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Wavefront Reconstruction with Diffused Illumination and Three-Dimensional Objects*

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Holograms of transparencies have been produced in diffused light. The reconstructions are free from flaws and are of a quality comparable to pictures produced by conventional photography with incoherent light. Holograms of three-dimensional scenes have been produced by reflected light. Such holograms produce three-dimensional reconstructions having all the visual properties of the original scene: parallax between near and distant objects, a requirement to refocus the eyes when viewing objects in different parts of the scene, and a stereo effect equal to that of ordinary stereo photography.

1. INTRODUCTION

N the wavefront reconstruction process of Gabor,[1] the Fresnel diffraction pattern of an object is re-orded and subsequently used to produce an image of e original object. Such a record is called a hologram. the recording process, the phase of the incident lumination is lost. However, it was shown by Gabor at when the diffracted waves from the object are ttended by a strong coherent background, the loss phase is of less importance and a fairly good image of e original object can be recovered from the intensity cord alone.

In a paper by the authors,[2] it was shown that a two-eam interferometric process, whereby the object ansparency is placed in one beam and the two beams re brought together to produce a Young's fringe attern, yields a hologram from which a reconstruction high quality can be obtained.

The present paper discusses a number of subsequent evelopments, the major ones being the diffused-il-mination hologram and the hologram of three-imensional scenes.

A hologram made from a diffusely illuminated object n yield a reconstruction which is entirely free from e flaws that normally occur in reconstructions. Such flaws result from dust particles, etc., in the optical system.

The two-beam technique, when adapted to the photography of three-dimensional solid objects instead of transparencies, produces reconstructions which resemble to a high degree the original objects, e.g., they are three-dimensional and exhibit a parallax between near and more distant objects.

2. THE BASIC PROCEDURE

Since the fundamentals of the two-beam process were described at length in a previous paper,[2] they will be given here in the most summary manner.

A conceptually simple way to produce a two-beam hologram is shown in Fig. 1(a). An object transparency, located at plane P_1, is illuminated with monochromatic, spatially coherent light, and a Fresnel diffraction pattern of the object is formed at plane P_2. Adjacent to the object is a prism, which intercepts a portion of the incident beam and deviates it through an angle θ, so that it becomes superimposed, at plane P_2, on the object-bearing portion of the beam. The superposition of the two beams creates a fringe pattern which is superimposed on the Fresnel diffraction pattern of the object. The illumination at P_2 is recorded by a photographic plate; this process produces a square-law modulation, in which the amplitude portion of the Fresnel diffraction pattern amplitude-modulates the fringes, and the phase portion phase-modulates the fringes. The fringe pattern thus becomes a modulated

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[1] D. Gabor, Nature **161**, 777 (1948); Proc. Roy. Soc. (London) **197**, 454 (1949).

[2] E. Leith and J. Upatnieks, J. Opt. Soc. Am. **53**, 1377 (1963).

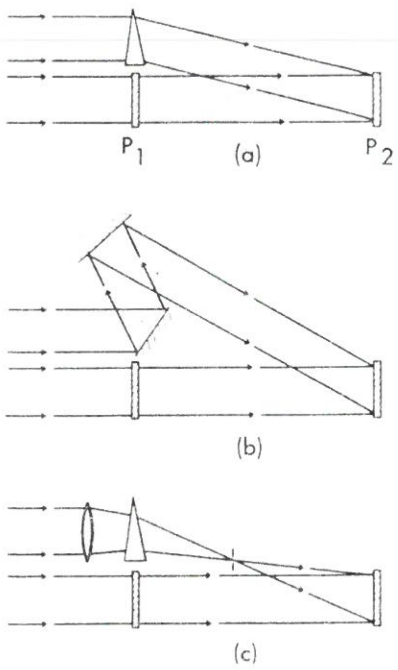

FIG. 1. Methods of introducing the reference beam. In (a), a prism is used; in (b), a pair of mirrors are used; in (c), a lens, prism, and pinhole in combination are used.

carrier, analogous to the *temporal* carrier wave used in communication systems.

Alternatively, the hologram can be thought of as a diffraction grating, and this viewpoint is a convenient one for describing the reconstruction process. When illuminated with monochromatic, spatially coherent light, the hologram produces a zero-order spectrum and a pair of first-order spectra. One of the first-order spectra forms a real image, and the other a virtual image. Whereas a conventional diffraction grating has only inadvertently introduced irregularities, which give rise to undesired ghost lines, the hologram diffraction grating has deliberately introduced irregularities, which give rise to complete, well-defined images.

While the prism method of producing the interference fringes is tutorially attractive, it is not the optimum way to achieve experimental results because a prism introduces astigmatism unless the incident light is accurately collimated. Any aberrations in the non-object-bearing beam (to which we have given the designation *reference beam*) are incorporated onto the hologram and degrade the reconstructed images, just as if the aberrating elements were in the object-bearing beam. Mirrors are preferable for deviating the reference beam, and results of the highest quality have been obtained in this way. A single mirror, in the conventional Lloyd's mirror arrangement, has produced good results. An even better arrangement is to use a two-mirror system, as shown in Fig. 1(b), which permits the light to be incident on the mirrors at nearly normal incidence instead of at nearly grazing incidence as in the Lloyd's mirror arrangement. This method also permits the mirrors to be of a size comparable to the hologram-recording plate, whereas the Lloyd's mirror must, in general, be much larger than the area over which the fringes are generated.

Another arrangement which is highly satisfactory is shown in Fig. 1(c). A prism is used in combination with a lens. This lens can be of extremely poor quality without affecting the image quality. The lens causes the reference beam to be brought to a focus at some position between planes P_1 and P_2. This focused spot is the spread function for the lens–prism combination and will be degraded by the aberrations of these optical elements. However, if a pinhole, with a diameter equal to the resolution of the ideal or aberration-free spread function of the system, is placed at the position of the point image, the aberration will be removed. The pinhole removes the aberrations by removing those light rays whose position of intersection with the focal plane has been altered by the aberrations. The resulting hologram and its reconstructions are free from the aberrations of both the lens and the prism. However, the lens still exerts the effect of its focal power on the reconstructed images, but it now acts like a perfect lens. The pinhole attenuates the reference beam by whatever proportion of the light misses the pinhole, but this loss is a small price to pay for what is achieved.

3. DIFFUSE ILLUMINATION

Suppose that, in the optical system shown in Fig. 1, a diffusing element such as opal glass is placed between the source and the object, thus causing the object to be illuminated with diffused coherent light. The hologram made in this manner thereby acquires several interesting and useful properties.

An objection which the reader may raise is that the diffuser destroys the coherence of the light, thereby making a reconstruction impossible. Indeed, the light thus diffused behaves in some ways as if it were incoherent, but it retains those properties which are essential to the wavefront reconstruction process. The light impinging on the object is no longer a well-defined wavefront, but instead has a phase and amplitude which vary randomly from point to point. These phase and amplitude relations, however, are time invariant, in contradistinction to the case of incoherent illumination.

The two-beam hologram made in this manner reconstructs, as before, to produce a real and a virtual image in the first-order diffracted waves. The reconstructed images have acquired an interesting property: they can now be observed visually without an eyepiece or other optical aids. The virtual image can be seen by looking through the hologram as if it were a window, and the real image can be seen suspended in front of the hologram. If the diffuser had not been used in making the hologram, the reconstructions could not be thus observed. To explain why this is so, let us consider what happens when one observes a transparency which is illuminated from behind with a point source. Except for some scattering, the observer receives light only from that part of the transparency which lies on the line between the point source and the pupil of the eye; his is usually a negligible portion of the transparency. However, if a diffuser is placed between the source and the transparency, then light from all points of the transparency reaches the eye and the transparency is seen in its entirety.

This argument readily applies to the hologram case case if one thinks of the hologram as reconstructing not only the transparency, but also the diffusing plate. Thus, the observer sees the reconstructed image as if it were illuminated by a diffuse source.

Another consequence of the diffusing plate is that the hologram acquires a different appearance. In the conventional, single-beam hologram, each object is converted into a Fresnel diffraction pattern with definite structure; for example, the letter *o* becomes a series of concentric circles. Also, coarse structure in the object tends to persist rather than lose its identity. Similar effects occur in the two-beam holograms described previously,[2] except that the diffraction pattern of the object is largely submerged by other effects produced by the reference beam. However, in the diffuse type of hologram, no recognizable Fresnel diffraction patterns or surviving coarse structures are discernible. The light from the object, when it impinges on the hologram plate, has a uniform, fine grain-like structure like the grain of photographic film. This pattern is completely homogeneous and always has the same appearance, irrespective of the object. The observable structures en in the hologram of Fig. 2 are diffraction patterns produced by dust particles, etc. in the reference beam. They neither contribute to nor degrade the reconstructed images in any apparent way.

Another interesting property of the diffuse-illumination hologram is that, since each point on the object illuminates the entire hologram recording plate, the plate can be broken into small fragments, and each piece will reconstruct the entire object. As the fragments become small, resolution is, of course, lost, since the hologram constitutes the limiting aperture of the wavefront-reconstruction imaging process.

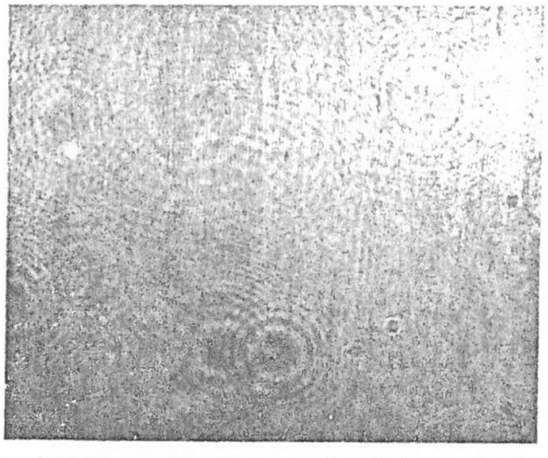

FIG. 2. Hologram of two transparencies which were illuminated with diffused coherent light. The transparencies were placed 14 and 24 in. from the hologram recording plate, in such positions that neither obscured the other when viewed from the position here the hologram was recorded.

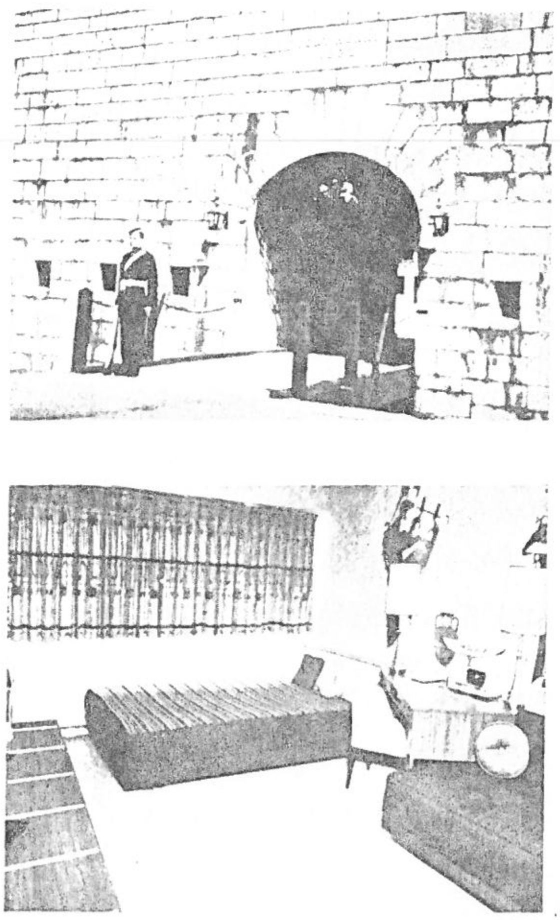

FIG. 3. Reconstructions of two transparencies which were recorded in the hologram shown in Fig. 2.

Possibly the most significant property of the diffused illumination hologram is that local imperfections in the optical elements no longer observably degrade the process. It is well known to experimenters in this field that any scratches, dust, pits, etc., on the hologram recording plate or on other elements of the optical system, cause annoying diffraction patterns that appear in the reconstructed image. These can be minimized by careful technique, but, in practice, never completely eliminated.[3] They can be observed, for example, in the reconstructions in our previous paper.[2] They are not products of the wavefront reconstruction process *per se* but arise from the use of coherent illumination. In the diffused illumination holograms, such imperfections are, to all appearances, completely removed from the reconstructed image. Thus, not only is extremely careful

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[3] A technique used by Kirkpatrick and El-Sum goes far toward minimizing these flaws by rotating in a continuous manner some of the optical elements about the optical system axis; J. Opt. Soc. Am. **46**, 825 (1956).

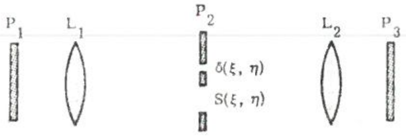

FIG. 4. Fraunhofer diffraction method. Semi-diffusing ground glass at P_1 causes, at P_2, a bright spot on axis, surrounded by diffused light. An opaque mask at P_2 has two openings: a pinhole on axis which passes the focused spot of nondiffused light, and an off-axis aperture in which the object transparency $S(\xi,\eta)$ is placed. The hologram is made at plane P_3.

technique no longer necessary, but the holograms can be scratched, handled so as to receive fingerprints, and otherwise abused without noticeable deterioration of image quality. The reconstructions shown in Fig. 3, for example, are entirely free of such imperfections.

The diffused-illumination hologram is, in fact, more immune to defects of the recording plate than is a picture recorded by conventional photography. A scratch, loss of a piece of the emulsion, etc., in the hologram case does not entail a loss of a part of the picture, since each point on the object spreads its effect over the entire hologram plate. Gross portions of the hologram record can be damaged or removed, yet no portion of the reconstructed image suffers noticeable deterioration.

A further advantage of this type of hologram (and this advantage applies also, to a lesser extent, to the nondiffused-illumination holograms) is that the dynamic range of the photographic process is greatly increased. Small, very bright areas in the object have their energy spread over the entire recording place, and in reconstruction are restored to their proper level. Intensity ratios of 10^4–10^5 between the brightest regions and the smallest distinguishable intensity steps have been observed in the image; this represents a dynamic range of 40 to 50 dB. Even greater ranges seem achievable experimentally.

Some of the properties thus described can be more fully understood by recognizing that the hologram represents an encoding of the original object transparency, or signal. There are, in fact, two distinct encoding processes manifested in this hologram technique. The first is a simple dispersion, in which each resolution element of the object is encoded into a function which occupies the entire hologram plate. Such dispersion-encoding is manifested by, and indeed is fundamental to, all wavefront reconstruction techniques. With diffused illumination, the dispersion is much greater than is usual in previously described methods. The second encoding process embodied in the diffused-illumination technique involves increasing the signal bandwidth by convolving the spatial-frequency spectrum of the object with that of the diffused illumination, which can be thought of as a noise-like signal with a broad, uniform, spatial-frequency spectrum. When the object transparency is illuminated with diffused coherent light and transformed into a hologram, the spatial-frequency spectrum of the hologram thus tends to be much greater than that of the object transparency. Such encoding introduces a redundancy into the hologram in that more bandwidth is recorded than is required for the information content of the signal. This, philosophically, is the basis for the insensitivity of the method to the above-mentioned imperfections, which may be designated noise.

A theoretical analysis of the diffused illumination technique is necessary for any complete treatment, but is outside the scope of the present paper.

An interesting possibility is to superimpose the diffraction patterns of two different transparencies onto a single hologram.[4] This is demonstrated in Fig. 2. In Fig. 3, both pictures have been recovered without any trace of cross-modulation effects. Each picture is without flaws.

The superposition can be achieved in various ways. The object transparencies can expose the hologram simultaneously, using a single reference beam. The two object transparencies would be located at different positions in space and the reconstructed images would similarly be separated. This method we call coherent superposition, since the light from one transparency is coherent with that from the other.

Other methods of superposition include that of multiple exposure, with one object at a time exposing the plate. To provide a basis for separating the reconstructed images of the two object transparencies, the transparencies can occupy different, nonoverlapping positions in space; alternatively, the reference beam can be differently directed for each exposure. These methods may be designated incoherent superpositions. Both the coherent and the incoherent methods have been satisfactorily demonstrated.

4. FRAUNHOFER DIFFRACTION HOLOGRAMS

Another type of diffused-illumination hologram is produced by recording the Fraunhofer, rather than the Fresnel, diffraction pattern. An interesting way to produce such a hologram is shown in Fig. 4. A plate of partially diffusing ground glass is illuminated by a collimated beam of monochromatic spatially coherent light. The plate diffuses only a portion of the transmitted light. A lens L_1 brings the nondiffused portion to a point focus on axis at plane P_2. The diffused light surrounds the point image. An object transparency is placed at P_2 in the diffused light, to one side of the point image. An opaque mask at P_2 then blocks the remainder of the diffused light, but contains a pinhole that allows the point image to be transmitted. A second lens reimages the ground glass at plane P_3 and at the same time collimates the nondiffused light, which then is used as the reference beam. A hologram is made by photographically recording the illumination at plane P_3.

As in other diffused-illumination holograms, the reconstruction can be made visually by looking through the hologram when it is placed in a coherent, mono-

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[4] This idea is similar to the theta-modulation concept, as described by A. Lohmann, J. Opt. Soc. Am. 53, 1351 (1963).

chromatic beam of light. As before, two images are reconstructed, but they can no longer be designated as the real and virtual images, since both form at infinity. They are symmetrically positioned about the zero-order spectrum. A reconstruction from such a hologram is shown in Fig. 5.

Since the mathematical description of two-beam holograms given previously[1] is not entirely applicable to this configuration, a separate analysis is presented here. The semidiffusing plate has the amplitude transmittance

$$t(x,y)=a_0+n(x,y), \qquad (1)$$

where a_0 and $n(x,y)$ give rise to the nonscattered and scattered components of transmitted light, respectively; $n(x,y)$ can be thought of as a random or noise-like quantity. The lens L_1 produces the Fourier transform of Eq. (1), producing at P_2 a distribution of light whose vector amplitude represents the function.

$$T(\xi,\eta)=a_0\delta(\xi,\eta)+N(\xi,\eta), \qquad (2)$$

where $\delta(\xi,\eta)$ is the Dirac delta function, $N(\xi,\eta)$ is the Fourier transform of $n(x,y)$, and ξ, η are spatial-frequency variables, arising from the Fourier transformation.

Since the object transparency is introduced at the plane P_2, which we have designated the Fourier transform or spatial-frequency plane, the transparency will be designated as $S(\xi,\eta)$. This function is multiplied with $N(\xi,\eta)$, and the lens L_2 takes a second Fourier transformation, producing

$$\chi(x,y)=a_0+n(x,y)*s(x,y), \qquad (3)$$

where $s(x,y)$ is the Fourier transform of the object transparency $S(\xi,\eta)$, and the $*$ indicates a convolution.

The recording process produces a square-law detection, resulting in

$$\chi(x,y)|^2=|a_0|^2+|s_0(x,y)|^2 \\ +a_0s_0(x,y)+a_0s_0^*(x,y), \qquad (4)$$

where $s_0(x,y)=n(x,y)*s(x,y)$.

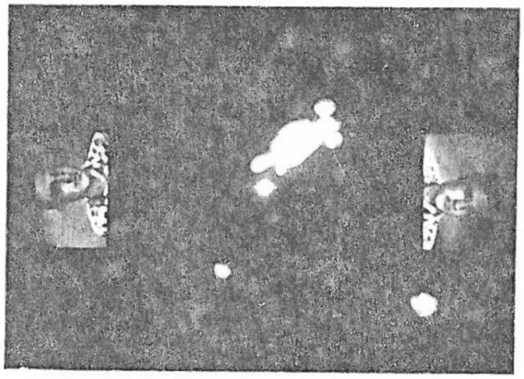

FIG. 5. Reconstruction of a Fraunhofer diffraction hologram. th real and virtual images form at infinity and are thus located the same plane, but in axially symmetric positions.

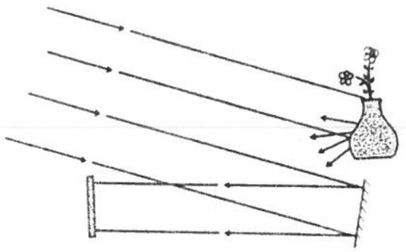

FIG. 6. System for making a hologram in reflected light. The hologram recording plate receives light reflected from the object and from the mirror.

The reconstruction is then accomplished by placing the hologram in a beam of coherent light and using a lens to take the Fourier transform of the hologram, producing the result shown in Fig. 5. This lens can be that of the eye, if the observer looks through the coherently illuminated hologram. In the Fourier transform plane, the term a_0^2 is just the attenuated image of the Dirac delta function that produced the reference beam. The term $|s_0|^2$ produces the noise-like distribution of light around the source, and can readily be discerned in Fig. 5.

The two remaining terms have, respectively, the Fourier transforms $a_0N(\xi,\eta)S_0(\xi,\eta)$ and $a_0N^*(-\xi,-\eta)\times S_0^*(-\xi,-\eta)$. The first is an image reconstructed just as the original object appeared in the diffused illumination. The second is a similar image, but each point on this image is reflected about the origin with respect to the corresponding point in the first image. This is the image that is generated by the square-law process and corresponds to the real image in the case of the Fresnel diffraction hologram.

5. THREE-DIMENSIONAL PHOTOGRAPHY

The basic concepts of wavefront reconstruction imply that three-dimensional objects should reconstruct as three-dimensional images, a fact recognized by Gabor.[1] The two-beam method has proved effective with three-dimensional objects. Holograms made from diffusely reflecting objects have, by virtue of this diffuse reflection, all the properties of the diffused-illumination hologram described in Sec. 3.

To photograph a solid, three-dimensional object by the wavefront reconstruction method, an arrangement like that shown in Fig. 6 is used; this is a fairly obvious adaptation of the techniques shown in Fig. 1. A monochromatic, spatially coherent source illuminates the object to be photographed. Reflected light from the object exposes the photographic plate, which is placed at some convenient and noncritical distance from the object. A high-quality mirror, located adjacent to the object, intercepts a portion of the coherent illumination and reflects it onto the plate. This provides the reference beam against which the phase of the object is compared. The mathematical description of the process is identical with that given previously[2] for making holograms from transparencies.

Reconstruction occurs when the hologram is placed in a monochromatic coherent light beam. Either the real or the virtual reconstructed image may be observed

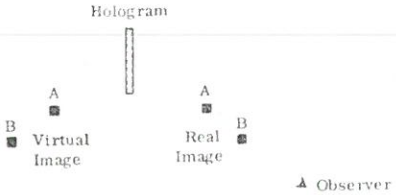

FIG. 7. Diagram showing geometry of objects in the real and virtual images. This diagram is presented as an aid to the text in describing a curious property of the real image.

visually. The virtual image is readily viewed by looking into the hologram as if it were a window. This image has all the appearance of the original object. A three-dimensional effect exists which is equal to that produced by ordinary stereo photography, but here the effect is obtained without the need for a stereo pair of photographs. The reconstruction has some additional properties not produced by ordinary stereo photography. For example, if the observer moves his head while viewing the reconstructed image of the scene, he will observe a change in perspective in the image. There is a parallax between near and far objects which is exactly that which occurs when viewing the original scene. If the observer finds, at one viewing position, that an object in the foreground lies in front of and obscures the viewing of another object, then he can by changing position actually look around the obstructing object and see what lies behind it, just as he could do if viewing the original scene. The observer must refocus his eyes when shifting his observation from near to far objects in the reconstructed scene. Similarly, if the reconstruction is photographed with a camera, the effects of finite focal depth are evident; it is necessary to stop the camera lens if a reasonable depth of field is to be achieved.

The real image forms in front of the plate and can be readily photographed by placing a photographic plate at some suitably chosen position, which, of necessity, is a compromise position, since the image is three-dimensional and thus cannot be imaged on a plane. For visual observation, however, the virtual image is preferred. The real image can be observed visually, but the observer may have some initial difficulty in coordinating his eyes when so doing, for reasons possibly having their origin in physiological optics. If this difficulty is overcome, the results are rewarding, for then one can see the entire reconstructed image suspended in space between himself and the hologram plate.

The real and virtual images are for the most part identical; however, the real image has a curious property not possessed by the virtual image. This is described with reference to Fig. 7. When one observes the virtual image, he will see object A in front of object B, and when the two objects are in line, object A will obscure object B, as indeed it should. To observe the real image, the eye is placed at the position indicated in Fig. 7, in which object B is closer to the eye than is object A. As the observer moves his head, the parallax between A and B is in accord with their positioning. The curious feature is that when the objects A and B are brought into alignment, it is the object B rather than A which is obscured. The near object disappears and one sees the far object through the hole created by the disappearance of the near object.

In making a hologram of a scene in reflected light, two conditions must be met which do not arise when the object is a transparency. First, the coherence length of the source must be greater than the maximum difference in light path between the reference beam and the object beam. Thus, the depth of the scene cannot be greater than the coherence length of the light source. When a laser is used as the source, it should be carefully adjusted so as to eliminate nonaxial modes, otherwise the coherence length is reduced to only a few inches. An electronic spectrum analyzer has been useful both as an aid in tuning the laser and as a laser monitoring device during the exposure.[5]

Second, the reflecting object must remain stationary to less than about $\frac{1}{8}$ the wavelength of the illuminating light for the duration of the exposure. This restriction is not severe for a pulsed laser. For example, if the pulse duration of a laser operating at 6238 Å is 3×10^{-8} sec (30 nsec), an object moving at 2 m/sec will move only $\frac{1}{10}$ the wavelength of the light during this exposure, and a good hologram can be made.

Examples of three-dimensional reconstructions are shown in Figs. 8 and 9. Figure 8 shows a reconstruction of an HO-gauge model railroad engine and various other objects. A hexagonal wrench was placed in the foreground so as to introduce parallax effects. The published print was made from the real image by placing a photographic plate at the position of best focus. To obtain sufficient depth of focus so as to bring the greater portion of the scene into focus, it was necessary to restrict the illumination to only a small portion (about 1.2%) of the entire hologram, i.e., the hologram was stopped just as if it were a lens. The average focal

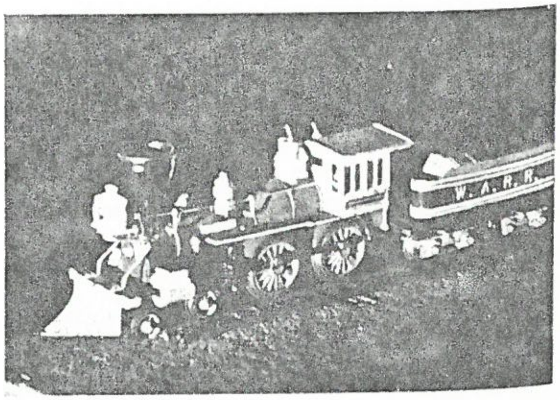

FIG. 8. Photograph of a three-dimensional reconstruction of a model train engine. This photograph was made from the real image after stopping the hologram from its full $f/4$ aperture down to about $f/48$. Note that even at this aperture the foreground is unsharp.

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[5] The use of this technique as an aid to producing holograms was suggested and demonstrated to the authors by F. B. Rotz.

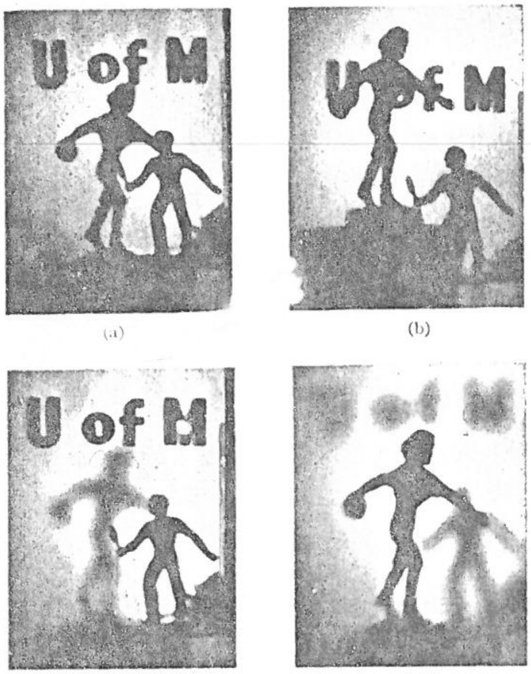
(a) (b)
(c) (d)

Fig. 9. Reconstruction of a three-dimensional silhouetted scene, consisting of plastic letters about 1.5 in. high and two metal statues about 4 in. high. The virtual image was photographed using a camera with the lens stop at $f/8$ for (a) and (b); these two photographs were made with the camera at different positions in order to show the parallax between near and far objects. Photographs (c) and (d) were taken with the camera lens at $f/2.3$, which decreased the focal depth. The camera was focused on different planes in (c) and (d). Note that in (c), only the word *of* is in sharp focus, and in (d), only the head and one arm are in sharp focus.

length of this hologram is about 18 in. and its dimensions are 4×6 in. Thus, the hologram is about $f/4$, and was stopped to about $f/48$. Even with this setting, the foreground of the scene is unsharp. Further, it was necessary to tilt the recording film plane so as to orient its position with that of the train. It is apparent that the reconstructed scene, for the hologram at full aperture, extends through many hundreds of focal depths. The quality of the image is good despite the severe restriction of the hologram aperture.

Figure 9 shows the reconstruction of a silhouette, made by placing various objects in front of a sheet of opal glass, which was then illuminated from behind. The letters U of M are attached to the surface of the glass, and the two metal statues are located 3 and 20 in. from the glass. The reference beam was introduced by diverting a portion of the coherent illumination around the scene by means of a Lloyd's mirror arrangement.

To demonstrate the three-dimensional properties of the reconstruction, appropriate combinations of photographs are shown in Figs. 9(a) to 9(d). These were made by photographing the virtual image with a conventional camera, which was placed at different positions and set at various f-stops. Figures 9(a) and 9(b) show the virtual image from two different positions; the parallax is evident. The camera lens was set at $f/8$ in order to provide an adequate depth of focus to encompass the entire scene. Figures 9(c) and 9(d) show the same scene with the camera lens set at $f/2.3$. Here, the depth of focus is small, so that when the camera is focused on one part of the scene, other parts are quite unsharp.

6. MULTICOLOR WAVEFRONT RECONSTRUCTION

Using the superposition techniques described at the end of Sec. 3, it is possible to produce reconstructions in full color. We could, for example, illuminate a scene with coherent light in each of the three primary colors, and the hologram would receive reflected light of each color.[6] Three mirrors could be placed at different locations about the periphery of the scene. Each mirror would receive light of only one color; thus, three reference beams, one for each color, would impinge on the plate and produce the required interference effects with light of the same color reflected from the scene. The resulting hologram would comprise three incoherently superimposed holograms.

To reconstruct, we can place the hologram in the same position that it occupied during the exposure, and illuminate it with the three reference beams. Each beam would interact with each of the three hologram components, producing a total of nine virtual images (as well as nine real images). Three of these images would exactly coincide and produce, at the position originally occupied by the object, a reconstructed virtual image of the object in full color. The remaining images, which are, for example, the red-light reconstruction from the blue-light component of the hologram, etc., would form in other angularly displaced positions and would thus cause no problem. Hence, a three-dimensional image, in full color, can be obtained from a black and white hologram record. This process is related to the Lippman color process,[7] except that the process described here does not require that the emulsion be sufficiently thick as to constitute a three-dimensional storage medium.

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[6] It has been pointed out, by an anonymous reviewer, that an object illuminated by monochromatic light in three primary colors may not produce the same color rendition as would the object if illuminated by ordinary white light. This could happen if the wavelength variation of object transmittance or reflectance were not a smooth, slowly varying function of wavelength.

[7] G. Lippman, J. Phys. 3, 97 (1894).