying head-down is a direct optical projection scheme developed by Vought in the mid-70's. The principle is the same as that of an opaque projector in which a solid, opaque material is projected without the assistance of transparencies, hence its designation as OTOPS (Opaque Target Optical Projection System).

The overall projector concept is shown in Figure 5.4 and can be described as follows. A gimballed aircraft model is intensely illuminated from all sides. Image light is then collected by relay optics that include a 40:1 zoom capability. After reflection from a gimballed mirror, a real image is projected onto the inside of the dome for viewing by the pilot trainee.

The principal advantage of OTOPS is that it offers better resolution than most TV-based systems. In addition, color capability is inherent to the direct projection scheme. A color TV-system would require a special color camera and a bulky video projector, while providing only medium resolution. A disadvantage of OTOPS, however, is its size; obstructions need to be minimized in an ACM dome. Also, the advent of higher resolution cameras and projection tubes makes a video solution simpler and often less expensive.

Concerning the sky/earth projector, in practice it is not so simple to implement as it might appear. Ideally, the device would be a single gimballed globe capable of projecting sky, earth, and demarcation line representing the horizon. When illuminated by a point source at its center, and when positioned at the center of a dome, an undistorted image could be projected if viewed from the dome center as well. Unfortunately, both the projector and observer can not occupy the same space. Also, the gimbal mechanism would occult part of a single globe; hence, the globe must instead be two hemispheres separated by a gimbal mechanism. To avoid distortion, care must be exercised to change the light source position in each hemisphere as a function of projector orientation. This entails additional hardware on the projector, adding to size, weight, and cost. Techniques have been developed, however, to minimize these annoyances. One scheme uses the three gimbal drives already present on the projector to position the light sources inside the globes.

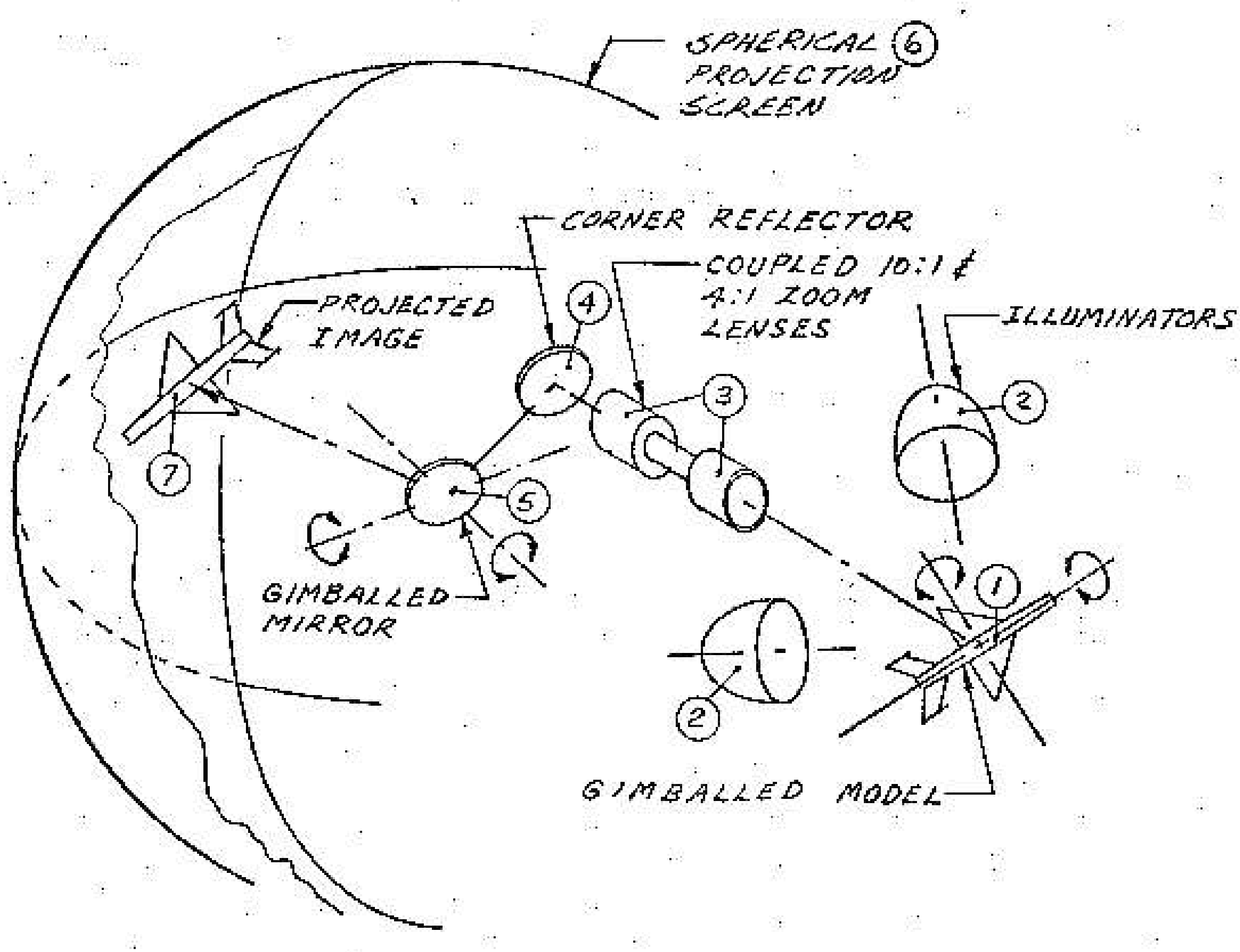

FIGURE 5.4 OTOPS PROJECTOR CONCEPT

6.0 Boom Operator Part Task Trainer

The boom operator is a member of the Strategic Air Command KC-135 refueling tanker crew and a key player in the mid-flight transferal of fuel between aircraft. After the tanker and receiver position themselves 50' apart, the boom operator must coordinate the remainder of the exercise. He does this while lying prone at the aft end of the tanker, peering through a small window 19" from his face. The boom is actually flown using a control stick just to operator's right side. The boom is initially held on center line and pitched down by 30°; the inner extendable part of the boom is set to about 10' extension using a left-hand control. The boom's position is visually checked through the window and cross-checked with instruments located below the window. Using verbal commands or director lights, the boom operator coaches the receiver aircraft to contact position; its refueling receptacle is now two feet from the end of the boom. The boom operator extends the boom until its nozzle is seated and locked in place. Figure 6.1 illustrates this configuration.

One important difference between this task and those typical to normal flight is that the focus of attention is not near-infinite imagery, but rather the boom nozzle which is neither the closest nor farthest object. At contact, the upper end of the boom is 8' from the trainee, the nozzle is 50' away, the receiving aircraft nose is 150' closer than the tail, and the background is distant. Thus, successful training requires that relative distance be judged accurately. Relative distance is perceived using four cues: relative size, occultation of one object by another, stereopsis, and parallax. The first three are present to some degree all the time; the fourth only comes into play with lateral head motion. Parallax is probably the primary cue at a 50' distance since it provides the most accurate information concerning relative distance between nozzle and receptacle.

One technique used for satisfying the Boom Operator Part Task Trainer (BOPTT) requirement was developed by Farrand Optical Company and designated "True View System." Figure 6.2 illustrates the configuration of this particular BOPTT. Imagery is derived from three sources:

1. A gimbal-mounted 1:100 scale model of a receiver aircraft (B-52) that is viewed by a rail-mounted TV camera for projection by a GE Light Valve,
2. A 16 mm film strip to provide terrain background, and
3. A servo-driven boom model.

The display system consists of a Pancake™ Window, a terrain input screen, and a receiver aircraft input screen; a beamsplitter permits both screens to be near the input plane of the Pancake. The boom model is mounted just in front of the aircraft input screen and positioned to ensure that its apparent depth is correct. The terrain screen is positioned to appear at infinity. The aircraft screen is servo-controlled in position and tilt to appear in the proper image plane—at the right distance—as it approaches the contact point from a distance of 1.25 miles. Aircraft size is controlled by translating the pickup camera on the range bed and by over- and under-scanning the camera raster.

Display FOV is 60° H x 30° V, only 20% smaller than that of the actual aircraft. Limiting resolution is approximately 4.5 arc minutes per pixel horizontally and 5.4 arc minutes per pixel vertically. Peak brightness is about 5 ft.L. on the receiver aircraft. Because of the optical combining of terrain background and aircraft by the beamsplitter, it is possible for terrain imagery to "bleed through" the aircraft image. To prevent this, background brightness is limited to less than 1 ft.L.

The ability of this system to simulate variable apparent distance allows important cueing, and it is achieved as follows. When looking through an infinity display, there is one object plane (A) for which the corresponding image (A') will appear at infinity (see Figure 6.3). An object lying closer to the infinity display (say, B) will produce an image (B') that appears at a closer distance. Thus, objects can appear at distances ranging from about eight feet to infinity depending on where they are positioned in foreshortened optical space.

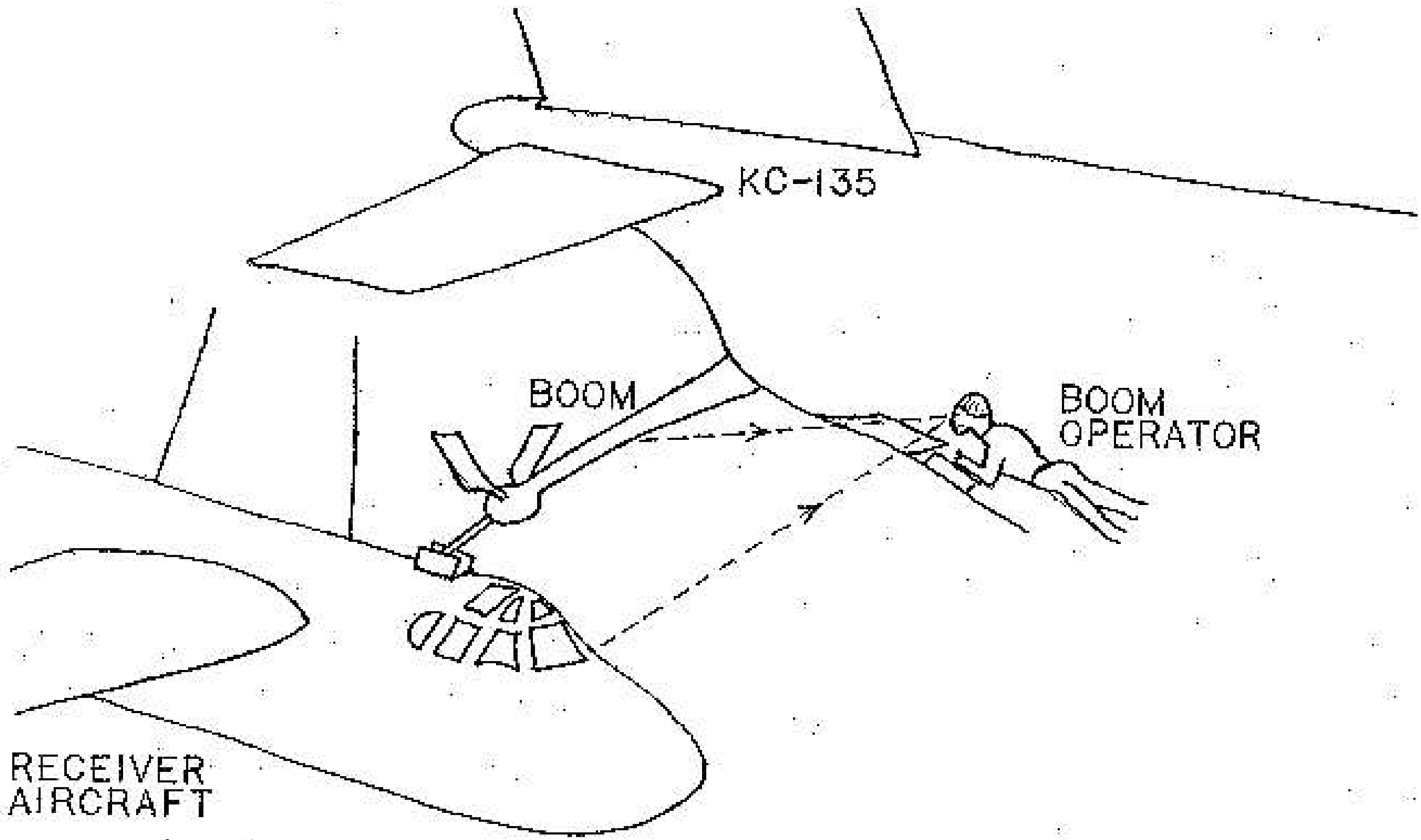

FIGURE 6.1 TYPICAL AERIAL REFUELING OPERATION

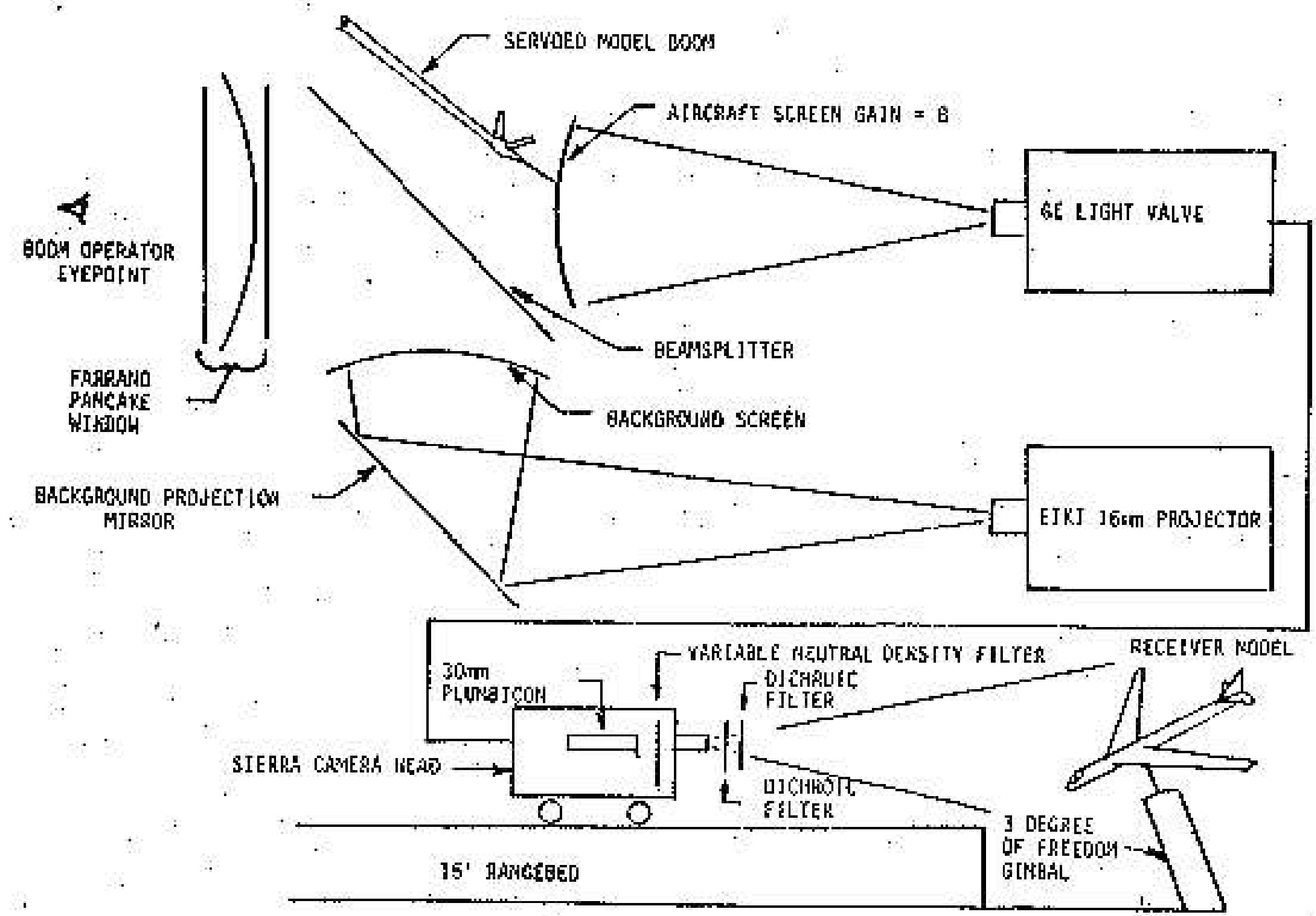

FIGURE 6.2 SCHEMATIC DRAWING OF BOPTT

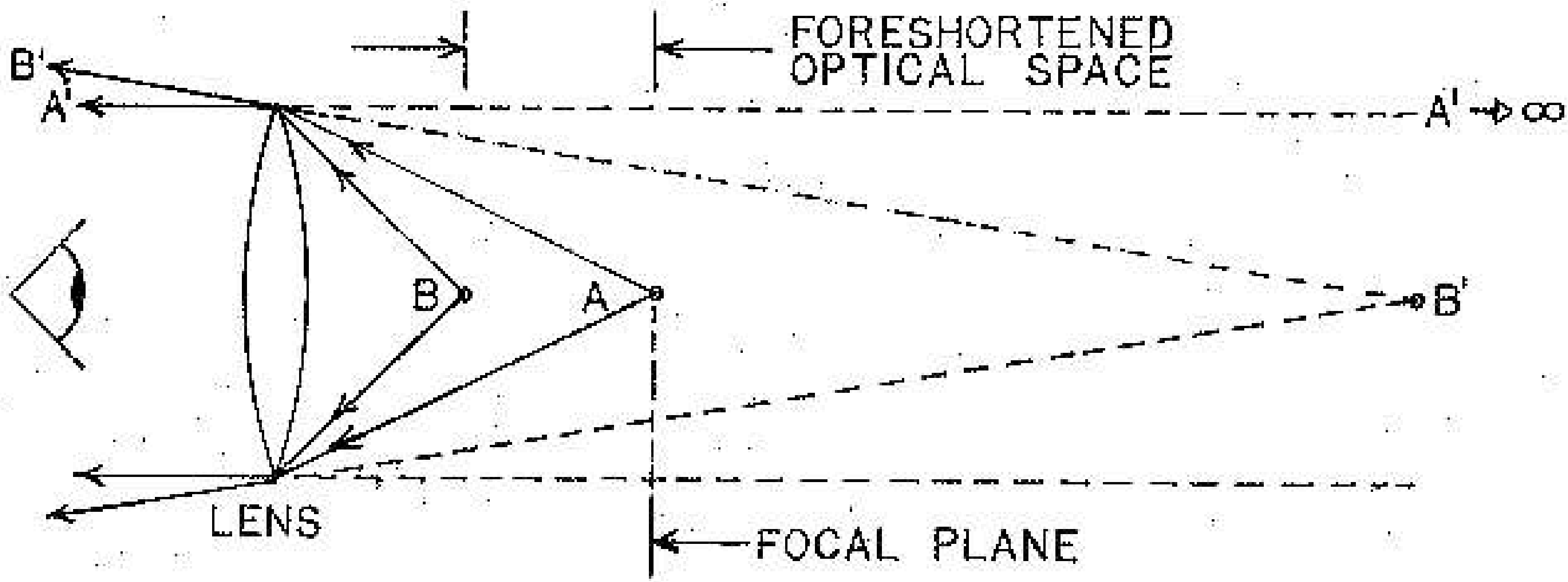

FIGURE 6.3 PRINCIPLE UNDERLYING "VARIABLE APPARENT DISTANCE"

Based on this principle, the terrain input screen is positioned at Point A to create an image at infinity. The aircraft input screen is servo-driven between positions so that its apparent distance varies between 1.25 miles and 50'. In addition, this screen can be tilted back by roughly 6° to make the tail of the receiver aircraft appear farther away then the nose during the contact phase of the exercise. The boom model is physically present in the foreshortened optical space and tilted; hence, the top appears close and the nozzle end appears more distant. During the contact phase the nozzle of the boom actually touches the aircraft input screen, ensuring both appear at the same distance.

All in all, careful positioning of input screens and modelling of a boom for this nonlinear foreshortened optical space result in accurate judgement of relative distance. Furthermore, the presence of a physical boom model in front of the aircraft input screen provides both stereopsis and parallax cues. For example, as the boom operator moves his head left and right, different parts of the aircraft will appear to him from behind the boom. Similarly, each eye will observe a slightly different perspective, thus making for stereopsis.

The BOPTT also provides visibility effects for the receiver aircraft and simulation of day, dusk, and night lighting conditions. Visibility is controlled using contrast adjustments at the TV camera. At night, contrast is decreased towards black so minimum visibility produces a totally dark image. During dusk and day, contrast is decreased towards white so minimum visibility yields a completely white image. Time-of-day simulation is accomplished with a combination of video level control and a special model color scheme. In the actual aircraft, various lights are turned on during night refueling operations. These include navigation and wingtip lights, lights which illuminate areas of the receiver aircraft fuselage, overwing lights that illuminate the leading edge of the receiver aircraft's wings, and a set of lamps located in the receptacle slipway to illuminate it for the boom operator.

Simulation of these lighting effects begin with painting the model aircraft in the color scheme shown in Figure 6.4. The entire aircraft is painted green, with different shades of green and black detailing used for picture enhancement. Areas appearing brighter at night, such as the cockpit windows and leading edges of the wings, are painted blue. The area illuminated inside the receptacle is painted red. During daytime operation, the B/W TV camera is unfiltered so that the multi-colored model appears in shades of gray. The blue and green paints are matched so that the entire wing appears uniform. For night operation, a subtractive green dichroic filter is put in front of the camera lens. Since blue and red are transmitted, the leading edge of the wing and receptacle are readily visible to the boom operator whereas the fuselage is barely discernible. The receptacle light is turned on and off by inserting a second subtractive dichroic filter for the red.

The BOPTT was well-received at Castle AFB; it is typically in use 16 hours/day and five days/week. Using it has allowed the Air Force to eliminate three of the hour-long practice sessions needed in the actual aircraft by a student to reach proficiency. However, some problems still persist with the trainer. For example, the paint used on the models is a phosphor paint that provides the needed spectral reflectance permitting the dichroic filters to do their job. Unfortunately, these paints age under the intense light necessary for obtaining good brightness out of a Pancake Window. The result is that lighting cues are lost during the night simulation. This and other difficulties have been the subject of further research.

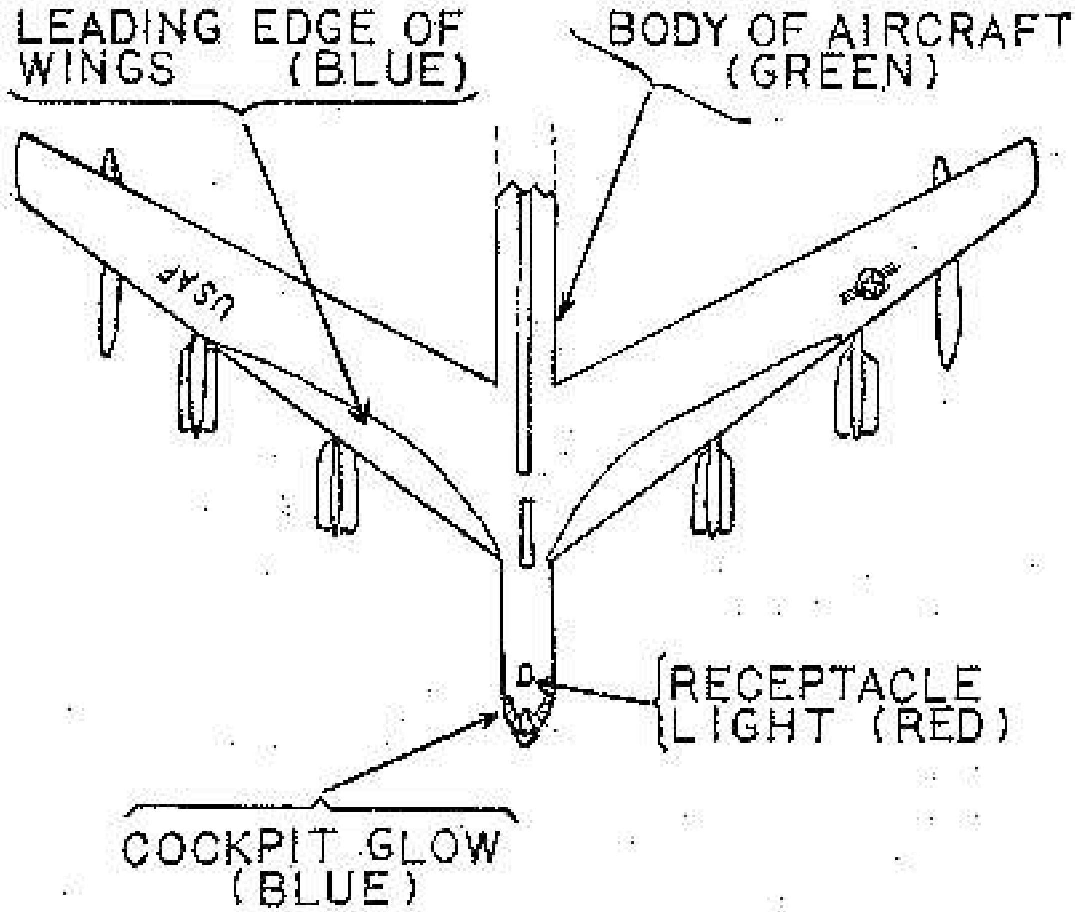

FIGURE 6.4 COLOR SCHEME FOR MODEL OF B-52 REFUELING AIRCRAFT

7.0 Celestial Sphere Simulation

As in conventional flight simulation, the problem in space flight simulation is generation and display of sufficiently realistic visual scenes for an astronaut. Important visual cues for their training include (i) The total celestial sphere, (ii) Rendezvous and docking scenes with space craft, (iii) Views of earth from orbit, and (iv) For lunar missions, views of the moon and earth from orbit, mid-course, and during descent and landing; the latter from inside the LEM. Non-CGI techniques for these cues exist; however, simulation of the celestial sphere is the topic of interest.

The technique to be described was developed by Farrand Optical Company and has been successfully used during the 1960's on the Mercury Simulator, T-27 Space Flight Simulator for the USAF, the Gemini Mission Simulators, the Apollo Mission Simulators, and the LEM Mission Simulators. Figure 7.1 illustrates the concept in its simplest form. The three major components are:

1. A gimballed spherical black globe that is embedded with ball bearings and separately illuminated,
2. A relay system comprised of a spherical relay mirror and beamsplitter, and
3. A virtual image system consisting of a 54" radius spherical eyepiece mirror and beamsplitter that can collimate an object or real image for an observer.

The globe is 27" in diameter. Embedded in the surface are aluminized ball bearings that act as convex mirrors and serve to simulate individual stars. The position of each ball bearing corresponds to the true Right Ascension and Declination of the star as measured from the center of the globe. In addition, the ball diameter is chosen to correspond to the star's magnitude (i.e., brightness), with smaller diameters used as magnitude number increases (i.e., brightness decreases).

Figure 7.2 illustrates the principle underlying the use of ball bearings. A bearing of radius **r** acts as a convex mirror of focal length **r/2**. When illuminated by a point source at distance **L**, a minified virtual image of the point source (here, an arc lamp) is formed inside the bearing at a distance **r/2** from the center; size reduction is by a factor of **r/2L**. Normally, the brightness of each minified virtual image would be identical. However, for a distance **L** much greater than radius **r**, the largest of these images (corresponding to stars of magnitude -1) subtend less than 1 minute of arc at the observer's eye; hence, it is not resolved. The eye tends to spread the perceived image to a size corresponding to its limiting resolution. In so doing, the apparent brightness is no longer proportional to source brightness. Instead, it becomes proportional to the total energy reflected by the ball bearing. This energy is proportional to the cross-sectional area of the ball bearing. Thus the brightness of each star can be controlled by varying the ball size, the dependence being a function of $\mathbf{r}^2$.

Viewing of the globe begins with the optical relay system forming a unity magnification aerial image of the globe at the focal plane of the eyepiece mirror. The virtual image system then collimates the aerial image for presentation to the observer. Because the minified virtual images all lie on the surface of the globe and the globe radius matches the focal plane curvature of the spherical eyepiece mirror, the simulated stars appear at infinity. In addition, since the virtual system forms a pseudoscopic image in which a convex surface appears concave to the observer, the effect will be one of viewing the globe from the center rather than the outside. As a result, the simulated stars will appear not only collimated with proper brightness, but will possess the correct Right Ascension and Declination as well. Using one of the windows of the Apollo Simulator as an example, Figure 7.3 illustrates deviation of simulated star location from actual star location as a function of field angle. As shown, deviation anywhere within the 110° field is less than 3 mrad.

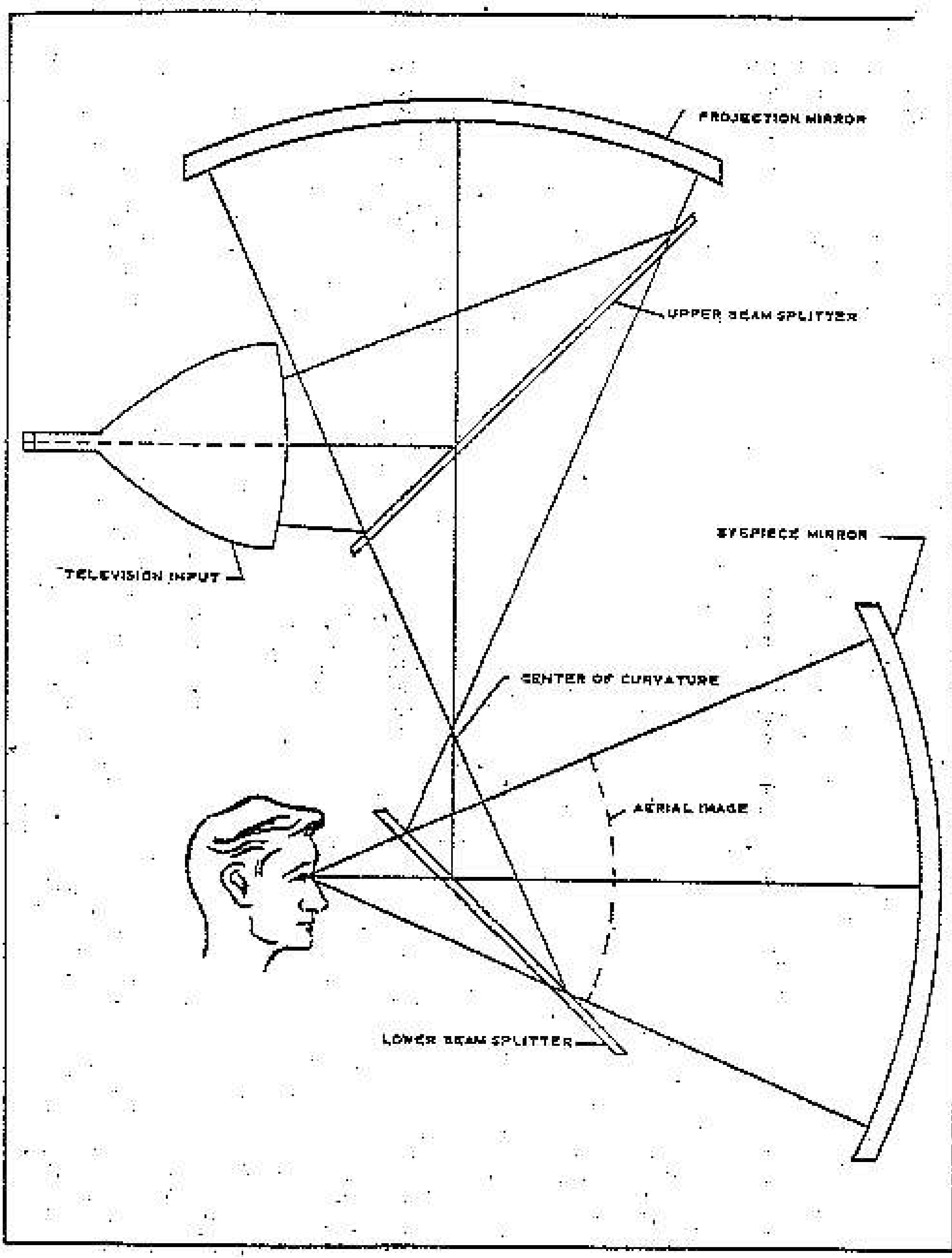

FIGURE 7.1 TWO-MIRROR VIRTUAL IMAGE SYSTEM

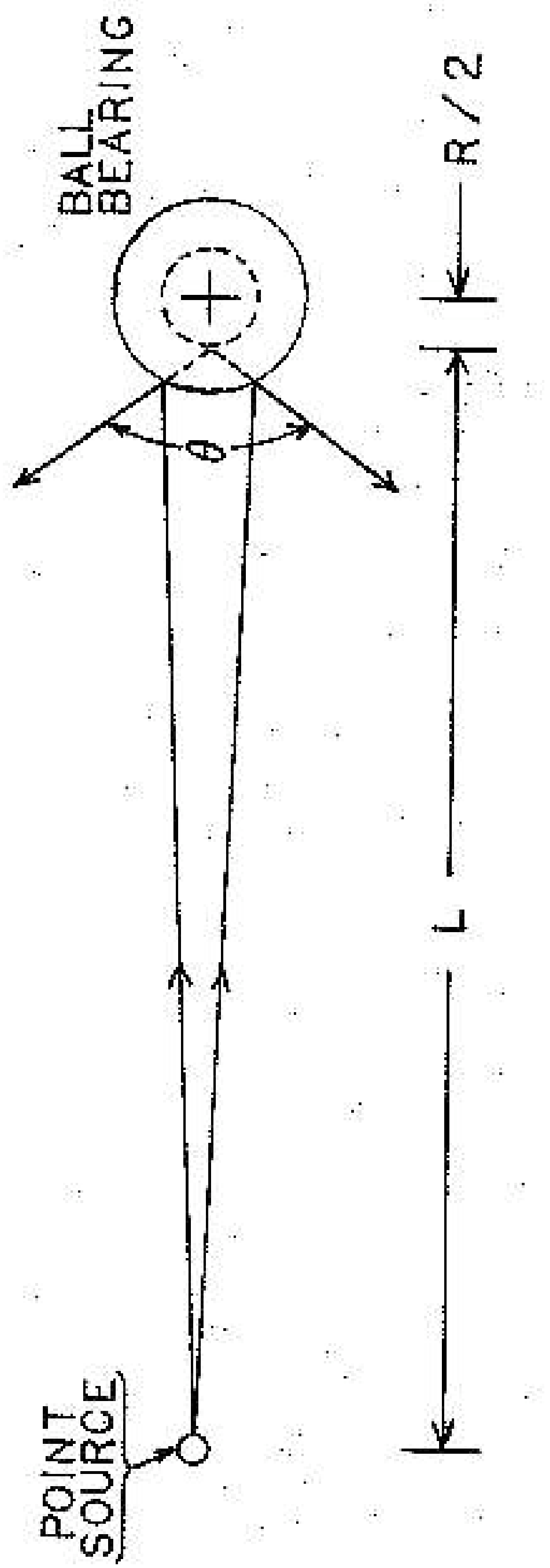

FIGURE 7.2 USE OF BALL BEARING AS A CONVEX MIRROR

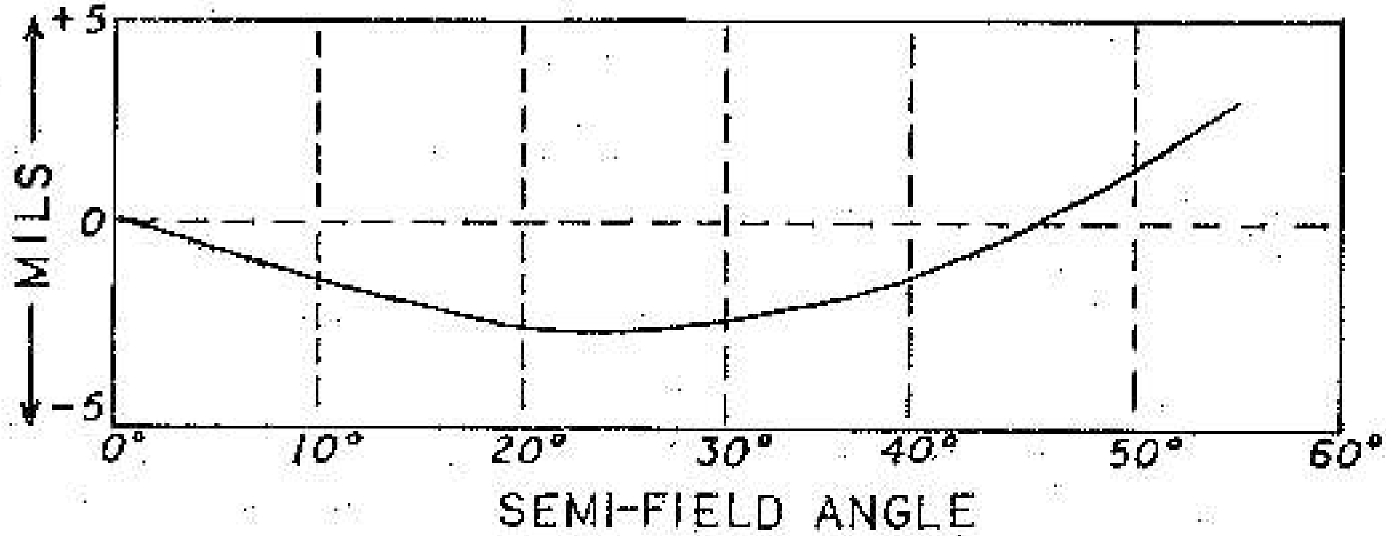

FIGURE 7.3 CELESTIAL SPHERE MAPPING ERROR
(ACTUAL ANGLE - IDEAL ANGLE)

The globes are hollow with torque motors mounted inside to permit rotation at rates as low as a fraction of earth's rate (15 deg/hr). In a simulator the sphere can move according to the pitch, yaw, and roll of the spacecraft. A schematic of one window of the LEM simulator is shown in Figure 7.4. The celestial sphere input, the sphere illuminator, relay optics, and virtual image optics are all apparent. In addition, a second input is provided for images of the lunar surface or Command Service Module. This latter imagery is derived from either (i) A probe/model board system or (ii) A variable-magnification strip-film projector used in rear-screen projection and in conjunction with an optical probe.

8.0 CAPTV System

The CAPTV (Computer Animated Photographic Terrain View) concept was pursued by LTV Aerospace and Defense Co. to provide visual simulation with a scene realism generally found only in photograhic imagery. The first such system was monochrome; however, a follow-on effort was conducted to provide a full-color visual for the Navy's A-7E Weapon System Trainer. This system was located for a time at Jacksonville NAS.

CAPTV is based on having a 3-D array of photographs taken by an airplane above an area (i.e., database) of interest. The photographs are taken at pre-determined geodetic positions throughout the gaming area. The photos are scanned, formatted, and eventually stored in random-access video discs. During a simulated mission, the pilot is free to maneuver anywhere within the gaming area defined by the database. For any point in the flight trajectory, the visual system selects and recalls from memory the 360° photograph most closely corresponding to aircraft position. This photo is digitized and placed in buffer storage. To match perspective as seen from the pilot's eyepoint, the image is stretched, skewed, rotated and translated in a piece-wise continuous transformation. This manipulation of the digitized scene, as illustrated in Figure 8.1, continues at an eyepoint update rate of 30 Hz until the pilot is closer to an adjacent photo. At that instance the next photograph is processed and replaces the previous photo. Before being displayed, the new photograph would have been recalled from disc memory on a next-most-likely basis, digitized, and placed in a second buffer memory in preparation for use. This process occurs repeatedly during the simulation exercise, allowing the pilot to fly freely and smoothly through a finite 3-D array of still images.

Off-line image generation of the high resolution, full-color database begins with exposure of 9" color film using a seven-lens camera that produces distortion-free hemispherical coverage 360° in azimuth and 100° in elevation. Figure 8.2 shows six of the seven views obtained after a single exposure of the camera directly above an airfield. The gaming area is portioned to contain a large number of eyepoints distributed in several altitudes and in several straight and/or cross tracks. The density of photographs varies inversely with altitude to provide the same degree of smoothness in all areas of coverage. A typical weapon delivery mission, including a target area, approach and departure corridors, and take-off/landing zone, requires roughly 6,000 pictures.

The Record Processor System (see Figure 8.3) converts the photographic imagery into video signals suitable for storing on Video Tape Recorders (VTRs). A flying spot scanner scans the film; the resolution is 4,000 pixels vertically and horizontally. The scanning is done in steps because of film size, after which the seven views are assembled into a single frame. The three color components are separately digitized and formatted so each composite picture is made up of 72 NTSC frames. These frames are stored on 1" videotape or laser disc. Usually pieces of a complete scene are stored on three separate videotapes to permit more rapid access during playback. During the record process, luminance and color balance of each view in every scene can be manipulated to ensure accurate edge registration, brightness uniformity, and color balance. Objects which move during photography can be removed. Corrections are enabled by the corrector block and a semiconductor memory, the Scene Storage System (SSS), which can store 256 NTSC frames.

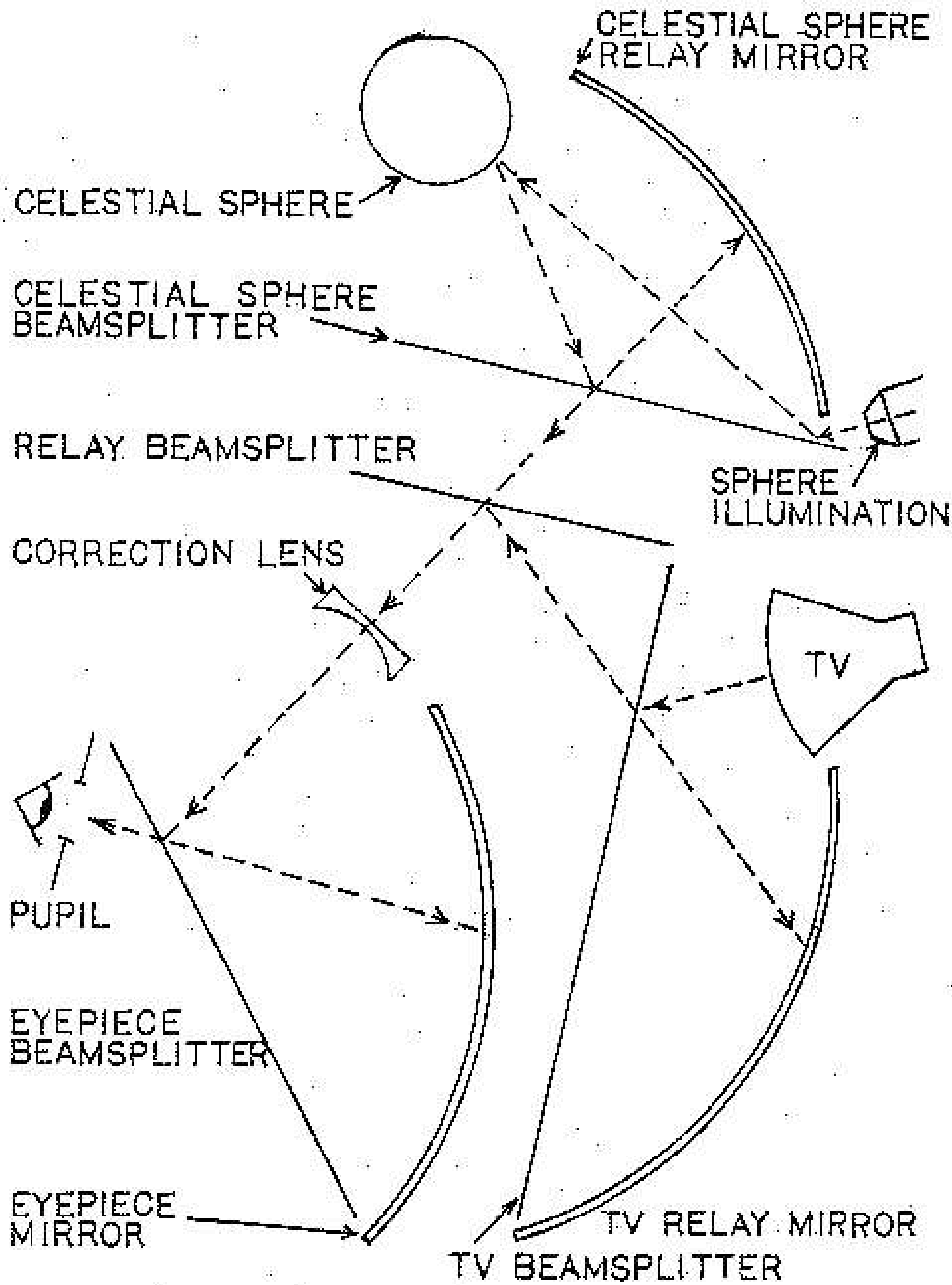

FIGURE 7.4 FRONT WINDOW SCHEMATIC OF LEM

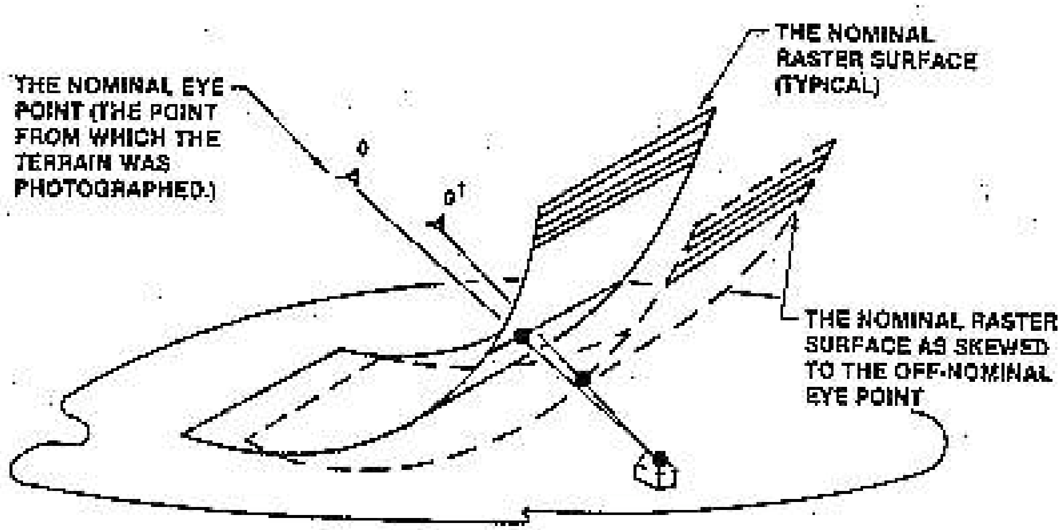

FIGURE 8.1 ACCOMMODATING A MOVING EYEPOINT WITH RASTER SKEW

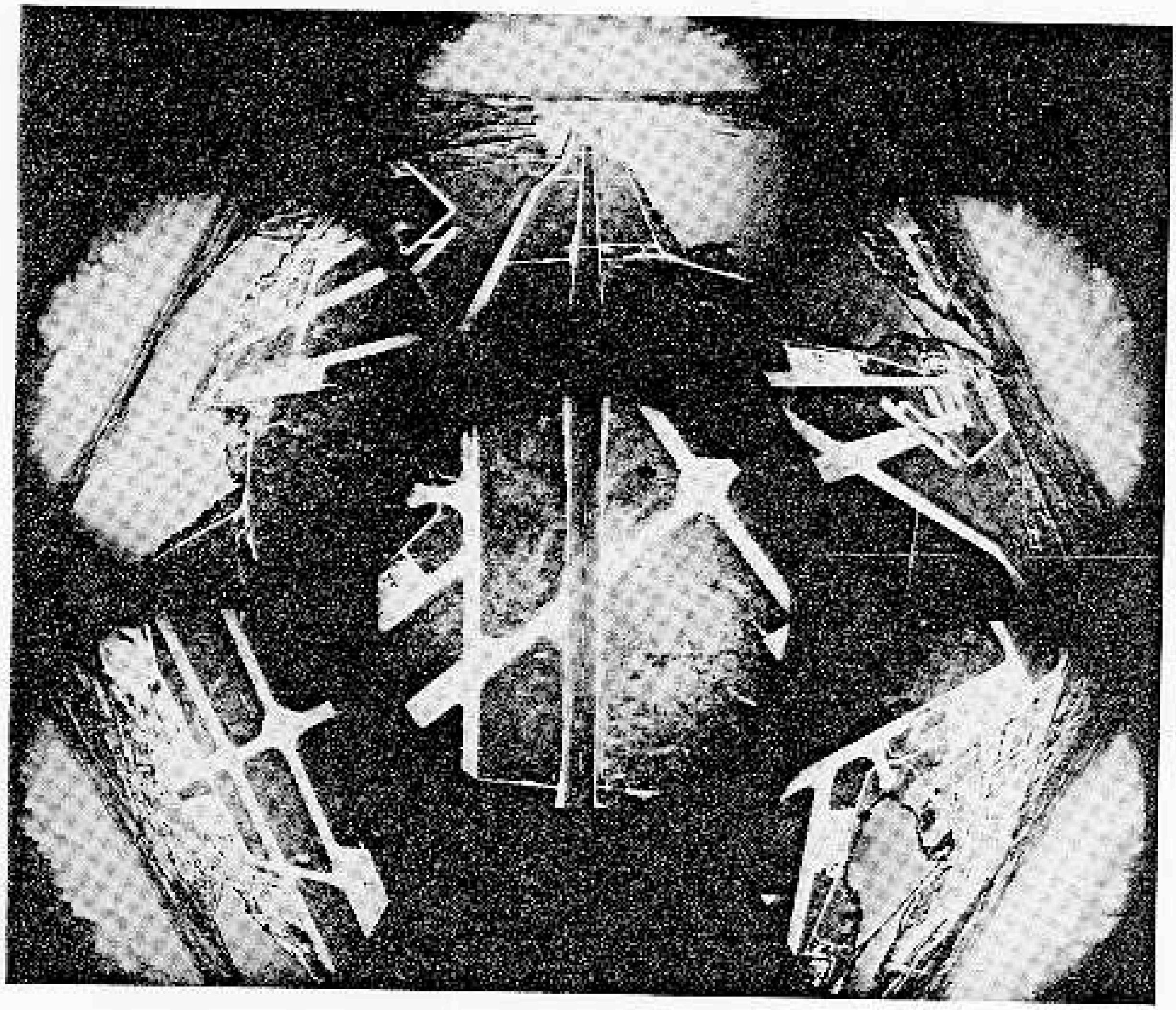

FIGURE 8.2 TYPICAL TERRAIN EXPOSURE; 6 OF 7 VIEWS SHOWN

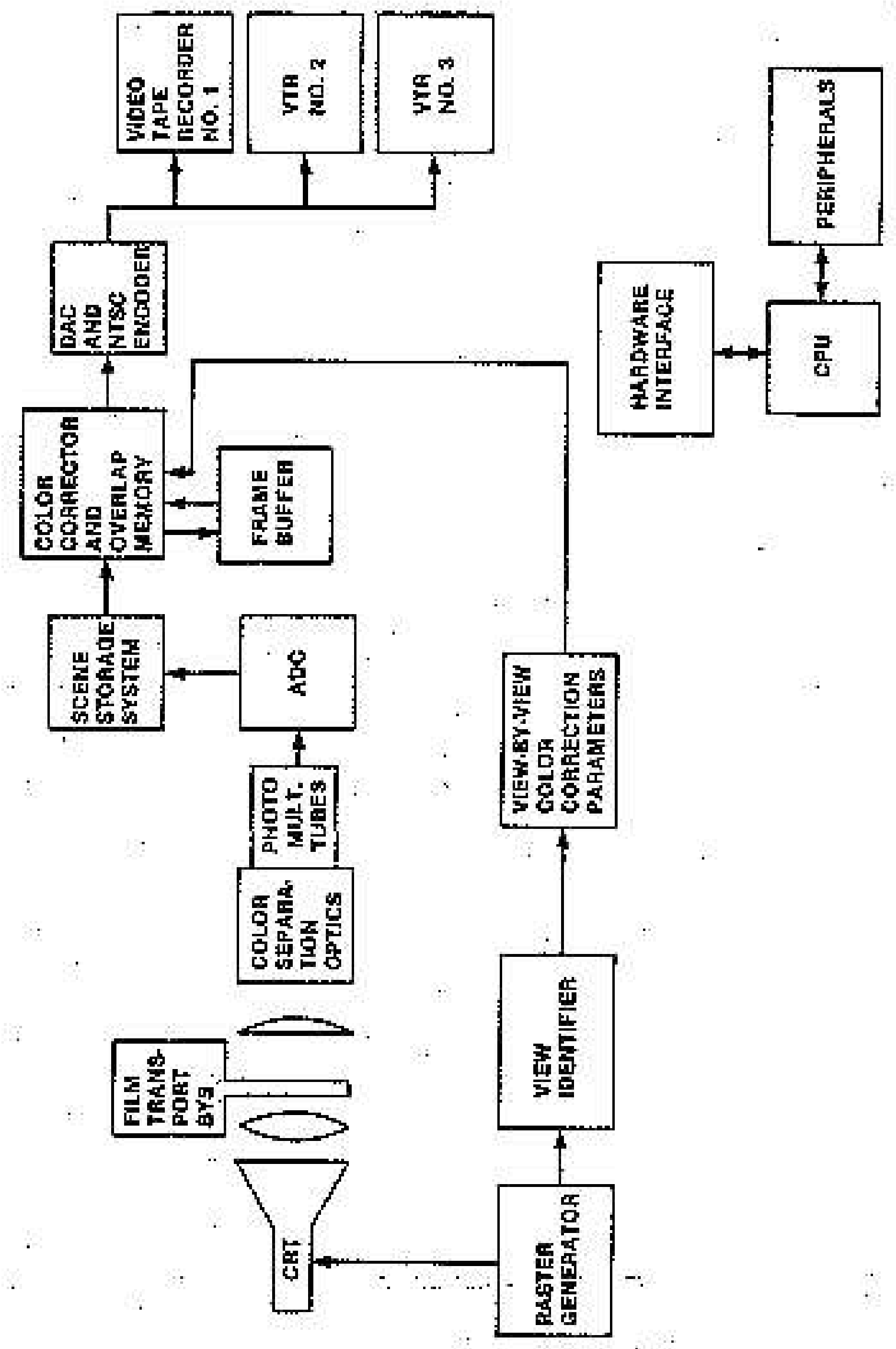

FIGURE 8.3 RECORD PROCESSOR SYSTEM

During the editing portion of the record process, each scene is photogrammetrically analyzed to locate its precise geodetic position. The information, along with aircraft attitude derived from an Inertial Measurement Unit attached to the 7-lens camera, becomes an integral part of the database and aids in proper sequencing of scanned scenes on the videotapes. Databases recorded on the 1" VTR's are then transferred to 16 video discs for playing on 16 DiscoVision 720 industrial players. Each disc can store up to 54,000 NTSC frames, or the equivalent of 700 color terrain scenes.

The real-time, on-line playback system, as shown in Figure 8.4, consists of four main subsystems. The Video Storage System (VSS) is the first encountered and contains 16 video discs and players that hold the terrain database in an analog format. Its purpose is to make available to the Host Computer large segments of the desired data in anticipation of the real-time needs of the flight simulation. The data is distributed over the 16 discs and sometimes stored redundantly in order to optimize its retrieval. Any frame can be located and accessed in a maximum of eight seconds, though nearby frames can be accessed in much less time. Each player operates independently, but are rotationally synchronized. Only three disc players transfer data at the same time; the others are usually searching for those scenes most likely to be needed next.

The Video Digitizer System (VDS) takes quasi-NTSC analog composite video from the VSS, digitizes it, and passes it to the Scene Storage System (SSS) as compressed, component video (see Figure 8.5). The VDS has three identical channels since it must service up to three video disc players simultaneously. Also provided by the VDS is the interface to the Visual System Computer.

The SSS is a dual buffer having two sections of 128 tracks each. Each track can store the digital video information present in one NTSC frame. Video information can be written into or read from either section; i.e., the input side can become the output side when new data is needed, or vice versa. The SSS accepts up to three channels of data from the VDS and outputs multiplexed Y, I, and Q digital data to the four Cell Processor Systems (CPS) simultaneously.

The CPS receives digital luminance and chrominance data for a scene from the SSS (See Figure 8.6). Under software control, it selects the portion visible to the pilot through a single window and transforms the data of this “key frame” to correspond to the instantaneous location of the pilot's eyepoint, and outputs analog signals for display. It also converts YIQ format to a RGB format, performs low-pass filtering, simulates haze, inserts a blue sky above the horizon, and provides a means for the Visual Computer to replace a number of scene pixels. These replacement pixels include at the least a light point surrounded by a black square for automatic alignment purposes.

In the case of the A-7E simulator, the display system consists of a multiple rear screen projection system comprised of six channels mosaicked as shown in Figure 8.7. Total FOV is 180° H x 140° V, thus potentially providing the entire forward FOV available from the A-7E cockpit. However, only four of the six windows can currently be operated simultaneously since each window requires its own CPS. Each channel is comprised of an 875 line, color GE Light Valve Projector that projects onto a screen via two or more folding mirrors. The screens are of a special lenticulated design and are manufactured by Phoenix Communications (now part of DaLite Screen).

The principal advantage of CAPTV imagery over CGI is the guaranteed real-world accuracy of the database. This permits mission training in which terrain and targets can appear as they would during an actual mission. Currently, however, this benefit cannot be properly appreciated because it takes 2-3 months to convert photographic imagery to CAPTV imagery. Vought hoped to reduce this turn-around time to several hours by 1990. In the meantime, one way of overcoming the problem is by photographing in advance those locations where armed conflict is likely to occur. Satellite pictures can be used to this end. Items such as sides of buildings (not seen in a straight-down shot) can be added, and a horizon can be recreated using Army mapping data.

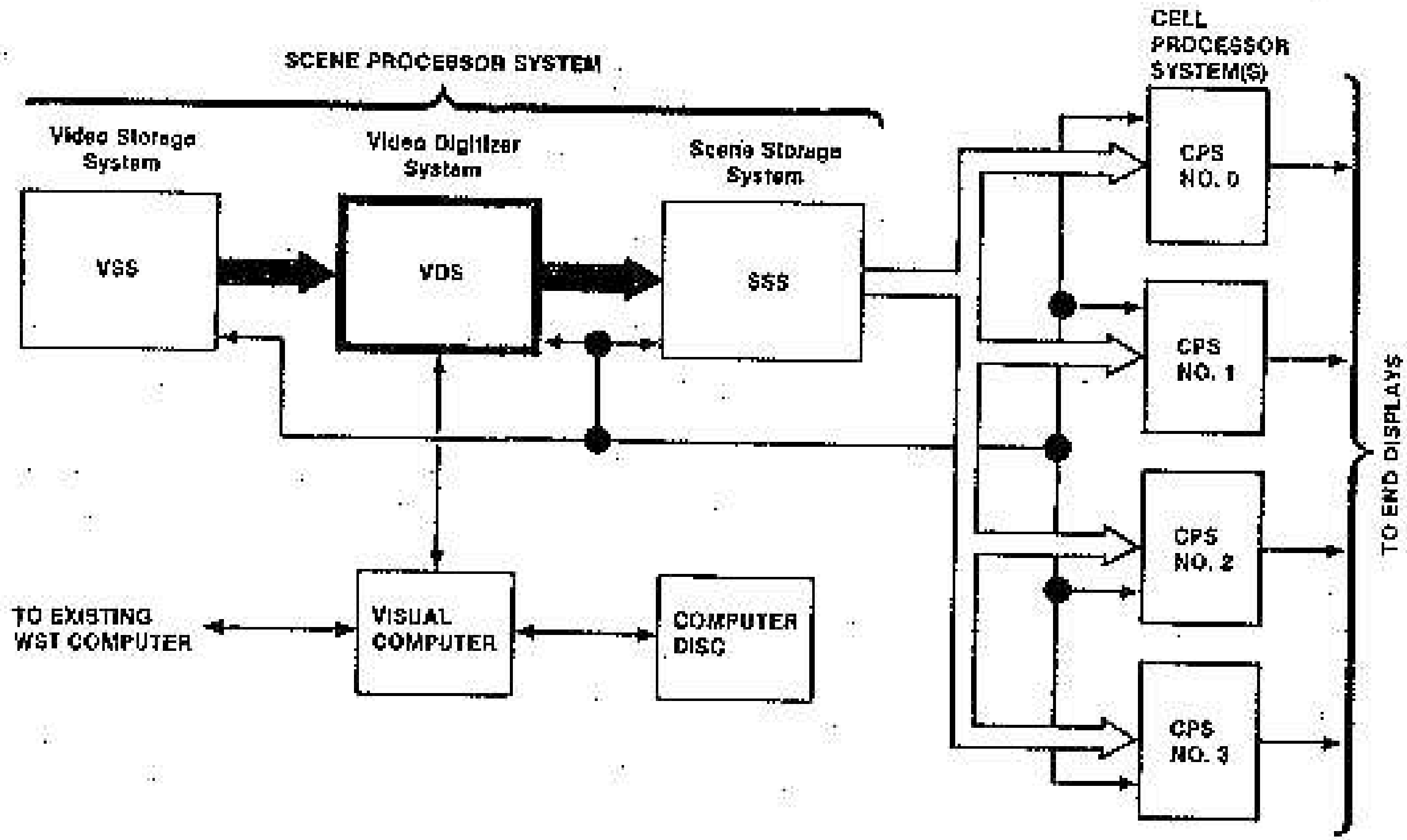

FIGURE 8.4 VISUAL ON-LINE PLAYBACK SYSTEM

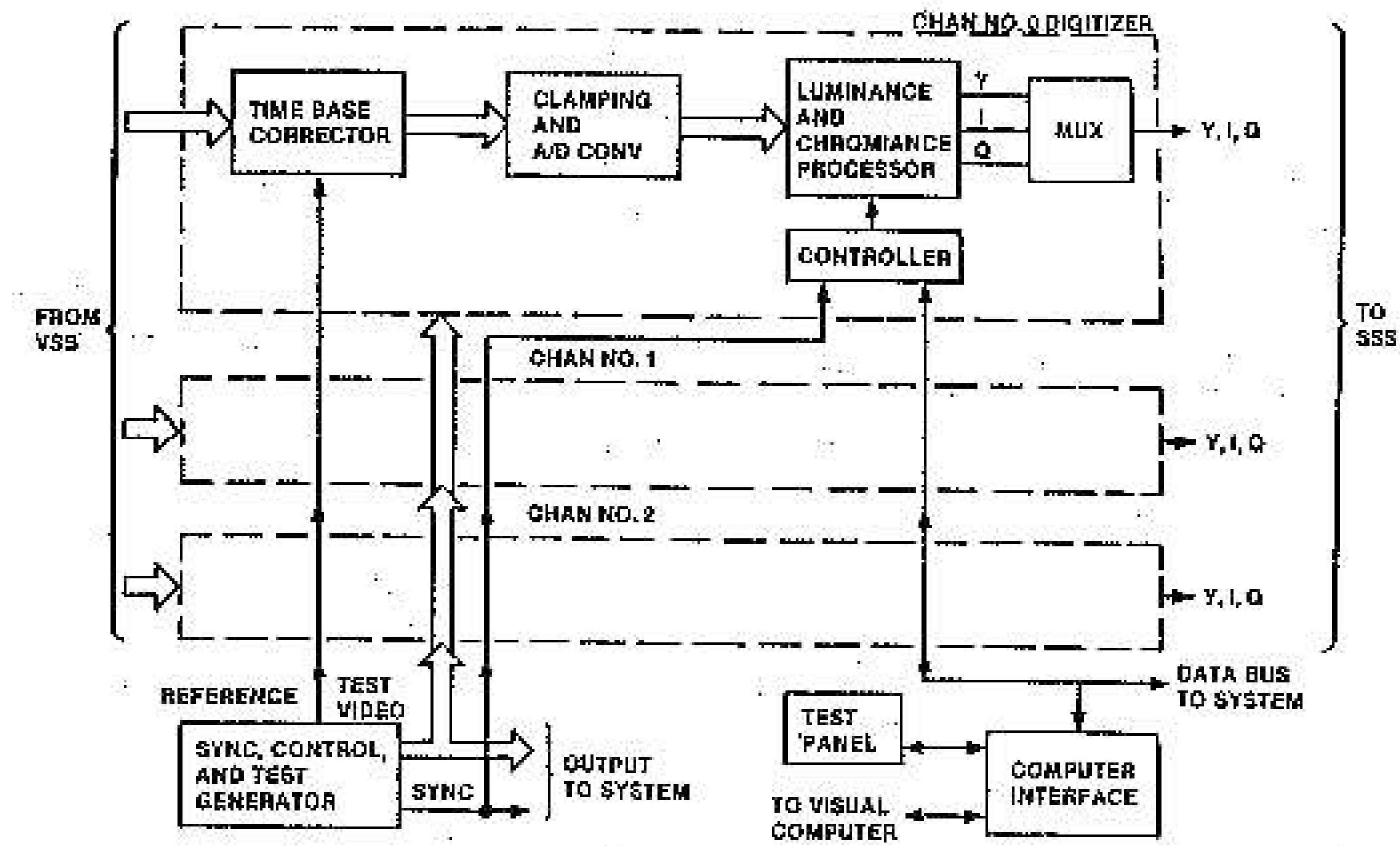

FIGURE 0.5 VIDEO DIGITIZER SYSTEM

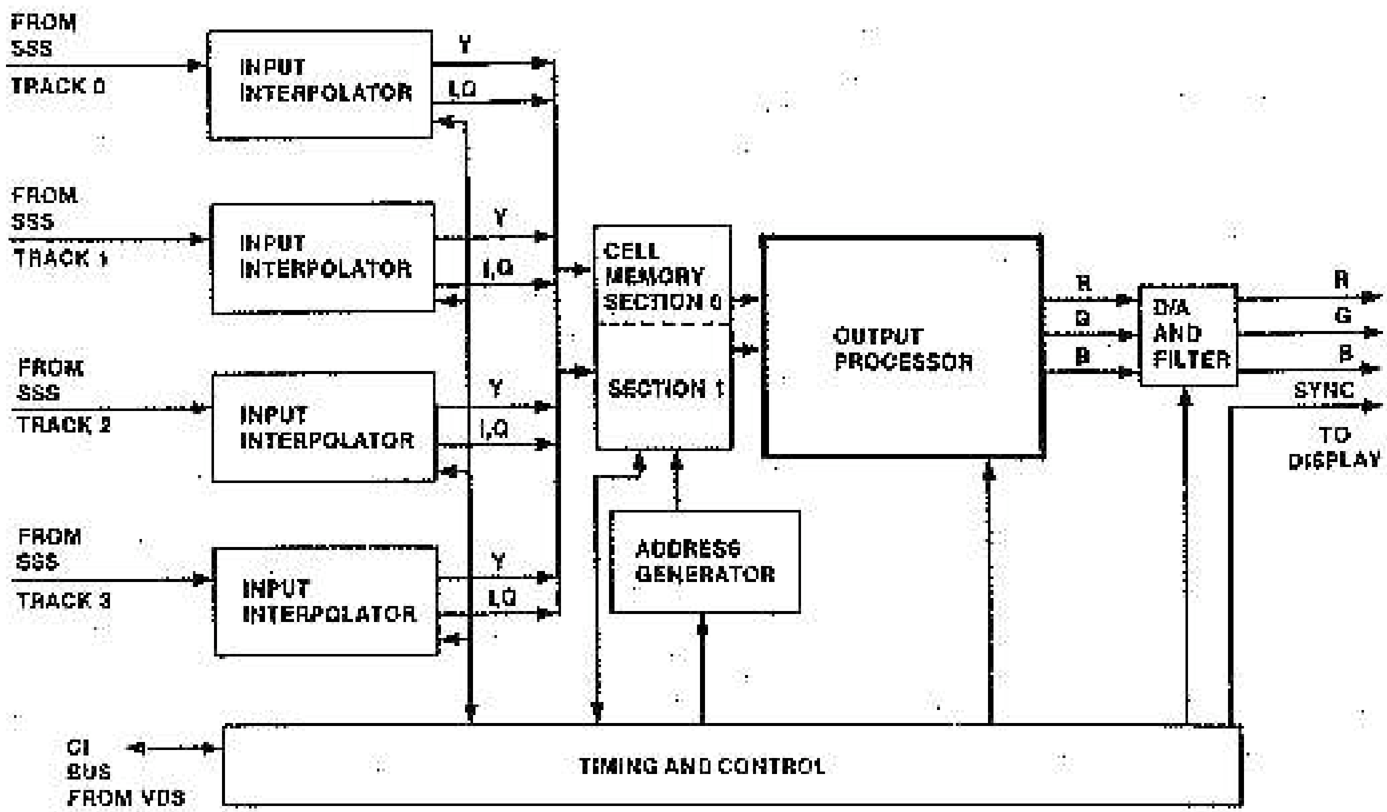

FIGURE 8.6 CELL PROCESSOR SYSTEM

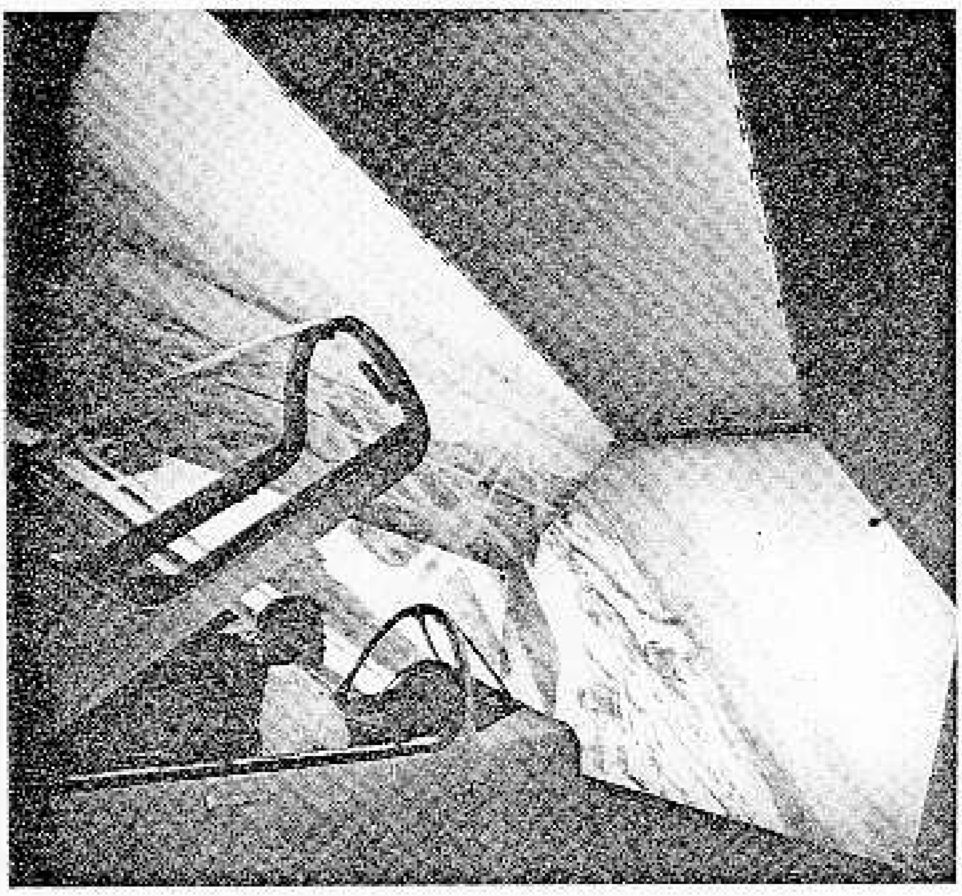

FIGURE 8.7 FOUR CHANNELS OF IMAGERY AS IT APPEARS IN THE A-7E SIMULATOR

Several problems are present in the existing A-7E implementation of CAPTV. A fundamental one is that image transformations operating between key frames work for 2-D surfaces but not 3-D terrain or objects. Good results are obtained only at high altitudes or over flat terrain. For example, buildings tend to lean over at 45° when the eyepoint is between key frames at low to medium altitudes. Vought is currently developing the capability to define "Separate Region Mapping" to allow a selection of 3-D objects to be transformed differently than 2-D portions of the image.

Another problem is that the transition from one key frame to the next is apparent to the pilot; it produces a noticeable "glitch" in the image. This can lead to a fair amount of activity in the peripheral field. Learning to ignore such activity during simulated flight might be a source of negative training for a pilot needing to be alert to AAA and SAM threats appearing in his peripheral vision during actual combat.

Other problems include:

1. Visible artifacts in the database due to preprocessing of data to obtain workable video discs,
2. The difficulty of insetting moving targets or weapons effects in a realistic manner, and
3. Portraying a broad range of weather conditions accurately.

The first issue will probably disappear as video disc technology comes to maturity. The other problems may be partially overcome, but not to the extent possible in a CGI system.

9.0 IVEX VDS 1000

The VDS 1000 is a visual image generation scheme utilizing laser videodiscs in conjunction with specialized video signal processors and scene interpolation software. In a sense, it uses computer-generated imagery. However, it's different from CGI in that it stores the CGI in compressed and coded form on laser videodiscs and retrieves it during real-time operation. In principal, this approach can eliminate the polygon construction limitations of real-time CGI systems and result in a system with capacity equivalent to approximately 1 million polygons.

Scene realism is achieved via highly detailed object rendering complemented by extensive texturing of terrain and cultural features (where appropriate). All texturing is integrated into the database and is visible regardless of distance from the eyepoint. This attribute permits closure cueing which would not be present otherwise.

A standard full-color database is 50 nm x 50 nm and includes runway with markings, plus flat terrain with a variety of texturing. Complete 6 degree-of-freedom movement is accommodated at 60 Hz update rates. Visibility and variable FOVs are also provided. Visual effects such as cloud deck, ambient lighting, and dynamic targets or objects are available as options. Improved light points for duskJnight simulation require an optional light point generator. Additional specifications are listed below.

- Full daylight, continuously variable time-of-day, plus evening/dusk capability
- 60 Hz update; 30 Hz frame rate
- Three-field fixed synchronous transport delay
- Raster-scan output
- Power consumption less than 1 kW/channel
- Modular; Housed in standard 24” rack
- Serial interface to Host Computer via RS-232 or RS-422 protocols
- Database changeable by switching videodiscs
- Haze calculation based on slant-range

Aside from richly textured detail, a presumed advantage of this system is lower cost than a comparable CGI system. Disadvantages, however, would include difficulties in implementing dynamic coordinate systems, implementing extensive lighting or special effects without producing insetting artifacts, and quickly modifying existing databases. In addition, terrain relief and 3-D objects require special handling in the hardware/software and complicate implementation.

10.0 Summary

The attempt here has been to show by example that CGI is not the only tool for satisfying visual simulation requirements. Applications exist in which the full flexibility of CGI is not required, thus making its cost unjustified. An example is the horizon requirement in an ACM simulator. Other times CGI simply does not provide the needed fidelity. Examples of this include simulation for (i) Certain low-level flight tasks, (ii) BOPTT, and (iii) Celestial Sphere.

The seven techniques presented are by no means all-inclusive. One noteworthy exception is the Singer VAMP (Visual Anamorphic Motion Picture) system that serves as a landing trainer. It is based on using a filmed landing sequence that is presented to the trainee, along with the added capability of optically distorting it to account for a limited range of deviation from the preferred glide slope. Another scheme worthy of mention is CGSI (Computer Generated and Synthesized Imagery), a project at Honeywell that was supported by the U.S. Army and Navy. CGSI attempts to combine CGI and video disc technology to obtain performance and realism superior to either technology by itself. Specifically, it generates a CGI background and then populates it with highly detailed objects photographed and stored on videodisc. The large storage capacity of the discs is exploited to allow multiple views of objects to be stored. These views, often separated by only 1° in either azimuth or elevation, allow real-time processing to be minimized with (presumably) only a small price to be paid in terms of perspective accuracy.

Regardless of which image generation scheme is applied, the true measure of performance is the quality and quantity of training provided. An inexpensive IG that allows the purchase of several visuals is no bargain if it proves inadequate to the training task. Similarly, an IG that is expensive and overkill for a particular application is cutting into the quantity of training by depleting a finite training budget. An old rule of thumb worth resurrecting and abiding by is: “Get the right tool for the job!”

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