LUNAR SURFACE HOLOGRAPHY EXPERIMENT INSTRUMENT FEASIBILITY DEMONSTRATION

by

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SECTION I

INTRODUCTION

A. BACKGROUND

The present contract developed from an earlier proposal, "Lunar Surface Holography",[1] submitted jointly by the University of Arizona and Hughes Aircraft Company to NASA on 20 October 1969. The purpose of this contract is to demonstrate the feasibility of the lunar surface holography experiment by fabricating and evaluating a prototype holocamera and playback system. This final report describes the design and construction of the holographic system, provides the results of tests made on the system, and makes a detailed estimate of the size, shape, and weight of an Apollo qualified version of the holocamera.

The prototype holocamera was built to demonstrate the particular function of examining in detail small areas of the lunar surface layer. However, it should be clear that other functions of possible interest in lunar surface investigations can be achieved with simple design changes. Examples are: (1) covering a larger object volume of approximately 5 cm diameter by 10 cm deep, with 10 to 20 μm resolution; (2) incorporating auxiliary optics to allow precise positioning of a particular object in the field of view; and (3) modifications to allow recording objects even though they may be in relatively inaccessible areas. It should also be stated that although the prototype was built to resemble a lunar surface instrument, it has many nonessential features which are designed for ease of demonstration and examination of the holocamera rather than astronaut usage.

B. STATEMENT OF THE PROBLEM

The lunar soil, which is not necessarily representative of the optical surface layer, has a median grain size of 62 μm and a modal grain size of 20 μm (Ref. 2). Over 95% of the soil by weight consists of particles larger than 8 μm, while the number of particles increases with decreasing grain size to at least 1 μm (Ref. 2 and 3). Adequate observation of the optical surface layer thus requires resolution of at least a few microns. The problem encountered in making optical observations at high resolution is indicated by the fact that a diffraction-limited lens with an effective relative aperture (f/number) F, resolves about $F\lambda$ on the short conjugate side of the lens and has a depth of field of approximately $F^2\lambda$, where λ is the light wavelength. For 5 μm resolution, $F \lesssim 10$, giving a depth of field of approximately 0.05 mm. This is the familiar *optical slicing* effect observed in the use of a microscope. An ordinary photograph taken through a high resolution optical system, necessarily at a fixed focus, therefore provides information over only a very limited depth. Coverage of a 2 mm deep surface layer with 5 μm resolution would thus require an astronaut to set up and manipulate a photographic microscope on the lunar surface and record 40 to 50 images at each site. The astronaut has neither the manual dexterity nor adequate time to perform these tasks. A stereo-pair photograph does not alleviate the problem because it is still a fixed focus recording. The compromise represented by the Apollo Lunar Surface Closeup Camera (ALSCC) (Ref. 4) is to put the film on the short conjugate side of the lens, in a camera-type optical system, thereby gaining depth of field and field of view but losing resolution. The ALSCC allowed *in situ* observation of a 72 x 83 mm lunar surface area with an in-focus resolution of 85 μm and a depth of field of about 1 cm in a single stereo-pair photograph. These are the only *in situ* observations to date offering even moderately high resolution.

The alternative provided by holography is to record the actual light wave[5] scattered from the surface under observation. The wave is reconstructed from the returned hologram and an aerial image of the entire object volume is formed. Various layers of this image can be observed and/or photographed through the appropriate optical system. The depth of focus for high resolution imagery is still quite small at any particular focal setting, but scanning of the object volume has been transferred from the lunar surface to the earth. Thus, although the depth of field at a given focus setting is quite limited, focus can be adjusted over a considerable range, to provide a much increased usable depth of field. It is this ability of a hologram to record a light field rather than a light intensity distribution that is exploited in the lunar holocamera.

SECTION II

HOLOGRAPHIC CONSIDERATIONS

Since a hologram is an optical interference pattern, a light source of adequate coherence must be used, and the pattern must be held stable during the recording period.[5] For holograms of a diffusely reflecting object, this implies a source with a high degree of transverse coherence and a longitudinal coherence length of at least twice the depth of field to be covered in the object space. Relative movement between the object and the holocamera must be less than about 1/10 of the source wavelength (i.e., less than 0.1 μm during the hologram exposure). These requirements are discussed in Ref. 1 as they pertain to the lunar holocamera and the choice of a pulsed ruby laser light source.

A hologram can record an unfocused image of an object directly, or can record the image space of a magnifying relay lens. The research and design period preceding this contract showed that in order to achieve 5 μm resolution reliably in a conservatively designed system, a magnifying relay lens must be used. This is because high resolution requires a low effective f/number, and it is difficult, even in the laboratory, to reduce aberrations adequately in such a holographic imaging system. The relay lens requires less resolution and angular field of view from the hologram and therefore reduces the f/number requirements on the hologram. This approach has the disadvantage of the depth of field and the field of view being limited by the range of object distances and angles over which the relay lens can achieve high resolution. The system concept is illustrated in Fig. 1. For completeness, Appendix A consists of a discussion of the

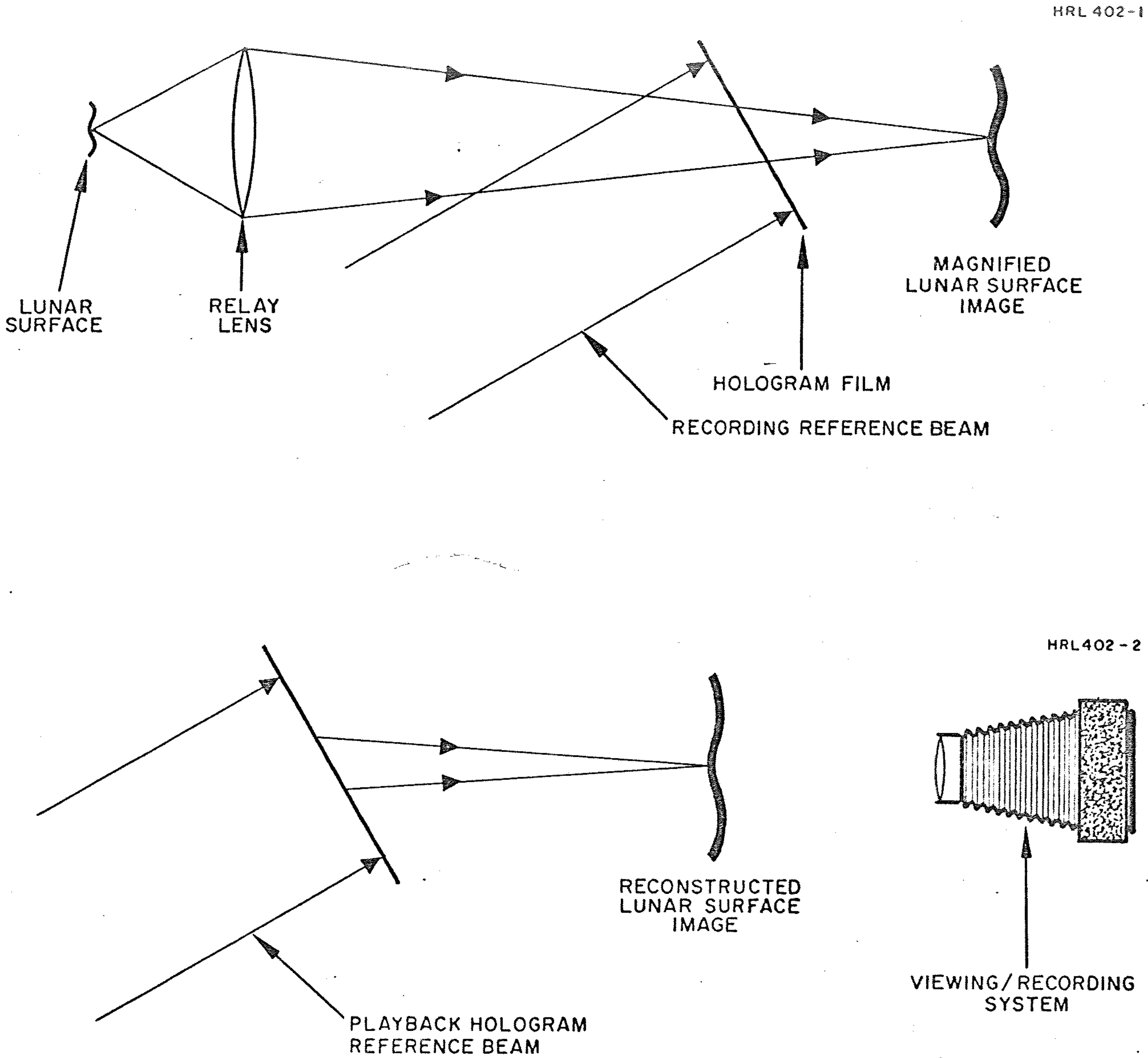

Fig. 1. The Holographic System Concept, Using a Magnifying Relay Lens. Top: Recording (Moon) Bottom: Playback (Earth).

limitations on resolution in holography as they pertain to the present system.

The other holographic consideration of importance is *speckle*, the random interference pattern observed in images that are recorded with coherent illumination. We have found that speckle is the limiting factor in obtaining high resolution performance with the holocamera. The speckle effect is shown in Fig. 2. Speckle is characterized by a 100% modulation of the image by a two-dimensional random pattern of light and dark spots of approximately the same size as the system resolution limit.[6] This pattern is visually very distracting and reduces the usable resolution in the image by a factor of two to five, depending on the object characteristics. Two techniques for reducing the effect of speckle were found to be usable in the present application. They consist of using a time varying diffuser in the playback system to trade off some resolution for speckle contrast reduction[7] and superimposing multiple images of one object, each image having an independent sample of the random speckle distribution.[7,8] The diffuser technique was found to be capable of providing 4 μm resolution. However, it was decided to add the superposition technique in an effort to achieve higher resolution and better image quality (see the second and third monthly progress reports). The modified design requires recording multiple holograms of the same object with different speckle patterns; the resulting images then can be incoherently superimposed[8] to reduce speckle contrast with no loss, and hopefully a gain, in resolution. Implementation of this modified design is described briefly in the next section.

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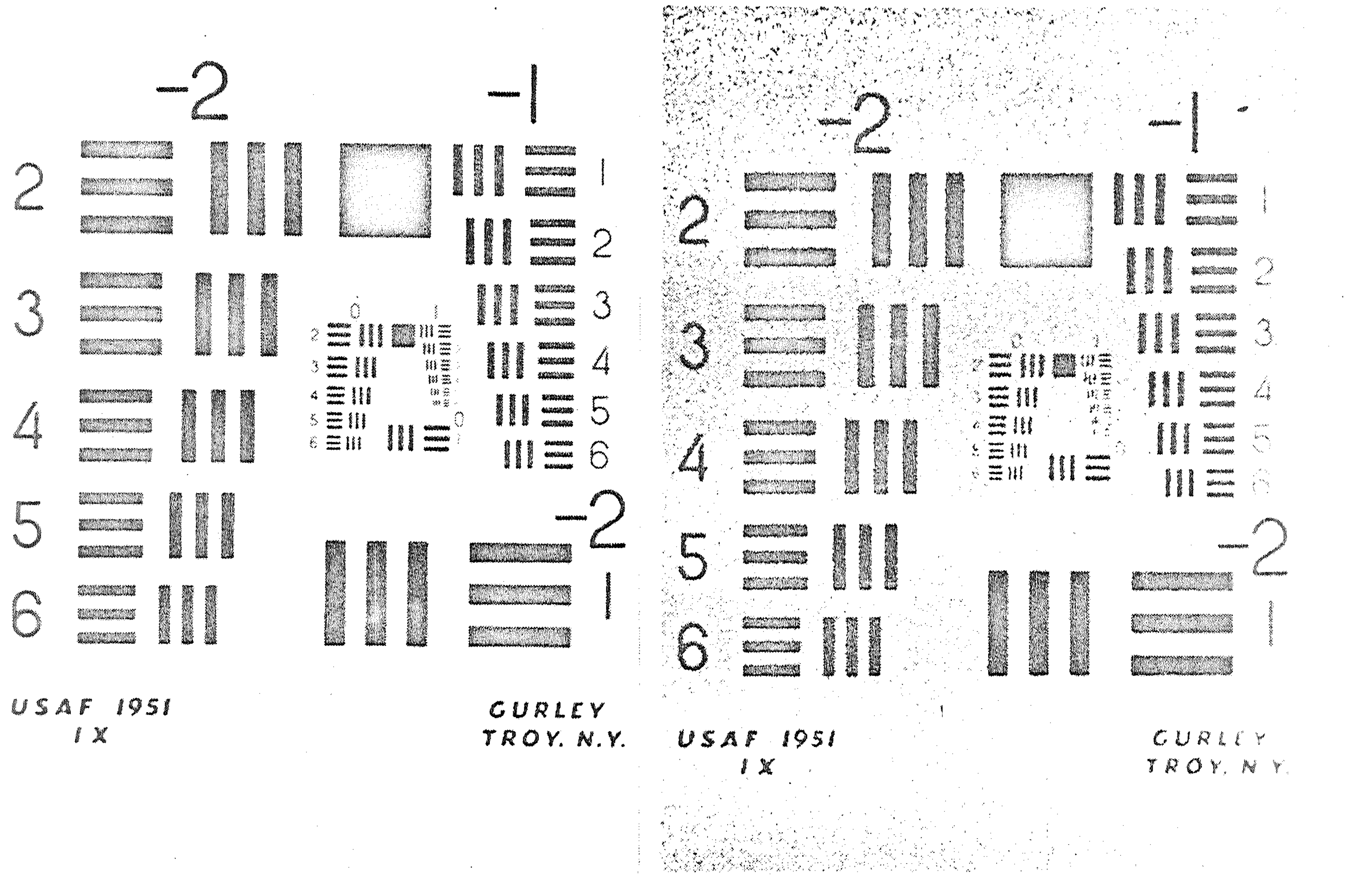

INCOHERENT ILLUMINATION   COHERENT ILLUMINATION

Fig. 2. Photographs of a Resolution Chart with Incoherent and Coherent Illumination.

SECTION III

HOLOGRAPHIC SYSTEM DESCRIPTION

The light source for the prototype holocamera is a mode-controlled, pulsed ruby laser with a pulse duration of 100 to 150 μsec, operating at 0.694 μm. The object is illuminated with an optical system that allows modification of the speckle pattern without changing the subjective characteristics of the illumination. A magnified image of the object is formed by a high quality relay lens. A 50 mm diameter collimated reference beam is used to record the wavefront holographically, forming this record on a 60 mm wide strip of film. A series of four holograms of each site is recorded automatically, with independent speckle patterns formed by adjusting the illumination. The sequence of four exposures requires about one minute to complete. Power is supplied by a silver-zinc battery pack. The holocamera is operated by a single push-button switch that is momentarily depressed to initiate the sequence. A red indicator light remains on during the sequence.

The hologram recording design allows hologram playback using a continuous He-Ne laser at 0.633 μm wavelength with no degradation of the image, despite the wavelength shift. Furthermore, the design provides straightforward access to both the primary and conjugate holographic images.[5] The playback system utilizes a time-varying diffuser plate to reduce speckle contrast at the expense of some resolution.[7] The availability of four holograms with independent speckle patterns provides the possibility of incoherently superimposing four images to reduce speckle effects and increase resolution.[8] Only rudimentary superpositions have been made (see Table I), but this technique should be quite useful if it is more fully developed.

Table I is a set of specifications for the holocamera.

TABLE I

PROTOTYPE HOLOCAMERA SPECIFICATIONS

Size: Case exterior: 12 in. x 13 in. x 6-1/8 in.

Weight:* 17.4 lb (with film)

Image characteristics with 23.6 mm focal length, NA 0.2 relay lens:

- Field of view: 4.5 mm diameter
- Depth of field: 4 mm
- Primary magnification range: 5X to 30X
- Resolution: 4.1 μm with one hologram
2.5 μm with superposition of 4 holograms**
2.0 μm with superposition of 6 holograms**

Light source: Pulsed ruby laser

- Wavelength: 0.694 μm
- Output energy: Approximately 20 mJ (exposure set for 10% reflectivity)
- Pulse length: 100 to 150 μsec
- Transverse coherence: Diffraction limited
- Longitudinal coherence length: 25 cm

Film: Eastman Kodak FW1248-1 holography emulsion

- Format: 61.5 mm wide, roll film; 48 mm diameter hologram
- Capacity: 24 exposures (6 four-hologram sequences)

Operation: Pushbutton switch initiates automatic sequence of four holograms; sequence duration is approximately 60 sec.

- Option: Changing two cams provides six holograms per sequence; duration approximately 90 sec.

Power source: Silver-zinc batteries

- Rating: 21 V, 0.05 A-hour (approximately 90 exposures)

*See Section VII for weight breakdown.

**Estimated performance; see text.

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SECTION IV

DETAILED DESCRIPTION OF HOLOCAMERA

The basic mechanical structure of the holocamera is an aluminum honeycomb panel 10.5 mm thick with 0.5 mm thick faces. Inserts have been bonded into the panel to provide for component mounting and optical and electrical feedthrough. All components are mounted on this honeycomb panel, the exterior case serving primarily as a light and dust shield. In the prototype instrument the exterior case is aluminum sheet approximately 2 mm thick; this is strong enough to allow mounting two support feet and two handles to the case rather than directly to the honeycomb panel. The action of positioning the holocamera on a surface opens the shutter in this prototype model. Two exterior views of the holocamera are shown in Fig. 3.

Components are mounted on both sides of the honeycomb panel. One side, shown in Fig. 4, has primarily the holocamera optics and is designated the *optics side*; the other side, shown in Fig. 5, has primarily the laser head and laser electronics and is designated the *laser side*. The battery pack is on the laser side, and the laser energy storage capacitors are on the optics side. DC motors are provided to advance the film and adjust the object illumination. Cams on these motor shafts operate microswitches to control the automatic sequence of four exposures.

The laser system was originally built for a military rangefinder[1] and was modified for use as a holographic source during the Hughes-funded research and design phase preceding the present program. The laser, modifications, and performance tests are described in Appendix B. The high degree of

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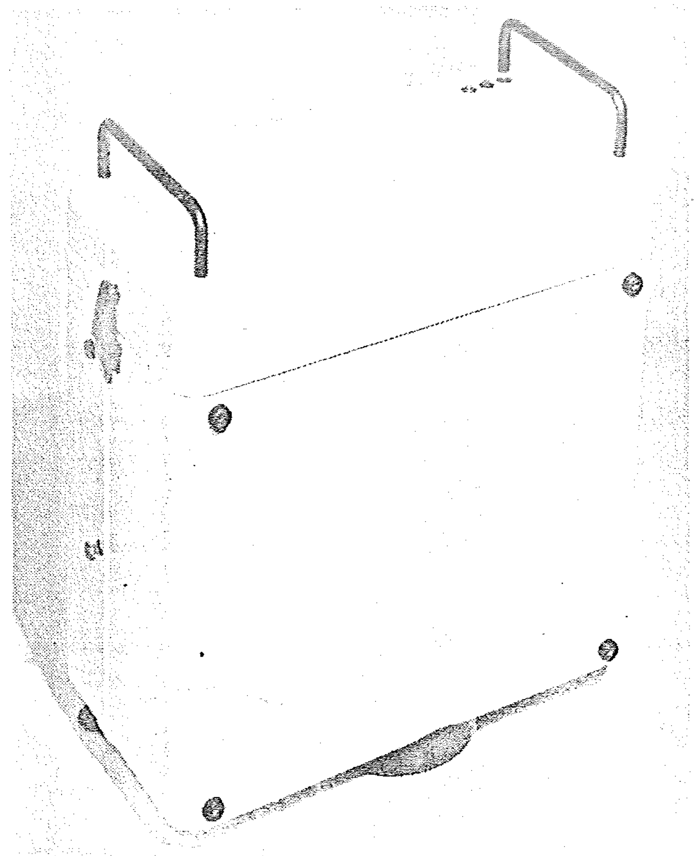

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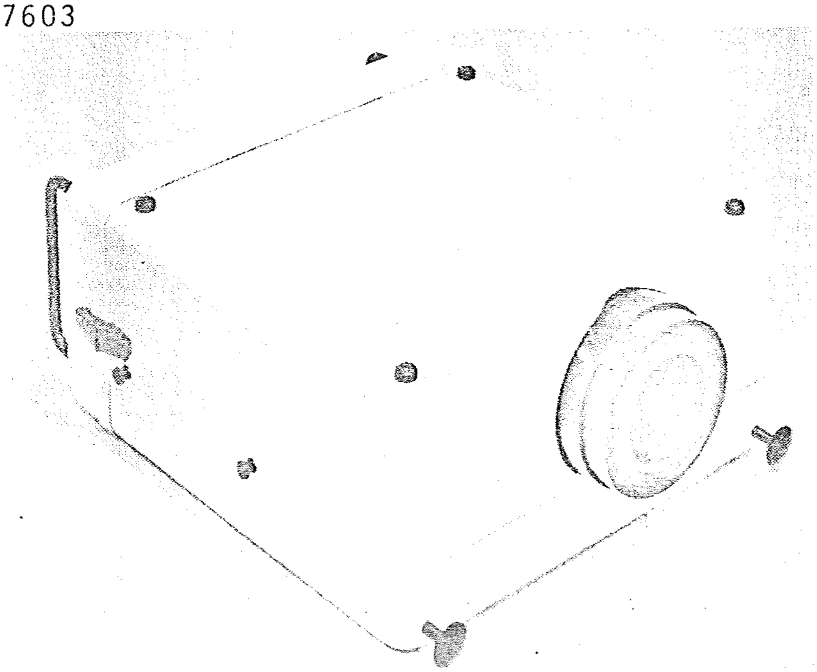

Fig. 3. The Prototype Holocamera Exterior.

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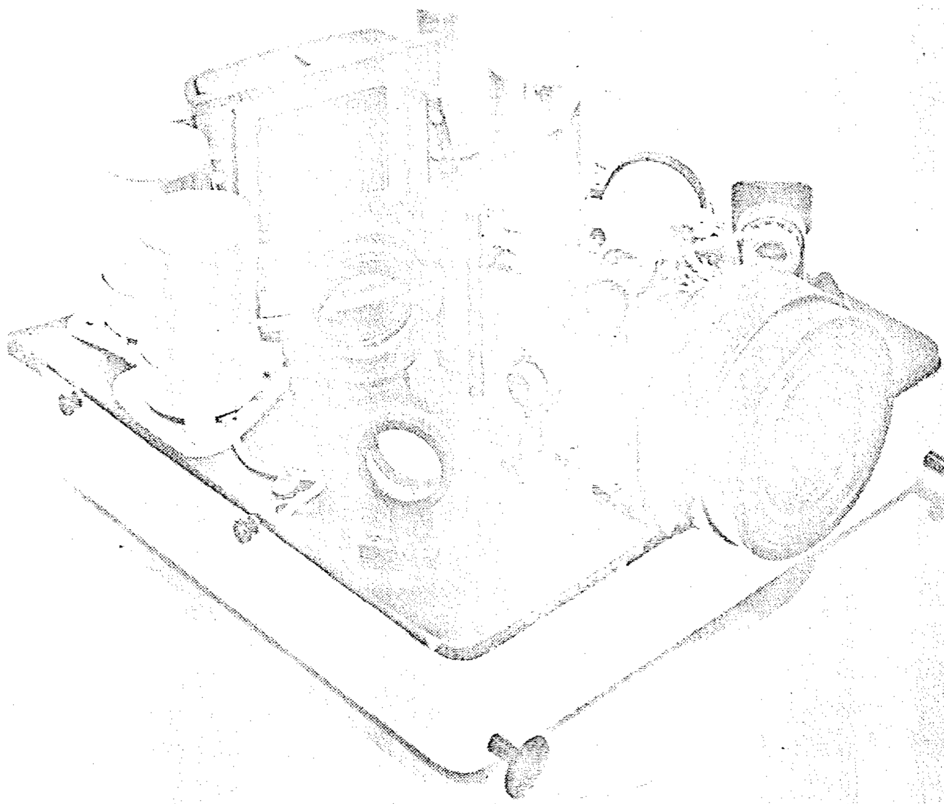

Fig. 4. The Prototype Holocamera Interior: Optics Side.

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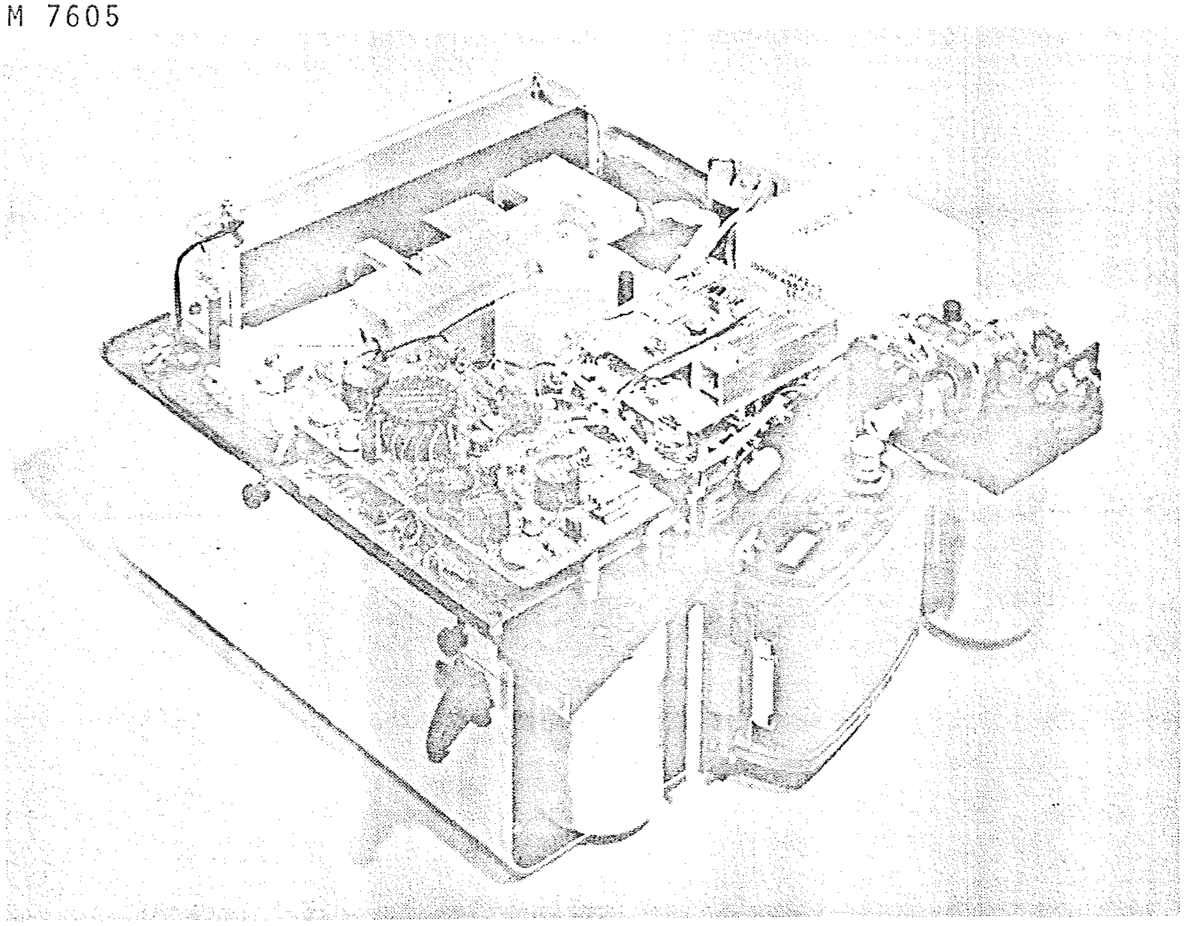


Fig. 5. The Prototype Holocamera Interior: Laser Side.

transverse coherence and a longitudinal coherence length of 25 cm, combined with excellent stability and reproducibility, provide a very high quality source for holography.

Figure 6 is a schematic diagram of the holocamera optics. The laser output is fed through the honeycomb panel to the optics side by a high reflectivity dielectric mirror. A 45° dielectric beamsplitter removes about 15% of the laser output for the reference beam. This beam passes through a 50 mm, f/4 recollimating telescope to provide the reference beam. The remainder of the laser output is used to illuminate the object through the optical system diagrammed in Fig. 7. This illumination system allows the speckle pattern to be modified by rotating the wedge plate, which deviates the beam by 6 mrad, but does not change the illumination angle or subjective quality of the illumination. The last optical surface in the illumination system is ground to act as a scatterer. This assures a completely changed speckle pattern in the image with a small rotation of the wedge plate, and provides diffuse illumination of the object. In order to keep the illumination speckle pattern produced by the ground surface finer than the image speckle pattern produced by the relay lens, the angle subtended by the ground surface at the object is made larger than the angle subtended by the relay lens entrance pupil at the object. Although designed for 6.3X magnification, the 23.6 mm focal length relay lens performs satisfactorily over a range of magnifications from about 5X to more than 20X, giving a depth of field of 4 mm. The holocamera geometry and the lens characteristics provide a 4.5 mm diameter field of view. The optimum relay lens would have a focal length of about 75 mm and would be corrected to provide high resolution over a 1 cm diameter field with a depth of field of about 1.5 cm; somewhat lower resolution

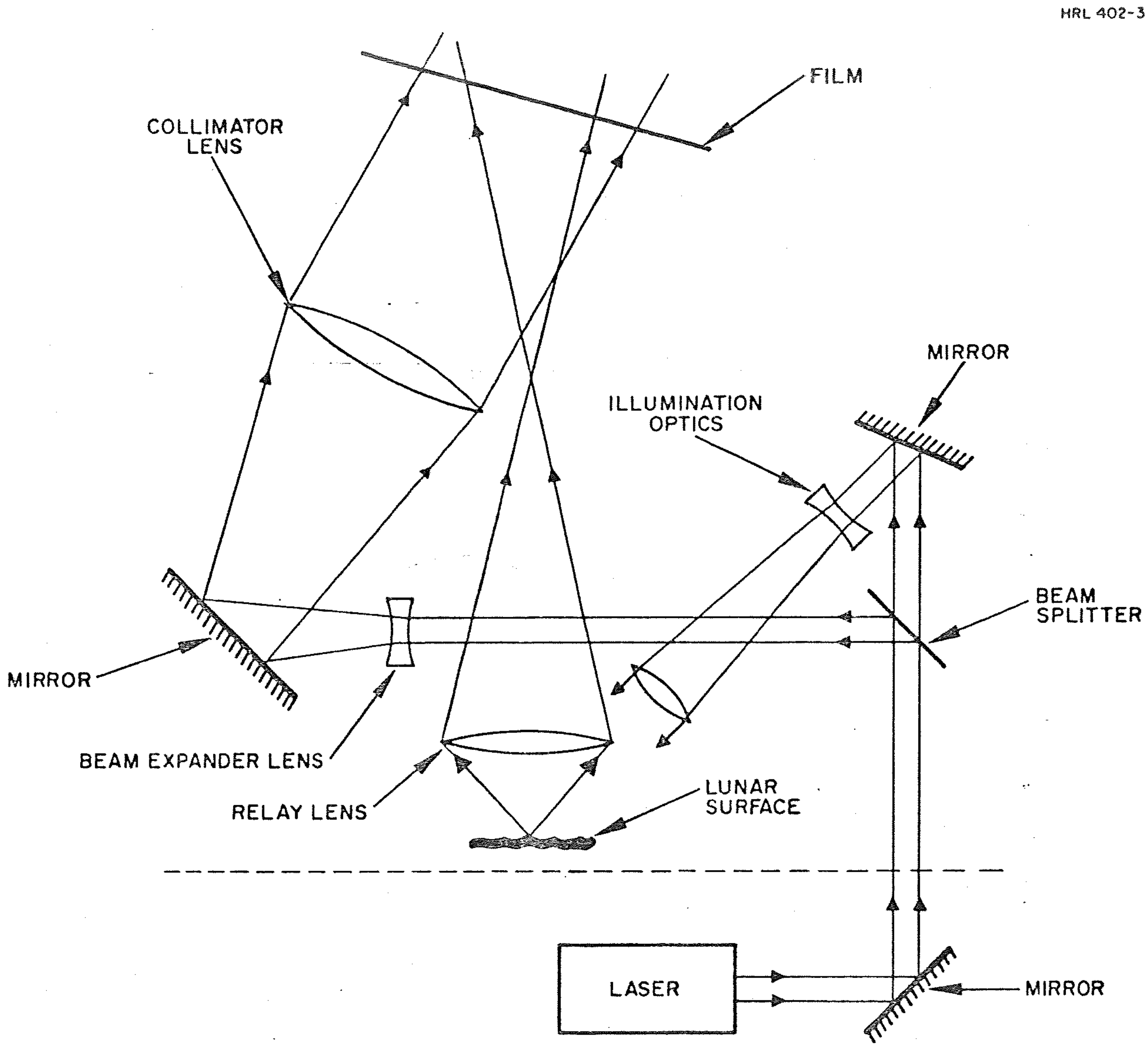


Fig. 6. Schematic Diagram of the Prototype Holocamera Optical System.

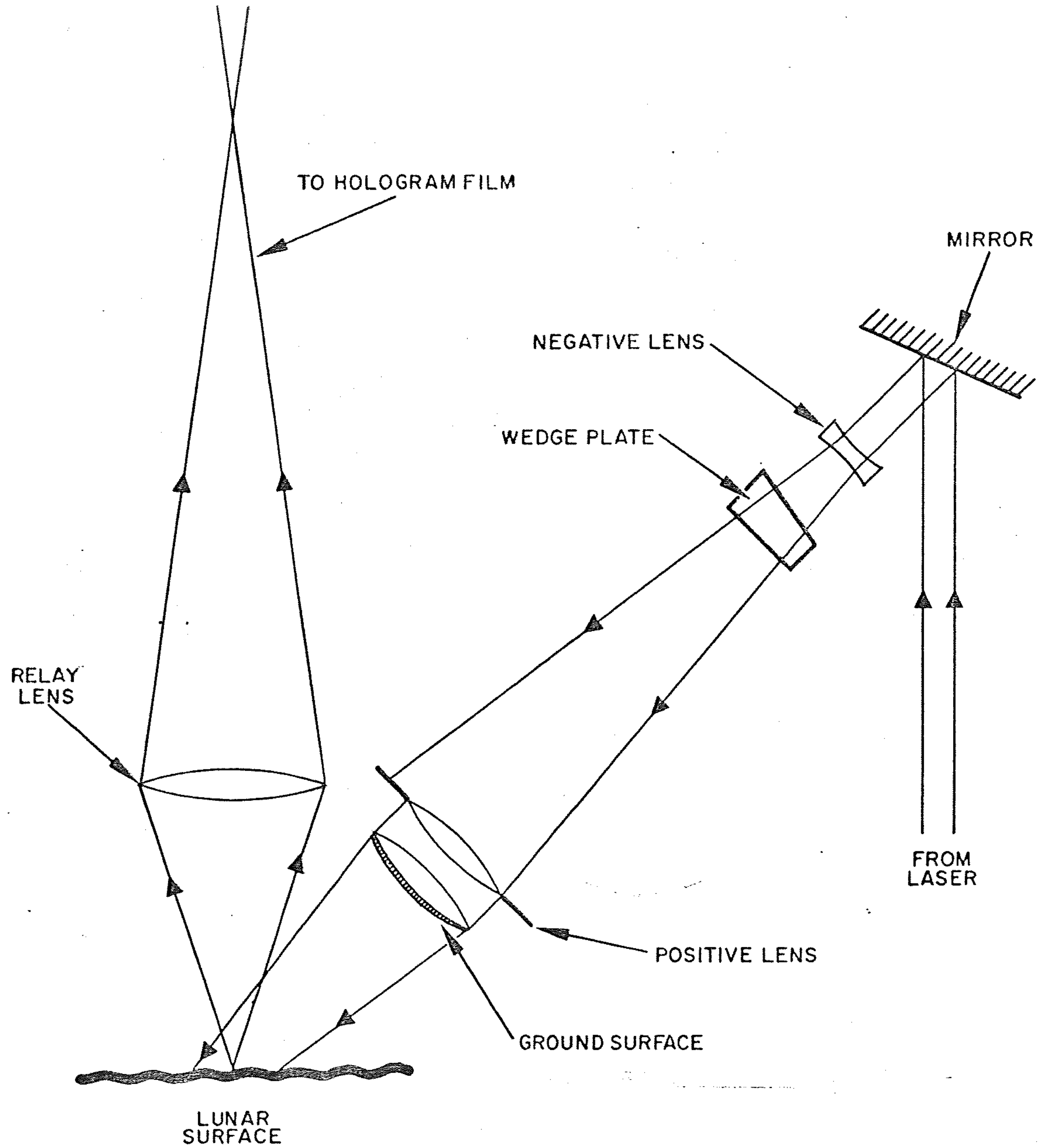


Fig. 7. Schematic Diagram of the Prototype Holocamera Illumination Optics.

would be available over a still larger volume. Design and manufacture of this lens is straightforward, but there was not sufficient time to acquire it for this program (see the first monthly status report). The reference beam is nominally oriented at 30° to the object beam; the normal to the film plane is coplanar with the object and reference beams and bisects the angle between them. The latter arrangement minimizes aberrations[9] (see Appendix A).

The automatic operation of the holocamera is initiated by a single pushbutton switch and is controlled by cam-microswitch assemblies driven by the dc motors which advance the film and rotate the wedge plate. Varying the number of exposures per sequence only requires changing two of these cams. A block diagram of the holocamera electronics is shown in Fig. 8(a). The control is sequential, with the completion of one function initiating the next function. The film is advanced at the beginning of the sequence and after each exposure, leaving a blank frame between each set of four holograms. The illumination is adjusted by rotating the wedge plate before each exposure. The exposure is triggered when the laser completes its charge cycle. The entire sequence of four exposures requires about 60 sec; this time increases slightly with temperature and as the battery charge is depleted. The time sequence of events is shown in Fig. 8(b).

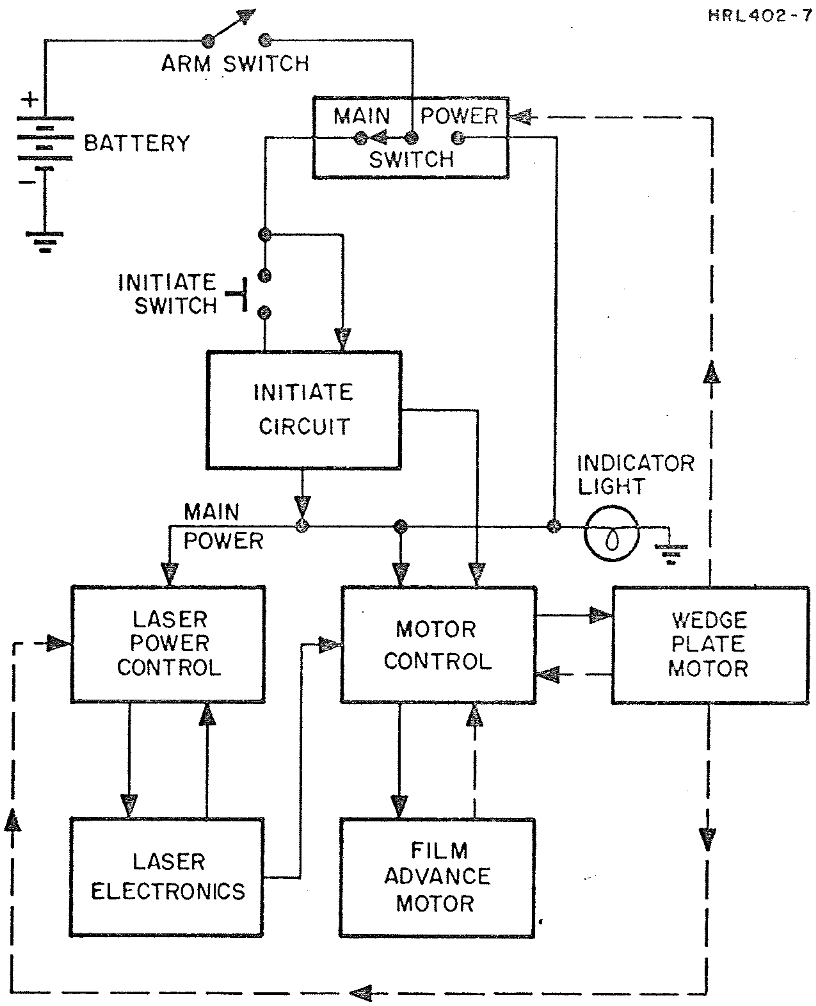


Fig. 8(a). Block Diagram of the Prototype Holocamera Electronics.

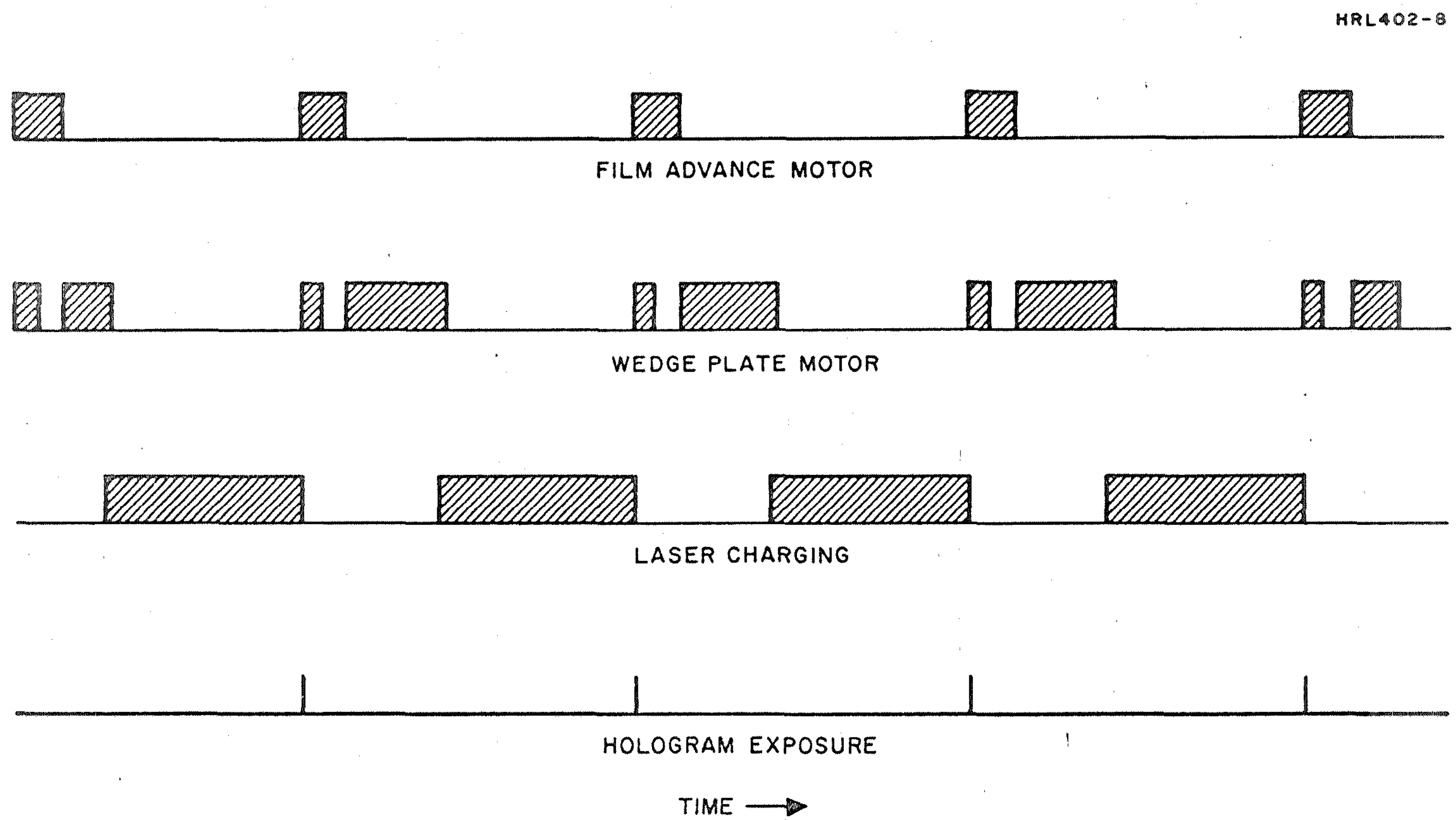


Fig. 8(b). The Prototype Holocamera Operational Sequence.

SECTION V

PLAYBACK SYSTEM DESCRIPTION

The normal image reconstruction system is straightforward, consisting of a continuous He-Ne laser (0.633 μm wavelength), a collimator to provide a reconstruction reference beam, and a fixture to hold and orient the hologram.[5] An adjustable, time-varying (rotating), diffuser plate is inserted in the collimator to provide controlled speckle contrast reduction.[7] The system is shown schematically in Fig. 9. The hologram is oriented in the playback system by minimizing astigmatism in the image. A specular point in the image is best for this procedure, but any image detail is adequate. There is a wide choice of systems for viewing and recording the reconstructed image: The image can be viewed directly on a ground glass screen or photographed by placing film at some level in the reconstructed image space; an eyepiece or a low power microscope can be used to visually examine the image; or a camera can be used to photograph the image. In practice, several of these techniques are used on each hologram. It is noteworthy that a camera used to record the image can be adjusted to compensate for the differences in magnification present in different levels of the image space. One can thereby duplicate directly the constant-magnification imagery that would be observed by focusing a microscope through the object volume.

No equipment was developed for direct superposition of images from the set of four holograms produced by the holocamera, since the contract did not allow time nor provide funds for this work. Some superposition work was done by

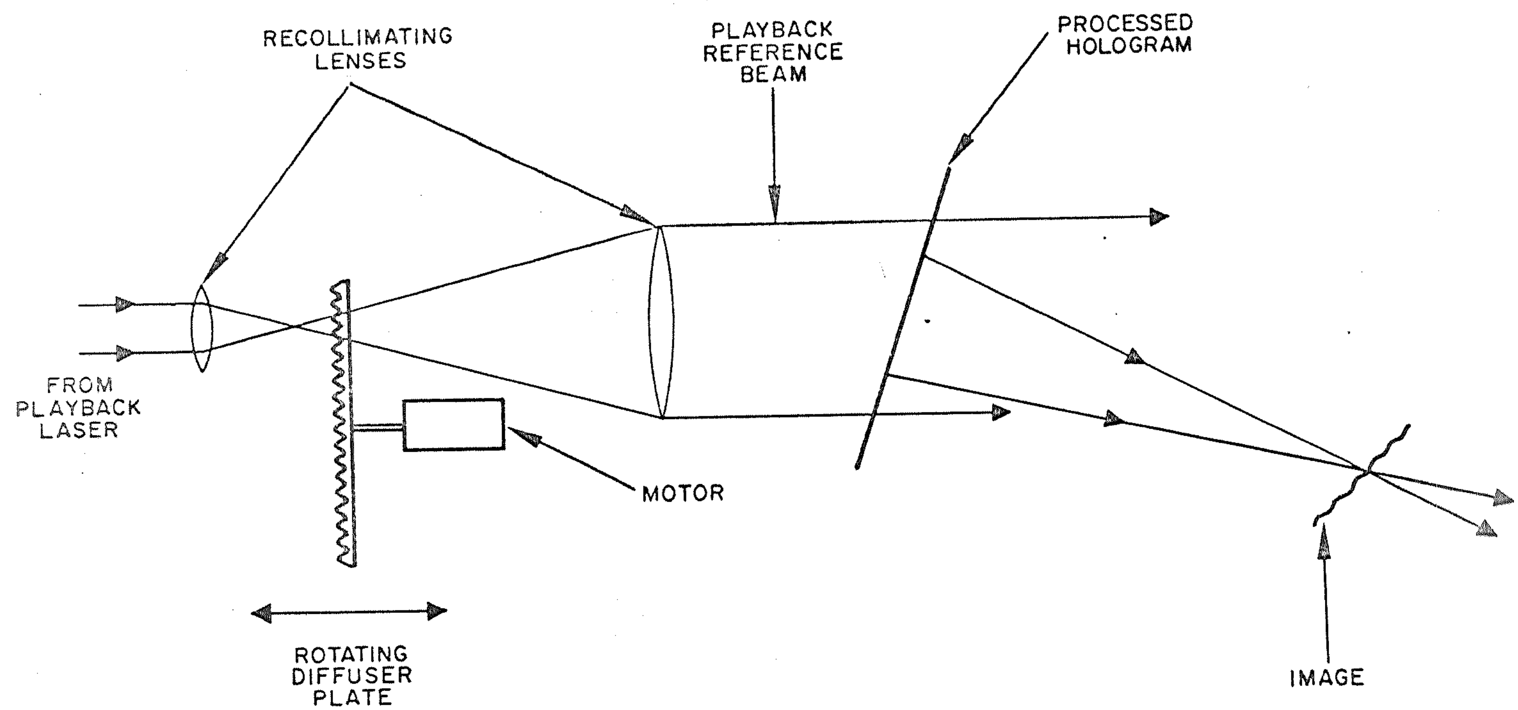
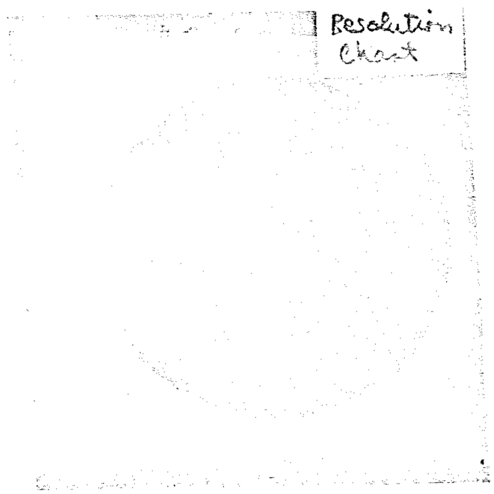


Fig. 9. Schematic Diagram of the Playback System.

photographing each hologram image separately and aligning the resulting transparencies. This work is described and the results discussed in the next section.

LUNAR HOLOCAMERA HOLOGRAM AND PLAYBACK INSTRUCTIONS

A hologram recorded with the holocamera described in this report is included in the envelope attached below. This hologram is included to demonstrate directly the quality of the holography that can be performed with the holocamera. The following paragraphs describe the procedure for viewing the hologram to obtain the maximum image quality. Less careful playback procedures will also provide a usable image, however with less than ideal performance.



The hologram playback configuration is shown in Fig. 9. The hologram must be held flat during playback, or several aberrations will be introduced into the reconstructed image. The hologram film can be held between a piece of plate glass and a flat metal plate with an aperture approximately 60 mm in diameter for this purpose. The plane of the hologram should be vertical, and the upper and lower edges of the film should be horizontal. The identification tag should be in the upper-right-hand corner when viewing toward the playback reference beam. The axis of the playback reference beam should lie in a horizontal plane and make an angle of approximately 15° with respect to the normal to the hologram plane. This angle should be adjustable for fine "tuning" the image. The reference beam should be collimated and should be 50-55 mm in diameter. When played back in this configuration the hologram will form a reconstruction of the image space of the relay lens, as indicated in Fig. 9. An image of the relay lens pupil will also appear as a sharply defined disc.

When the playback reference beam angle is improperly adjusted, the reconstructed image shows astigmatism. A fine adjustment of this angle is made by varying the angle while observing the reconstructed image with a 10X to 20X magnifier. Astigmatism can be observed on any fine image detail; however, a specular point is preferable. The reference beam angle is then adjusted so that the astigmatism disappears.

The image can be observed directly on a ground glass screen inserted into the image space, or it can be recorded with a close-up camera. Some further magnification is usually desired in this recording. The focus and position of the camera can be adjusted to provide the desired magnification and plane of focus. For maximum resolution the camera lens should not vignette the reconstructed beam. A 90 mm focal length, f/19 camera lens has been used quite effectively. For maximum image contrast, an aperture should be positioned at the relay lens pupil image to block scattered light outside the pupil image.

SECTION VI

RESULTS

A. GENERAL

The type of imagery produced by the prototype holocamera is indicated by Fig. 10, which shows a conventional photograph of a microcircuit at about 1.5X, and a photographic recording at 43X over-all magnification made from a hologram taken by the holocamera. The latter picture, which was taken with the camera focused on the face of the microcircuit in the holographic image, shows approximately a 2 by 2.5 mm area from the 4.5 mm diameter area covered by the holocamera field of view. It can be seen that edge detail is resolved to at least 2 μm. The illumination, which is at approximately 45° from the viewing direction and from one side only, is not appropriate for this object, but is very useful for granular materials where the added relief information aids in interpretation. It is apparent that the holocamera functions as a low to moderate power microscope, providing the ability to focus over a depth of 4 mm. The depth of focus at a given focal setting is about 10 μm for the maximum resolution; this is inherent in high resolution viewing and demonstrates how essential it is to be able to focus through the object space. It is possible, and sometimes quite useful in interpretation, to view the reconstructed object through a low power stereo microscope; however, considerable resolution is sacrificed.

Figure 11 shows photographs taken from a single hologram of *artificial moondust*,[11] with an over-all magnification of 32X. At this magnification the speckle grain size is

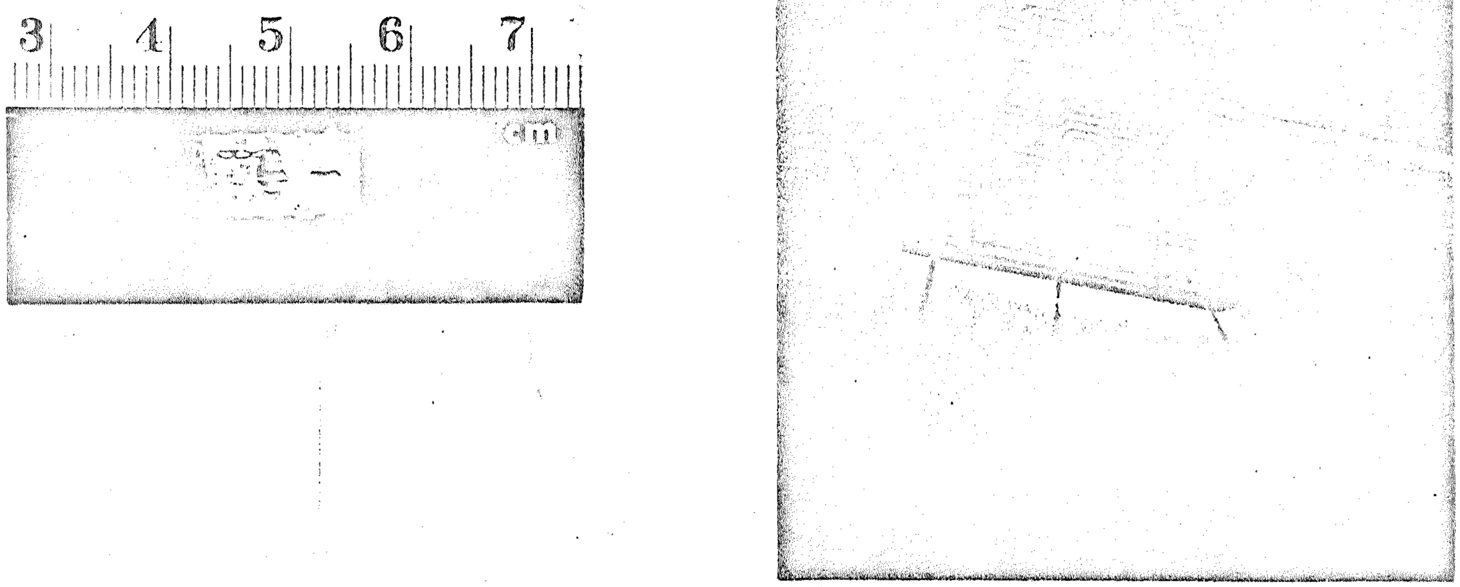


Fig. 10. Left: Ordinary Photograph at 1.5X of Microcircuit and Centimeter Scale. Right: Photograph of 1 mm Square Microcircuit Chip at 43X, Taken of Holographic Reconstruction.

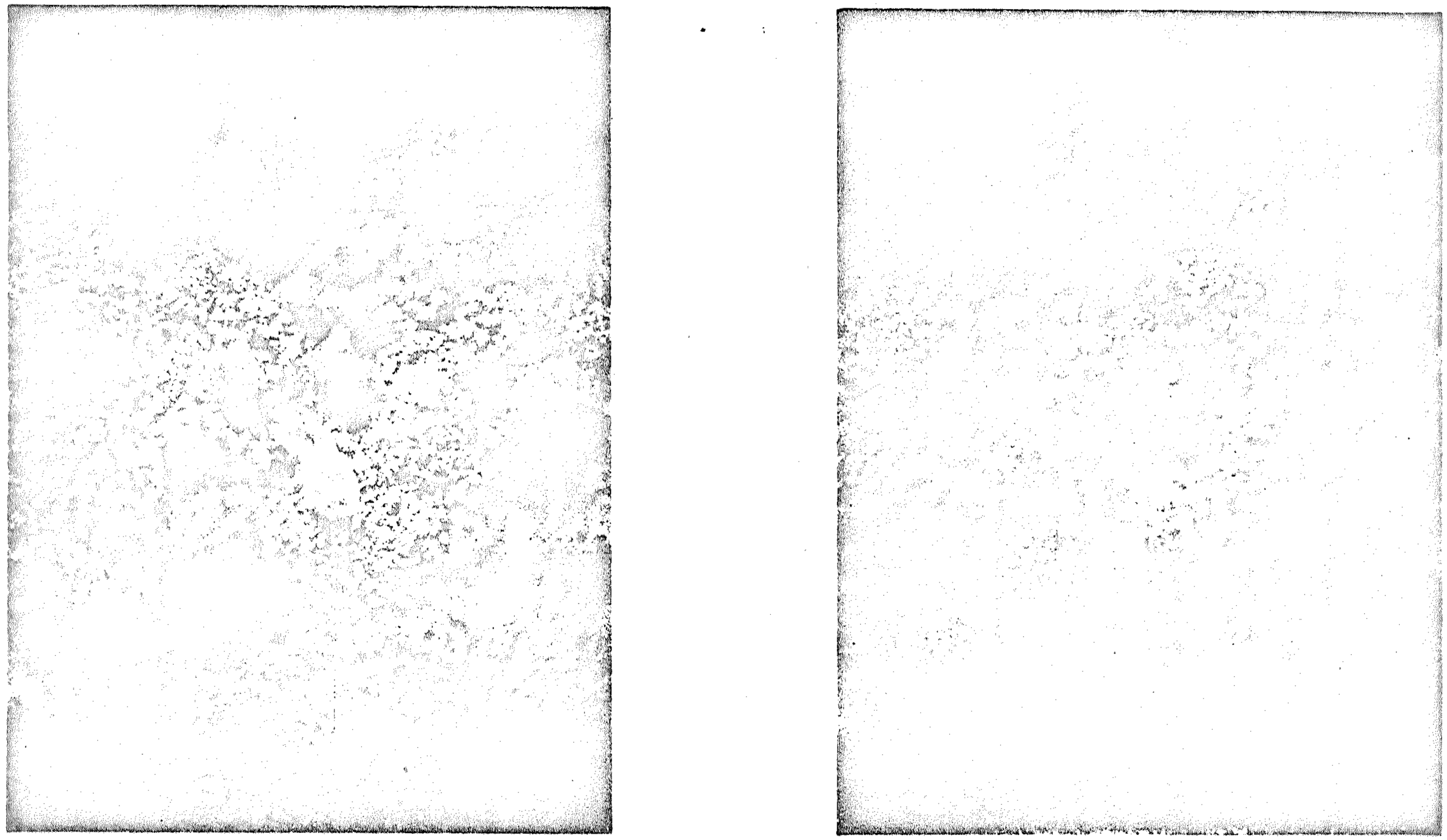


Fig. 11. Photographs of Holographic Image of Simulated Lunar Surface at 32X. The Left Photograph is Focused Approximately 0.2 mm Deeper into the Surface Layer than the Right Photograph.

apparent but not very distracting. The right-hand photograph is focused approximately 0.2 mm higher in the object than the left-hand photograph. This illustrates the ability to focus through the reconstructed image with the viewing/recording system. Close examination of this image allows one to determine the distribution of particles to scales as small as 5 to 10 μm, depending on the characteristics of the site. At higher magnification the small-scale texture of the object is lost in the high contrast speckle, and one cannot distinguish a small clump of grains from a larger, angular grain. Improvement of texture in the image can be accomplished by reducing speckle contrast, utilizing the rotating diffuser plate or superposition techniques. These techniques are discussed in Section VI-E.

The holograms recorded with the prototype holocamera are of excellent quality. The hologram and image quality can be characterized by the diffraction efficiency of the hologram, the signal-to-noise ratio, and the dynamic range in the image. To measure these quantities, the hologram is played back so that a real image of the relay lens pupil is formed. For diffuse objects this image is uniformly illuminated. We define diffraction efficiency (D.E.) and signal-to-noise ratio (S/N) as

$$\text{D.E.}(\%) = 100 \frac{I_{pupil}}{I_{reference}} \frac{A_{pupil}}{A_{hologram}} ,$$

and

$$\frac{S}{N} = \frac{I_{pupil}}{I_{adjacent}} - 1 ,$$

where I_{pupil} is the light intensity in the pupil image, $I_{adjacent}$ is the light intensity adjacent to the pupil image, $I_{reference}$ is the light intensity in the reference beam in front of the hologram, A_{pupil} is the area of the pupil image, and $A_{hologram}$ is the area of the hologram. This definition of S/N neglects the contribution of hologram nonlinearities to the noise, but is adequate for this study because the nonlinearities are small. We observe a diffraction efficiency of about 0.1% and a S/N of 100 to 250. The dynamic range of the image depends on the type of object; for a diffuse object which is half light and half dark, the dynamic range is 2(S/N). This is a good estimate of the minimum dynamic range. The maximum dynamic range possible would be obtained if the entire hologram exposure came from a single specular point, and would be S/N times the ratio of the area of the field of view to the area of the specular point image, or maximum dynamic range $\approx 5 \times 10^6$ (S/N). This situation is extremely unlikely, since specular points and facets typically contribute only a small fraction of the total object beam. A situation which could very easily occur is to have an object where 100 specular points and facets (from glassy beads and crystalline fragments) contribute a total of 0.1% of the object beam. In this case the dynamic range would be 50 (S/N). This example demonstrates why it is very difficult to record the holographically-produced image on photographic film; the latter's dynamic range is usually greatly exceeded.

B. RESOLUTION AND IMAGE QUALITY

In discussing the resolution capabilities of the prototype holocamera, a distinction must be made between resolving a specular point and resolving details of a diffuse object.

For a specular point, the system operates essentially at the diffraction limit of the relay lens, or $0.5\ \lambda/NA = 2.5\ \lambda \approx 1.8\ \mu m$. Diffuse detail is degraded by speckle effects and is typically resolved only to about 4 μm. Edges of objects usually show resolution between these limits. If the object is relatively large and smooth, the edge resolution can be as good as 2 μm.

Quantitative resolution tests were made using a diffusely reflecting copy of the standard USAF bar chart resolution test target, providing dark bars on a white background. The copy was made on an electron beam recorder and suffered only a slight loss of resolution from the original. This bar chart provides a realistic test of resolution because, although it is higher contrast than some objects of interest, it has a large preponderance of white area, which, according to the discussion of dynamic range in Section A, will minimize the contrast (dynamic range) in the image.

Figure 12 shows some resolution chart images taken from individual holograms. The effects of speckle are apparent at the higher magnification. For one image the time-varying diffuser plate was used to somewhat reduce the speckle contrast; in this case the loss in resolution is small. The original holographic image shows resolution to element 1 of group 7, or a bar width of 4.1 μm. At lower magnifications the effects of speckle are not apparent. For a speckle size of 1.8 μm, the over-all magnification must be about 30X or larger for the speckle to be resolved by the eye (which can resolve only to about 100 μm).

The effect of the time varying diffuser plate can be seen in Fig. 13. This object was prepared by sprinkling 100 to 125 μm glass beads on surface covered with incompletely dry black brushing lacquer, thus forming a low reflectivity,

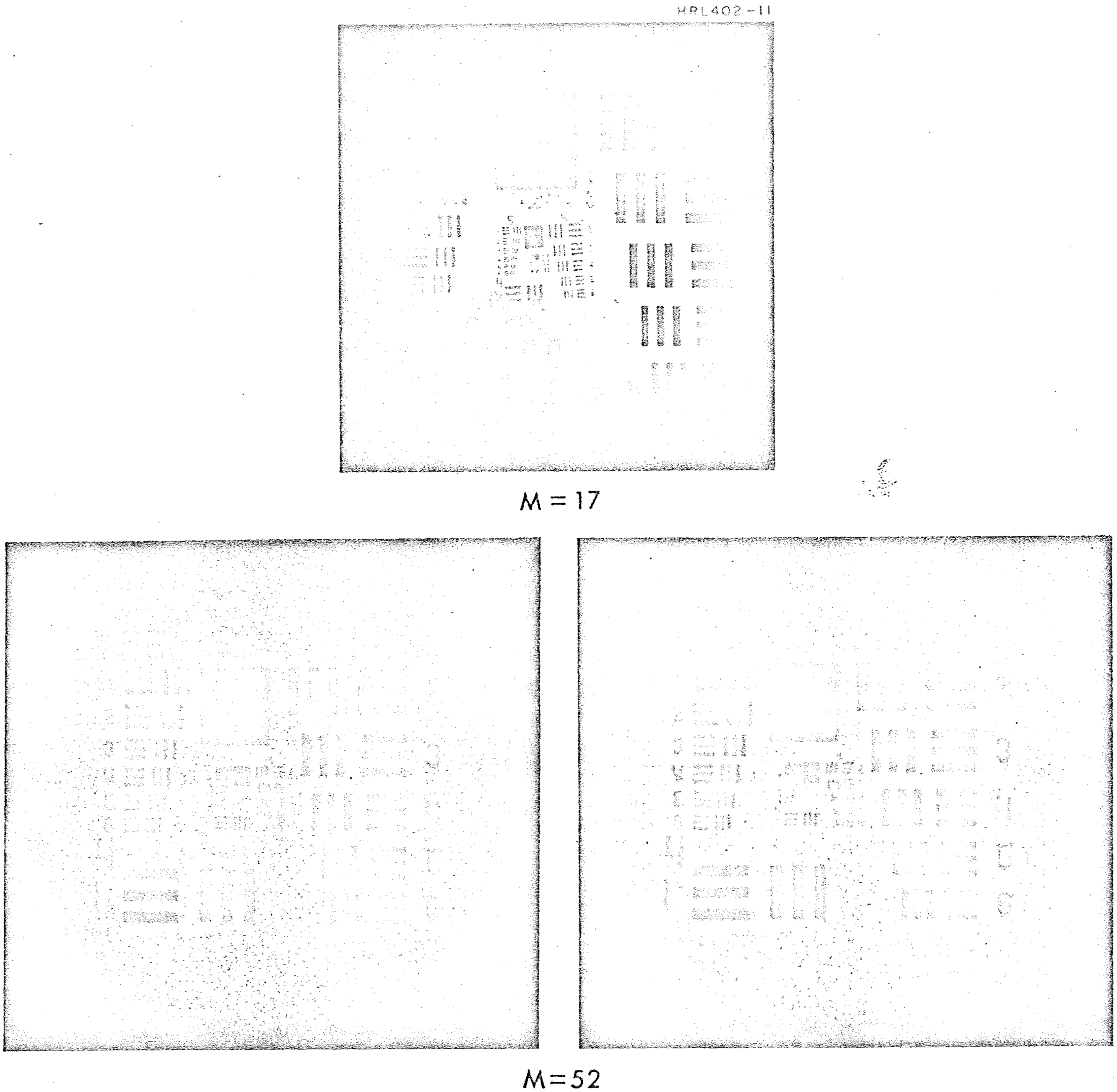


Fig. 12. Resolution Chart Images Taken from Single Holograms. Top: 17X; Bottom Left: 52X with no Speckle Contrast Reduction; Bottom Right: 52X with Moderate Speckle Contrast Reduction from Rotating Diffuser Plate.

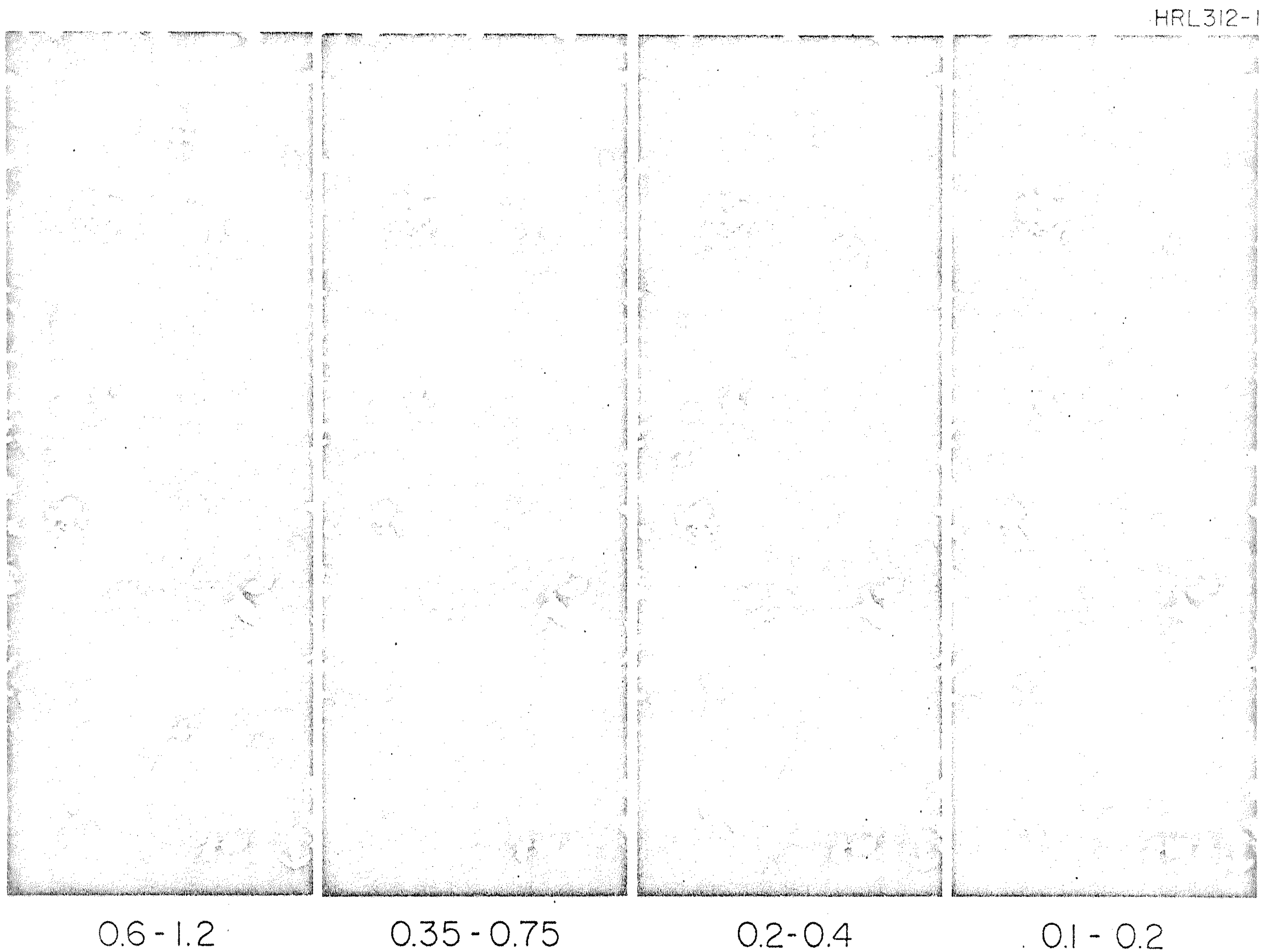


Fig. 13. Images of 100 to 125 μm Glass Beads on a Black Surface, Taken from a Single Hologram, with Varying Degrees of Speckle Contrast Reduction from Rotating Diffuser Plate. Numbers are Proportional to the Speckle Contrast, which Decreases from Left to Right.

low contrast object which is difficult to record. It should be noted, however, that the dynamic range in the image is large because of the specular points, which are overexposed in the photographs. The diffuser plate was adjusted in the playback system to produce varying degrees of speckle contrast reduction. It is apparent that image textural quality can be considerably improved without a large loss of resolution; the main loss is in image sharpness. The numbers in the figure refer to the ratio of the dimension over which the reference beam phase is constant to the dimension covered by the out-of-focus image of a specular point on the hologram. This number is a measure of the loss of resolution/ sharpness due to the diffuser plate, the smaller the number, the greater the loss of resolution. It is important to note that with the holographic system this tradeoff between improved textural quality and high resolution can be varied at will while the observer is focusing through the image.

Superposition of multiple images offers the possibility of reducing speckle contrast while increasing resolution and sharpness. Since speckle is essentially a granularity effect, the granularity in a multiple image superposition should vary in inverse proportion to the square root of the number of images superimposed. The simplest way to demonstrate this improvement experimentally is to multiply-expose a conventional photograph using coherent illumination that is adjusted between exposures to alter the speckle pattern. The results of this procedure are equivalent to perfect superposition of a set of separate images. Figure 14 shows the results of superimposing images in this way, with illumination similar to that used for the holocamera. Four exposures provide approximately a factor of two improvement in resolution compared with a single exposure, as expected by the granularity argument.

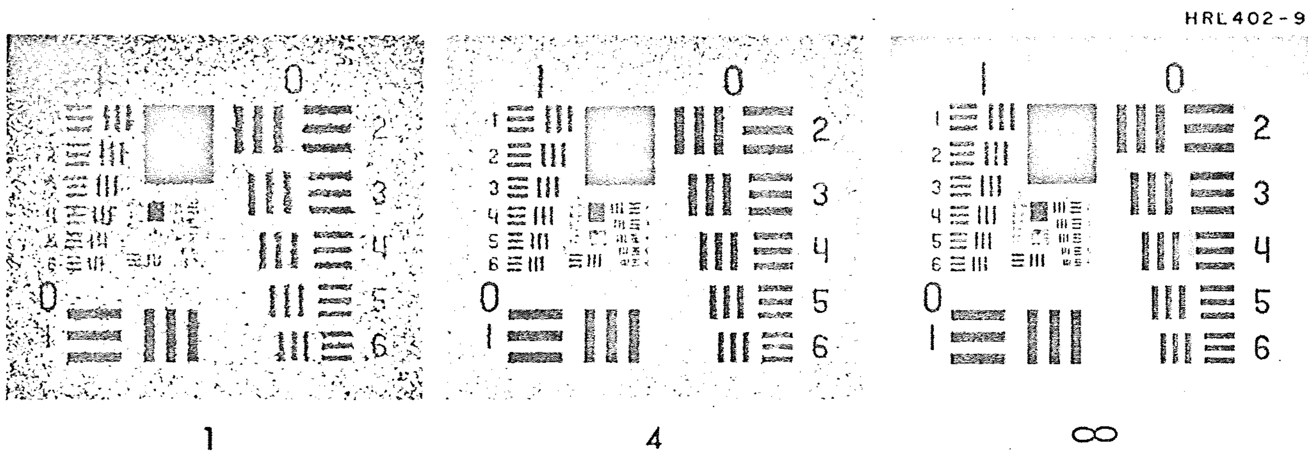


Fig. 14. Photographic Superposition of Images with Coherent Illumination. Left: Single Image; Center: Four Images; Right: Infinite Number of Images (Incoherent Illumination).

Moving the wedge plate continuously during the exposure provides the equivalent to superimposing an infinite number of images and gives results equivalent to using white light illumination.

The holographic equivalent to the above experiment is a perfect incoherent superposition of the four images from the separate holograms produced by the holocamera. The superposition would have to be done directly, without intermediate photographic steps. This requires a rather complex system, and development of these techniques is outside the scope of the present program. Availability of the direct superposition technique would provide the ability to focus through a high resolution image, having very reduced speckle contrast, while retaining the dynamic range and noise properties of the holographic image. Furthermore, the time-varying diffuser plate could be used simultaneously and could be adjusted at will to further reduce speckle effects while examining the image. Because of these characteristics, direct superposition would be particularly valuable for image interpretation.

We have studied a simpler technique to provide superposition of the four images, *viz.*, to record each of the four images photographically with the same magnification and then superimpose the four resulting transparencies. This technique suffers from several disadvantages: (1) loss of ability to focus through the object volume, (2) increased noise because of light scattering from four grainy emulsions separated by the film base layers, and (3) limited dynamic range. The primary difficulty is in registration, but residual magnification differences, differential emulsion distortion during processing, and geometrical effects from stacking multiple emulsion-base layers also cause degradation. In addition, proper final alignment can only be accomplished using the superimposed set of transparencies with reduced speckle contrast.

Figure 15 indicates the results we have been able to obtain by stacking individual photographic recordings of the four holographic images made by the holocamera. The reduction of speckle contrast is quite marked, with a corresponding improvement in image quality. The effect is perhaps more striking with the bar chart object than it would be for some objects, because the bar chart tends to produce a low contrast image. The effect on resolution is less pronounced, however, if the final adjustment of each image could be done after the superposition was accomplished, we believe that an improvement in resolution comparable to that shown in Fig. 14 for four exposures could be realized. With direct superposition of the holographic images, the effect on both resolution and image quality should be quite pronounced, and this, combined with the ability to focus through the image and to use the diffuser plate at will, should produce very high quality imagery which would be straightforward to interpret.

Superposition of holographic images is similar to two other problems; *viz.*, superposition of multiple images to reduce the effects of film granularity and superposition of color separation negatives. Both of these problems have been dealt with satisfactorily.[10] The limiting factors are light scattering and residual distortions in the individual images. Light scattering reduces the accuracy of the alignment, and distortions reduce the size of the area which can be effectively aligned. In the latter case, visual observation and manual adjustment are quite effective in improving localized areas of the image. The improvement in granularity

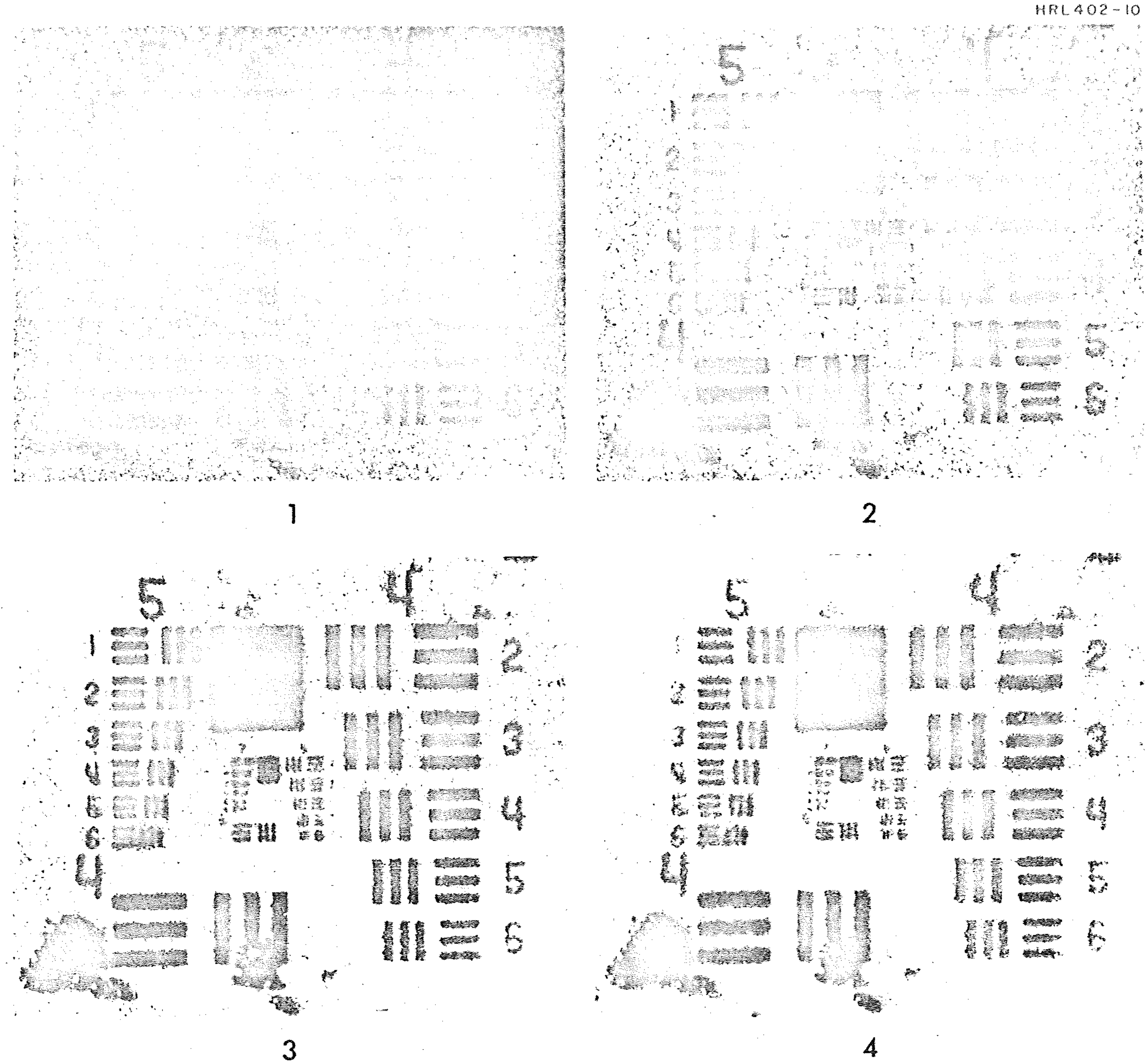


Fig. 15. Superposition of 1,2,3, and 4 Holographic Images, Showing Reduction in Speckle Contrast and Increase in Image Contrast.

goes approximately as the square root of the number of separate images. This is in agreement with our studies of photographic superposition of speckled images, and indicates that approximately a factor of two improvement in resolution should be available from four images. Although the holographic problem is more difficult than the above problems because there is an additional degree of freedom, *i.e.*, the image depth, this added difficulty should not affect the final imagery.

C. POLARIZATION MEASUREMENTS

The interference pattern forming the hologram is proportional to the vector dot product of the electric fields of the reference and object beams. This fact provides the possibility of recording the effect of the object on the state of polarization of the light reflected from it.[12] Since the laser output is inherently polarized, essentially all that is required is a half wave retardation plate in the reference beam, and the making of two exposures (holograms), one for each of two perpendicular polarization directions. The reference beam polarization is rotated 90°, via the retardation plate, between the two exposures. The reference beam thus performs the function of a polarizing element and allows the object to be viewed in light polarized parallel to and perpendicular to the polarization direction of the illumination. Since different materials should have different effects on the polarization state of the reflected light, this represents a potentially powerful technique for classifying lunar surface particles.

We performed some initial experiments using 1 mm diameter specular and diffuse steel balls, approximately 1 mm silicate sand grains, and 100 to 150 μm grains of crushed

San Marcos Gabbro. The ratio of brightness in the image with the same polarization as the illumination to the brightness in the image with the opposite polarization was about 20:1 for the specular steel balls, 5:1 for the diffuse steel balls, nearly 1:1 for the sand grains, and ranged from 2:1 to 1:3 for selected San Marcos Gabbro grains. Figure 16 shows photographs taken from the holographic images.

The results of these preliminary experiments show that measurement of the polarization components of the scattered light is possible. The experiments were not adequate to show how much information can be obtained regarding composition of granular materials.

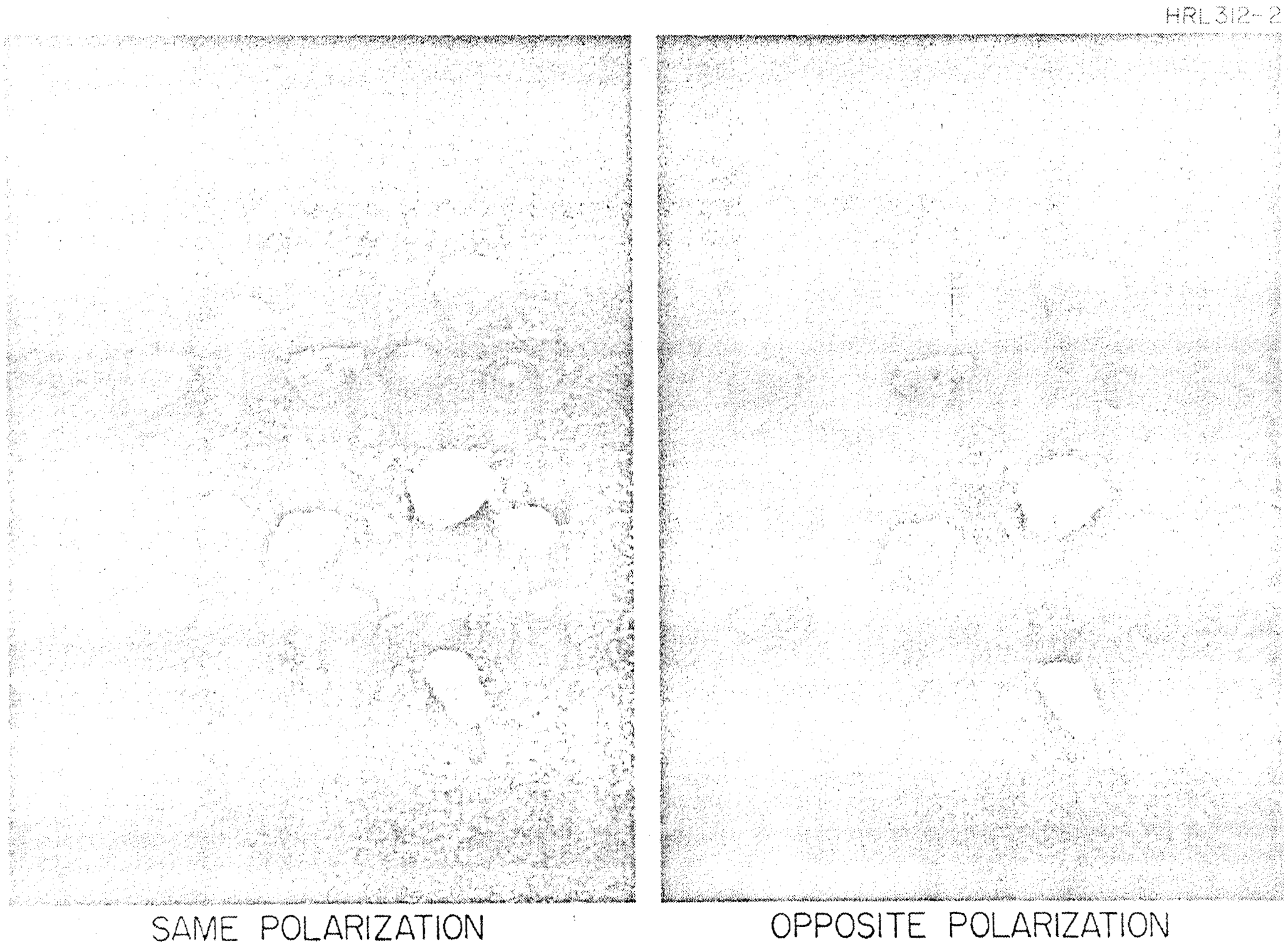


Fig. 16. Photographs of Holographic Images Taken with the Reference Beam Polarized in the Same Direction, and Perpendicular to, the Object Illumination Beam.

SECTION VII

SPACE QUALIFICATION

Since there would be no operational interface between the holocamera and the Apollo spacecraft, the holocamera can be considered separately except for questions of astronaut safety.

The laser output presents no potential danger to the astronaut, even in the extremely unlikely event that his eyes should be exposed to the output. This is because the laser is operated at very low levels and because the illumination diverges rapidly upon leaving the holocamera optics. The only possible dangers would be harmful emissions from the batteries or the energy storage capacitors and rupturing of the capacitors. These factors are discussed in the following. All other considerations deal exclusively with holocamera operation.

A. THERMAL BEHAVIOR

The mechanical construction of the holocamera is designed to minimize the effects of temperature changes on alignment. The honeycomb base is not in direct contact with the external environment, and is an all-aluminum construction; this should prevent thermal gradients in the support structure. The optical layout is designed to minimize the effects of thermal expansion, and the reference beam expander lens and illumination optics are somewhat over-filled by the laser output in order to compensate for any misalignments that might occur. Orientation and alignment of all other components are not critical (with the exception of components inside the laser head, which are discussed in the following).

The film used by the holocamera will be somewhat sensitive to fogging by high temperatures; however, the inherently low exposure sensitivity (approximately 30 $ergs/cm^2$ compared to about 0.1 erg/cm^2 for the Tri-X emulsion) will minimize the effect. Also, fogging does relatively little harm to holographic imagery since it only contributes slightly to the light scattering noise.

The laser head is the part of the system that is most sensitive to misalignment. The mechanical design of the head provides an extremely rigid and stable support for the optics. This is perhaps best illustrated by the fact that the rangefinder laser meets military specifications. The laser head in the holocamera is mechanically identical to the rangefinder head. Although the small optical modifications (see Appendix B) made for use in the holocamera add somewhat to the alignment sensitivity, thermal tests performed during the rangefinder development show that there should be no degradation of the laser output.

Longitudinal mode control of the laser is sensitive to temperature changes because the optical resonances of the etalon output reflector change with temperature. This causes the laser to periodically change longitudinal modes as the temperature is varied and could modify the longitudinal coherence of the laser output. This would cause a spatial modulation of the holographic image brightness. Although we have made no systematic observations, the laser appears to have a tendency to multimode for about 0.5°C of a temperature range of about 5°C. At the low output levels required by the holocamera, this effect is greatly minimized. In fact, in using the laser to make some 100 holograms with no temperature control, we have never observed a hologram to be degraded by poor longitudinal coherence. If the mode shifting should prove to be a difficulty, the laser could be interlocked to not fire in the approximately 10% of the temperature range where poor longitudinal coherence might result. Also, since the effect of multimoding is to produce dark bands across the image, at least half of the image would still be available even with poor longitudinal coherence.

All other components in the holocamera system should be able to meet the thermal requirements for space qualification.

B. OTHER ENVIRONMENTAL CONSTRAINTS

1. Radiation

Although the optics and electronics are susceptible to radiation damage, the most radiation-sensitive part of the holocamera system is the film. The relatively low sensitivity of holographic emulsions again implies that the holocamera should require less protection against radiation than other photographic equipment used on the lunar surface.

2. Vibration and Acceleration

The capacitor mounts used in the prototype holocamera are not adequate for space qualification. With this exception, vibration and acceleration should pose no problem.

3. Vacuum

Neither the batteries nor the laser energy storage capacitors can be operated in a total vacuum. If the batteries used in the prototype are hermetically sealed with at least 5 psi, they are space qualifiable. The electrolytic capacitors used in the prototype may be space qualifiable if hermetically sealed. However, they probably would be replaced in the qualified holocamera. In any case, it will probably be necessary to enclose the capacitors in a hermetically sealed case at a relatively high pressure. The battery case and capacitor case would also prevent any dangerous emissions from leaving the holocamera and would remove any possible danger of a rupturing capacitor harming the astronaut.

4. <u>Relative Humidity</u>

The lunar holocamera system would be sealed against high relative humidity. However, it would be preferable to avoid exposure to moisture.

5. <u>Contaminants</u>

Dust, dirt, and grease present the same problem for the holocamera as for any high quality optical system. The relay lens and illumination optics are protected by a shutter assembly, and the remaining optical assemblies are not exposed to the case exterior. Although in the prototype holocamera the relay lens is only approximately 10 mm away from the surface being recorded, and is therefore susceptible to contamination from dust that is attracted by electrostatic forces, the Apollo version would have a longer focal length relay lens that would provide a greater object distance (approximately 80 mm).

C. LUNAR SURFACE OPERATIONS

Operation of the lunar holocamera would follow the same sequence as operation of the prototype: the astronaut would position the holocamera on the lunar surface, arm the instrument, and trigger the sequence of exposures. The handles and switches would be redesigned for astronaut usage. The astronaut would also be required to obtain conventional, low resolution photographs of the sites recorded with the holocamera. These could be made while the holocamera is operating at the next site. It should also be noted that the holocamera operation allows the astronaut to position the holocamera, initiate the sequence, and then leave to perform other tasks, returning at any convenient time to choose a new site or retrieve the film holder.

The present shutter assembly would exert a pressure of about 0.2 $lb\text{-}in.^{-2}$ on the lunar surface. Since the pressure/penetration ratio should be larger than 2 $lb\text{-}in.^{-2}$ $in.^{-1}$ (Ref. 13), the penetration of the prototype shutter assembly face into the lunar surface should be less than 0.1 in. (2.5 mm). The edge of the field recorded by the prototype is about 6 mm from the edge of this face, and thus might be disturbed. Although the 6 mm dimension could easily be increased to about 26 mm in the lunar holocamera, without modifying the present shutter assembly, it may be desirable to design a different shutter and positioning system.

Although light leakage into the holocamera is of course undesirable, the low sensitivity of the holographic film and the fact that the film is advanced immediately before and after each exposure minimize the effect on the holograms.

The film holder in the prototype holocamera carries enough film for 6 four-hologram sequences. Recording of more than six sites would require redesign of the film holder. No other changes would be necessary up to some 20 sites, when the battery rating would have to be increased. Accessibility and removal of the film holder for return to the LEM would be made easy to perform by the astronaut. The film holder is the only part of the holocamera that would have to be returned to earth.

D. WEIGHT AND SIZE ESTIMATES

A detailed breakdown of the prototype holocamera weight is given in Table II. The components that would probably be changed in a space-qualified model are the following.

1. Case

Approximately one-third of the weight of the prototype case is paint that would probably be replaced by a thin metallic reflecting film, and the 2 mm case thickness would be reduced by one-half. Larger controls and grips suitable for astronaut use would add some weight, so the qualified case weight is estimated at 0.9 kg.

2. Shutter Assembly

This component would probably be enlarged and lightened, with these opposing factors approximately cancelling for no weight change.

3. Dust and Light Shield

The dust and light shield for the laser head would be reduced to about one-quarter its prototype weight. The estimated weight is 0.04 kg.

4. Storage Capacitors

The laser energy storage capacitors would be replaced with hermetically sealed units, with a probable weight increase of 30%. The estimated weight is therefore 1.32 kg.

5. Battery Pack

The same battery pack would be used, but the prototype case would be replaced with a hermetically sealed unit. The estimated weight is 0.45 kg.

TABLE II

PROTOTYPE HOLOCAMERA WEIGHT BREAKDOWN

Item	Weight kg	Weight oz
Case	1.84	(65)
Shutter Assembly	0.300	(10.6)
Honeycomb Baseplate	0.499	(17.6)
Laser Head	0.779	(27.6)
Dust and light shield	0.165	(5.8)
Laser Electronics	1.265	(44.7)
Laser Energy Storage Capacitors	0.992	(35.1)
Battery Pack, with Case	0.390	(13.8)
Optics		
Collimator lens and mount	0.248	(8.8)
Beam expander lens and mount	0.035	(1.2)
Folding mirror and mount	0.041	(1.5)
Relay lens and mount	0.082	(2.9)
Illumination assembly	0.026	(0.9)
Feedthrough assembly	0.186	(6.6)
Mechanical		
Film holder	0.318	(11.3)
Film holder mount	0.120	(4.2)
Wedge plate motor, mount, and cam assembly	0.165	(5.8)
Film advance motor, mount, and cam assembly	0.143	(5.1)
Light baffles	0.035	(1.2)
Wiring and Hardware	0.14	(5)
Film	0.12	(4.2)
Total Weight	7.90	(279 oz) (17.4 lb)

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6. Feedthrough Assembly

The feedthrough assembly would be reduced in weight by about one-half, for an estimated weight of 0.09 kg.

7. Film Holder

The film holder would be redesigned to provide more capacity, with an estimated 50% increase in weight to 0.45 kg.

8. Film Capacity

The film capacity would be approximately tripled. The estimated film weight is 0.35 kg.

9. Relay Lens

The relay lens would be changed to a 75 mm focal length, NA 0.25 lens. This lens would be larger; the estimated weight is 0.2 kg.

The total estimated weight for the space-qualified holocamera is therefore 7.77 kg (17.1 lb).

The space qualified version should be essentially the same size as the prototype, so the case dimensions would remain about 12 in. x 13 in. x 6 in.

Some further weight and size reductions could be made by estensive use of lightweight materials and by redesign of the laser electronics. However, we consider these changes unlikely for an Apollo holocamera.

SECTION VIII

SUMMARY AND CONCLUSIONS

A prototype holocamera has been fabricated using a mode-controlled, pulsed, ruby laser. It is completely portable and is operable in moderate field environments. An automatic sequence of four holograms is recorded of each object. An object resolution of 4 μm is achieved by each individual hologram, and incoherent superposition of the four holographic images provides improved image quality and the possibility of improved resolution.

A playback system has been fabricated, using a He-Ne laser illuminator, which displays the high resolution image and allows visual study and photographic recording of the image. A preliminary study of techniques for superposition of the separate images has been made.

The prototype holocamera and playback system have been tested by recording and studying holograms of various objects, including resolution test charts and diffusely reflecting surfaces composed of fine, low contrast grains. The results of these tests are given and discussed in the above sections.

Single holographic images of resolution charts show resolution to 4 μm. Specular point resolution is approximately 1.8 μm, and edge detail shows intermediate resolution that can be as good as 2 μm. Individual images of fine grain material show the particle distribution to scales as small as 5 μm; however the finest scale texture is obscured by speckle effects. Utilizing the rotating diffuser plate in the playback system provides improved texture in the image, at the expense of some image sharpness. Superposition of multiple images, with different speckle in each image, greatly reduces speckle contrast and thus improves texture, image quality, and contrast. Present superposition techniques involve making photographic recordings at a particular focus setting, and therefore preclude focusing through a superimposed image volume. Since such focusing is very useful in object interpretation, more advanced techniques for direct, incoherent superposition of the holographic images are needed in order to fully utilize the hologram sequences provided by the prototype holocamera.

A complete set of specifications for the prototype holocamera is given in Table I. These specifications define the performance and operating characteristics of the prototype.

A detailed estimate of the size, shape, and weight of an Apollo qualified version of the prototype holocamera has been made and is presented in Table III as a set of estimated specifications for the qualified holocamera.

The state of equipment definition is very good. The anticipated modifications to the prototype design in order to achieve a space qualified holocamera are straightforward. Theoretical heat flow and stress analysis, based on detailed Apollo mission environmental specifications, and experimental studies of the stability of holocamera alignment and laser mode control with temperature change are needed to determine if any unanticipated modifications are required. Experience to date with the prototype holocamera has been very positive and indicates no problems.

TABLE III

ESTIMATED APOLLO-QUALIFIED HOLOCAMERA SPECIFICATIONS

Size: case exterior: 12 in. x 13 in. x 6 in.

Weight: 17.1 lb

Image characteristics with 75 mm focal length, NA 0.25 relay lens:

Field of view: 20 mm diameter, central 10 mm diameter at specified resolution

Depth of field: 15 mm

Resolution: 3.7 μm with one hologram
2 μm with superposition of 4 holograms
1.7 μm with superposition of 6 holograms

Light source: Pulsed ruby laser

Wavelength: 0.694 μm

Output energy: Approximately 20 mJ (exposure set for 10 % reflectivity)

Pulse length: 100 μsec

Transverse coherence: Diffraction limited

Longitudinal coherence length: 25 cm

Film: Eastman Kodak FW 1248-1 holography emulsion.

Format: 70 mm wide, roll film; 50 mm diameter hologram

Capacity: 80 exposures (20 four-hologram sequences)

Operation: Pushbutton switch initiates automatic sequence of four holograms; sequence duration is approximately 60 sec.

Option: Six holograms in 90 sec sequence.

Power source: Silver-zinc batteries

Rating: 21 V, 0.05 A-hour (approximately 90 exposures).

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APPENDIX A

LIMITATIONS ON RESOLUTION IN HOLOGRAPHY

The initial design objective of 5 µm resolution required consideration of several limitations on resolution. These limitations are due to diffraction, reference beam source size, source spectral linewidth, recording material characteristics, and speckle. The obscuring effects of speckle require the impulse response of the over-all imaging system to be considerably better than would usually be required to achieve 5 µm resolution: we have found that a point source image size of 1.8 µm allows a diffusely reflecting bar chart resolution target to be recorded to a bar width of 4 µm.

When a pulsed ruby laser is used to record holograms, it is convenient to use a continuous He-Ne laser to play them back. This change of wavelength from 0.694 µm to 0.633 µm also introduces aberrations that are unacceptable in some applications.

The above limitations will be discussed individually. They are discussed in more detail in Reference 5. It will be shown that in order to achieve a reliable, portable system, a magnifying relay lens must be used. With the relay lens, a He-Ne playback laser can be used.

Diffraction – If R is the distance of an object from a hologram of aperture D, the effective f/number is $F = R/D$, and the resolution limit due to diffraction alone is approximately $F\lambda$, where λ is the wavelength of the light used to record the hologram. In order to obtain 2 µm resolution with a ruby laser, $F \lesssim 2.5$.

Reference beam source size — The angle subtended at the hologram by a *point* in the image can be no smaller than the sum of the angles subtended at the hologram by the recording and playback reference beam sources. Therefore, high resolution requires small reference beam sources. This is best accomplished by using collimated reference beams. In this case the source angular size can be made equal to the diffraction limit, λ/D, of the collimator lens. For a 50 mm diameter lens the resulting image point size is about 3 μm.

Source spectral linewidth — A finite range of wavelength in the recording and/or playback sources produces a spread in the diffraction angle of the hologram and thereby a *smearing* of the image. If α_r and α_i are the angles to the hologram normal made by the reference beam and image beam, respectively, the spread in image angle is given by[5]

$$\Delta\ (\sin \alpha_i) = \frac{\lambda_p}{\lambda_r} \left(\frac{\Delta\lambda_r}{\lambda_r} + \frac{\Delta\lambda_p}{\lambda_p} \right) \sin \alpha_r \ ,$$

where λ_r and λ_p are the recording and playback wavelengths, and $\Delta\lambda_r$ and $\Delta\lambda_p$ are the wavelength spreads. The ruby laser with a 25 cm longitudinal coherence length and a multimode He-Ne laser each have $\Delta\lambda/\lambda \approx 3 \times 10^{-6}$. For reference and image angles of 15°, this gives an angular spread of about 1.5×10^{-6} rad and an image size of 0.15 μm at an image distance of 10 cm.

Recording material — The recording material can degrade the image by failing to record the hologram (due to a lack of response at the higher spatial frequencies) or by introducing phase errors into the reconstructed beam. By choosing a material with sufficiently wide spatial frequency response, the first limitation can be made negligible. Phase errors can arise from emulsion and base irregularities and from emulsion and base distortions during processing of the hologram. These phase errors are more pronounced with film than with plates, but even with plates the errors are important at f/numbers below about f/3. The phase errors can be largely eliminated by using thick plates in a liquid gate, but these are not feasible alternatives in a small, portable instrument.

Wavelength change – The aberrations introduced by making the playback wavelength different from the recording wavelength depend on several system parameters (for a discussion of these, see Reference 9). The conditions for minimizing the aberrations due to a wavelength change also minimizes the aberrations due to emulsion distortion. The aberrations for a wavelength change from 0.694 μm to 0.633 μm in the prototype system is shown in Fig. A-1 as a function of f/number, along with the diffraction limited spot size as a function of f/number. The aberration due to the wavelength change becomes quite large at f/2.5, which is the f/number required to obtain a 2 μm spot size.

The major limitations on direct, high resolution holography are therefore the reference beam source size and wavefront distortions caused by the recording material. It is impossible to use a He-Ne laser playback source for such holograms recorded with a ruby laser. Although the source size and distortion problems can be solved in the laboratory, it is not feasible to do so in a small, portable holocamera. These limitations are overcome by providing a magnifying relay lens to reduce the resolution required from the hologram, and operation at a larger f/number permits the convenience of a He-Ne playback source.

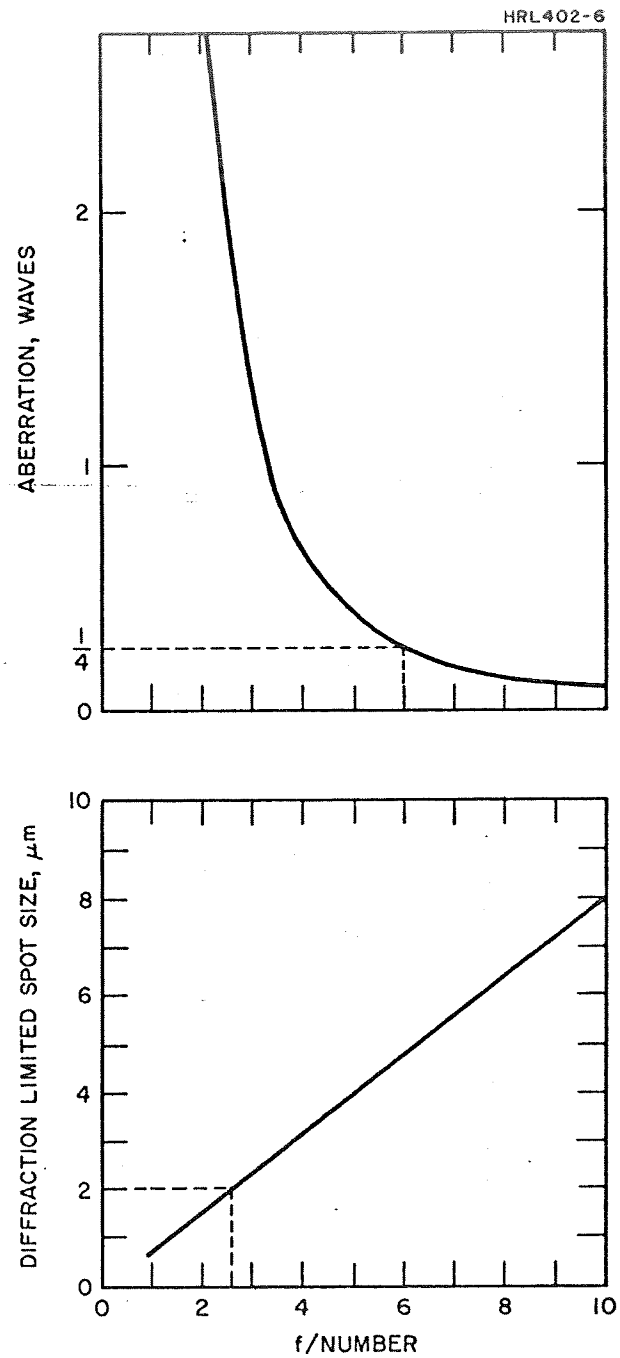

Fig. A-1. Top: Aberrations Due to Wavelength Change from 0.694 μm to 0.633 μm as a Function of Hologram Effective f/Number; Bottom: Diffraction Limited Spot Size as a Function of Hologram effective f/Number.

APPENDIX B

PULSED RUBY LASER DESCRIPTION

The ruby laser used in the prototype holocamera is basically the transmitter from the M60 tank rangefinder system developed and produced by Hughes. Three hundred of these systems were produced for the M60 A1E2 tank, and the holocamera laser was obtained from this production run. The M60 system has demonstrated a very high degree of reliability under conditions of vibration experienced in a tracked vehicle and under conditions of shock from the firing of 152 mm rounds. The system has satisfied extensive environmental testing.[14]

The cavity configuration of the rangefinder laser is shown in Fig. B-1. The folded cavity design provides a very rigid support structure. The pumping cavity has a semielliptical design that retains the high optical efficiency of a full elipse yet permits imbedding of the ruby in a solid aluminum block that provides a rigid mount and acts as a heat sink. In the rangefinder laser the resonant reflector acts as an output coupler with a high threshold for optical damage. The Q-switch prism is rotated at high speed to provide a short-duration pulse for the rangefinder.

A photograph of the prototype holocamera laser is shown in Fig. B-2. The semielliptical reflector has been removed from the pump cavity to show the ruby rod clamped in the heat sink block. Only three modifications were made to the production rangefinder laser head: (1) the roof prism was replaced by a high reflectivity flat dielectric mirror, (2) a 1.5 mm aperture was inserted into the cavity, and

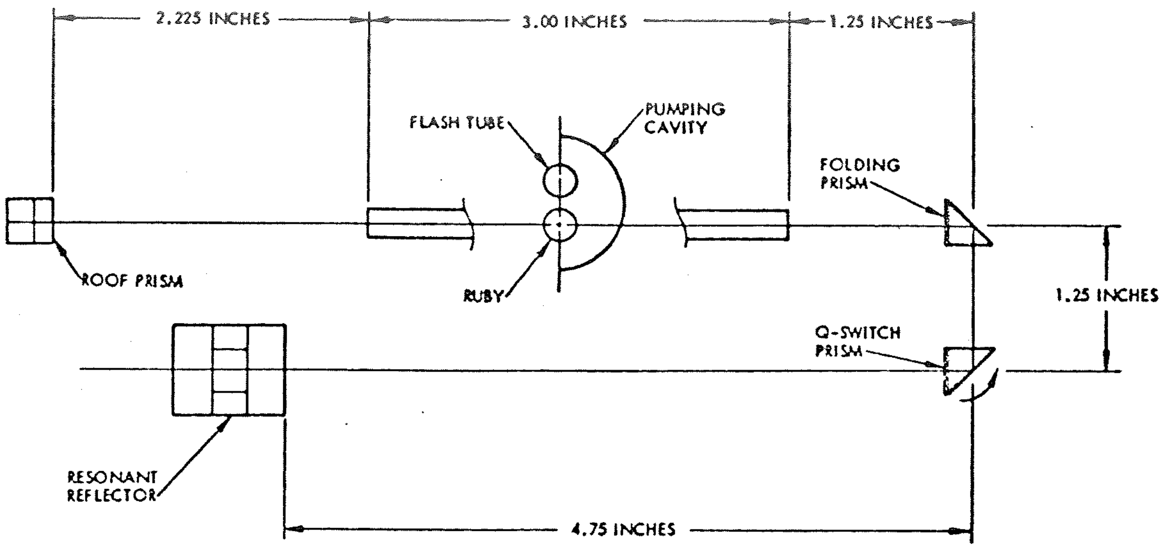

Fig. B-1. The Rangefinder Laser Cavity Configuration.

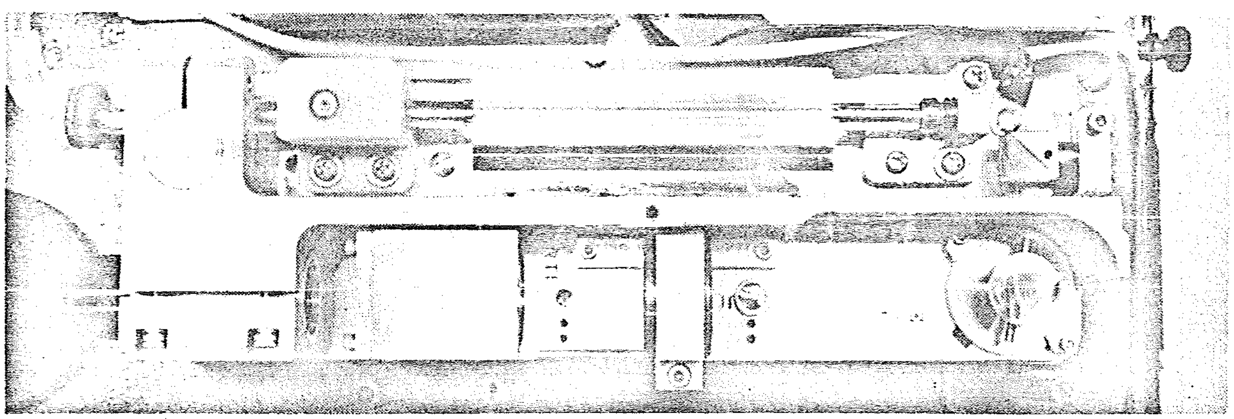

Fig. B-2. Photograph of the prototype holocamera laser head.

(3) the Q-switch prism was locked in permanent alignment (the motor and magnetic pickup were removed). The mirror and aperture provide transverse mode control, and locking the prism in place converts the laser to normal mode operation. The production resonant reflector provides sufficient longitudinal mode control to achieve 25 cm coherence length.

The transverse mode structure of the modified laser was studied by photographing the near-field and far-field intensity distributions in the output beam. These photographs showed a TEM_{00}-type mode, with the far-field beam divergence equal to the diffraction limit for the beam size, within experimental error. These results indicate that the transverse coherence is essentially complete.

The degree of longitudinal mode control was observed by recording the longitudinal mode structure with a Fabry-Perot interferometer and by measuring the longitudinal coherence directly with a Twyman-Green interferometer.

The Fabry-Perot interferometer measurements showed that the oscillation bandwidth of the laser was less than 0.1 cm^{-1}, the limit of the instrument's measuring range. This indicates that the longitudinal coherence length is larger than 10 cm. In the Twyman-Green interferometer measurements, the fringe visibility was observed as a function of path length difference. This direct measurement demonstrated a longitudinal coherence length of 25 cm, the path length difference at which the fringe visibility dropped to one-half its value at zero path length difference. This means the holocamera could record information over a 12.5 cm depth, compared to the 4 mm over which the relay lens operates well.

The modified laser has proven to be an excellent source for holography. Alignment is extremely stable, and no hologram made with the laser has been degraded by poor transverse or longitudinal mode control.

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