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HOLOGRAPHIC TERRAIN SIMULATION

Advanced Simulation Concepts Laboratory
Naval Training Equipment Center
Orlando, Florida 32813

December 1977

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ORLANDO FLORIDA 32813

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DENIS R. BREGLIA
JOSEPH F. MULSON
ALFRED H. RODEMANN
Advanced Simulation Concepts Laboratory

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Approved:

DR. J. F. HARVEY
Director
Research and Technology Department

NAVAL TRAINING EQUIPMENT CENTER

ORLANDO, FLORIDA 32813

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10 Denis R./Breglia,
Joseph F./Mulson
Alfred H./Rodemann

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A feasibility analysis of a holographic terrain simulation concept is described. Experimental work in which photographs of terrain are holographically stored and then displayed is evaluated. Advantages of holographic storage of analog images include multiplexing capability of several images stored at one location and the advantage of displayed image stability from a moving hologram array. Future efforts and investigations are outlined.

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SECTION I

INTRODUCTION

A wide variety of training systems require visual displays of simulated real world terrain. These displays all require a data base from which the display can be drawn and presented. This data base is currently one of three types; a three-dimensional scaled model board, a photographic storage, or a math model. All three of these have advantages and disadvantages. The purpose of this report is not to analyze all possible methods of terrain simulation but to investigate the feasibility of a holographic storage system which is essentially a variation of a photographic storage system.

SECTION II

SYSTEM CONCEPT

The system end goal is to provide a dynamic visual display to a trainee which is a function of his three-dimensional position within a gaming volume, his three-dimensional velocity vector, and his three-dimensional attitude coordinates.

The basic system approach is to fabricate an optical memory capable of storing a sufficient number of discrete views of the real world from perspective points throughout the gaming volume in such a manner that individual views can be displayed in a sequence corresponding to simulated real world motion along any three-dimensional curve within the gaming volume. The system concept ultimately requires display of a simulated real world scene in any direction from each perspective point, such that the simulation is not fixed to specific look directions or flight paths.

The system concept is divided in several consecutive phases. Wide-angle photographs are made from a three-dimensional matrix of perspective points above a real world terrain. Positive transparencies of these photographs are then used to record a two-dimensional grid of hologram locations. Each hologram location corresponds to a grid position in a horizontal plane. Each hologram location is multiplexed with several holograms corresponding to several different altitudes at the same horizontal coordinates. Upon illumination by a suitable laser source, the holograms reconstruct real images of the recorded transparencies. The real images are then reimaged by the same lens used to photograph the real world terrain. The simulated terrain is then presented on a screen.

SECTION III

HOLOGRAPHIC STORAGE

The advantages of holographic storage of analog optical data such as photographic transparencies over direct photographic storage are two fold; holographic recordings can be made such that no shutter is required when changing frames, and holographic recordings can be multiplexed such that more than one image can be stored in each film location. The first advantage is a property of a specific holographic recording geometry in which both the object and reference wave fronts incident on the recording material originate from optical infinity. This type of recording geometry is illustrated in figure 1.

The pertinent characteristics of this geometry are the collimation of the reference wavefront due to the spatial filter (SF_R) being located at the back focal plane of the reference objective (O_R) and the infinity image of the object transparency (T) due to its location at the back focal plane of the objective (O_T). A hologram recorded in this manner, repositioned at the hologram recording plane and illuminated with the conjugate of the reference wavefront, has the property of reconstructing a real image of the object transparency whose position remains constant despite translations of the hologram in its own plane. This results from the apparent location of the object being at infinity so that there is no change in the object location when translations are made.

Since there is no change in image location with plate motion, a second hologram, made with the same geometry, on an area of the recording adjacent to the first hologram allows one image to be replaced by another with no image motion or shuttering required.

The second advantage of holographic storage is multiplexing. Holograms made on a recording material which is thick with respect to a wavelength have an angular positional sensitivity which causes the reconstructed wavefront to extinguish as the angle of illumination is changed. This effect is similar to looking through venetian blinds. This effect can be utilized to multiplex several holograms on the same area of the recording medium.

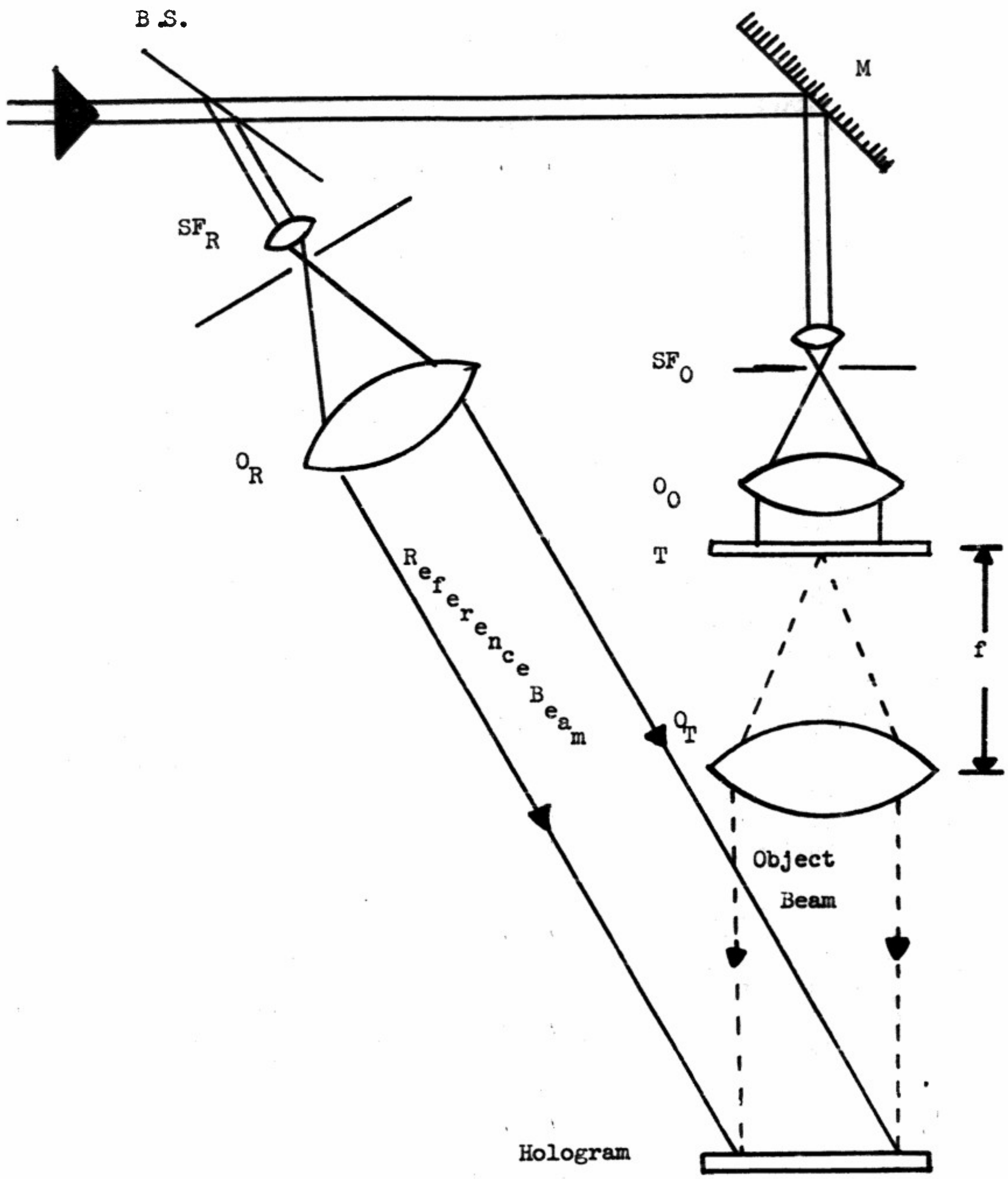

Figure 1. Hologram Recording Geometry

SECTION IV

EXPERIMENT

INTRODUCTION

Before proceeding with a full scale investigation into all system parameters, a preliminary feasibility model incorporating the system concept was fabricated using system components known to be less than optimum. This was done to have a working model suitable for testing experimental parameters of the various subsystems against the quality of the output display. The feasibility model used a 1:100 scale terrain model simulating a circular gaming area having a 60 meter radius. Photographs were then taken over a two-dimensional matrix of points located at a simulated altitude of 30 meters above the terrain. The photographs were recorded as a matrix of holograms on a single holographic plate, using a recording geometry as in figure 1. The recorded holograms were used to reconstruct the original images which were then projected back through the original camera lens to form a real image on a hemispherical screen. The display could be viewed directly or with a probe to make a relative quality judgment. Each parameter of all of the variables within each step could be varied and the effect of the change observed at the display. The variables within each step and the parameters which require further investigation will be discussed below.

TERRAIN MODEL BOARD

A 1:100 scale model board was constructed and used for the preliminary investigation to avoid the difficulties involved with obtaining real world terrain photography. Figure 2 shows the model board together with the gantry used to support and position the camera used to make the original photographs. The configuration of terrain features was chosen arbitrarily to be representative of a variety of terrains. This configuration was changed several times during the course of the experimental effort based on subjective aesthetic or photometric judgments of the display. Mechanical stability of the terrain and camera was a problem which was relatively easy to overcome in this laboratory experiment. However, in the case of real world photography suitable precautions will have to be made regarding image motion during exposure such that any motion blurring is within the tolerances for desired image quality. Positioning of the camera at the desired grid points could be easily controlled to 3×10^{-3} meters, equivalent to a real world accuracy of 0.3 meters.

PHOTOGRAPHY

Camera. There are several commercially available camera lenses which are capable of recording images of a hemisphere. A trade-off study will have to be made as to which lens/format combination is optimum for the quantity and quality of the aerial photography desired in a final system. A Fisheye Nikkor 7.5mm f/5.6 together with a Nikon F 35mm camera back was available in-house and was used for this experiment.

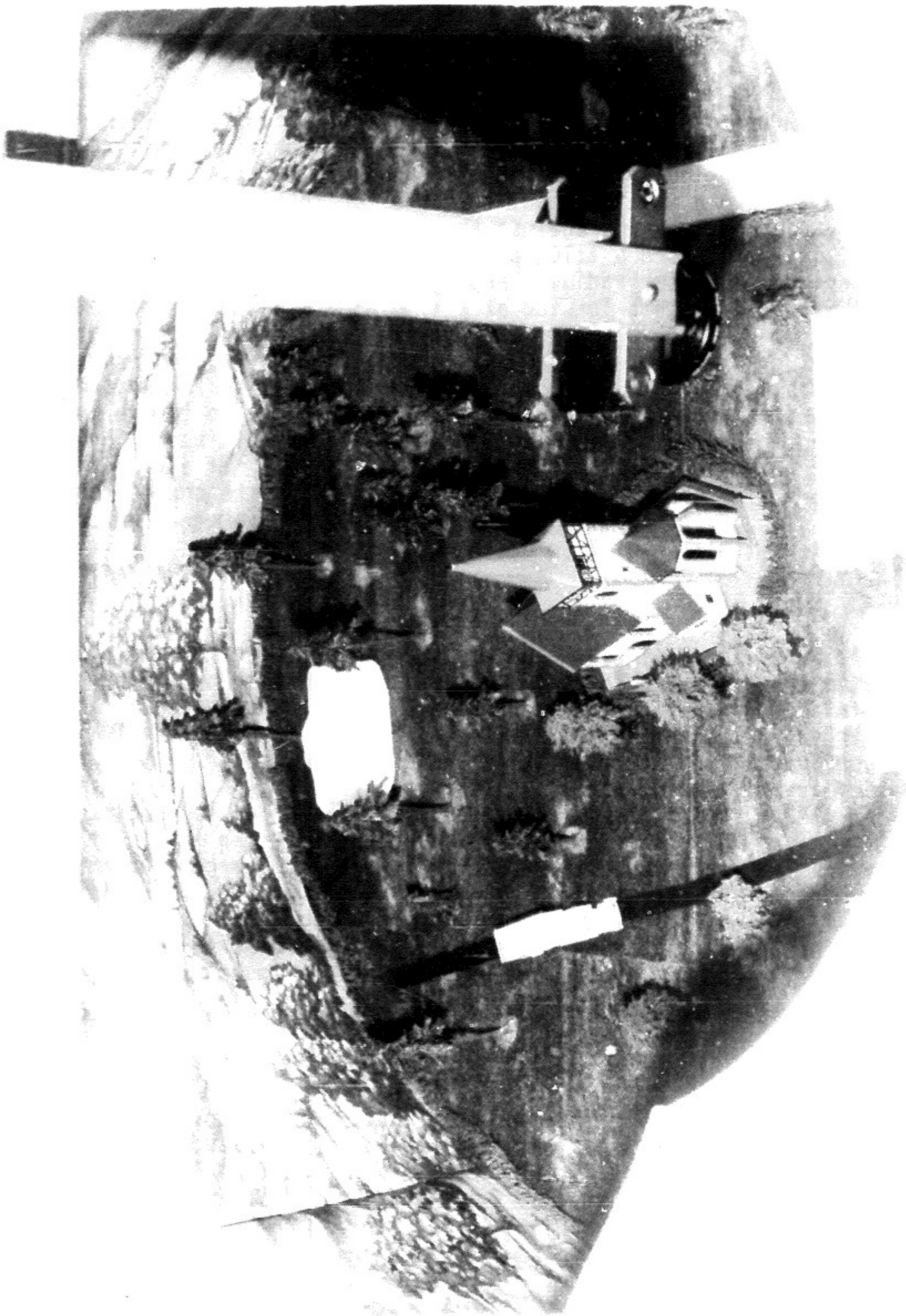

Figure 2. Modelboard and Camera

Scene Illumination. The illumination of the terrain scene requires some discussion. Natural sunlit terrain scenes have luminance variations spanning a range of approximately 200:1 (if specular highlights or glints are ignored). This is approximately the range apparent to a human observer at any one time. However, a human observer is usually willing to accept a much lower range of contrast ratio or gray levels in a display. For this experiment, the model terrain-illumination combination used was measured to have a contrast ratio of approximately 40:1. The illuminant used for this experiment was a 400-watt sodium vapor lamp. This lighting would be inappropriate for color photography due to its relatively narrow spectral output.

Film and Processing. The choice of film to be used in a final system is strongly dependent on the quality of the final display desired. Resolution requirements may preclude the use of color film for the original photography but the desirability of color display may require the recording of color separations on monochrome (black and white) film. However, hologram recording materials are essentially monochrome and the difficulties associated with multiplexing several multicolor images in the same hologram plate area would have to be investigated. Another general decision to be made involves the choice of reversal (positive image) or nonreversal (negative image) original film or processing. Reversal film processing reduces the number of image generations required but also limits the flexibility to experimentally vary tonal range and bias level of the object transparency to be holographically recorded. For the purposes of this experiment, nonreversal monochrome film was used for initial camera exposures. These negatives were then contact printed to positive transparencies for the holographic recording.

Several film-processing procedures were evaluated for both the original photography and the contact prints. In general, the holographic recording process tends to degrade the tonal range or gray levels produced in the display so the number of grey levels should be maximized in the input transparency.

Resolution is another area of consideration. The limiting resolution of the system is a function of all of the contributing system components. Each image generation tends to degrade the resolution of the previous generation. To minimize the degradation, each generation's resolution capability should be sufficient to allow the required display resolution to be attained. Note that image contrast plays an important role in determining resolution. For example, a camera lens which is capable of Rayleigh resolution of 100 line pairs/mm for a high contrast target produces a low contrast image at 100 line pairs/mm. In order to record this image, the film must be capable of resolving 100 line pairs/mm at low contrast. The same reasoning can be applied to a human observer viewing a display. Consider a display in which a simulated real world high contrast one arc minute target is just resolved. A human observer, who requires a high contrast object to resolve one arc minute could not resolve the display. Therefore, the ultimate display resolution requirements should be chosen with both contrast and resolution in mind. The camera-film-hologram recording-hologram readout generations should all be evaluated based on these requirements.

Perspective Points. As stated previously, the required pitch or spacing between individual perspective viewpoints will have to be determined as a function of minimum simulated speed of the vehicle being simulated, frame rate of display, maximum image motion allowed between frames, and simulated distance of closest approach. Experiments will have to be performed to determine these parameters before a quantification of pitch in both horizontal and vertical planes can be made. The computation of the total number of frames or film footage required for a given gaming volume can then be made. For the purpose of this experiment, photographs were made from a fixed altitude at the points noted on figure 3. The first set of nine photographs labeled A through I had a square pitch of 0.3 meters corresponding to a real world spacing of 30 meters between orthogonally adjacent frames. The second set of photographs labeled 1 through 24 were spaced at 2.5×10^{-2} meters corresponding to 2.5 meters per frame in the real world. The accuracy of camera location was controlled to a precision of approximately 2.5×10^{-3} millimeters. Angular orientation of the camera was not as precise due to the crude method of camera support used for the experiment. This problem of accurately positioning the camera with all six degrees of freedom controlled to a high precision when making the original photography of a real world terrain is difficult at best.

HOLOGRAPHY

Introduction. As previously stated, the geometry of the holographic recording must be similar to that of figure 1 if the advantages of holographic storage are to be realized. However, this constraint still leaves many variable parameters which must be optimized and traded off to obtain the optimum final display. These parameters together with a brief discussion of their effects on image quality are given in the following paragraphs.

General Requirements. All standard holographic recording schemes have two elements in common which do not require explanation and analysis in this report. These are: a stable, highly coherent laser light scorce and a vibration isolated platform on which to expose the holograms. The laser used for this experiment was a Spectra-Physics Model 165 Argon ion laser with an intracavity etalon for extended coherence. The spectral line used was 514.5×10^{-9} meter wavelength at an output beam power of approximately 0.8 watts maximum (adjusted for exposure time). The stability of this light was measured to be less than 180° phase change per hour when the laser was operated in a single mode as observed with a spectrum analyzer and fringe-producing unequal path interferometer. The platform used was a 1.3 meter wide by 2.6 meter long by 0.3 meter thick spring-mounted (natural frequency of $3H_z$) granite surface plate. The working surface of this platform was enclosed by a wood box to minimize air turbulence effects. The stability of this laser-platform combination has been demonstrated many times by the successful production of a wide variety of holograms.

Optical Components. In any optical system using highly coherent light, the surface quality of all optical components is extremely important. The presence of small anomalies such as dust, scratches, or fingerprints whose effects are

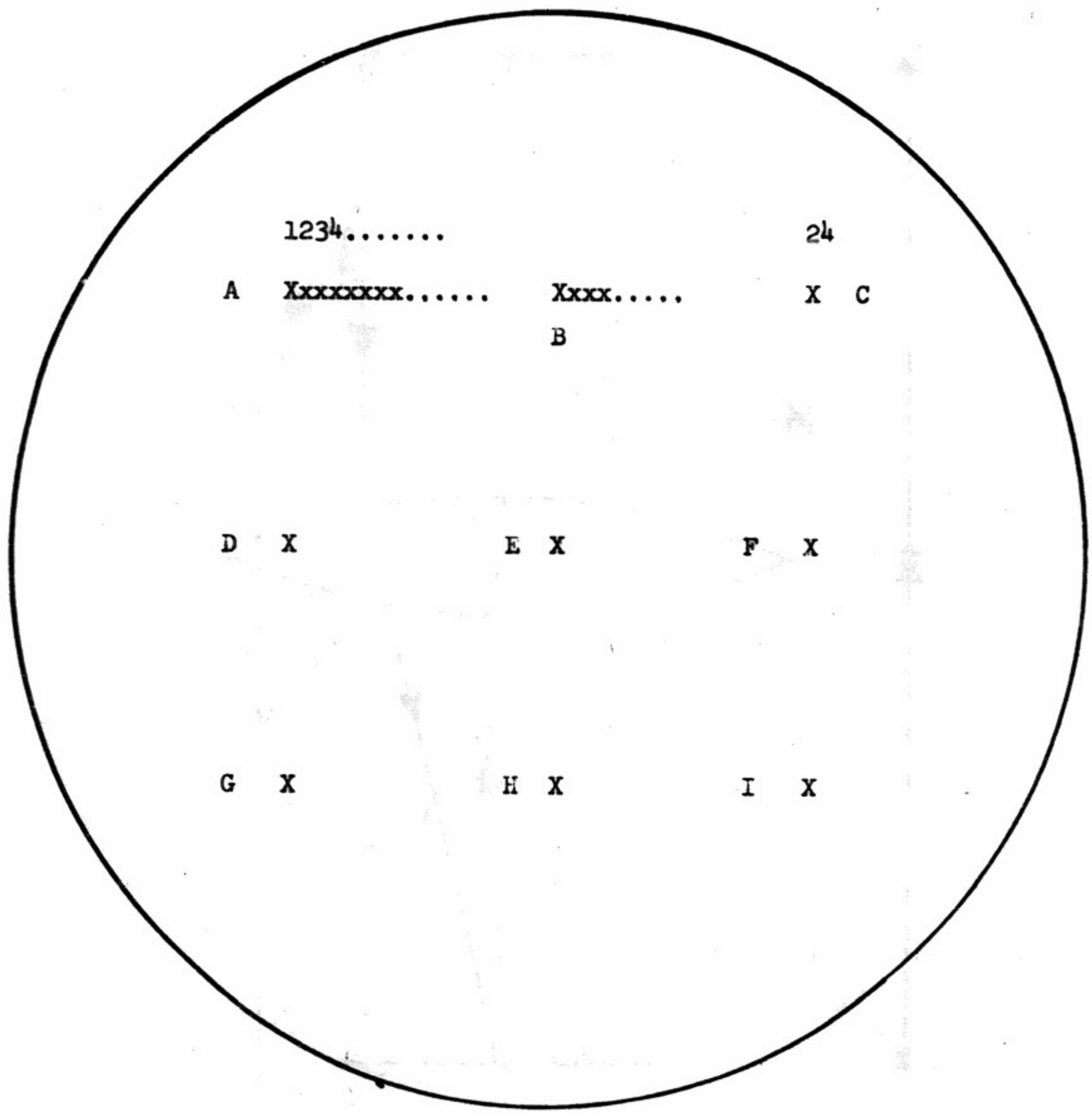

Figure 3. Location of Perspective Points

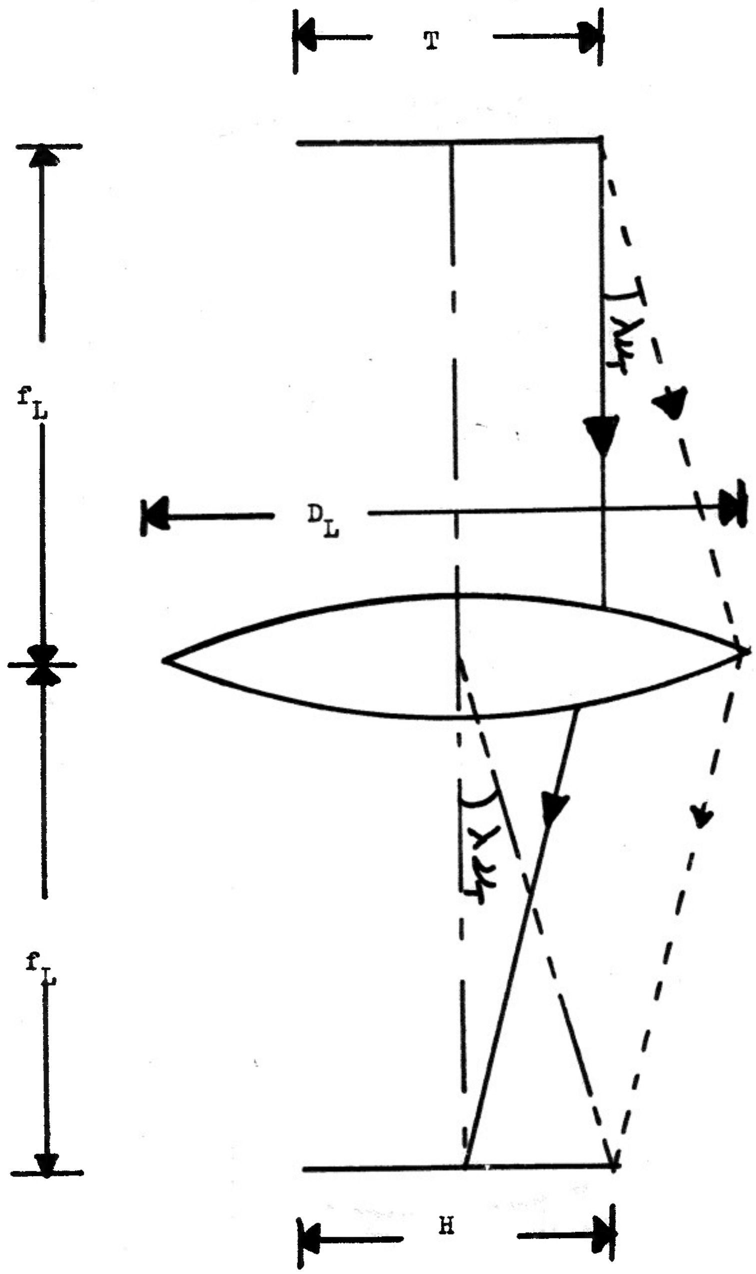

Figure 4. Lens Relations

unnoticeable in incoherent optical systems causes the production of undesirable fringing and other image defects. This effect is called coherent noise and is not to be confused with coherent speckle which is another deletrious effect of coherent light in imaging systems.

Coherent noise in the holographic image can be minimized by two techniques, beam cleanliness and redundancy. Both of these techniques were utilized in this experiment. The first was implemented by spatially filtering the object and reference beams to minimize the coherent noise due to all mirrors, beam splitters, and refractive optics preceding the spatial filters. Beam cleanliness was maintained by careful cleaning of all optical surfaces following the spatial filters.

Another technique for minimizing coherent noise is redundancy of illumination of the object. The effect of object illumination through a ground glass diffuser minimizes coherent noise but maximizes the detrimental effect of coherent speckle. A trade-off in redundancy occurs with the use of an finite array of illumination sources. For this experiment, a variety of arrays were evaluated for object illumination. These arrays included absorption grids contact printed from half tone screens, photo reduction of absorption grids, and random dot phase arrays photo-reduced onto dichromated gelatin plates.

Mechanical Components. The mechanical component used for positioning the object transparency is required to have an accuracy and repeatability consistent with the tolerance on position of the final displayed image. With an image format whose 23mm diameter represents an angular coverage of 180^{o}, the positioning accuracy is approximately 100 microns per degree of allowable angular image displacement. The positioning of the holographic plate holder is not as critical due to the positional insensitivity of the holographic geometry used. However, for the recording of many holograms on a single plate, the plate positioning apparatus must be capable of accurately moving the plate a fixed, known distance in both horizontal and vertical directions between exposures. The plate holder should allow exposure on only one plate position at a time and should not overlap exposures. For this experiment, the object transparencies were manually positioned in the transparency holder with consequent lack of accuracy in positioning. The holographic recording plate was also manually repositioned but a grid of apertures was placed in contact with the holographic plate so as to allow sufficient accuracy of exposure position by selectively obscuring all but one aperture for each exposure. These manual techniques, although sufficient for feasibility demonstration, would have to be refined and automated for a large number of holograms.

Variable angular positioning of the reference beam incidence angle was not a requirement in this experiment. However, a requirement for multiplexing will add another mechanical component to affect such changes in incidence angle of the reference beam.

The simultaneous variation of both reference beam angle and plate angle with respect to the object beam is desirable for maximizing the diffraction efficiency at the Bragg angle with a standard thick photographic emulsion hologram. However, the additional system complexity required to overcome the efficiency losses due to emulsion shrinkage or swelling is not worthwhile since the same effect can be accomplished with a recording material whose thickness is the same at the time of recording and display.

Beam Shaping Optics. The beam shaping optical components include the reference beam collimator, the object beam collimator, and the object transform lens. The basic requirement for the reference collimator is that it produce a highly collimated laser beam of sufficient uniformity across the cross sectional area which intercepts the holographic recording plate area to be exposed. For this experiment, the reference collimator was a 50mm aperture Tropel Laser Collimator Model 280. This collimator was designed for use with a He-Ne laser operating at 633 nanometers and had less than optimum performance at the 514.5 nanometer wavelength used. The collimator produced secondary reflections which led to noticeable nonuniform illuminance of the holographic recording plate.

The collimation of the object illumination beam is not as critical as the reference beam. However, maximum system throughput is attained when the wavefront is as near collimated as is practical. This consideration together with a requirement for uniform illumination of the object transparency led to the use of a 100mm Tropel Laser Collimator as the object beam collimator.

The function of the object transform lens is to image the object transparency at optical infinity. The choice of this lens is constrained by the transparency diameter and packing density and the hologram diameter. The restrictions may be calculated from the relations in equations 1 and 2. Figure 4 shows the physical significance of the parameters.

$$D_L \geqslant T + 2f_L \lambda \nu_T \qquad 1.$$

$$f_L \leqslant \frac{H}{\lambda \nu_T} \qquad 2.$$

In equation 1, D_L is the diameter of the transform lens required: for a given transparency diameter (T), maximum spatial frequency to be recorded from the transparency (ν_T), focal length of the transform lens (f_L), and wavelength of the illuminating light (λ). In equation 2, f_L is the focal length of the transform lens for a given hologram diameter (H) with λ and ν_T as defined above. For example, a hologram diameter of 5mm, an object transparency of 200 line pairs/mm and an object transparency diameter of 23mm yields a maximum allowable focal length of 50mm and a minimum diameter of the transform lens of 33mm if the maximum focal length is used. Similar calculations can be performed to match predicted system performance with end display requirements. For this experiment, a matched pair of transform lenses were available and convenient to use since one of the pair could be used for recording while the other was permanently mounted in the display geometry. The parameters of these lenses limited expected performance. The ratio of hologram diameter to spatial frequency recording capability was limited to 0.2. Thus, a 5mm hologram would record spatial frequencies less than or equal to 25 lines/mm. In figure 2, the hologram plane is placed at the back focal plane of the lens. This is the optimum position for the smallest hologram which can record the desired information. At any other plane, the hologram would have to be larger to capture the desired information. It also should be noted that resolution in coherent light is approximately half that of incoherent light.

Holographic Recording Material. There are several important characteristics associated with the hologram recording material. The prime consideration is that the material be capable of recording the high spatial frequencies associated with the interferometric recording process. The maximum spatial frequency ν_H is a function of the maximum interference angle (θ_M) between the object and reference beams and the wavelength (λ) of the light used. This relation is given in equation 3.

$$\nu_H = \frac{2 \sin (^{\theta}m/2)}{\lambda} \qquad 3.$$

In this experiment, the maximum object reference angle was approximately 20° leading to a spatial frequency recording capability requirement of approximately 700 lines/mm. This requirement is within the capability of a wide variety of recording materials.

The next characteristic important to consider is the diffraction efficiency capability of the recording material after it is processed and used to form the display. The light level of the display is a function of the laser illumination level, the diffraction efficiency of the hologram, transmission factors of the various optical components and gain of the display screen. These system parameters can be varied to give the desired display luminance.

Other characteristics of the recording material which should also be considered are: geometric distortion incurred during processing, availability of recording material in quantities desired, required processing procedures, handling and storage characteristics, stability of recorded image against bleaching or deterioration under effects of adverse environment such as high humidity or high laser illuminance, and cost.

For this experiment, the recording material used was Kodak 649-F emulsion on 100x125mm glass plates. The processing procedure used was standard for the production of low efficiency, absorption type holograms. No attempts were made to improve diffraction efficiency by the bleaching techniques described in the literature since the display luminance was adequate for evaluation purposes.

DISPLAY

The finished hologram arrays were displayed using the same laser which recorded them. The individual 100x125mm glass plate was mounted in a fixture which allowed it to be scanned in horizontal and vertical directions while maintaining fixed illuminating beam angle. The reconstructed wavefront was then intercepted by a duplicate of the transform lens used in the recording. The image formed by the transform lens is then reimaged on a hemispherical screen by the camera lens used to make the original photographs. Most of the parameters of the display system are determined by the holographic recording geometry. However, the diameter of the hemispherical screen and its surface finish are variables as well as the laser power density used to illuminate the individual holograms. The screen diameter used in this experiment was 330mm. The screen was finished with a diffuse white paint. Laser illumination of the hologram was approximately 500mw in a 10mm diameter hologram area.

In a final system design, there should be a capability of simulating change in viewing direction such as occurs with pitch, roll, and yaw variations in an actual aircraft.

SECTION V

RESULTS

INTRODUCTION

In this section, a brief description of the results of the experiments previously described will be given. In general, the results were fairly predictable and consistent within the constraints of the available equipment once the glitches, demons, monkey wrenches, poltergeists, goblins, imps, and bugs had been removed or at least compensated.

PHOTOGRAPHY

The terrain model was photographed as described in the previous section. The scene brightness range resulted in rather flat negatives when Panatomic-X film was used. An attempt was made to improve the subjective appearance of the negatives by using AGFA 10E75 35mm film. This film is used for holography and has a relatively high resolution and high contrast when compared to Panatomic-X. However, the net result was subjectively poor for the high contrast negatives. A trade-off was made by using Panatomic-X negatives with standard developing in Microdol-X. These negatives were contact-printed onto Panatomic-X which was then developed in D-19, a high contrast developer. The flexibility of this two step process allowed a wide range of negative contrast-contact print contrast variations to be evaluated. Figures 5 and 6 show projection prints of a typical Panatomic-X negative and a typical AGFA 10E75 negative.

Resolution measurements were made by photographing NBS resolution test charts with the same camera. A print of a typical measurement photograph is pictured in figure 7. Measured resolutions varied from 50 line pairs/mm on axis to 25 line pairs/mm at the edge of the field for the high contrast target. The low contrast target resolution measurements were approximately 20% less. Similar tests were made using the gantry camera mount over the terrain board. Figure 8 shows a typical test. The results of both tests agreed, verifying the stability of the mounting system.

The photographic gamma of the positive transparencies used was measured to be approximately 1.0 with the exposure-contact print method used.

HOLOGRAPHY

The holographic geometry was fixed at the outset of the experiment as described in the preceding section. The experimental effort, therefore, was directed toward evaluation of several object illumination schemes to optimize the image quality of the object as seen by the hologram. Any object illuminated by coherent light appears to have a granular speckle on it. This effect is more or less pronounced as a function of the roughness of the surface, the wavelength and coherence of the illumination, and the -number of the viewing system. The effect of speckle on image quality is demonstrated in figures 9 and 10. In figure 9, the resolution target was illuminated by diffuse incoherent white light. Figure 10 shows the same target with the only difference being that a laser was used for illumination. Although it is not apparent in

Figure 5. Panatomic X Negative Print

Figure 6. Agfa Negative Print

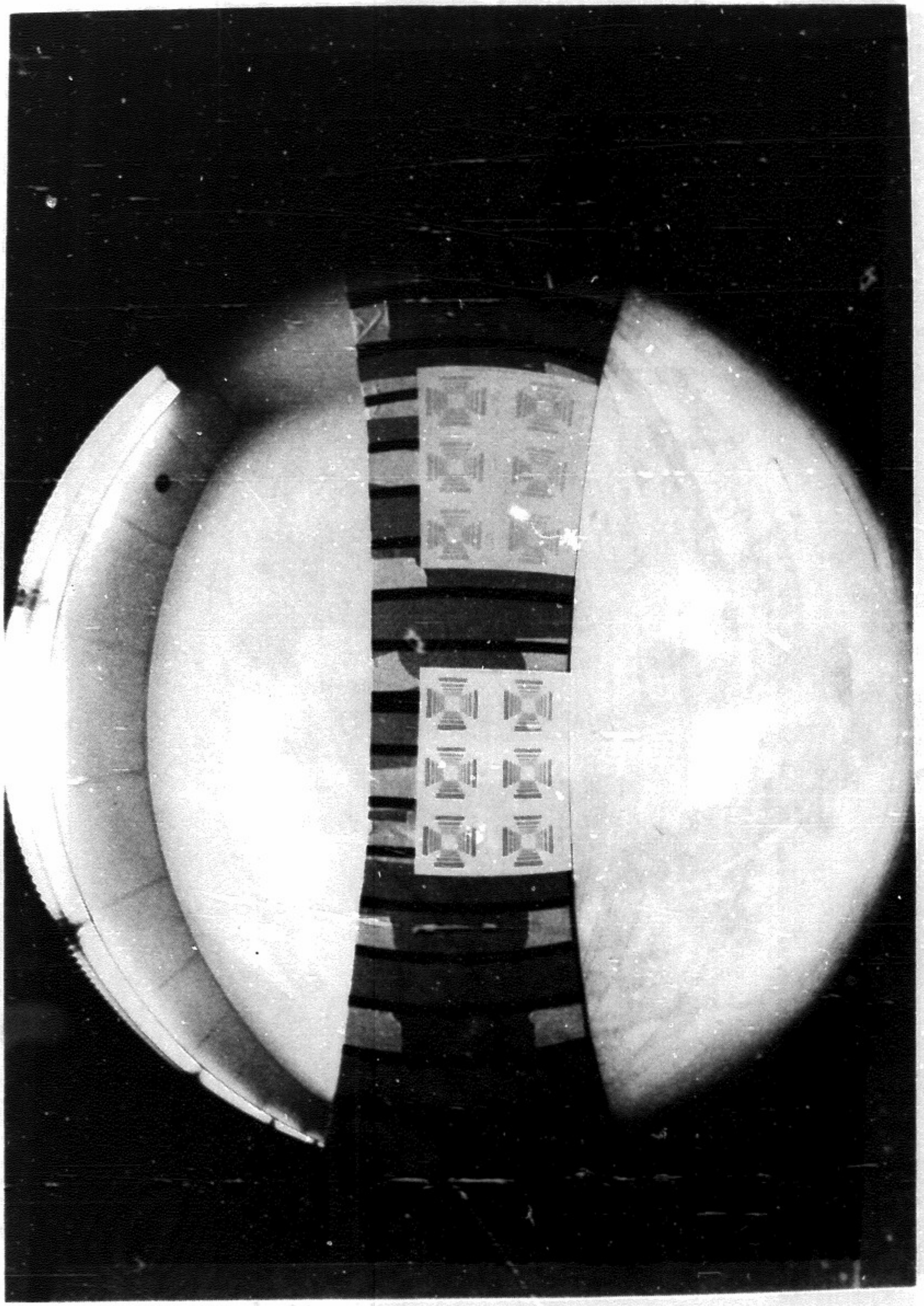

Figure 7. Resolution Test

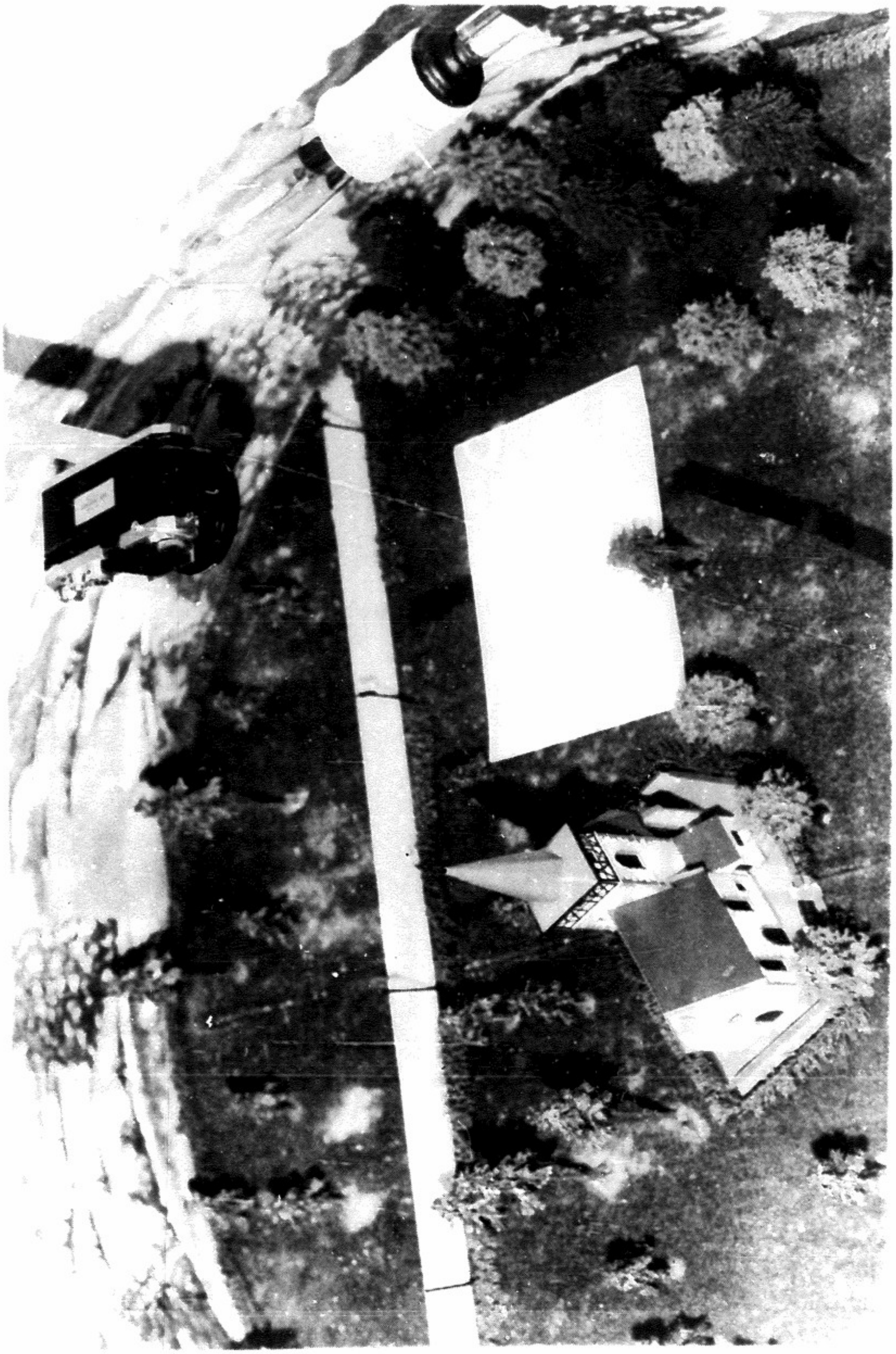

Figure 8. Terrain Resolution Test

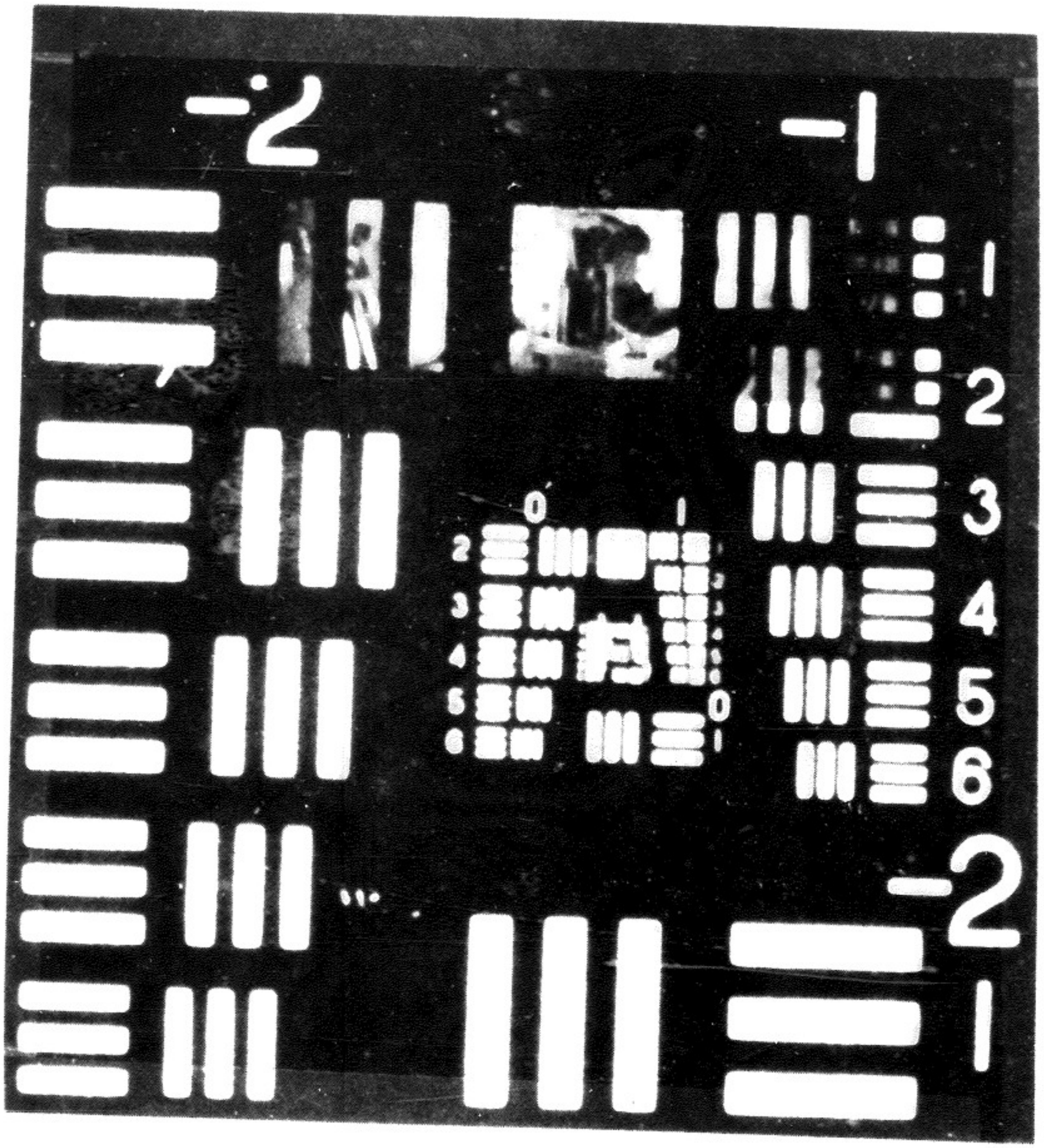

Figure 9. Resolution Target with Incoherent Light

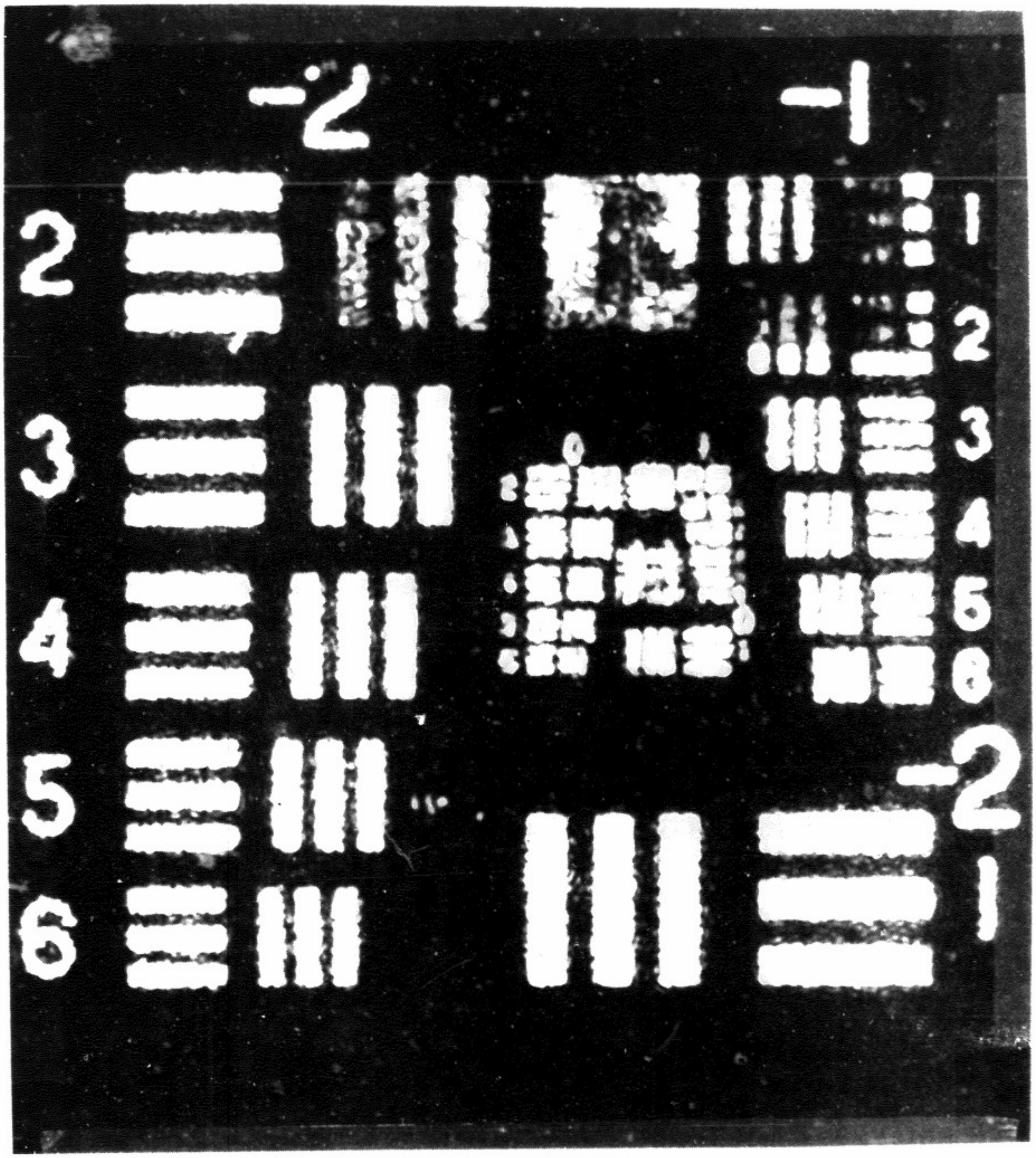

Figure 10. Resolution Target with Coherent Light

the reproduced photographs, an analog transparency was readily recognizable in the area adjacent to the -1,1 target in figure 9 but was completely unintelligible in figure 10.

Figure 11 shows the components in the object beam path. The object illumination could be varied by changing the character of the screen immediately proceeding the object transparency.

Figures 12 and 13 show the appearance of the object transparency when illuminated with the beam coming directly from the collimator (in figure 12) and illuminated with diffuse laser light generated by a ground glass at the screen position (in figure 13). The direct illumination had image defects associated with coherent noise due to imperfections in the optical train such as dirt, scratches, spurious reflections, etc. The diffuse illumination exhibited speckle.

A compromise between the two types of defects is realizable by redundant illumination. The mask used to generate redundancy was less than optimum but served to demonstrate the technique. The mask was fabricated from a 130 line-per-inch half-tone screen which was photoreduced to a 1300 line-per-inch, 40% dot screen on a 649-F photographic plate. Figure 14 shows the object transparency when illuminated by the 1300 line screen.

Most of the problems in the holographic recording involved mechanical positioning of the hologram recording plate and the object transparency. This lack of precision location of individual frames led to image displacements in the final display. Other experimental problems encountered were common to most holographic experimentation, i.e., optimizing display by variation of exposure, beam ratio, processing procedures, etc.

Display. The display geometry is shown in figures 15 and 16. The displayed images resolved approximately 20 lines/mm at a 5mm hologram size as predicted. The contrast of the holograms was poor and the overall noise was excessive. A typical displayed image is compared with the initial input in figures 17 and 18. An attempt to judge image stability as the hologram array was scanned was unsuccessful due to the inability to correlate image motion independent from that caused by object transparency motion between exposures when making individual holograms. Another result which will require correction in a final system is the fall off in illumination level between frames. This effect would be minimized by a larger illuminating beam.

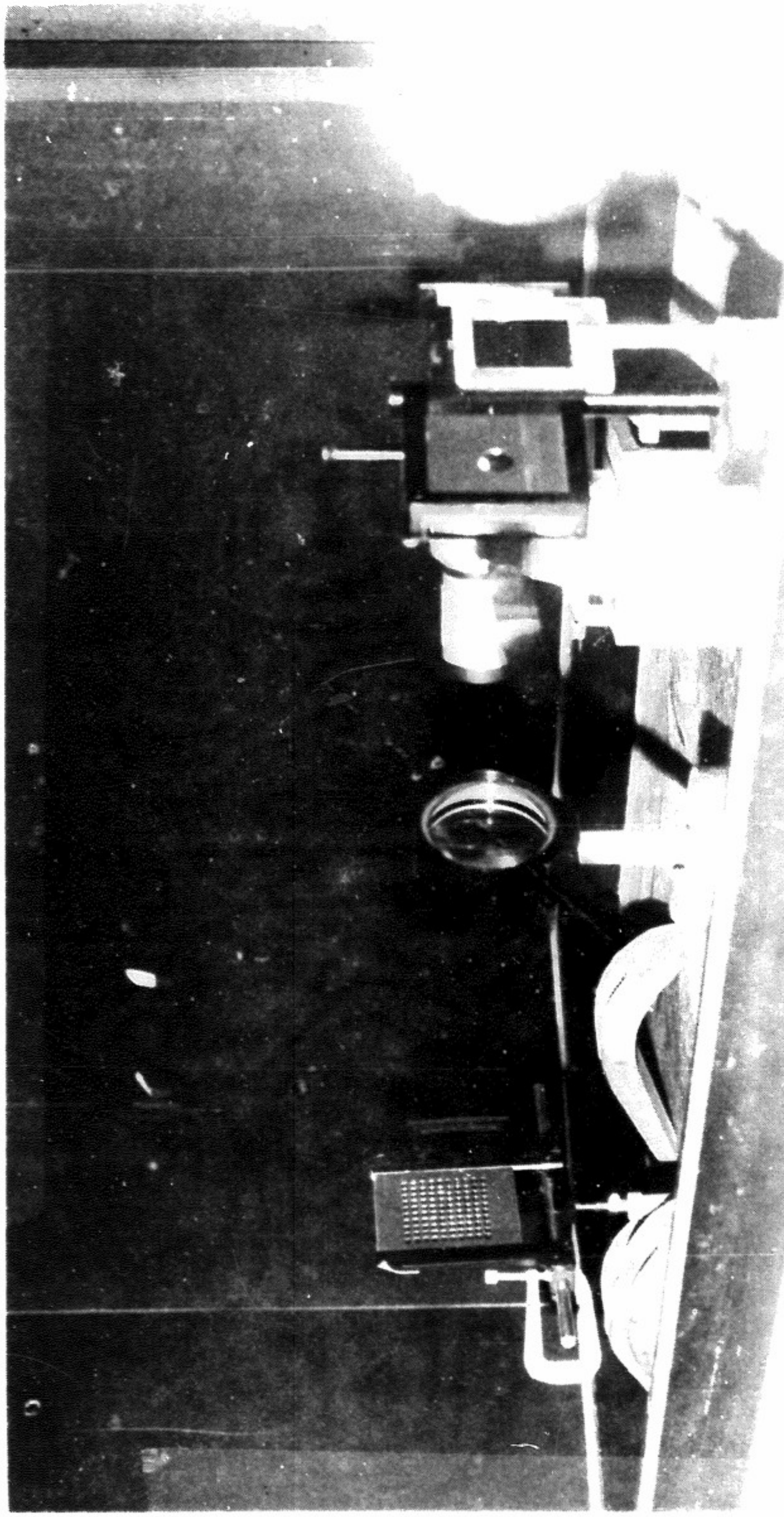

Figure 11. Object Beam Components

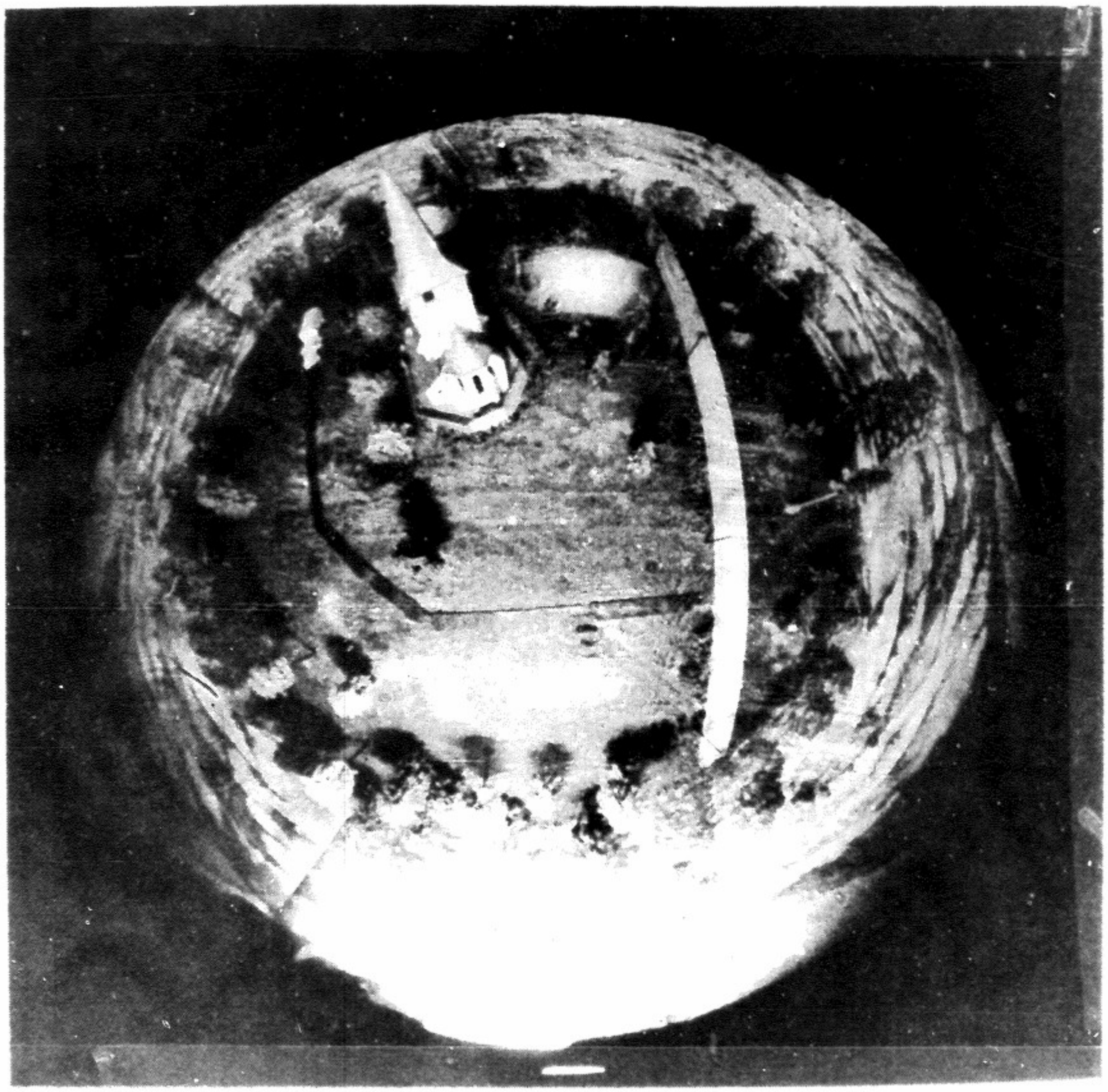

Figure 12. Direct Illumination

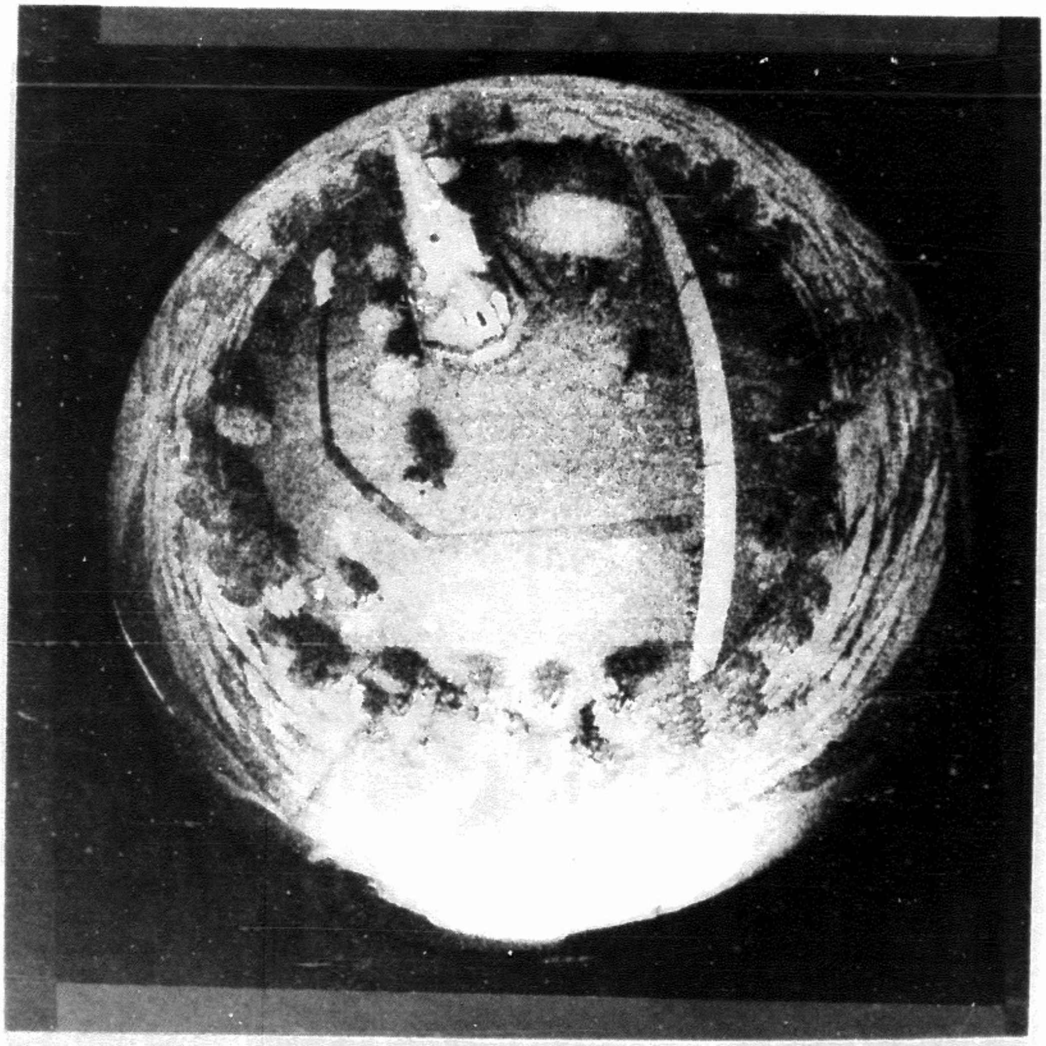

Figure 13. Diffuse Illumination

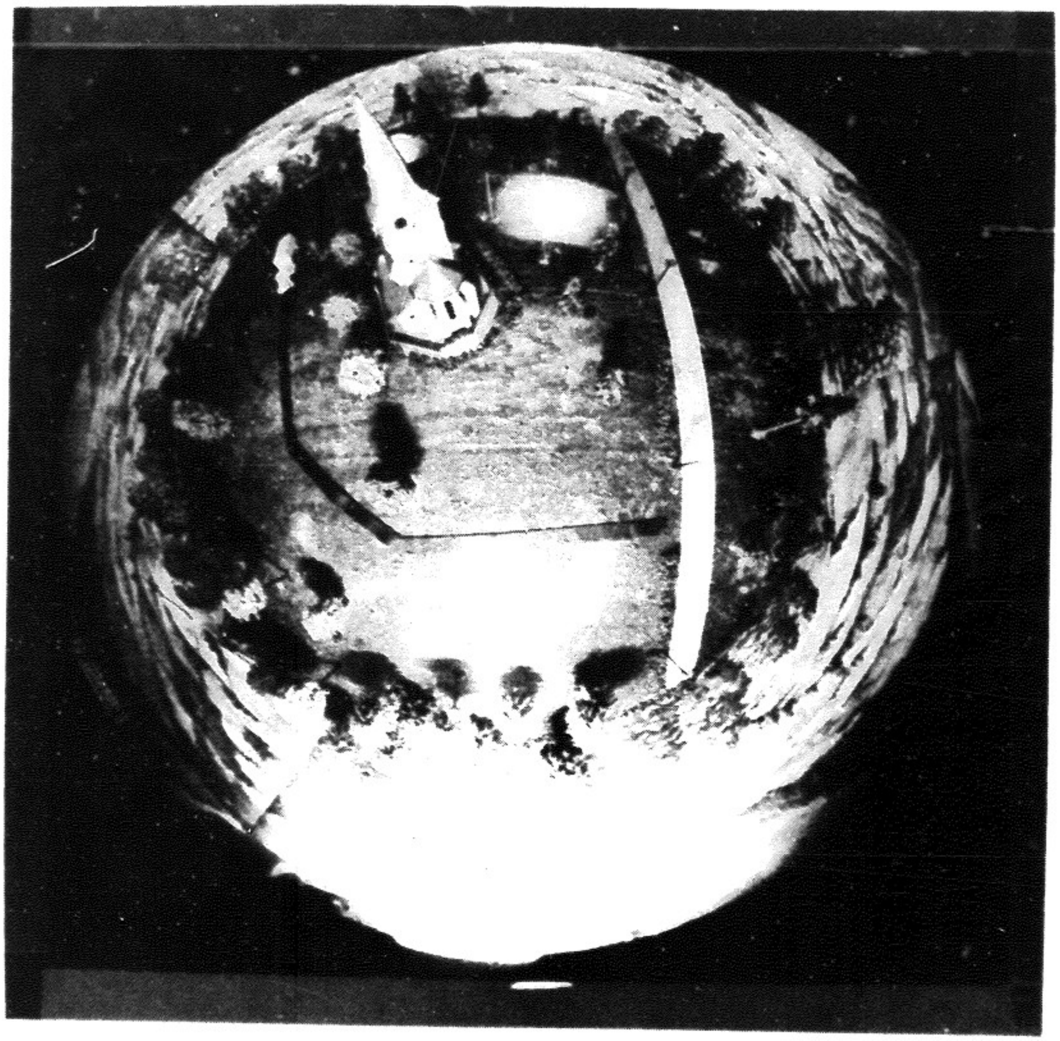

Figure 14. 1300 Line Screen Illumination

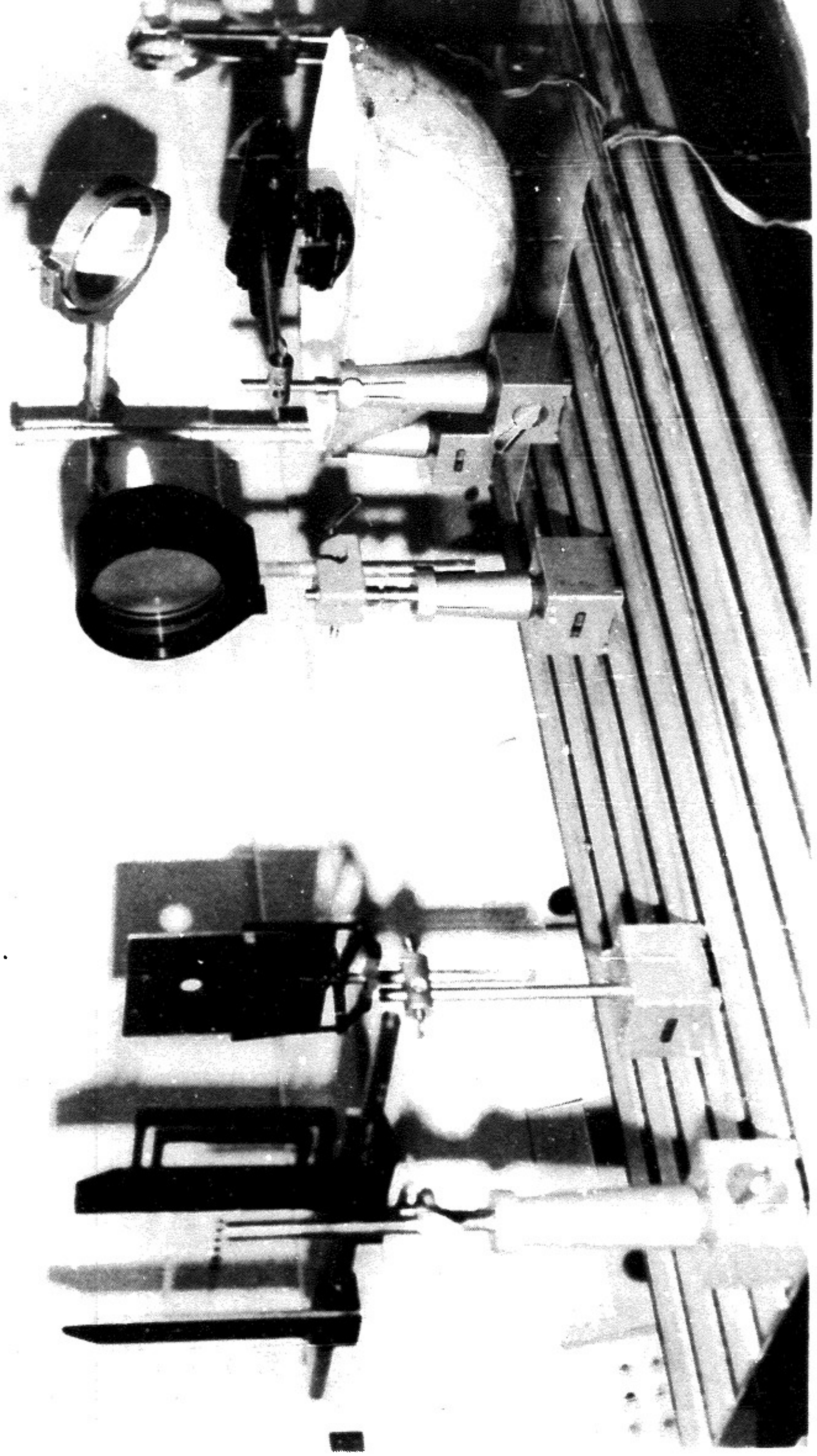

Figure 15. Display Geometry

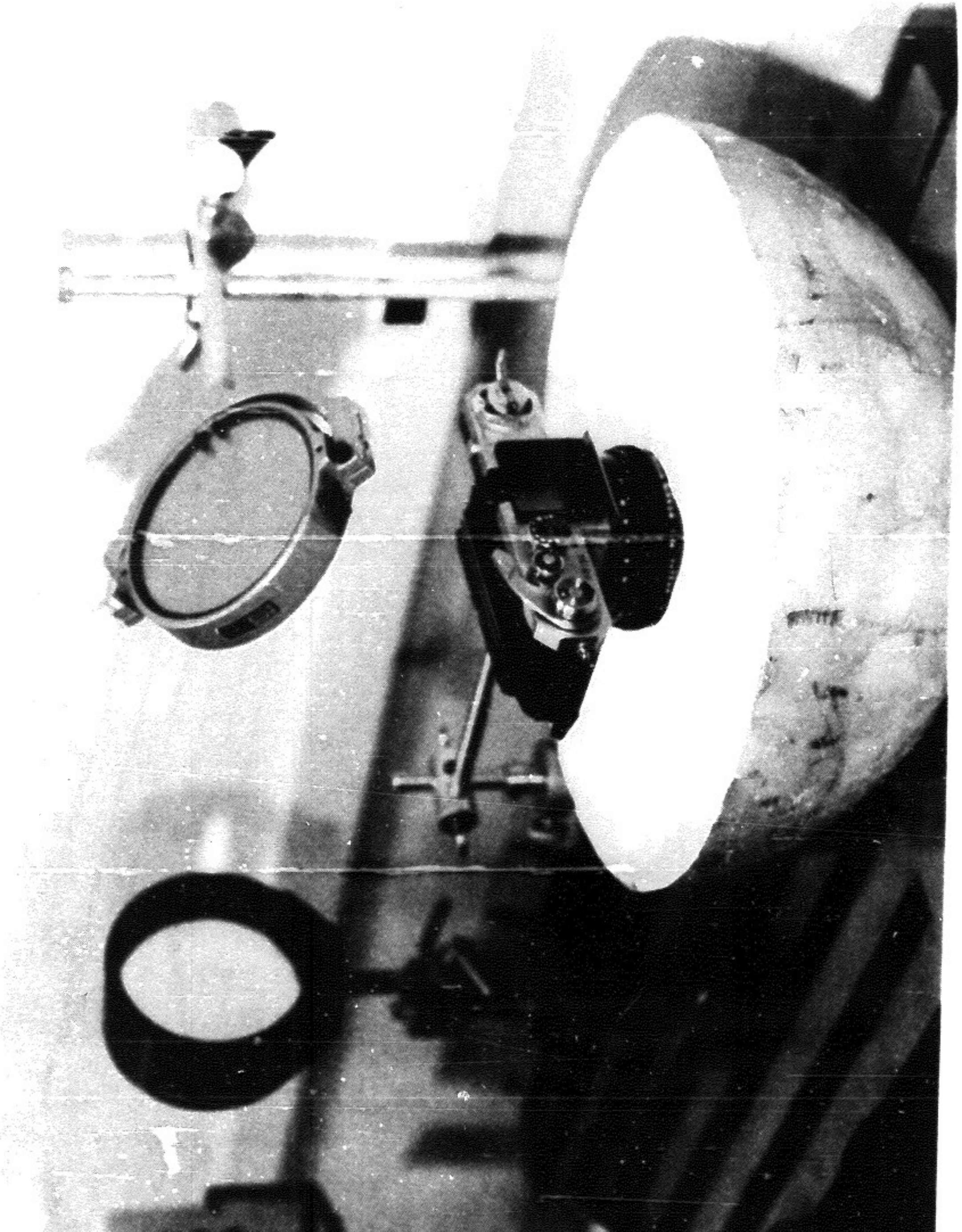

Figure 16. Projection

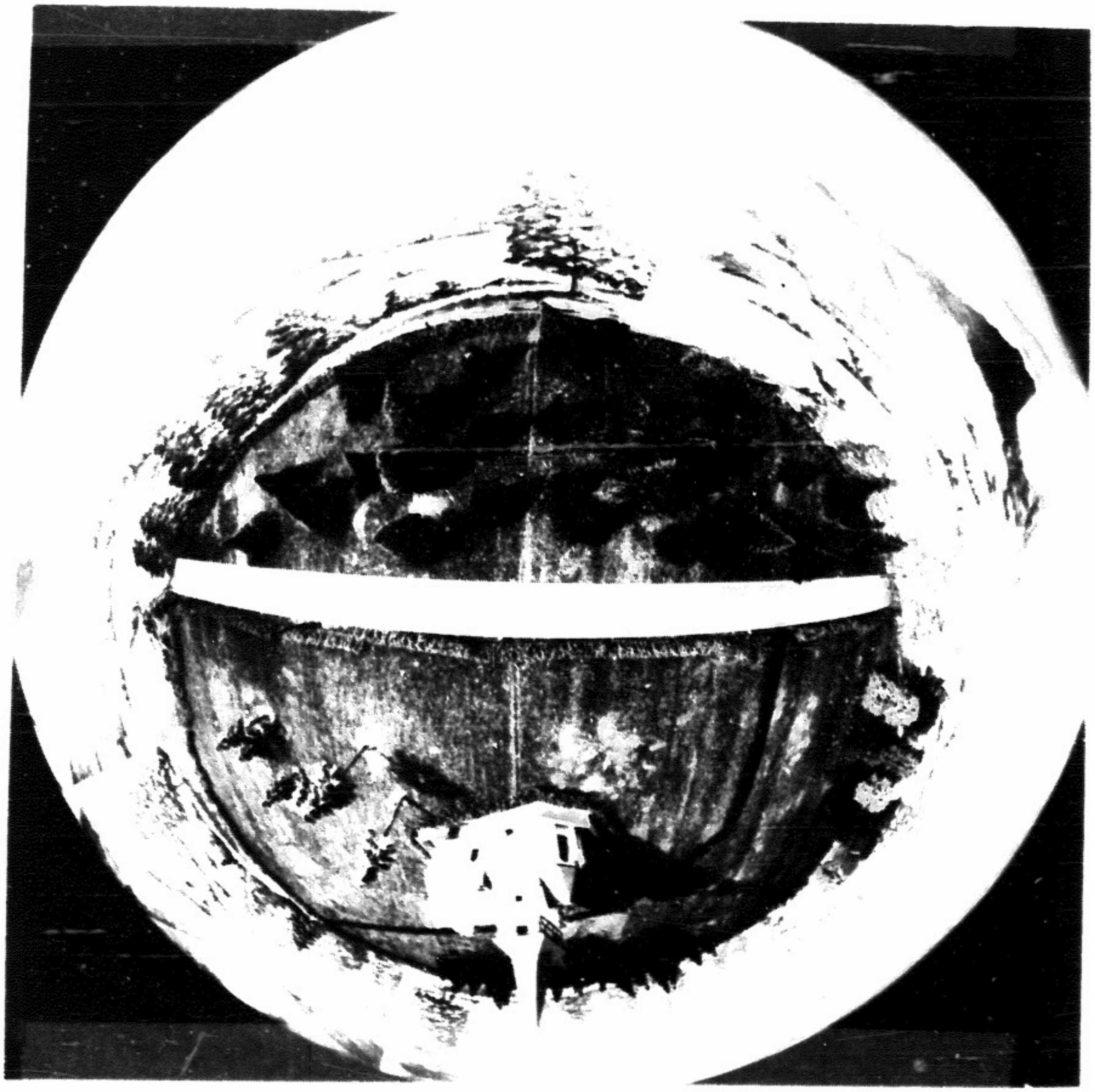

Figure 17. Initial Image

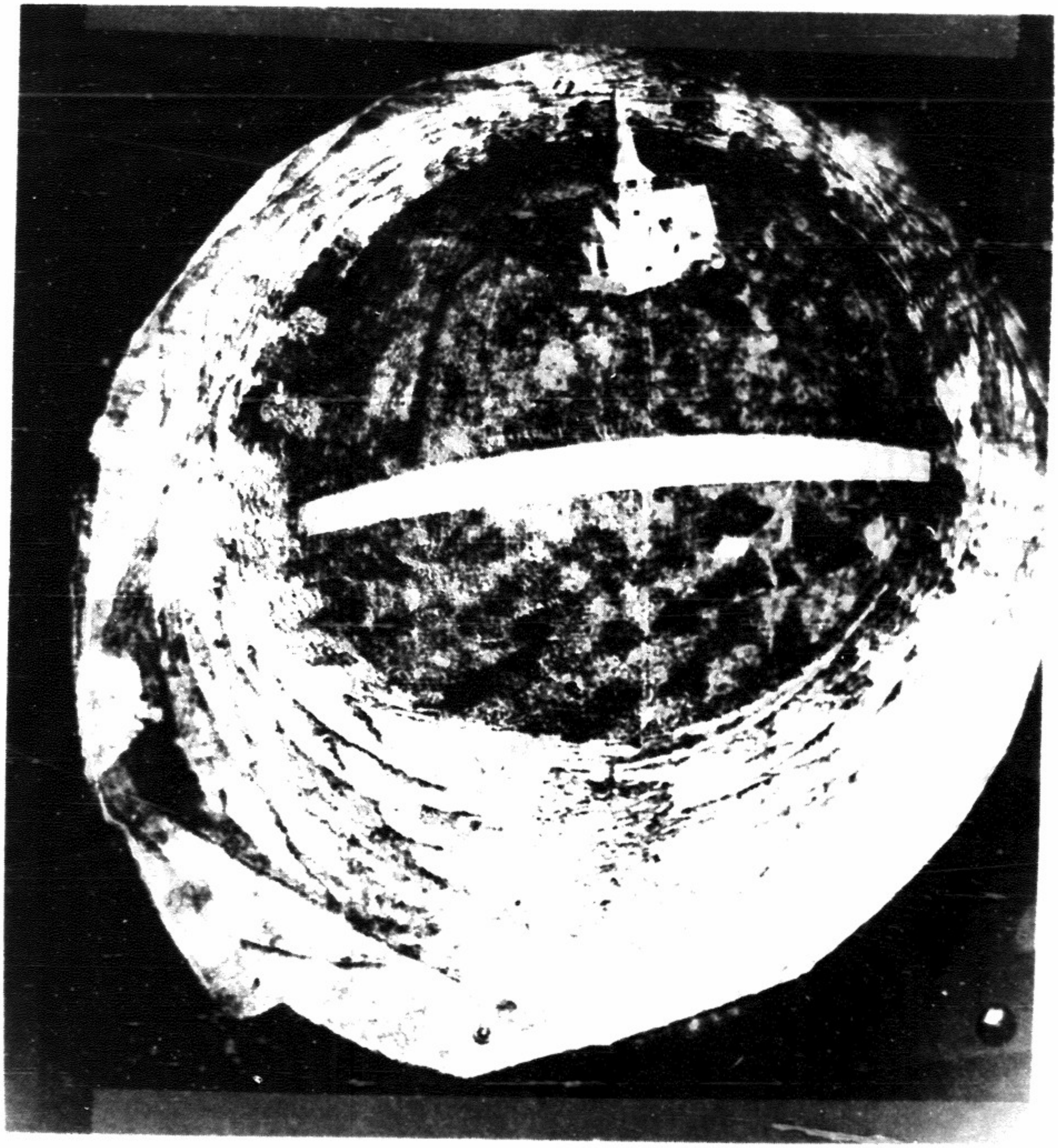

Figure 18. Final Image

SECTION VI

CONCLUSIONS AND RECOMMENDATIONS

The results of this initial feasibility study indicate the potential feasibility of all system components. However, further studies will have to be made to define a practical system design. The following paragraphs outline the various studies and experimental efforts required prior to system prototype design and fabrication.

REQUIREMENT

Current and future training requirements should be analyzed to determine the required size of the gaming volume as well as the minimum distance of approach to an object outside the gaming volume. The areas in which closest approach can occur should be quantified. The minimum and maximum velocities (speed and direction of travel in three dimensions) should be determined. Rotational angular rate maxima should be determined. The minimum allowable resolution for both high and low contrast targets for both monochrome and multicolor situations should be defined.

PHOTOGRAPHY

Based on the above requirements, a study should be made to determine the number of individual photographs required. A lens-camera-film system capable of exceeding the desired single frame resolution requirement should be chosen.

HOLOGRAPHY

A holographic recording system should be designed with the following system characteristics in mind: the input transparencies should be registered within the final resolution tolerance as translated into allowable film image motion, the hologram recording material should be capable of being indexed into position both in two translation degrees of freedom and one rotational degree of freedom, the reference beam should be capable of independently varying its incident angle to any of several discrete values without changing the point of incidence, and the entire system should be highly automated to minimize the time required to produce a large number of holograms.

DISPLAY

A display system should be designed which allows both apparent observation point translation in three dimensions and rotation of viewing direction about three axes (consistent with initial system requirements). The display geometry should be optimized together with the recording geometry so that display illumination has minimum fall off when changing frames.

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