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TABLE OF CONTENTS

HOLOGRAPHY

Laser Interferograms

R. M. Jones



## I. Introduction

In the proposed extension of Research Grant NSG 713 of February 1, 1966, it was proposed that moire fringes might be useful in viewing simple holograms and interferograms. An instrument was proposed which would pass two beams at a small angle to each other through the field being investigated. This device would reveal the difference in path length through two adjacent sections of the object thereby determining the gradient of the optical path length. (This might be a measure of, for example, the density gradient). However, it was determined that this instrument was similar to the Bates interferometer (1). Therefore, the investigation was modified to study the effect of a schlieren field on the holographic reconstruction of a grating or of a recorded interference pattern. The mechanism by which the reconstruction of the grating was formed was similar to the action of the Bates interferometer. The principal difference was that more than two beams were involved.

When a schlieren field is introduced between the hologram and the reconstruction, the reconstruction should be distorted. One should be able to render the distortions in a grating visible by the moire technique. In this method a grating of the same period is superimposed on the distorted grating.

When the undisturbed lines of the reconstruction are parallel to the lines of the grating, the field is evenly illuminated.

Where there are distortions, relatively broad dark and light bands appear which correspond to interference fringes. The use of the grating as described above corresponds to the use of a grating to reduce the order of a multiple-order interferogram.

## II. Work Performed

A preliminary experiment was performed to demonstrate the production of a zero or low-order interferogram from a higher order interferogram. Two collimated laser beams were brought together at an angle on a photographic plate, which recorded the interference lines formed. The plate, which was developed and returned to its original position, was a high-order interferogram of the two beams. With the plate back in place in the beams, the same pattern was incident on the plate. The two interferograms in exact alignment produced a single dark or light band, which was a zero-order interferogram. There was more than one fringe when the frequency of the lines (lines/mm) was altered by changing the angle of the beams, or when the recorded interference pattern was tilted at a slight angle to that produced by the beams.

These fringes were visible both on the plate and as a projected pattern behind the plate. The angle of the two beams was such as to give a line frequency of about 50 lines/mm. When a schlieren field was placed in either beam it became clearly visible. This arrangement was sensitive enough that even the hot air rising from a person's fingers was visible. Similar work has been reported by Brooks, Heflinger and Wuerker (2).

III. Conclusions

It is clear that the sensitivity of the method will be directly dependent upon the frequency of the grating (or interference pattern) that can be reconstructed. For example, with a coarse grating a relatively large distortion would be necessary to move a reconstructed line from a position overlapping a grating line to a position overlapping the space between grating lines. Work to date has been directed toward making holograms capable of reconstructing fine interference patterns. The finest interference pattern yet reconstructed had a frequency of 50 lines/mm. Efforts to reconstruct an interference pattern with a frequency of 100 lines/mm have not been successful.

Moire fringes have been produced by superimposing the reconstruction of the 50 line/mm interference pattern and the original interference pattern used to make the hologram. In this case it was necessary to allow the reconstruction to fall on a diffuser in order to render it visible because of the low light intensity of the reconstruction. Initial attempts to view a schlieren field with this arrangement have not been successful, and further work is required.

IV. Future Work

This investigation is being continued as a thesis topic by a graduate assistant. NASA will no longer be charged for his time on this project, but NASA equipment and supplies will continue to be used.

It will be necessary to improve the techniques used to align the reconstructions with the gratings. After achieving success in viewing schlieren fields using the 50 line/mm interference patterns, additional work will be performed to improve the quality of the reconstructions.

# The Sorting of Holographic Information for Transmission

R. M. Jones

## I. Introduction

It has been suggested that it may be of interest to transmit the information contained in a photograph in such a manner that the entire photograph would appear first in poor resolution with resolution increasing as additional information is included. The proposed device would sort the information in a photograph according to the size of the areas in the photograph. The sorted information could be scanned, such that information related to the largest areas would be transmitted first, with information related to smaller areas following. It appears that this can be done by making a hologram at the point focus of the information beam, as indicated in Figure 1.

1. The light and dark areas of a transparency diffract the light and cause it to reach the hologram at some distance from the point focus of the undiffracted light. Apertures, such as represent large photographic objects, would diffract the light that passes through them by only a small amount, with the greatest diffraction occurring near the boundaries of the areas. The smaller apertures, those representing small photographic objects, would diffract the light through a larger angle.

Thus, the diffracted light defining the large photographic objects will be found near the point focus, and that required for defining smaller objects and achieving greater resolution will be found further away from the point focus. If the hologram is reconstructed by scanning, beginning at the edge of the focused dot, the image should slowly build into the complete picture. Large objects should appear first, and then, as the hologram is scanned outward, the reconstruction would become more detailed.

## II. Work Performed

A "focus" hologram was made of a transparency using the arrangement shown in Figure 1. The lens had a focal length of 25 cm. The transparency was a Kodachrome 35 mm color slide. The interference filter was needed to reduce the intensity of the reference beam to approximately the diffracted light. This filter was designed for use at normal incidence, but in order to reduce the intensity to a sufficiently low level, it was used at a rather large angle. The hologram plate was exposed for 2 minutes and developed (Figure 2 shows the equipment arrangement for reconstruction). The reconstructions were made on Panatomic-X, 35 mm strip film. In place of scanning, a series of reconstructions was made decreasing the aperture of the stop.

Aperture sizes from 1.650 inch to approximately 0.095 inch were used. There was no readily noticeable change in the quality of the reconstruction as the aperture was decreased from 1.650 inch to 0.317 inch in diameter. From 0.317 inch to approximately 0.095 inch the quality of the reconstruction did deteriorate seriously. These small apertures approached the size of the overexposed area on the plate.

The reconstructions had the appearance that the transparency would have when viewed in a schlieren system; that is, the boundaries between areas were "lighted up". This was a result of the greater amount of diffraction occurring near the boundaries. This was encouraging, for it indicated that one could selectively transmit information related to the boundaries between areas, while transmitting little information relating to the broad areas of the photograph. The schlieren effect described above would not be observed except for the fact that the undeviated rays came to a focus on the photographic plate and overexposed it. Thus, the undeviated rays were not reconstructed in their proper intensity.

After having selectively transmitted the information described above, one might be able to artificially introduce "undeviated rays" at the receiver such that the reconstructed photograph would have the same appearance as the original. A more promising method of doing this would be to use another point focus at the receiving station, but this time use a graded filter to suppress the intensity of the most highly diffracted rays. Such a filter could be made photographically.

III. Future Work

In the continuation of this study, attempts will be made to spread the diffracted light over a larger area, perhaps by using a lens of longer focal length. This should allow a more critical test of the proposed method. Later it is expected that cylindrical lenses will be tested. These will produce a line focus rather than a point focus. A hologram of this type could be swept in a rectilinear pattern rather than in a circular pattern. At an appropriate time, tests will be made of the proposed methods of restoring the light intensity distribution of the original photograph.

# Pulsed Laser Holograms



Robert H. Gibbons

## I. Introduction

Pulsed laser holograms were first achieved in 1965 by two independent research groups: A. D. Jacobson and F. J. McClung of Hughes Research Laboratory (3) and R. E. Brooks, L. O. Heflinger, R. F. Wuerker and R. A. Briones of TRW Systems (4). Both groups used the two beam system of Leith and Upatnieks with Q-spoiled ruby lasers as the coherent light source. The exposure time for the pulsed laser holograms is of the nanosecond range, while conventional gas laser holograms require time exposures of 10 to 30 seconds. Thus, the pulsed laser hologram can record a transient phenomenon that would be lost to gas laser holograms. Rifle bullets have been captured in flight, and, using interferometric techniques, the bow shock waves formed as the bullet passes through air have been photographed and quantitatively measured with pulsed laser holograms (5).

## II. Work Performed

The work on pulsed laser holograms at the Graduate Institute of Technology has included duplicating the systems of Jacobson et al. and Brooks et al. (4) and improving upon them to obtain high quality holograms that can be reconstructed with gas lasers. The systems mentioned above were set up using focusing optics to collimate and enlarge the beam coming from the ruby laser. Although in some cases first order reconstructions were obtained with these systems, the images were not distinguishable. A private correspondence with Mr. Marvin Sachse of Korad Inc. (who manufactured the K IQ-P ruby laser used in these experiments) established the fact that focusing the 75-100 megawatt beam in air would ionize the air at the point of focus and would disrupt the coherence of the beam thereby making quality holograms more difficult to attain. It was then decided to build a vacuum chamber that would permit the beam to be focused in vacuo during collimation and to use a pinhole to "clean up" (spatially filter) the beam during collimation. Such a chamber was built, as shown in Figure 3. The beam enters through lens L1, is focused by this lens on a pinhole and exits the chamber through lens L2. The chamber collimates and enlarges the beam emitted by the ruby laser. From the chamber, the beam then traverses the optical system under study.

A pinhole mount was designed and built which permitted motion along three axes to align the pinhole with the focused laser beam. The pinholes were made by firing the laser at 0.010 inch thick stainless steel foil mounted in the movable pinhole mount. Vacuum was not used in making the pinholes. The pinhole was left in place and the chamber was sealed and evacuated. Tests were performed to select the best material for the pinholes (materials which would not be destroyed upon successive firings of the laser). Of the materials tested (stainless steel, nickel, nichrome V, brass, and aluminum), stainless steel was the best. The pinholes have not yet been used in making holograms.

The duplication of Jacobson and McClung's system is shown in Figure 4. This system was altered by adding the vacuum pinhole chamber developed at the Graduate Institute of Technology. From this optical system, holograms of a line drawing transparency were made on Kodak 649 glass plate film (resolution greater than 2000 lines/mm) and on Kodak High Definition Aerial Film Type 50-243 (resolution of 465 lines/mm). The duplication of Heflinger et al's system (4) with the addition of the vacuum chamber is shown in Figure 5.

## III. Conclusions

The vacuum chamber successfully eliminated the problems which occurred when the laser beam focused in air. With the vacuum chamber, successful holograms were obtained on both the glass plate film and the aerial film. The reconstructed images could be distinguished, but the image of the hologram made on glass plate film was more distinct because of the higher resolving power of that type of film.

Studies of the two methods of making pulsed laser holograms previously described and the experimental results obtained at the Graduate Institute of Technology have resulted in considerations of three important laser parameters which must be examined to obtain high quality ruby laser holograms. They are: (1) coherence length of the laser, (2) elimination of the longitudinal modes of the laser, and (3) elimination of the transverse modes of the laser. The coherence length, $\Delta L$, can be approximated by the equation $\Delta L = \Delta t \cdot c$, where $\Delta t$ is the pulse length of the laser ($\Delta t$ = 10 nanoseconds for the Korad K 1Q-P laser used in these experiments) and c is the speed of light (6). Therefore, the coherence length is approximately 3 meters. All path lengths must be kept within this figure.

Longitudinal modes of the laser can be eliminated by having equal path lengths and an equal number of reflections for the information and reference beams (7) or by having the path length difference between the information and reference beams equal twice the laser cavity length (8) (for the Korad K IQ-P laser, the cavity length is 17.5 inches).

Transverse modes are automatically eliminated by the K IQ-P laser used in these experiments, since it uses a passive Q spoiler with Cryptocyanine dye. This dye, which is opaque until the proper energy level is reached, breaks down to permit the photon beam to reach the rear mirror, thereby completing the resonant cavity conditions for lasing action and causing the laser to emit one giant pulse. The dye breaks down only at a localized area and acts as a transverse mode filter, since only modes parallel to the laser mirrors will penetrate through the dye (9).

The best material tested for pinholes is stainless steel foil 0.010 inch thick. Pinholes 0.0005 inch in diameter have been obtained but they were destroyed with as few as ten firings of the laser. Adjustments of the focus are needed to improve the lifetime of the pinholes.

## IV. Future Work

A technique will be developed to utilize the stainless steel pinholes in the hologram system. Other parameters will be studied, including the following topics: (1) effect of vacuum chamber pressure on the quality of pulsed laser holograms, (2) determination of the best optical arrangement to obtain high quality holograms; (3) determination of the best film for pulsed laser holograms, taking into account resolution and film speed; (4) proficiency with two dimensional transparencies leading to holograms of three dimensional objects; (5) effect of a moving object or moving photographic plate on the quality of the hologram; (6) effect of vibration on pulsed laser holograms; and (7) possible applications of the pulsed laser hologram techniques to high speed schlieren photography.

A portion of the work described above is being investigated as a master's thesis.

# Schlieren Holography-Ray Tracing

Robert L. Bond

## I. Introduction

Schlieren techniques have long been used in the study of fluid dynamics, especially gas dynamics. Classical schlieren studies are limited to the visual study of the transient phenomena in progress or to the storage of a particular time segment of the phenomena on film. Either approach presents a gross effect which limits the detail in which one can study segments of the schlieren field.

The purpose of this project is to exploit the ability of the hologram to record all of the information contained in the rays that have passed through a schlieren field. The availability of these data should permit a more detailed study of the schlieren field than has ever before been possible. In particular, one can measure both the angle and direction of deviation of individual rays.

The ability of a hologram to store information concerning the incident angles of rays striking it permits it to effectively store the original object through which these rays pass in route to the hologram. Reconstruction of this hologram produces the standard photographic image or, by selected techniques, it can be reconstructed as a shadowgraph, interferogram, or schlieren photograph.

If, instead of illuminating the entire hologram, a pencil beam of coherent light is used to scan the hologram, individual facets can be reconstructed. By measuring the distance that the spot of light is deviated by the hologram, determination of the angle of deviation caused by the original object can be made.

Therefore, the combination of the schlieren photograph and hologram into a single emulsion permits the freezing of moving phenomena so they can be studied in great detail (detail normally reserved only for static systems) at any time after the actual schlieren field has been removed. This technique has the same high sensitivity of standard schlieren systems with the additional freedom of knife edge placement in the reconstruction rather than in the original schlieren system. In addition, this system permits the study of deviations in two dimensions from one schlieren hologram.

## II. Work Performed

To date the experimental work has been directed toward determining the feasibility of using a hologram to study the angles through which rays are deviated by an object placed in the information beam. To permit a rational approach, simple static objects whose properties are well known or could be readily determined were used. Also, a continuous laser was used rather than a pulsed laser. However, the study of constructing suitable holograms with a giant pulsed laser has been carried on simultaneously. It was decided that the two technologies should be developed separately for the sake of simplicity and then combined after problems in both techniques had been solved.

Techniques of hologram construction and reconstruction were studied simultaneously to ascertain the optimum configurations of the optical systems and to minimize error in the readout of the deviated rays and their correlation to the ray deviation by the original object. Parallel carrier and information beams were used throughout the studies to minimize the difficulties associated with readout. Otherwise, it would have been necessary to scan the laser angularly as well as laterally. By the use of a continuous laser with greater than 50 mW output, the problems of reconstruction of the hologram discussed in the NsG 713 report of June 6, 1966 have been made considerably simpler.

Another problem that has continued to produce rather high error in the reconstructions is the serious aberrations present in the optics necessary to produce the large diameter, well collimated reference and information beams. To date, this problem has defied a suitable solution, but it is hoped that with highly corrected collimators and nearly ideal beam splitters the problem will soon be solved. The most accurate reconstruction so far was obtained with the apparatus diagrammed in Figures 6, 7 and 8. This process eliminated the tedious alignment techniques necessary with image holography discussed in great detail in the previous report. In Figure 6 the collimated reference beam, R, interfered with the collimated information beam, I, which had traversed the object, O. The resultant interference pattern was recorded on the film plate, $H_1'$, which upon processing became hologram $H_1$. In Figure 7 the hologram, $H_1$, is reconstructed forming a real first order image which interfered with a reference beam, R, at another film plate, $H_2'$. Upon processing $H_2'$ became hologram $H_2$. In Figure 8 the hologram, $H_2$, was reconstructed forming a real image O' which was the point-for-point analogue of the original object, O.

This multistep process has not only eliminated the necessity for precise alignment but has also corrected the inversion of the reconstructed image. The 50 mW continuous laser facilitates the use of an ordered array of apertures to define several pencil beams, permitting detailed analysis of a large segment of the schlieren field at one time. This technique is outlined in the NsG 713 report of June 6, 1966.

## III. Conclusions

It has been established that there is a close correlation between the angle through which a light ray is deflected by an object and the corresponding ray in an image hologram of the object. It has also been established that by using a multi-stage construction and reconstruction process a regular Fresnel hologram reconstruction produces an image that is a point-to-point analogue of the original object and therefore produces the same close correlation. It has been found that there are errors introduced by poorly collimated beams and proposed techniques for minimizing these errors have been made.

## IV. Future Work

The experiments performed thus far will be redone using corrected collimators to eliminate the major cause of error in the ray tracing procedure. After this correction is made, other sources of error will be determined and either eliminated or compensated for mathematically.

With the optimized system, the study will be extended to slow moving fluid systems in which the motion can be "stopped" by a simple mechanical pulsation of the continuous laser beam.

A study will be made to determine what information can be obtained from this two dimensional schlieren hologram of a "stopped" motion, how favorably this information content compares with classical schlieren photographs, shadowgraphs and interferograms, and what the limitations of the schlieren hologram technique are. Of particular interest is the possibility of extending the technique to a third dimension. In this case a second information beam passes through the object orthogonal to the first beam. The beam then interferes with a reference beam either on a separate photographic plate or on the same plate as the initial hologram. This adds two more degrees of freedom to the information known. However, the four degrees of freedom are not independent and therefore condense to the standard three cartesion coordinates.

There is a possibility that by certain three dimensional matrix array techniques a digital computer could be used to incrementally trace the rays throughout the volume defined by the two holograms. This would be completely analogous to tracing rays through a highly complex optical system with various interfaces, pertubations and refractive indices.

The ultimate use of these techniques for detailed study of fast moving fluid systems will require a giant-pulse ruby laser. Study of the techniques of giant-pulse laser hologram production will continue concurrently with the above research. At the time that both techniques are perfected the two will be combined to permit detailed studies of most dynamic flow systems.

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# Resolution Criteria in Holography

Jack G. Dodd and Landy Doyel

## I. Introduction

As a laboratory curiosity, holography has come a long way from the initial studies by Gabor (10), but as a method of photography it has been severely restricted by the theoretical requirements of a coherent light source and a high-resolution recording medium. Both of these requirements can be relaxed to some degree by proper experimental design (11, 12). The present study has been directed toward an evaluation of the effects of varying the resolution capabilities of the holographic recorder to determine what types of holographic systems are best suited to the production of acceptable holograms on relatively low resolution media.

The eventual goal of this project was forecast in an earlier report (13) where it was shown that some types of optical information could be transmitted with a narrower time-bandwidth as their Fourier transforms (holograms). Also, if a hologram is made using a diffused object beam reconstruction (with reduced resolution) of the entire image can be obtained by illumination of only part of the hologram. (Diffused beams were not used in this study.) The potential value of such a technique in telemetry is obvious. However, its effective implementation must rely upon a thorough understanding of which elements of the total recorded hologram are really essential to a successful reconstruction. Granite tables, high power lasers and super-high-resolution plates have all been invoked as necessary equipment (14). There is no doubt that holography is easy with such equipment, but this does not tell one in what ways a hologram can be poor and still produce a satisfactory reconstruction. Since transmission of a hologram using a limited time-bandwidth product will certainly degrade it in a manner related to the scanning procedure, it is necessary to determine which kinds of degradation are "preferable" and which kinds must be avoided.

The plan of work adopted was to choose a set of well-defined objects whose theoretical transformation properties were simply calculable so that direct quantitative comparison between theoretical predictions and experimental results could be made whenever desirable, and to make holograms and reconstructions of these objects, varying the essential experimental parameters one at a time.

## II. Work Performed

### A. Experimental Parameters

The objects chosen were two slits: one measuring 0.26 mm X 2 mm, and one extremely narrow slit, also 2 mm long; two Ronchi rulings of 100 lines/inch and 300 lines/inch, masked so as to present only a few (∿ 20) lines to the beam; and a picture. The experimental arrangement used for both generation and reconstruction of the holograms is shown in Figure 9. The reference-beam method of Leith and Upatnieks (15) was employed, with beam angles of approximately five degrees. The reference beam was derived not by a beam splitter but by reflecting part of the beam using two first-surface mirrors. This method avoids the multiple-reflection problem but requires a good large lens to collimate a beam, even for the small objects used in this study. Both reference and object beams were accurately parallel and equal in intensity to simplify the theoretical studies planned. The laser was an inexpensive OTI 0.3 mw He-Ne unit, which served admirably while it lasted, which was only about 100 hours.

For convenience and economy, 35 mm Kodak high contrast copy film was chosen to record the holograms. This film allowed the use of a 35 mm Exa single lens reflex camera body which greatly facilitated focussing and speeded up the actual hologram-making process. Reconstructions were made by removing the reference beam mirror, replacing the object by the hologram and moving the camera laterally on the cross-slide to intercept the reconstructed real image. Panatomic -X film was employed for reconstruction. Since the objects used were step functions in intensity, nothing could be determined about grey scale reproduction but only resolution in the Rayleigh sense (16).

B. Program

The basic study consisted of making the best possible hologram of each object on a scale that permitted recording the central maximum and at least the first three diffraction orders on each side of the maximum. In reconstruction, various orders were masked out to determine the effect of their loss on the quality of the reconstructed image, using the known properties of the object as a guide. From the point of view of telemetry each diffraction order to be transmitted consists of a certain number of bits and it is obviously desirable to transmit as few orders as permissible.

C. Data

The first object, shown in Figure 10 in reconstruction, was a slit so narrow that only the central maximum of the diffraction pattern fell on the film. It is evident that the slit reconstructs as a slit. In evaluating the quality of the reconstruction it should be kept in mind that focus of the reconstruction is critical, and a slight departure of the film from normal incidence causes noticeable aberration. What is important is that only the central diffraction order of the object is necessary to permit a recognizable reconstruction of a slit. This case will be discussed later in the report. The second object, shown in Figures 11A through 11E, was a slit measuring 0.26 mm X 2 mm.

The following convention will be used to simplify discussion: if the central maximum and each of the first diffraction orders were used for the reconstruction, this would be denoted by the symbol 101. If the central maximum and the first three orders on one side were used, the designation would be 0123. If a particular order were blocked, its place would be taken by a cross, e.g. 1X1 denotes a reconstruction made using the two first-order sidebands but blocking out the central maximum. Using this notation the slit reconstructions are as follows:

Table 1

| Figure | Orders |
|---|---|
| 11A | 01 |
| 11B | 101 |
| 11C | 012 |
| 11D | 01234 |
| 11E | 3210123 |
| 11F | 4321X1234 |

It is evident there is little basis to choose among the various reconstructions, except the last. Close examination does show that the edges of the slit in Figure 11A are not as sharp as in subsequent reconstructions. It is difficult to determine if this effect is related to the supression of sidebands or is simply a variation in focus during reconstruction. In the reconstruction of this slit using the central order only, the slit is reconstructed, although with some degradation, just as in the case of the narrow slit. Note the effect of suppression of the central order in Figure 11F. The "ghosts" marking the slit edges would not reconstruct at all in a perfect hologram containing all diffraction orders.

The third object consisted of a 300 line/inch Ronchi ruling, masked down to 21 lines. This masking was necessary to prevent overlapping of orders on the hologram. Figures 12A through 12F are reconstructions from a single hologram using the orders designated:

| Figure | Orders |
|---|---|
| 12A | 0 |
| 12B | 01 |
| 12C | 101 |
| 12D | 21012 |
| 12E | 3210123 |
| 12F | 321X123 |

This object has been most instructive, especially since the theory of formation of exactly such an image has been treated in detail in the literature (17).

Figure 12A shows most graphically what the contribution of the central order is: it defines the picture area. However, it gives no information about what lies within that area. All such information is carried by the sidebands. In Figure 12B a single sideband has been introduced and now it is possible to see the structure of the picture. However, the representation is not accurate; in a Ronchi ruling, light and dark spaces are equal in width and "step-function" in intensity. This is not at all the appearance of Figure 12B; the bright lines are too narrow. The addition of another first order sideband, as in Figure 12C, improves the appearance only slightly. Evidently, first order sidebands enable one to count picture elements within an area, but not to evaluate intensity distributions accurately.

Figure 12D, containing 21012, definitely shows the "squareness" of the Ronchi lines, but the dark areas are still too large. Figure 12F, containing three orders on each side of the central maximum, shows an accurate reproduction of the ruling except for some "noise" between the lines. This "noise" is present in all reconstructions and is visible in this print only because of slight underexposure. It is caused in part by film grain. Figure 12F shows the remarkable result of suppressing the central order. The ruling is well reproduced, but each line is doubled. This is predicted by theory.

The fourth object was also a Ronchi ruling, 100 lines/inch, masked to present a 7-line object. The complete series is not shown because no new information was revealed by it. The two photographs that are shown, Figures 13A and 13B, are from holograms made on Kodak high-contrast copy film and Panatomic-X, respectively, to show the effect of the holographic recording medium on the quality of reconstruction. The magnifications are unfortunately not the same, but in any case the high noise level of the Panatomic-X hologram is evident.

Figures 14A and 14B show the reconstruction of holograms made on high contrast copy and Panatomic-X film; the effect of the noise is indeed evident. It should be emphasized that the difference is not caused by insufficient resolving power of the Panatomic-X, at least in the ordinary sense, but rather is caused by grain size. This point will be discussed in the next section.

## III. Conclusions

### A. The Film

The first obvious result of these studies is that one can make acceptable holograms on material other than 649F spectroscopic plates, but that something better than a good fine-grain general purpose emulsion is needed. One tends to blame the film resolving power of Panatomic-X for the difficulties encountered in its use, but as usually defined, the resolving power is adequate for the objects and beam angles encountered in this study.

To see that this is so, consider the geometry shown in Figure 15, which shows the extreme rays from a narrow slit impinging on the hologram plane to form an interference pattern with the reference beam. The nominal reference beam angle is actually a median angle between $\beta$ and $\gamma$, the extreme angles formed with the parallel reference beam by the diffracted object rays. The spatial frequency generated by two coherent parallel beams striking the surface at angles $\beta$ and $\gamma$ is

$$\omega = \frac{\cos \beta - \cos \gamma}{\lambda} \qquad (1)$$

where $\omega$ is the spatial frequency that must be recorded on the film. In all cases employed in this study, the reference beam angle $\beta$ is within 5 degrees of 90 degrees so cos $\beta$ is nearly 0. Since the object-hologram distance of 1m is large compared with the hologram size of 3.0 cm, $\gamma$ is even closer to 90 degrees. Therefore, to an excellent approximation

$$\cos \beta \sim \sin \left(\frac{\pi}{2} - \beta\right)$$
$$\cos \gamma \sim \sin \left(\frac{\pi}{2} - \gamma\right)$$

and

$$\omega = \frac{\gamma - \beta}{\lambda}. \qquad (2)$$

Of course, the sign of $\omega$ has no significance insofar as considerations of resolving power are concerned. In magnitude, the maximum value of $\gamma$ was approximately 0.019 radians, and for the studies reported here, $\beta$ never ranged far from 0.05 radians.
With $\lambda$ = 6328 Å,

$$\omega_{max} \approx 110 \text{ lines/mm}. \qquad (3)$$

This is within the resolving power of Panatomic-X by a factor of two. Since the resolving power of high contrast copy film is only twice that of Panatomic-X, and Panatomic-X should be good enough, it is obvious that the difference between holograms made on the two media cannot be explained on this basis. The reason for the difference is the grain size. What needs to be explained is why a grain structure considered excellent in ordinary photography is completely unacceptable in holography.

The explanation rests in the mathematical properties of the Fourier transform, of which the reconstruction of a hologram is the optical analogue in two dimesions. Briefly, high spatial frequencies in a hologram reconstruct as low spatial frequencies in the final image, and conversely. In Panatomic-X the grain size is sufficient to scatter some of the reconstructing beam as if it were a holographic pattern from some original object. In fact, the object that would generate such a hologram is simply a fairly coarse pattern of random noise, and that is exactly what is reconstructed from such a hologram.

Naturally, any emulsion has some grain. However, the finer the grain the larger the mottles in the reconstructed noise will be until, in the case of contrast process film and especially the 649-F spectroscopic plates, the mottles are so large that they overlay each other rather completely and cancel out. The noise level is also lowered by the fact that high resolution emulsions have a much lower inherent fog level than ordinary emulsions, and so the random grain pattern is almost absent except where exposure has occurred. This is far from true in ordinary emulsions, as can be vividly demonstrated by interposing an unexposed, developed film of Panatomic-X in a laser beam and observing the intensity of the scattered light. Some image degradation probably occurs also because of distortion of the laser beam wave front by non-uniform film and emulsion thickness.

B. The Aperture

In ordinary optical imaging, the resolving power of a system is determined by the numerical aperture, defined as the sine of the half-angle of the cone of rays accepted by the objective from a point source on the axis. If Rayleigh's criterion for resolution is applied, then the approximate number of lines/mm of the object that can be resolved is given by

$$N = \frac{D}{1.22 \lambda L} \qquad (4)$$

where D is the diameter of the limiting field stop (lens) and L is the distance from the object to the field stop. In holography, the hologram is the field stop. From the dimension of the hologram and its distance from the object in the studies reported here, $D/L \approx 0.015$ and $N \sim 50$ lines/mm. This resolution has been approached even on high contrast process film. Sections of the fence in Figure 14A correspond to line densities of $\sim 5$ lines/mm and obviously at least twice this figure could have been resolved.

C. Suppression of Sidebands

From the preceding discussion it is clear that masking of higher-order sidebands during reconstruction is entirely equivalent to reduction in the numerical aperture of the hologram. For example, consider a fairly wide slit filled with lines, such as the masked Ronchi ruling shown in Figure 12B. The sidebands are spaced at distances (18)

$$X_n = \frac{n\lambda L}{d} \qquad (5)$$

where L is the distance from the object to the hologram and d is the distance between the lines to be resolved. As Figure 12B shows, a single sideband is sufficient to enable one to count the lines contained, if not to determine their shape. From Equation 5 with $n = 1$,

$$X_1 = \frac{\lambda L}{d} \quad . \tag{6}$$

If this first sideband and the central order must both fall on the hologram then its diameter must be at least $D \approx X_1$. The number of lines/unit length that the object contains is $N = 1/d$, and substituting these two quantities in Equation 6,

$$N \approx \frac{D}{\lambda L}. \tag{7}$$

Compare this with Rayleigh's criterion, Equation 4: they are essentially identical. Another way to define Rayleigh's criterion is that the system must record at least the central order and first sideband of the highest spatial frequency to be reproduced.

D. Reference Beam Angle.

The function of the reference beam is to provide a "carrier" which can be "frequency-modulated" by the object ray. The resulting beam, which is to be recorded on the hologram, will generally carry a range of spatial frequencies at the hologram position from $\omega_r$ to $\omega_o$, where $\omega_o$ is the extreme absolute value of the "beat-frequency" between the two beams, e.g. as given by Equation 2 in the case of a small object; and $\omega_r$ is the spatial frequency corresponding to the nominal interference pattern when no object is in the beam. To record such a beam, the resolution of the film must be adequate. Also, the interference frequency must never pass through zero, since the recording emulsion cannot distinguish sign but only magnitude of an interference fringe, and the reconstructed image would always overlap the zero-order reconstructing beam. This is equivalent to a loss of information, and therefore to a loss of resolution in one sense. This condition was satisfied by more than a factor of two in every case in these studies. This overkill was of no advantage; in fact, one wants $\omega_0 = 0$ if possible so that the highest spatial frequencies to be recorded will still be well within the film's resolution capabilities.

E. Beam Intensity Ratios

Little attention has been paid by most workers to the relative intensities of the two beams. The conditions, in fact, are not critical and are usually adequately met in any reasonable experimental arrangement. The essential point is that the object beam be no stronger than the reference beam. Nature usually takes care of this automatically through absorption by the object (in the case of transparency). Of course one wants the object beam not to be too weak, or it will not record well. In the arrangement decribed in this case, the two beams were rather closely equal in intensity.

F. Laser Characteristics

For transparency work, the type of laser was found to be unimportant except:

1. It must be intense enough to permit reasonable exposures (0.3 mw was sufficient).

2. It must operate in a single transverse mode. Confocal mirrors cannot be used unless detuned.

3. The path difference between reference and object beam trajectories should be small compared with the laser cavity length, or at least near an integral multiple of twice the cavity length. This prevents destructive interference

between different longitudinal modes which cannot normally be suppressed.

## IV. Future Work

It is now understood how to make holograms and how to predict in advance what the quality of a reconstruction will be, using familiar media. However, the effects of the kind of degradation that telemetry might produce have not been investigated. One might expect two different kinds depending on whether digital or analogue transmission is employed.

In the former case the result will be essentially similar to introducing "grain" in the hologram, except that the digital grain will be a periodic array instead of a random pattern. It should be possible to remove any known periodic pattern by imposing the inverse pattern during reconstruction, at least in principle. Degradation will come from sampling size restrictions and from loss of bits. In the latter case, there will be some "fine-grain" noise that can be filtered out since its effective frequency will be higher than the spatial frequencies that must be transmitted. However, the components of noise in the bandwidth required for transmission of the holographic information cannot be so filtered. This noise corresponds roughly to bit loss in digital transmission. In addition, bandwidth restrictions may attenuate higher spatial frequencies. This corresponds to sampling size restriction in digital transmission. Both kinds of transmission therefore introduce characteristic kinds of information loss. Both kinds of hologram degradation can be "faked" in the laboratory, and the resulting reconstructions can be evaluated. Some of the proposed techniques are:

A. Digitalization

The noise of digitalization is rather difficult to simulate accurately. In actual digital transmission the hologram would be represented as a rectangular array of primitive areas, each designated by digital, positional and density information. On reconstruction, the marks of the digital "grid" would have to be erased in some manner.

Since digital sampling of a signal must be carried out at a rate at least twice as high as the highest frequencies to be reproduced and because the basic grating is a fairly high-frequency signal, the digital grid necessary for holographic transmission must be fine. It is possible to generate such a grid by re-exposing an exposed but undeveloped hologram to a fine set of interference fringes, rotating the hologram 90 degrees and re-exposing again to provide a rectangular screen superimposed on the hologram image. This simulates to some extent the noise of spatial digitalization. It does not seem possible by present techniques to simulate density digitalization, and theoretical studies are underway to determine how serious this omission will be.

The digital noise can be removed easily during reconstruction of the hologram. In fact, if the digital grid has a periodicity higher than twice the holographic pattern, it will reconstruct (as a rectangular array of points) spatially entirely separate from the reconstructed image. The situation is analogous to the well-known experiment of recording two different holograms on the same plate by using two different reference beam angles. On reconstruction, the two images are spatially separable.

This should not be construed as saying that all effects of digital noise can be spatially filtered out. Some decrease in effective aperture will result from the obscuring effect of the digital grid, and this will degrade the reconstruction. The purpose of simulation is to evaluate the seriousness of this degradation.

B. Bandwidth Limitation

In analogue transmission, a limited time-bandwidth product may restrict the maximum frequency that can be transmitted. Should this attenuate some of the higher hologram frequencies, some corresponding degradation in reconstruction will ensue. To simulate this effect one needs to record a hologram on an essentially grainless medium whose resolving power is insufficient to reproduce the highest frequencies. Since the maximum frequency present at the hologram can be changed merely by changing the reference beam angle, a set of holograms will be made from a given object using a group of reference beam angles that span the resolution limit of an essentially grainless medium (possibly a color film) and the effect of loss of the higher frequencies on reconstruction quality will be observed.

C. Bit Loss

During digital transmission, some bits will probably be lost, in the sense of being replaced by noise (bits that do not carry picture information). To simulate this kind of noise accurately is not easy. A satisfactory simulation has not yet been devised, even on paper, short of actually performing a noisy transmission experiment. This may be the best thing to do.

D. Bandwidth-Included Noise

In analogue transmission, noise that falls within the transmission bandwidth cannot be filtered out. Simulation of this noise can be achieved by interposing a plate during reconstruction containing random spatial frequencies of the desired bandwidth. The plate contrast will be equivalent to the noise amplitude. Such a "noisy" plate can be made in the following manner: make several Gabor holograms of an unexposed, developed, fairly grainy film, choosing the film-to-hologram distance so that the highest spatial frequencies recorded at the hologram are of the order of the highest spatial frequencies of the hologram to be reconstructed. A series of widely varying exposures should produce a selection of noise equivalent amplitudes that can be quantitatively described in terms of mean contrast over a plate.

# Factors Contributing To The Degradation of Holographic Images

George S. Ballard

## I. Introduction

In recording and reconstructing holograms, a number of factors have had a great influence upon the ultimate resolution and "eye pleasing" characteristics of a given holographic image. In many cases, holographic images were seriously degraded or appeared grainy and, at times, the entire real image could not be focused in any one plane. These effects became noticeable in observing holograms made from 35mm slides containing a large amount of fine detail. It was therefore decided that an attempt should be made to identify the factors which tend to degrade the hologram image and eliminate each of them from the hologram recording process, which would result in a high quality image. Then each of these factors could be introduced separately and compared with the above "standard" image in an attempt to observe the effects of each.

## II. Work Performed

A National Bureau of Standards lens resolution test chart was used as an object. The chart was photographed on Kodak 35mm Kodachrome film. This resulted in a grainless transparency which contained a series of lines whose spacing varied in increments from 7 to 52 line pairs/mm. Any degradation in the resolution of images of this object would be convenient to detect and evaluate.

Holograms of transparencies made with diffuse illumination produce images more pleasing to the eye than those made by direct transmission of laser light through the transparent object (19). Also, holograms made with diffuse illumination have the ability to reconstruct the entire image of scene, even when only a small part of the hologram is utilized. However, it has been observed that all of the holograms made locally using diffuse illumination gave images which were as poor in resolution and exhibited a high background noise which appeared as "grain" in the images. It was decided that diffuse illumination would not be used in the attempt to obtain a high quality "standard" image.

The effect of aperture and film resolution have been discussed at length elsewhere in this report. The aperture chosen for the standard hologram was sufficient to insure the resolution of the finest detail in the object. Kodak 649-F photographic plates were chosen for recording the hologram.

The light transmitted or scattered by an object is duplicated holographically if the hologram is illuminated by a beam with the exact characteristics of the reference beam used in recording the hologram. Thus, if one wishes to work with the virtual image, he need only replace the hologram in the original reference beam and in the same position in which it was made. In this case, aberrations in the reference beam are of no consequence as they will be present in both the recording and reconstructing processes. If, however, the real image is recorded and studied, it is necessary to illuminate the hologram with a beam that is the exact conjugate of the original reference beam, including aberrations. This can be done for abberation-free lenses, perfectly mounted and aligned. In the practical case, however, one can only hope to approach this ideal situation. It would seem beneficial to use parallel light for the reference beam for this study because parallel light is its own conjugate. No lenses would need to be moved between recording the hologram and reconstructing the real image. Abberations in the system would still degrade the real image, but these can be minimized. Therefore, a parallel beam four inches in diameter and with a wave front flat to within 1/10 of a wavelength was used as the reference beam. The image formed by using this beam as a reference and also in reconstruction will exhibit unit magnification. This property is also desirable, as magnifications other than unity introduce distortions in the images formed (20).

The hologram was made as shown in Figure 16. Object-to-hologram distance was 42 1/2 cm, and the reference angle was 10.8 degrees. The exposure time for this hologram was 1/2 second. After development, the hologram was replaced in the reference beam and the real image was recorded on film. The full range of line spacings present in the original object were resolved. The image was in focus across the entire pattern.

Now that a hologram had been produced which reconstructed a high quality image, the various factors which were suspected of causing degradation of images could be introduced into the system. One item of concern was the possible effects of air currents in either the object or the reference beams. Thermal air currents were caused to flow in region A of Figure 16, and a hologram was recorded. The air currents were isolated from the reference beam so as to have no effect upon it. Upon reconstruction, the hologram gave a dim image in which no lines could be resolved. The air currents apparently had caused the light passing through the object to fluctuate randomly across the film plate, preventing the recording of information.

The same air currents were then caused to flow in the reference beam (region B of Figure 16). These currents were isolated from the object beam. A hologram was recorded, and upon reconstruction it was noted that lines with a spacing of 18 line pairs/mm were resolved in the image. This resolution was far below that of the "standard" hologram. The degradation of resolution in the image was apparent. Although this resolution was better than for the case where air currents were recorded in the object beam, it should be pointed out that the reference beam was four inches in diameter while the object beam was smaller (5 mm by 8 mm). It appeared that portions of the reference beam were not affected by the air currents continuously and, when undisturbed, recorded some useable information.

Whenever diffuse illumination had been used in recording holograms locally, resolution had fallen off and a grainy background noise appeared. Rigden and Gordon (21) state that a grainy background is characteristic of images formed with diffuse coherent light, and that apparent grain size is a function of the aperture of the system only. They also state that variations or beats in the image appear to have approximately a periodic spacing of $2f\lambda/D$, where D is the width of the optical system (Figure 17). This variation is the observed granularity. The major portion of the granularity was apparently caused by coherent light meeting and interfering at an angle, $\psi$, to form an image. This angle was determined by the aperture of the system. Figure 18 shows a hologram and reconstructed real image of an object. A real image of the diffuser was also formed at plane 1 or plane 2, depending upon how far from the object the diffuser was placed when the hologram was recorded. The diameter, D, of the hologram and the distance, 2f, from it to the object image plane determined the extreme angle $\psi$ of rays meeting to form an image of point P. Provided the diffusing material was of sufficient size to completely illuminate the object and the hologram recording plate during recording, its distance from the object was unimportant as far as grain was concerned. It did not affect the angle $\psi$. This distance affected the light available for recording the hologram.

To confirm these ideas, holograms were made using Kodak Fine Ground Glass as a diffusing medium. The glass was placed at region C, Figure 16. The diffuser was located 3/8 inch behind the object. The placement of the diffuser cut down on the light comprising the object beam to such an extent that the reference beam had to be attenuated in order to preserve the ratio of intensities between these two beams. Exposure time for this hologram was two full minutes, or an increase by a factor of 240.

The real image obtained from this hologram resolved lines with a spacing of 16 line pairs/mm. The image was more pleasing to the eye than the holograms made without diffuse illumination, and the characteristic granularity was not obvious. By masking off the outer portions of the hologram with an iris, the aperture was decreased and its effect was noted on the image. The size of the grain increased, and in doing so caused previously resolved lines to be buried in the grain structure of the image. The spacing of the smallest grain structure observed was measured for a hologram diameter of 1 cm. This measurement agreed closely with the size predicted by calculating 2f $\lambda/D$. The spacing of the grain was approximately 1/36 mm while the smallest lines which could be resolved were 1/11 mm, or 11 line pairs/mm. It is interesting to note that in calculating the minimum distance between lines which can just be resolved by an imaging system one would use the formula

$$d = \frac{\lambda}{2 \sin \theta} \qquad (8)$$

where, for small angles, sin $\theta$ is D/4f. Substituting,

$$d = \frac{\lambda \, 2 \, F}{D} \qquad (9)$$

is obtained, which is the identical formula used to find the periodic spacing of the grain. One would apparently be looking for details in the image which are of the same size and spacing as the grain. If the line spacing in the image is considered as a signal frequency and the grain as a group of sampling points, an analogy can be drawn from communication theory. Terman (22) states that a signal wave can be reconstructed by sampling if the number of samples per second exceeds twice the highest frequency contained in the wave. In the hologram image, one can infer that the original image frequency in line pairs/mm can be reconstructed if the number of samples/mm exceeds twice the highest frequency in the image. In the experiment performed, a three-to-one ratio was required to observe any resolved lines. Thus, for the case of diffuse illumination, the numerical aperture does not determine resolution directly. Numerical aperture determines the noise level, which in turn limits the resolution.

The diffusing material was moved to a location 5¼ inches behind the object to observe if there was any affect upon the grain or upon resolution. This location corresponds to region D in Figure 16. The hologram thus recorded gave a real image in which there was no observable difference between either the resolution or the grain size when compared with the previously discussed hologram.

A hologram was recorded in which the film plate was exposed for three equal periods and the diffusing material was moved slightly between exposures. This should give the same effect as when the number of scattering centers on the diffuser was increased. Again, the image obtained showed no significant differences from the others recorded with diffuse illumination.

The grain size apparently is a function only of the aperture of the system. It cannot be eliminated entirely, but can be minimized by increasing the aperture. The grain size masks detail in the image and limits the resolution of the image. Two to three times the calculated aperture is required to resolve a given pair of lines when diffuse illumination is used. With diffuse illumination, the exposure time for recording a hologram was increased appreciably. A hologram was made identical to the "standard" hologram, except the laser was attenuated so that the exposure time was the same as for the cases with diffuse illumination. The image formed from this hologram contained lines with a spacing of 26 line pairs/mm. Factors such as vibration, laser instability and thermal expansion or contraction of components, which are not obvious factors for relatively short exposure times, can become important as exposures become longer. The hologram obtained in this instance resolved lines with only half the spacing as the standard hologram, and its resolving power was better than holograms exposed for the same time interval but with diffuse illumination.

It was also of interest to observe the effects of air currents upon holograms made with diffuse illumination. To do this, the diffusing material was again placed 5¼ inches behind the object transparency. Thermal air currents were then caused to flow in the reference beam at region B in Figure 16. A hologram was recorded, and upon reconstruction it was observed that lines with a spacing of 13 line pairs/mm were resolved. This is close to what was observed when no air currents were present. Since it has already been demonstrated that these currents should deteriorate the image, it can only be speculated that the disturbance which was introduced was of relatively minor significance in combination with the other factors already present.

The air currents were introduced into the object beam between the diffuser and the object. This location was between regions C and D of Figure 16. The hologram thus produced reconstructed a real image in which lines as close as 26 line pairs/mm were resolved. This is the same resolution as was obtained without the diffuser. The results of placing air currents in object and reference beams while using diffuse illumination were not as anticipated. At first, it appeared as if these currents either had little effect upon resolution or else improved it. Any attempt to explain these results would be pure speculation. A microscopic examination of the various diffuse holograms recorded showed no discernable differences in any of them, and was of no help in explaining the results. Further work is required, especially to determine whether the hologram obtained with air currents between the diffuser and the object was the result of circumstance or if, somehow, the air currents had the effect of averaging out the grain.

Although not directly associated with the above study of hologram image quality, other work has been performed in an effort to develop proficiency and increase familiarity with other types of holograms. Holograms have been made of diffuse objects which exhibit all of the three-dimensional characteristics of the original scene. A few holograms have also been made which can be reconstructed with white light. Although the images formed from the latter are not considered to be of good quality, they do compare favorably with examples of similar holograms made in other laboratories.

## III. Conclusions

A number of factors other than aperture and film resolution adversly affect hologram image quality. Aberrations in the lenses used to form reference beams limit resolution and make it impossible to focus the entire image in one plane. Granularity in images arises from the use of diffuse illumination. The grain structure limits resolution and is irritating to the eye. The grain cannot be eliminated, but may be minimized by increasing the aperture of the system. Grain structure is not affected to noticeable extent by moving the diffuser nearer or farther from the object. Air currents and factors arising from long exposure times adversely affect resolution. For the case of diffuse illumination, however, thermally induced air currents did not detract from the resolution and in one case improved it.

## IV. Future Work

Further work is required to evaluate the effects of air currents upon the hologram images. The following series of holograms will be made:

1. A control hologram will be made without artificial air currents. No diffuser will be used. The laser output will be attenuated to require an exposure time of approximately two minutes.

2. Air currents will be induced in each of several places. These will be in the reference beam and also in the object beam, both in front of and behind the object.

3. A hologram will be made by utilizing diffuse illumination. No induced air currents will be present.

4. The same air currents will be induced as in No. 2 above, but this time with diffuse illumination.

The evaluation of the images formed from these holograms should provide additional information as to the effects of air currents on the images.

In an effort to reduce the exposure time required for diffusely illuminated holograms, it is planned to substitute a holographic image of a diffuser for the actual diffusing medium. A hologram can be made by using the light diffused by Kodak Fine Ground Glass as an object beam, as shown in Figure 19. Upon reconstruction, the diffracted first order beam which contains the image of the ground glass will illuminate an object transparency, which will serve as a new object beam (Figure 20). Although the image of the diffuser will not be as intense as if the ground glass itself were illuminated by the laser, it will not scatter over $2\pi$ steradians as the actual diffuser would. Instead, almost all of the available light will pass through the object transparency and expose the hologram recording plate, resulting in an expected reduction in exposure time and better image quality.

# DYNAMIC MEASUREMENTS

## Transducer Calibration

V. E. Horn



## I. Introduction

The study of the feasibility of measuring extremely small oscillatory motions such as might be associated with the calibration of miniature accelerometers has been primarily directed toward upgrading of equipment and technique. The measurement of small oscillatory motions of 20 angstroms and larger should allow the calibration of any miniature accelerometer in the frequency range from several kilocycles up to 100 kilocycles per second. If a calibration technique for such transducers can be made practical, the laser interferometer will provide means of measuring both the excursion and frequency of vibration of the transducer.

A measurement of 20 angstroms results in an electrical signal from the interferometer that lies within the noise of the present system. The primary effort at the present time is directed toward learning what components in the system contribute to the noise level and what may be done to reduce their undesirable properties. Improvements on the interferometer up to the present time have resulted in a reduction by a factor of 10 in noise and instability of the overall system. Therefore, the lower limit of detection of oscillatory motion is considerably smaller than that measureable in earlier work.

## II. Work Performed

As reported in the Progress Report of June 6, 1966, one of the first steps taken to reduce the system noise was to mount the entire interferometer on a 30 by 30 by 4 inch marble slab polished on one side. This slab was in turn mounted on four air pads to provide isolation from random vibrations of the floor. The air pads were calculated to have a vibrational period of from one to two seconds. At the time this assembly was completed, only small and extremely noisy lasers were available.

The laser was mounted on the isolated table with the associated optical and electrical equipment. Even though the table provided a more stable mounting system, it was immediately evident that the laser noise was greater than could be tolerated. Therefore, a quieter and more powerful laser (10 milliwatts cw Spectra Physics Model 112) was ordered to be used for this particular project. Meanwhile, techniques for actually measuring vibration and reducing the data to usable information were studied with the small interferometer table.

If the measurement of vibration is to be performed with only one voltage measurement from the photo mixer, it is mandatory that the center of the oscillatory motion (and thus the rest point of the light modulation) be located half way between the maximum and minimum of a quarter wave interference band. This results in an electrical signal that is equal in amplitude on either side of the rest point. Figure 21A shows the interference signal received from motion centered as described above and Figure 21B shows the interference signal received from motion not in the centered condition. The determination of the actual amplitude of movement from the latter signal would require measurement of the maximum and minimum of the signal. Two calculations would be required, with the difference between the end point positions resulting in the actual excursion of the surface. However, in the previously mentioned condition, where the rest position of the interference lies in the center of the light band, the interference signal will be symmetrical about the rest point. Therefore, only one measurement will result in complete knowledge of the movement; provided of course the movement is less than one quarter of a wave.

It became necessary to provide a method for changing the length of the reference path of the Michelson interferometer relative to the active path to enable the rest point of the interference signal to be positioned at the center of a light band. The first attempt at adjusting the interferometer path lengths employed a differential micrometer capable of reading one millionth of an inch movements. The micrometer itself proved satisfactory; however, any attempt to rotate the micrometer screw upset the entire system so that the device had to be remotely operated by some type of motor, which of course became considerably more complicated than necessary. However, the micrometer screw did allow scanning through quarter wave peaks so that the measurement of the peak-to-peak amplitude of quarter wave interference could be performed without driving the transducer. At the time this work was being carried out the vibration source was a Western Electric Dynamic Microphone with a small reflector mounted on the moving diaphragm. Another one of these microphones was installed in the reference path and used to adjust the length of that path by applying D.C. voltage to the coil to the microphone. This way the diaphragm could be made to move to and remain at any desired position.

The only problem with this assembly was that when the current to the microphone was changed it resulted in a small but significant change in the temperature of the microphone, so that it was difficult to maintain a fixed path length. The entire interferometer was moved to a new precision table and used with the larger and less noisy laser previously mentioned. The new table consisted of a two thousand pound granite block with an extremely flat surface.

This block was mounted on air feet similar to those used on the marble table but somewhat larger so that approximately 12 pounds of air pressure was required to suspend the granite table. The period of this table has been determined to be between one and two seconds. The overall system noise was reduced considerably by the application of the larger and more massive mounting for the interferometer and the new laser. This laser was guaranteed to have not greater than 1% peak-to-peak intensity modulation short term. In attempting to further reduce the noise level from the photo mixer, a small broadcast receiver was altered to accept a mechanical filter in place of the first IF transformer. This mechanical filter was resonant at 455 KC with 3db down point at $\pm$ 1½ KC. The signal from the photo mixer was then mixed with the local oscillator signal generator creating a 455 KC side band which passed through the filter and amplified. This resulted in a reduction of noise by a factor of two.

The amplitude of the signal that passes through the mechanical filter is a direct function of the amplitude of the signal from the photo mixer (assuming the local oscillator is a constant amplitude). The use of this secondary measurement has been temporarily suspended in favor of a more direct method. A variable band pass filter, which will allow setting the band pass of the system at any desired width and at any particular frequency will be used.

The upper and lower end of the filter response is adjustable from one hundred cycles to 10 megacycles. In addition to working on the system noise, consideration was given to the best possible configuration for the interferometer. It is necessary that the reflected radiation from the interferometer not be reflected back into the laser, since this results in additional interference which causes variation in the amplitude of the light arriving at the interferometer. Although various designs (such as off angle) were tested, each resulted in some reduction in the quality of the signal from the photo mixer because the beams from the reference and working paths did not arrive at the photo mixer with the proper wave front relationship. Therefore, it was decided to use corner reflectors so that the returned beam from each reflector would be offset by the dimensions of the corner reflector, thus eliminating the possibility of radiation being reflected back into the laser.

## III. Conclusions

Work performed on this project to date indicates that the interferometer method of measuring oscillatory motion with a Michelson interferometric and a laser source appears to be practical. The lower limit of such measurement will finally be set by the noise created at the laser source. At the present time the best source available has approximately ¼ of 1% amplitude modulation short term. This would allow a measurement of 20 angstroms with better than a two-to-one signal-to-noise ratio which should be satisfactory for accurate measurement. However, there are a number of drift and stability considerations that must be understood before the noise of the laser becomes the limiting factor.

## IV. Future Work

In the near future the effort will be toward determining what elements within the system truly influence the stability and what can be done with these elements in order to improve the overall technique. Ceramic crystals were recently employed for vibratory sources and the immediate results are encouraging. However, little data are available from the system using the crystals since they have been employed only recently. One immediate benefit is that the range has been extended to 100 KC. At the present time, more sensitive crystals are being purchased in order to lower the required driving energy for a given transducer excursion.

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FIGURE 1

THE SORTING OF HOLOGRAPHIC INFORMATION

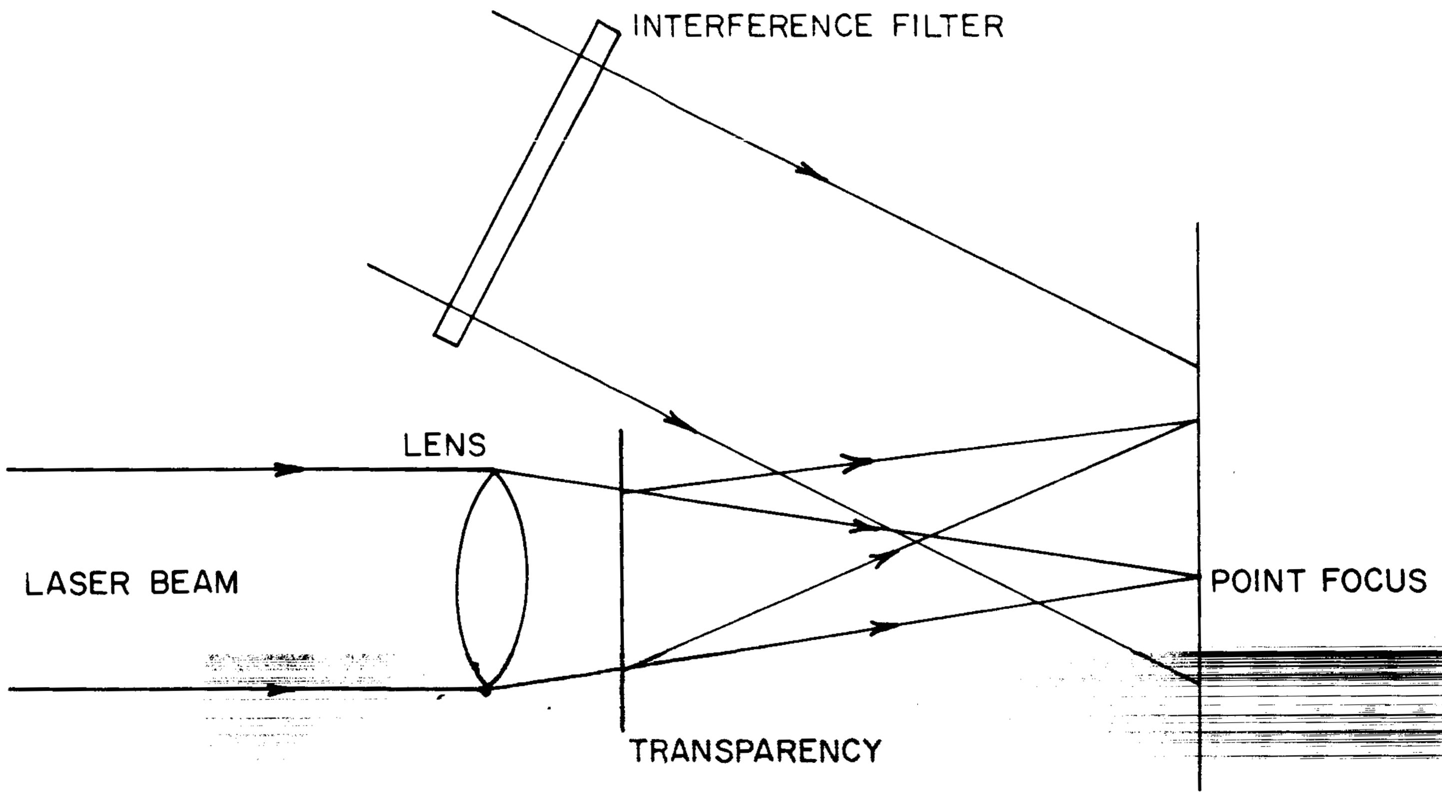



FIGURE 2

APPARATUS FOR RECONSTRUCTION

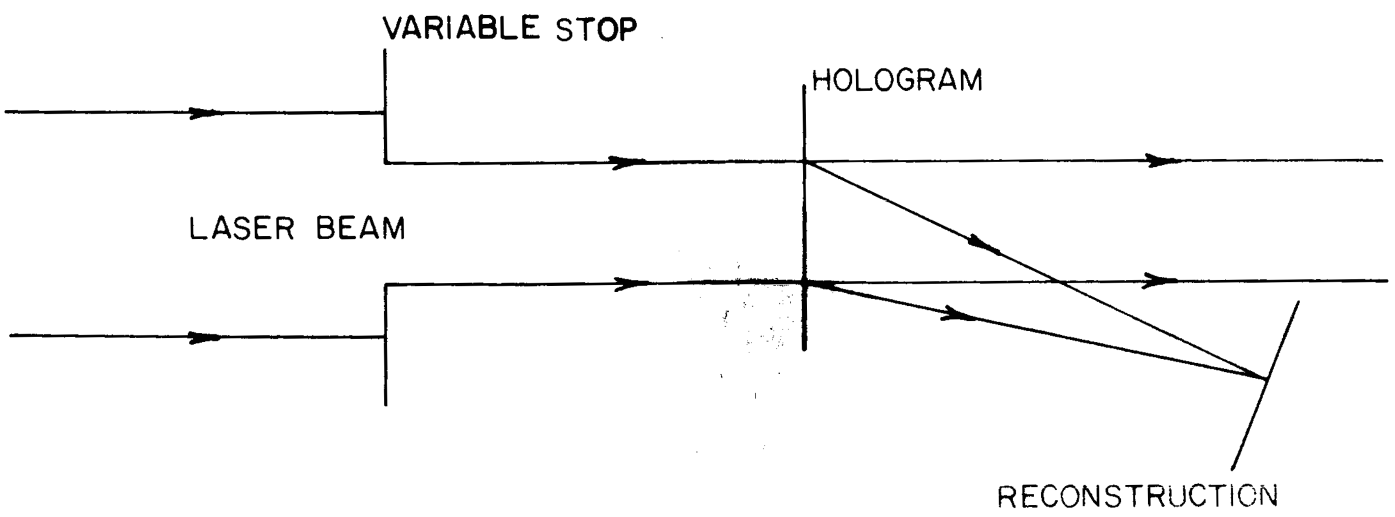


FIGURE 3

VACUUM CHAMBER WITH PINHOLE

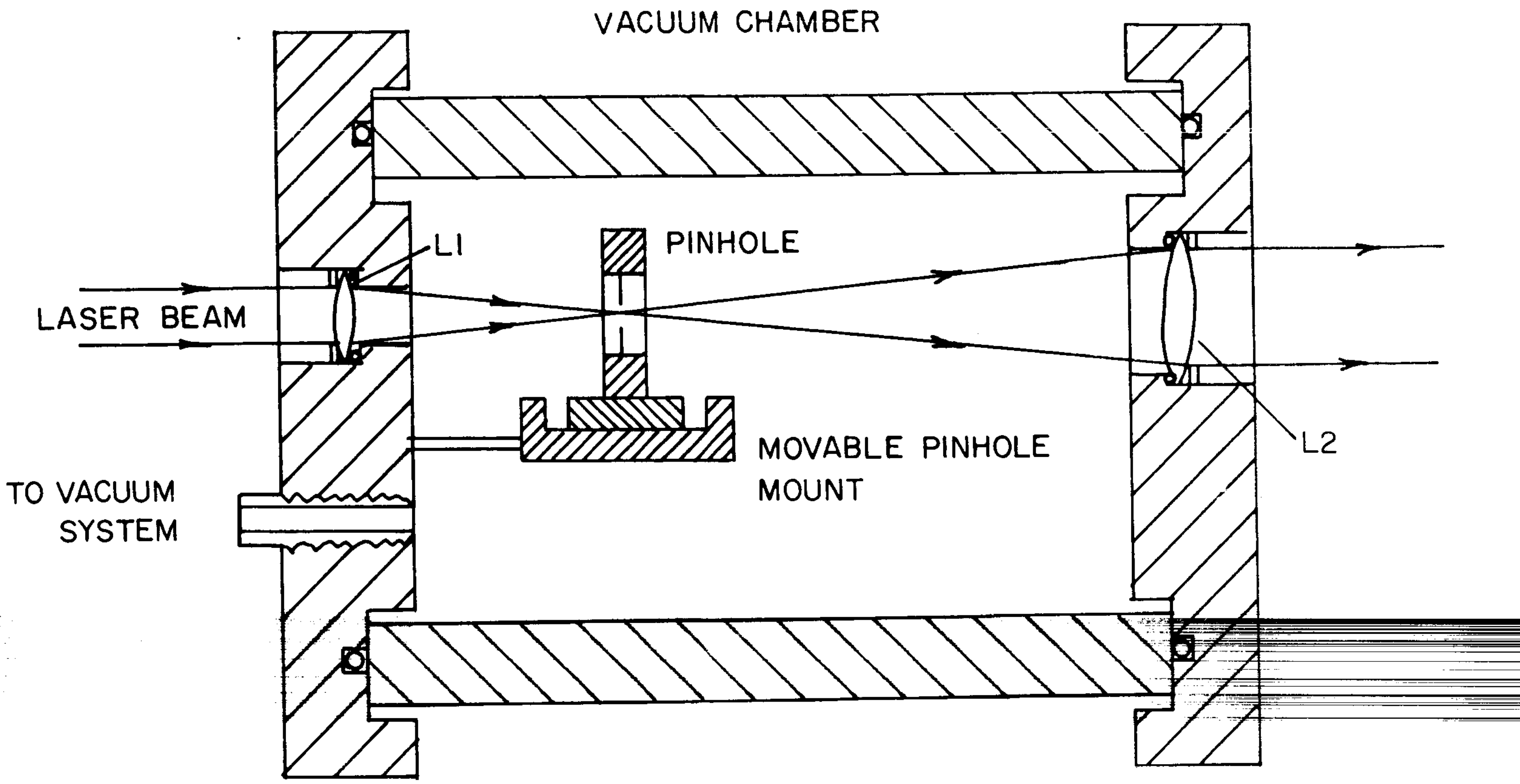



FIGURE 4

JACOBSON-McCLUNG SYSTEM WITH VACUUM CHAMBER ADDED

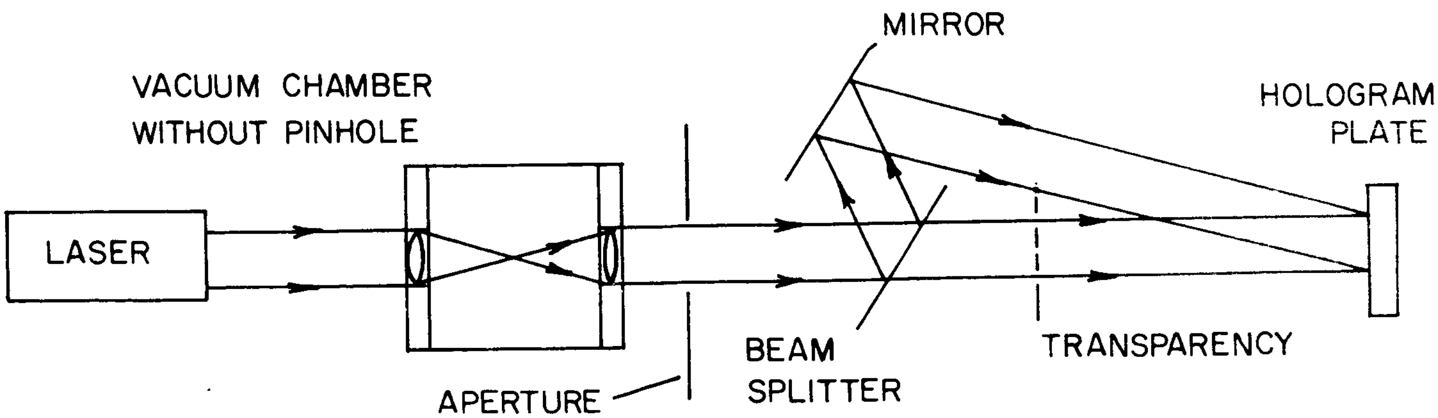


FIGURE 5

BROOKS - HEFLINGER SYSTEM WITH VACUUM CHAMBER ADDED

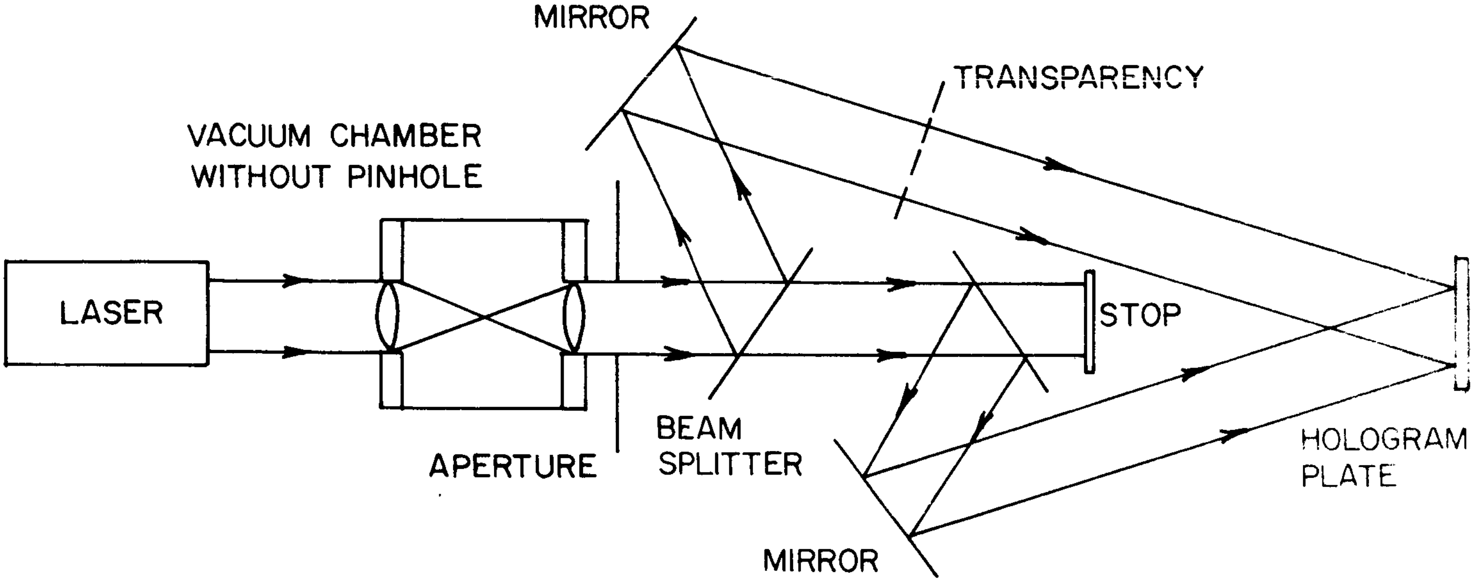



FIGURE 6

SETUP FOR CONSTRUCTION OF FIRST HOLOGRAM

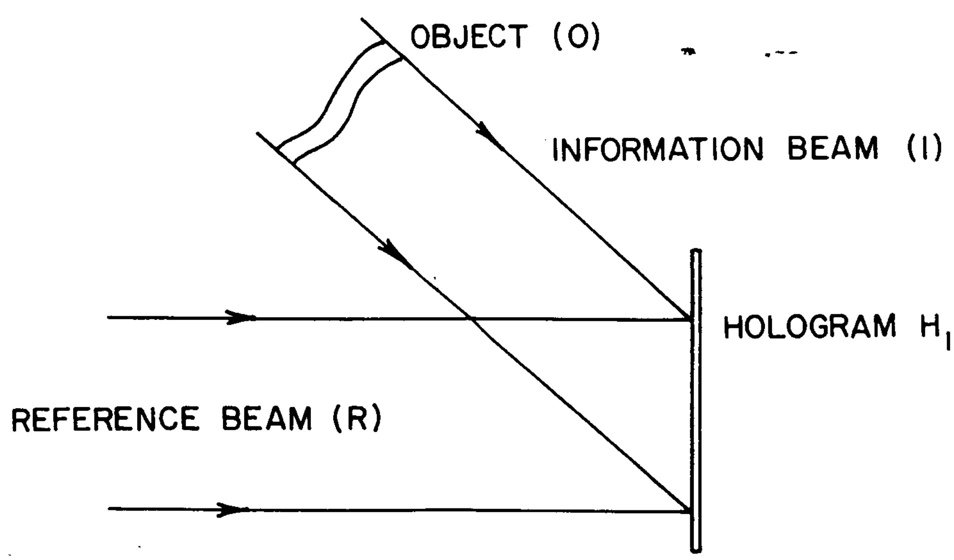


FIGURE 7

SETUP FOR MAKING HOLOGRAM OF PSEUDOSCOPIC REAL IMAGE

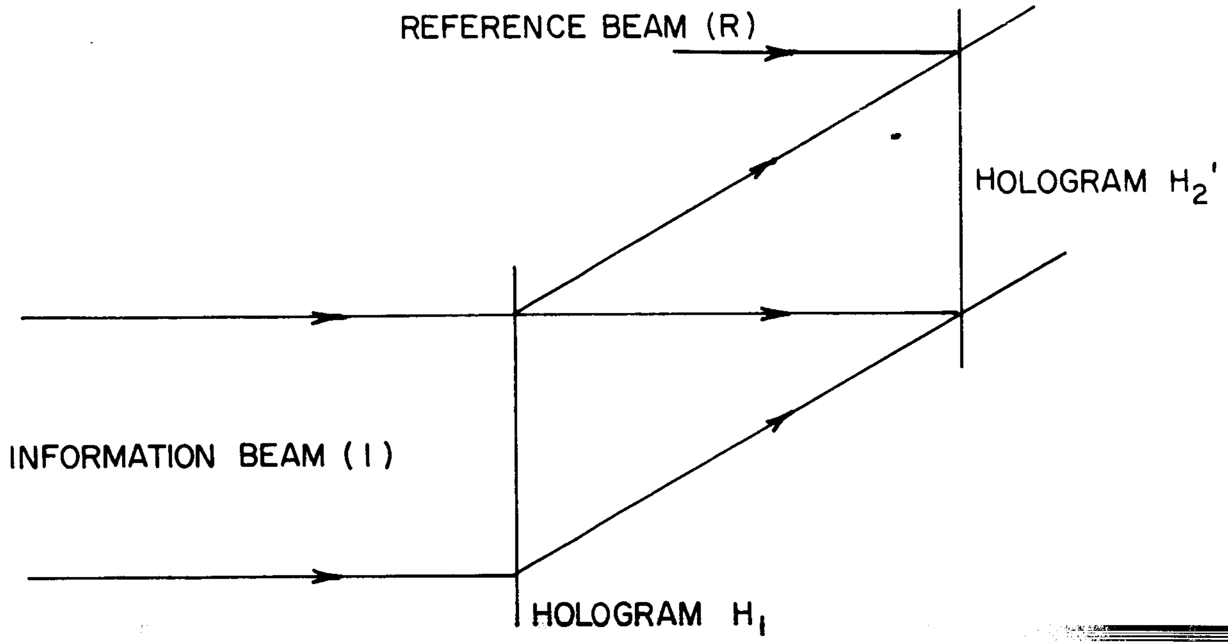



FIGURE 8

HOLOGRAM RECONSTRUCTION SETUP

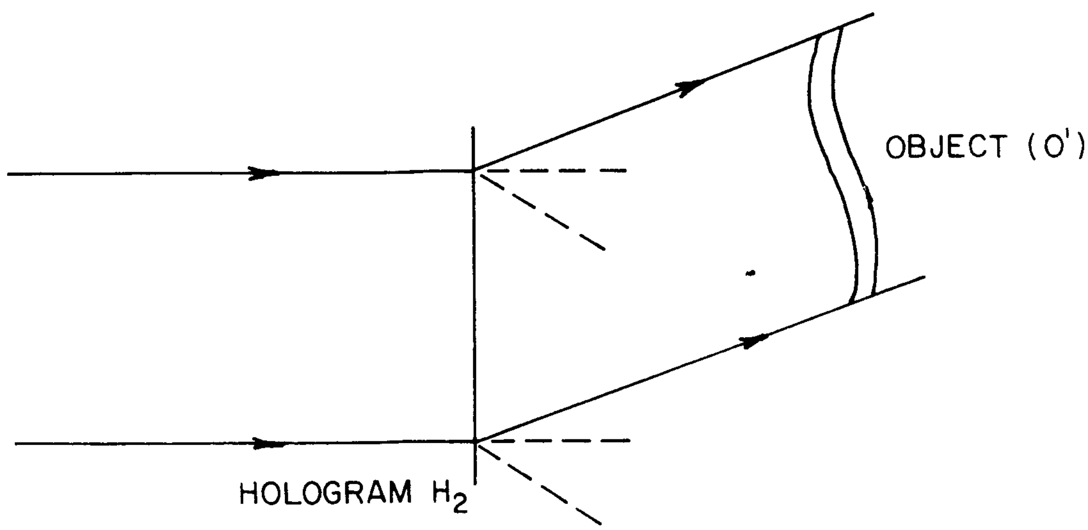
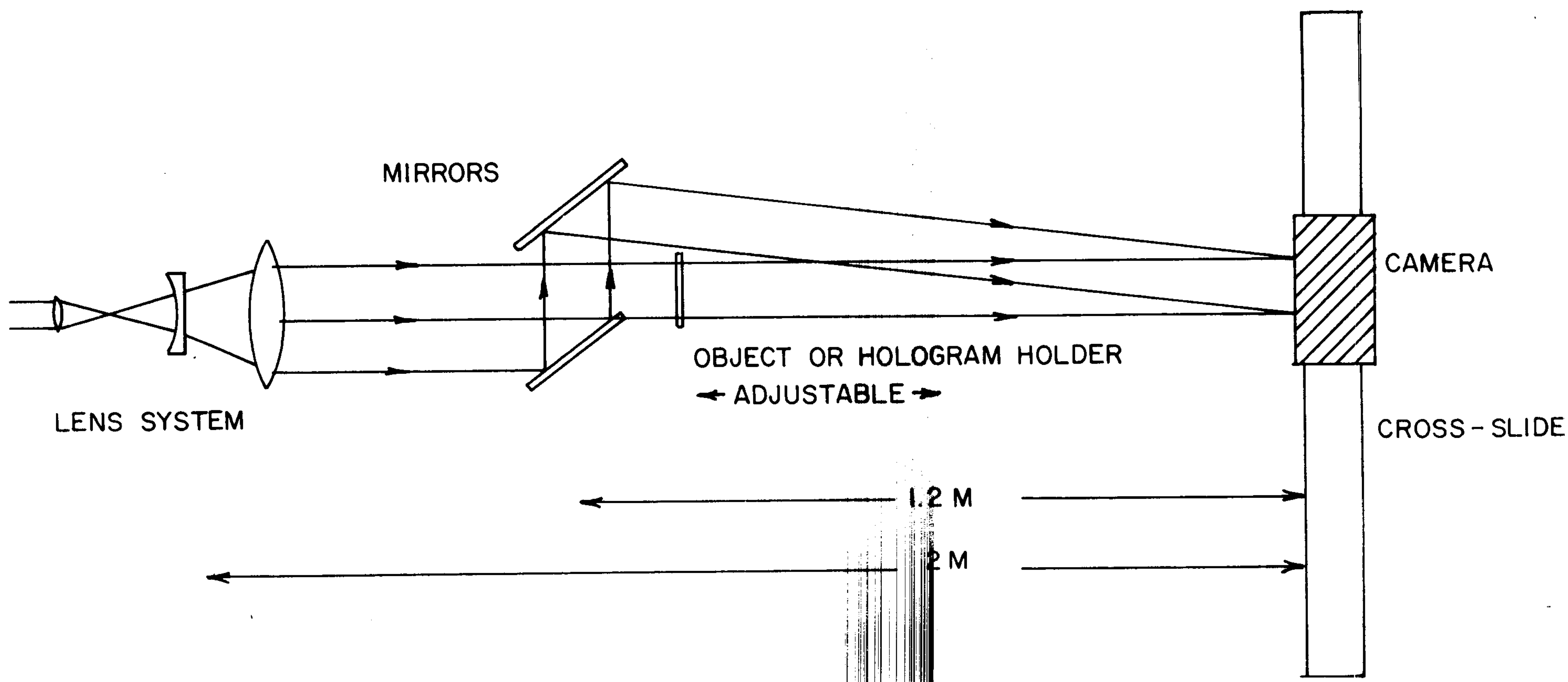


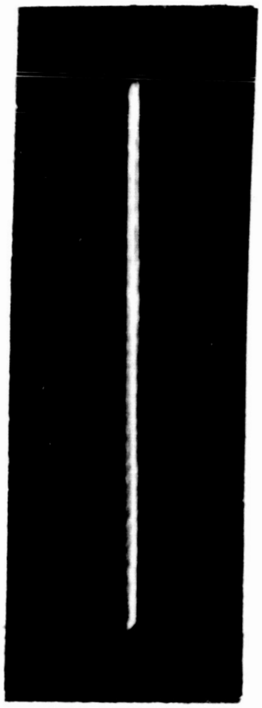
FIGURE 9

EXPERIMENTAL ARRANGEMENT

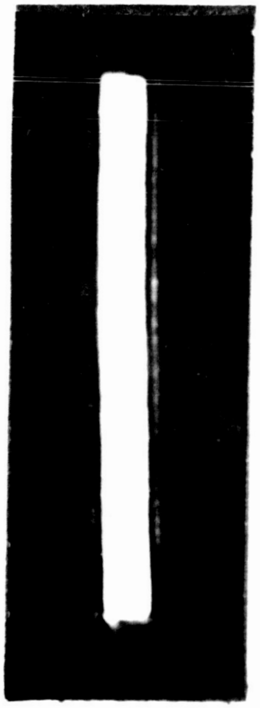


FIGURES 10 AND 11

RECONSTRUCTIONS OF A SINGLE SLIT

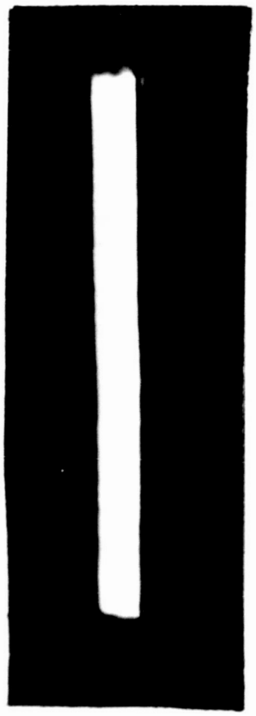


10

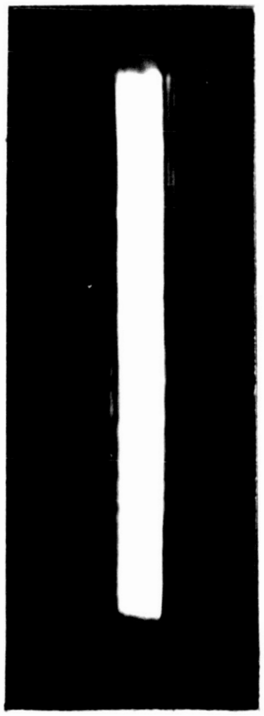


11A

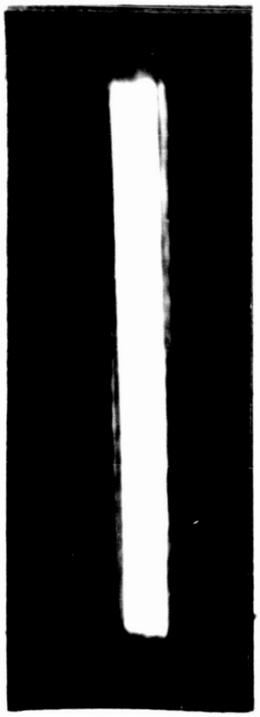
B



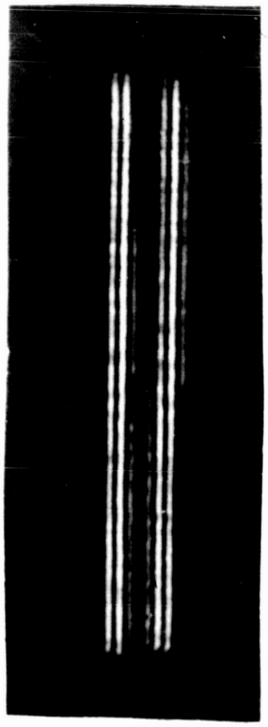
11C



11D



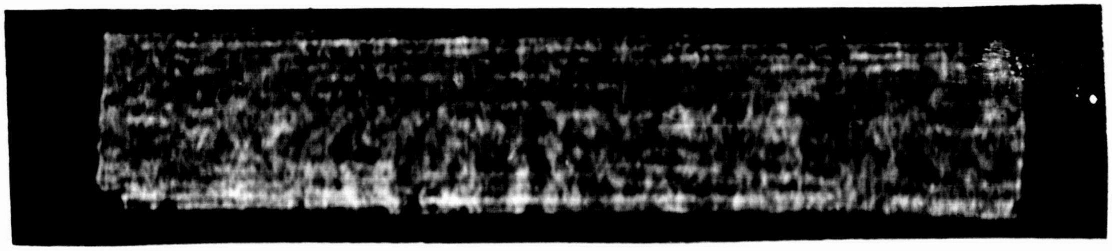
11E



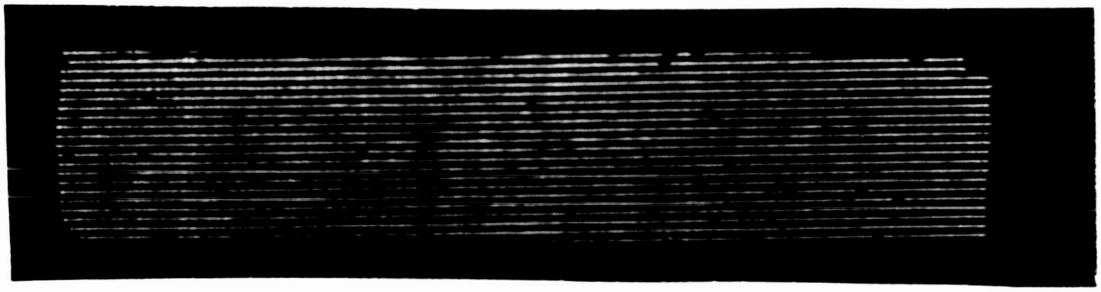
11F

FIGURE 12

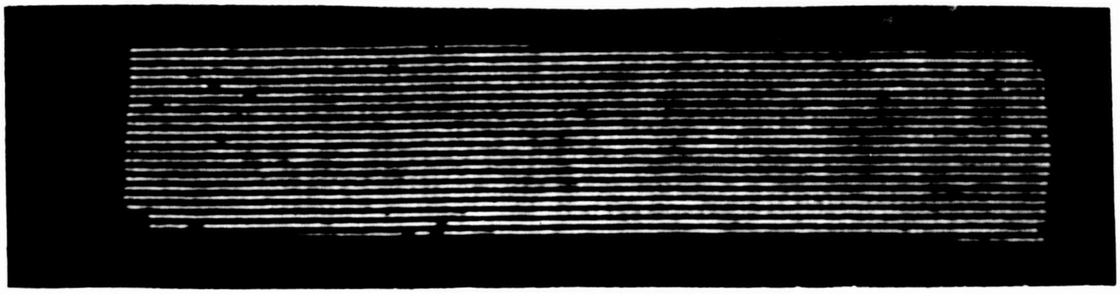
RECONSTRUCTIONS OF MULTIPLE SLITS



12 A



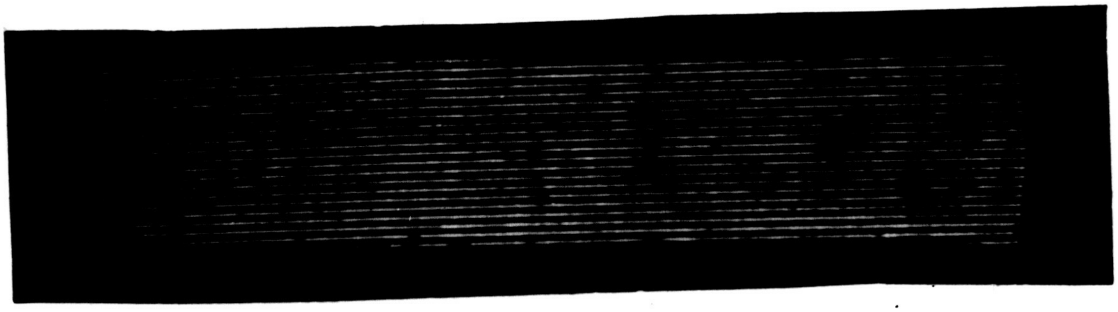
12 B



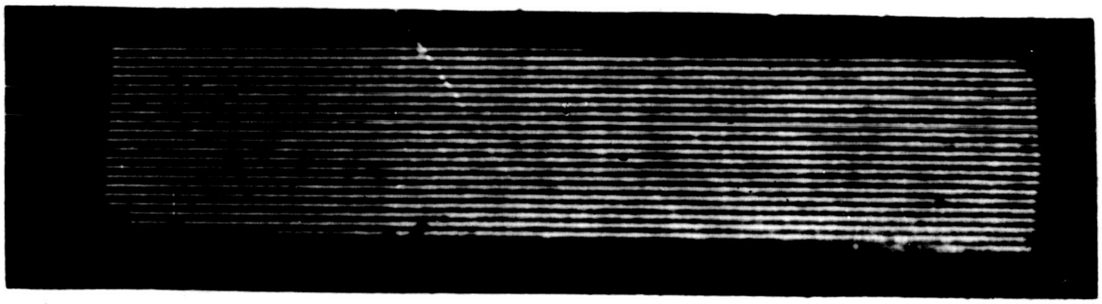
12 C

FIGURE 12

RECONSTRUCTIONS OF MULTIPLE SLITS



12 D

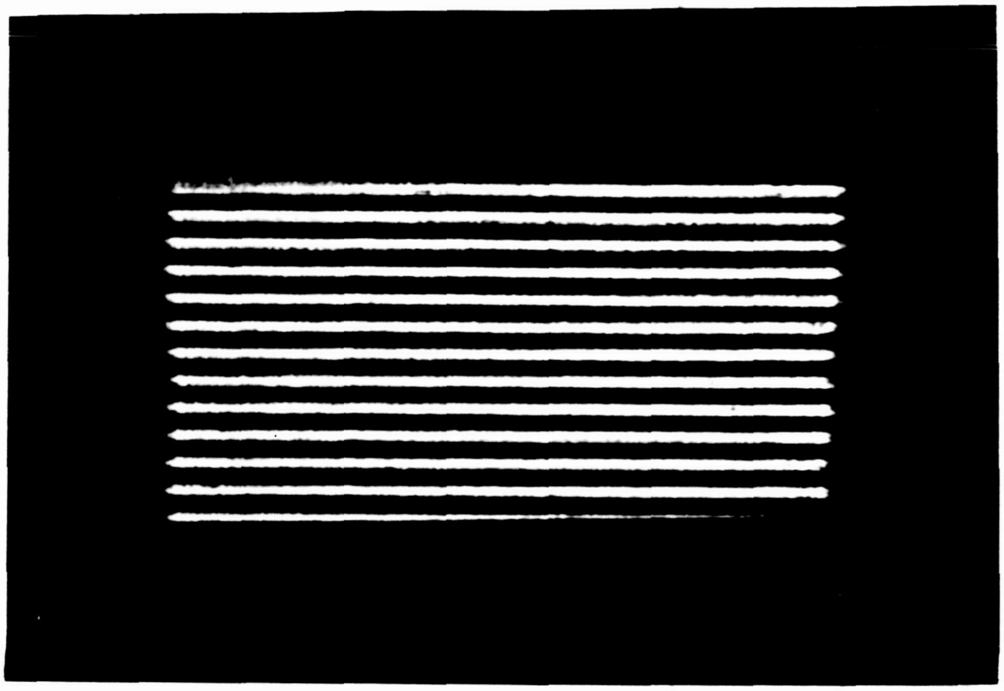


12 E

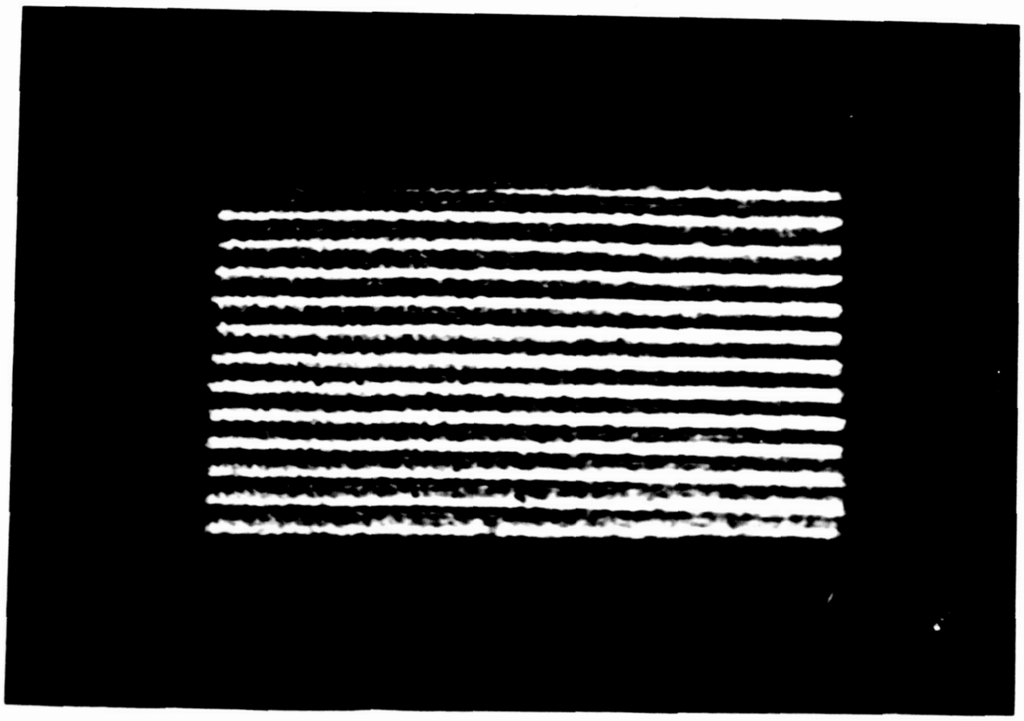
12 F

FIGURE 13

RECONSTRUCTIONS OF MULTIPLE SLITS



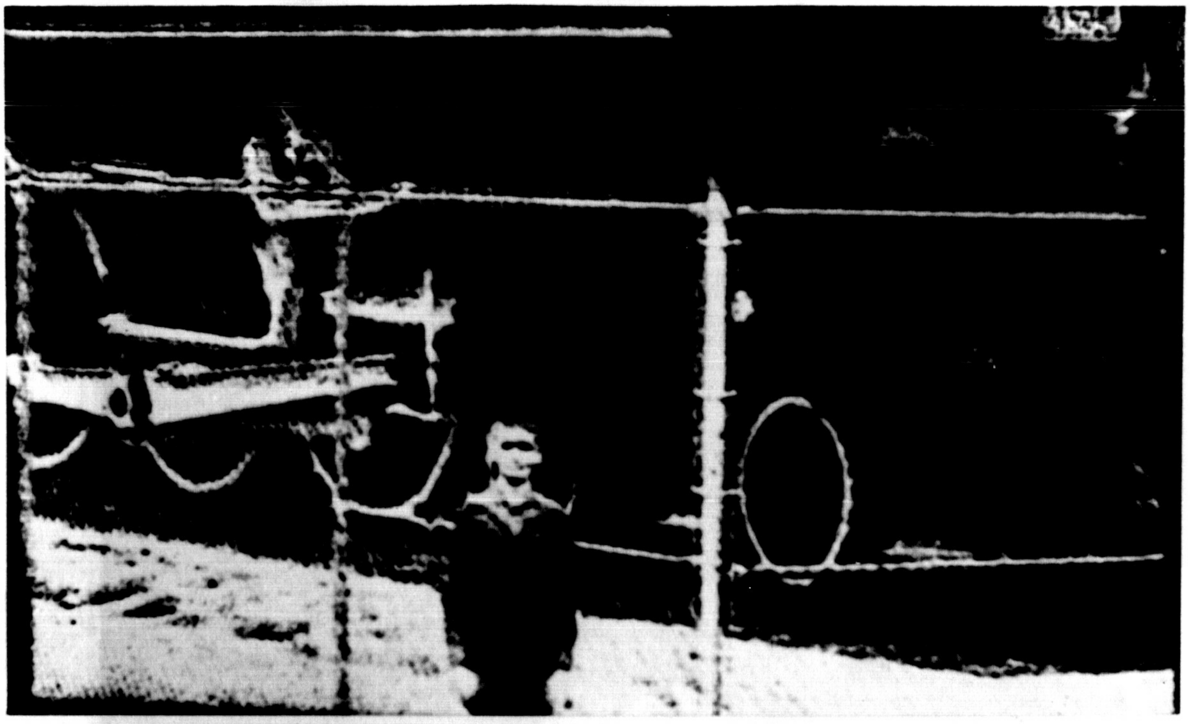
13A



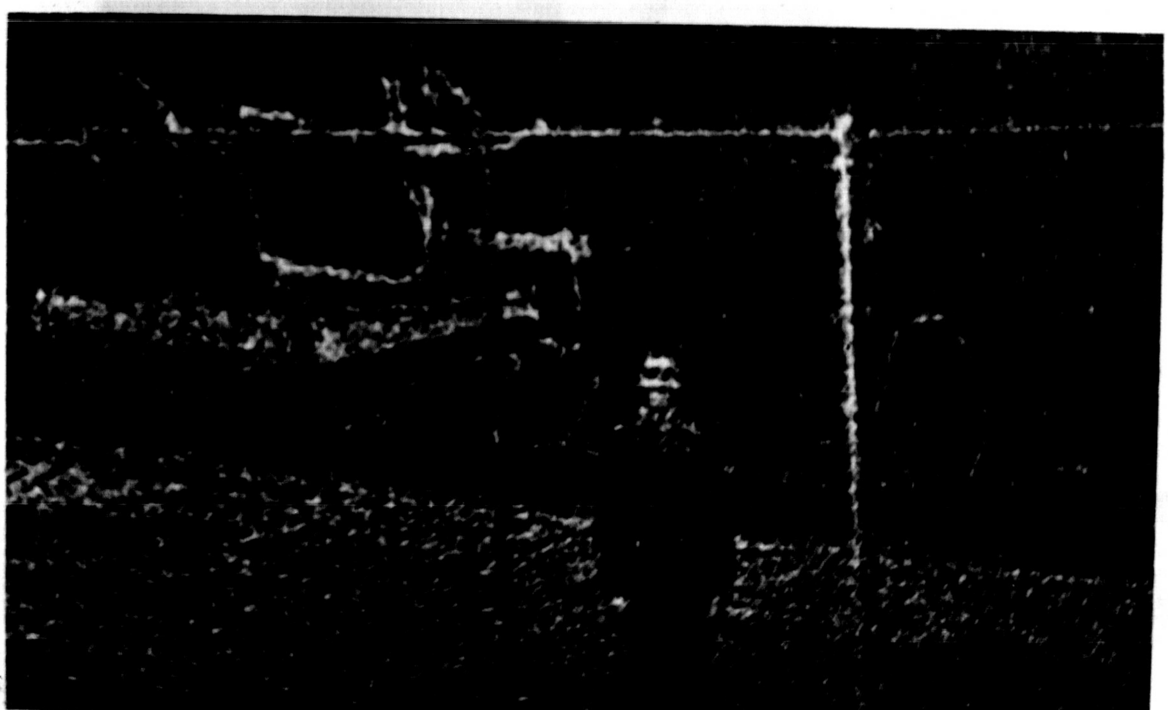
13B

FIGURE 14

RECONSTRUCTION OF A PHOTOGRAPH



14 A



14 B

FIGURE 15

EFFECTIVE BEAM ANGLE VARIATION

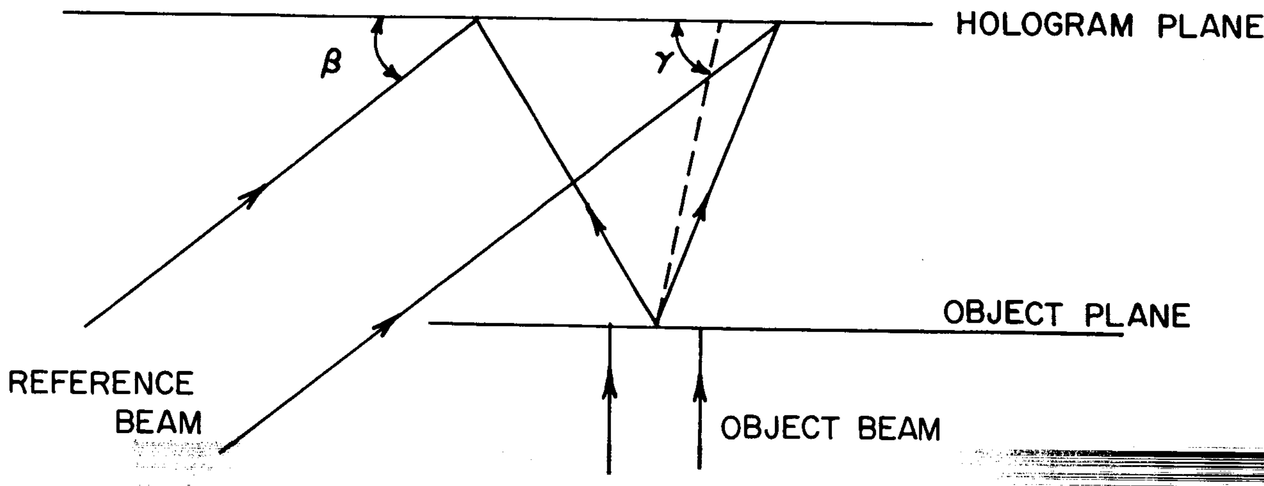



FIGURE 16

HOLOGRAM-MAKING SYSTEM

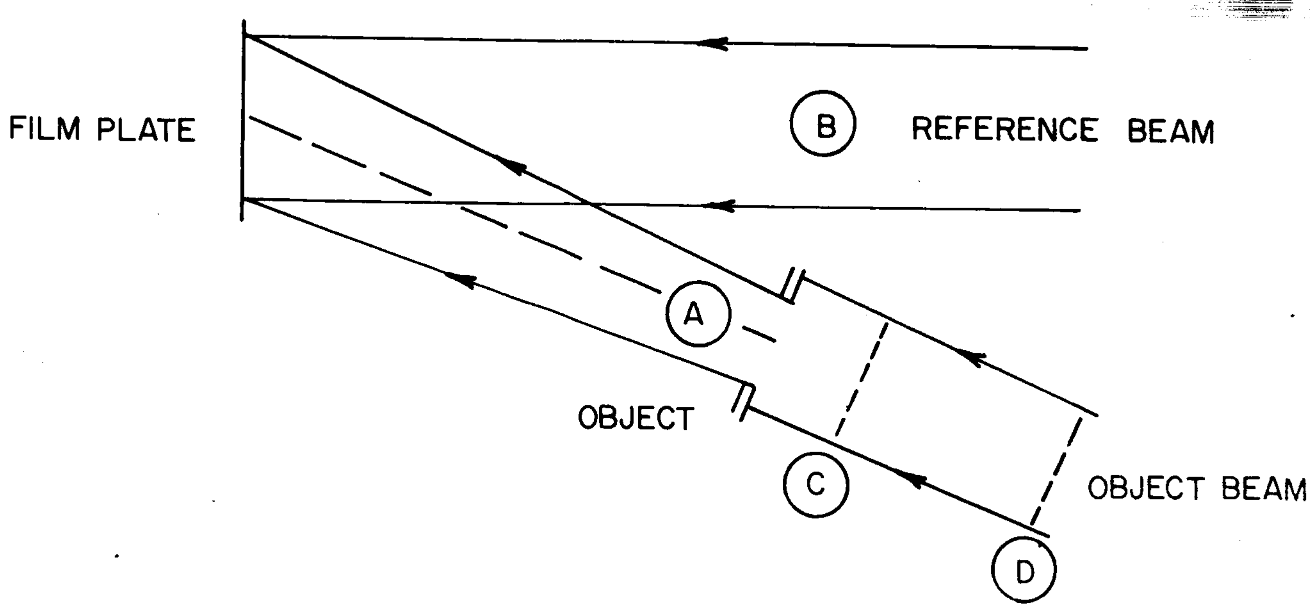


FIGURE 17

IMAGE GRANULARITY AS A FUNCTION OF APERTURE

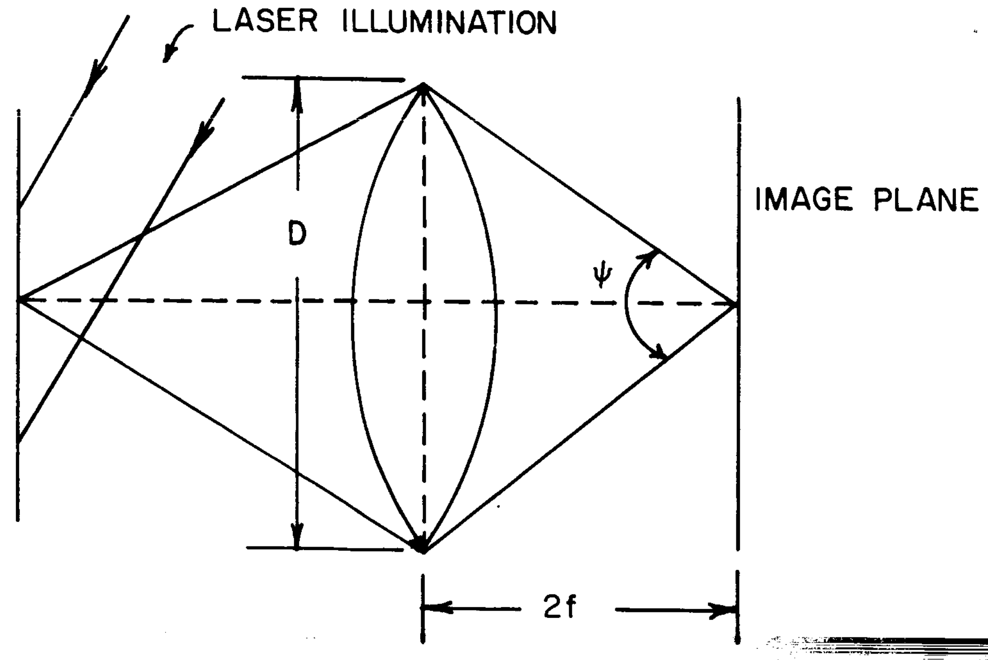



FIGURE 18

HOLOGRAM AND RECONSTRUCTED REAL IMAGE OF AN OBJECT

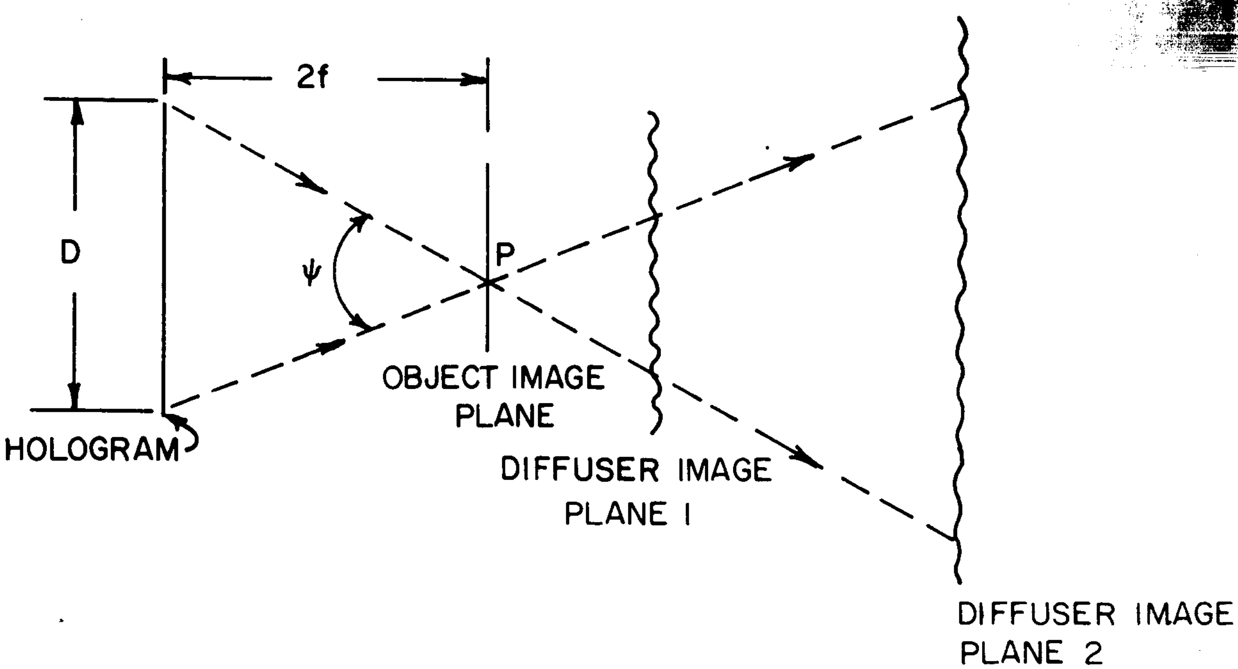


FIGURE 19

SYSTEM FOR MAKING A HOLOGRAM OF A GROUND GLASS SCREEN

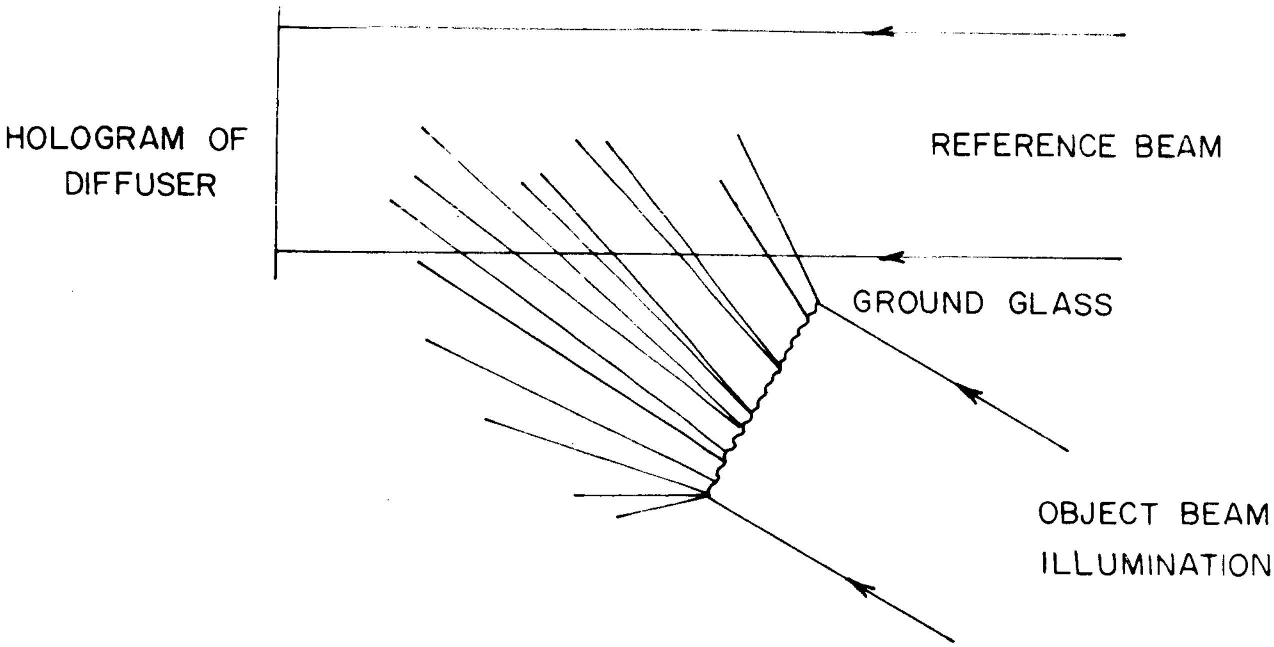



FIGURE 20

USING THE GROUND GLASS IMAGE TO ILLUMINATE AN OBJECT

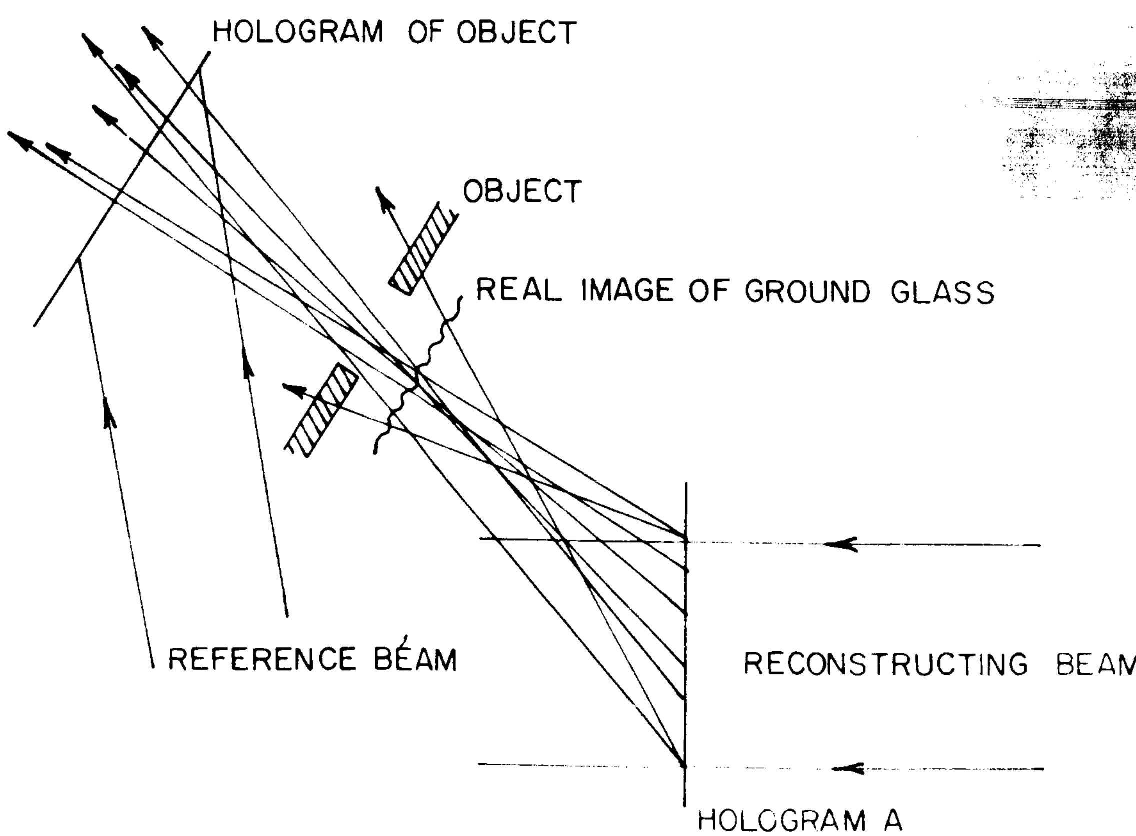


FIGURE 21A

INTERFERENCE SIGNAL RECEIVED FROM CENTERED MOTION

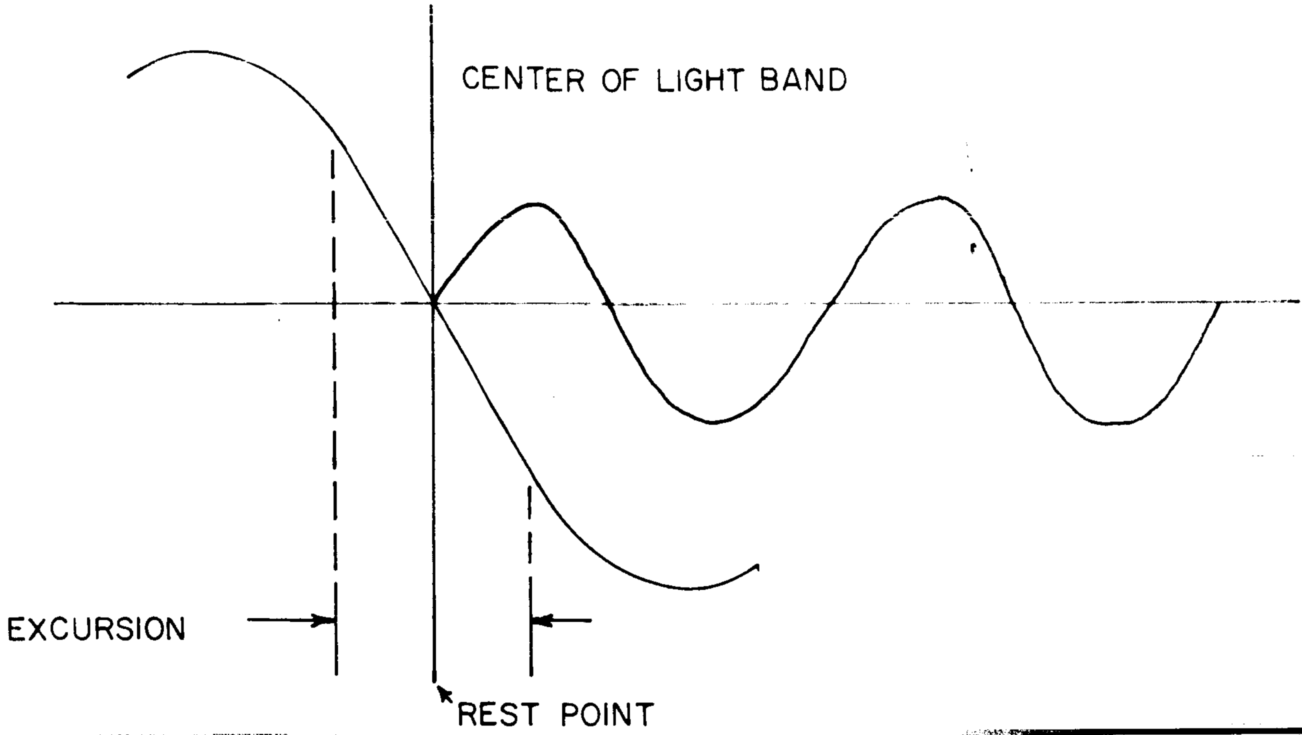



FIGURE 21B

INTERFERENCE SIGNAL RECEIVED FROM UNCENTERED MOTION