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Holography

The fundamentals, properties, and applications of holograms are reviewed.

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Holography—sometimes called three-dimensional (*1*) lensless photography—is the art of freezing a light wave into a photographic plate by means of another (reference) beam, and reviving it by laser or white-light illumination. The object is revived in true three dimensions, in monochrome or in natural colors. Two waves can be frozen in, one after the other, and revived together. This has opened up the new technology of nondestructive testing of vibrations and stress by holographic interferometry.

Holography has produced new methods of photographic storage by allowing several hundreds of pictures to be recorded in an emulsion which in ordinary photography is capable of storing one only. Other applications of holography range over pattern and character recognition, new methods of microscopy, production of spectroscopy gratings of unprecedented quality, deblurring of imperfect photographs, looking through turbulent media, synthesis of images of nonexisting objects, new methods of cassette television (which take advantage of the insensitivity of holograms to scratches and dust), and 3-D cinematographic image projection.

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The principle of holography is applicable to wave phenomena other than light. Microwave holography has for a long time scored notable successes, and the field of acoustical holography is opening up. One application may be a new x-ray–like form of ultrasonic "sonoradiography," for use in medical diagnostics.

A hologram is the photographic record of the interference pattern formed at the photographic plate when two sets of coherent (laser) light waves interfere. One of these sets acts as a reference wave, and the other is the (coherent) light reflected from the scene to be recorded (Figs. 1A and 2A). When this photographic record is developed, and again illuminated with the laser light reference beam, the original scene is presented to the viewer as a reconstructed image (Figs. 1B and 2B). This image manifests such vivid realism that the viewer is tempted to reach out and try to touch the objects of the scene. The hologram (the photographic plate) is like a window, with the imaged scene appearing behind it in full depth. The viewer can look through it from any direction. In order to see around an object in the foreground, he simply raises his head or moves it to the left or right. Figure 3 shows another two photographs (two views) through a single, laser illuminated hologram; by focusing through the hologram, selected depths of the field may be brought into sharp focus, all from the same hologram.

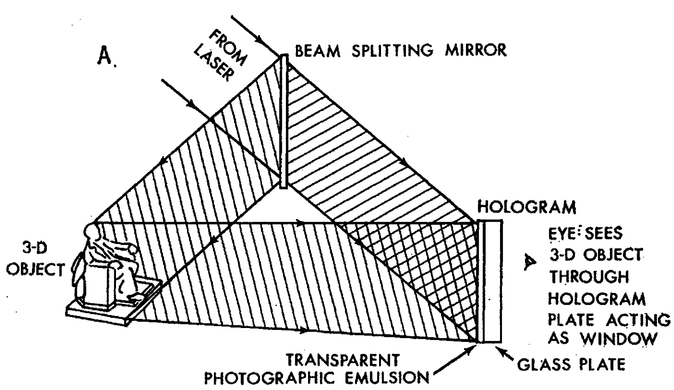
Gabor (*2*) conceived of holography in 1947 and coined, at that time, the name hologram from the words *holo* (complete) and *gram* (message). Unfortunately, adequate sources of the special coherent light needed to demonstrate the full capabilities of holography were not available at that time, and for many years only modest effort was applied to the concept. In 1963, Leith and Upatnieks (*3*) introduced the laser to holography; and the subsequent advances made by Leith and his co-workers and by Stroke and his co-workers (*4*) led to a tremendous explosion in holography development, an explosion that had its "ground zero" at the original base of operations of Leith and Stroke—the University of Michigan in Ann Arbor (*5*).

Coherence and Interference

The light waves generated by a laser are unusual because they are extremely regular and because they are highly monochromatic (single wavelength) waves. Laser light is highly coherent; that is to say, interference effects between the light itself and laser light reflected from the scene are strongly pronounced. When one set of coherent waves meets a second similar wave set, strong addition effects (constructive interference) and subtraction effects (destructive interference) occur.

Making a Hologram

Two sets of light waves are made to interfere in forming the hologram (Fig. 1). One set is that issuing from the scene (a very complicated set), and the other is the reference wave, usually a simple set of plane waves. In reconstructing the originally recorded scene, an identical plane wave reference set is made to illuminate the developed photographic plate (the hologram) just as it did when the hologram was made. In Fig. 1A, light from the same laser is



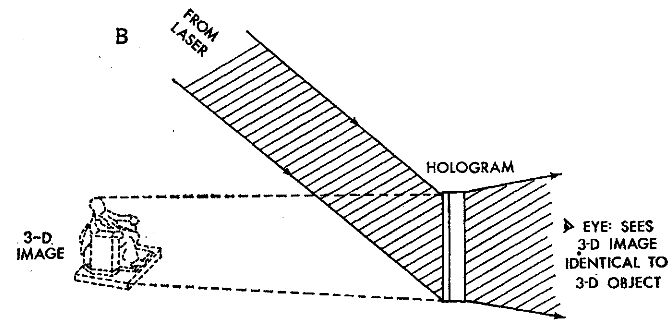


Fig. 1. (A) Hologram recording arrangement. (B) Holographic image reconstruction arrangement.

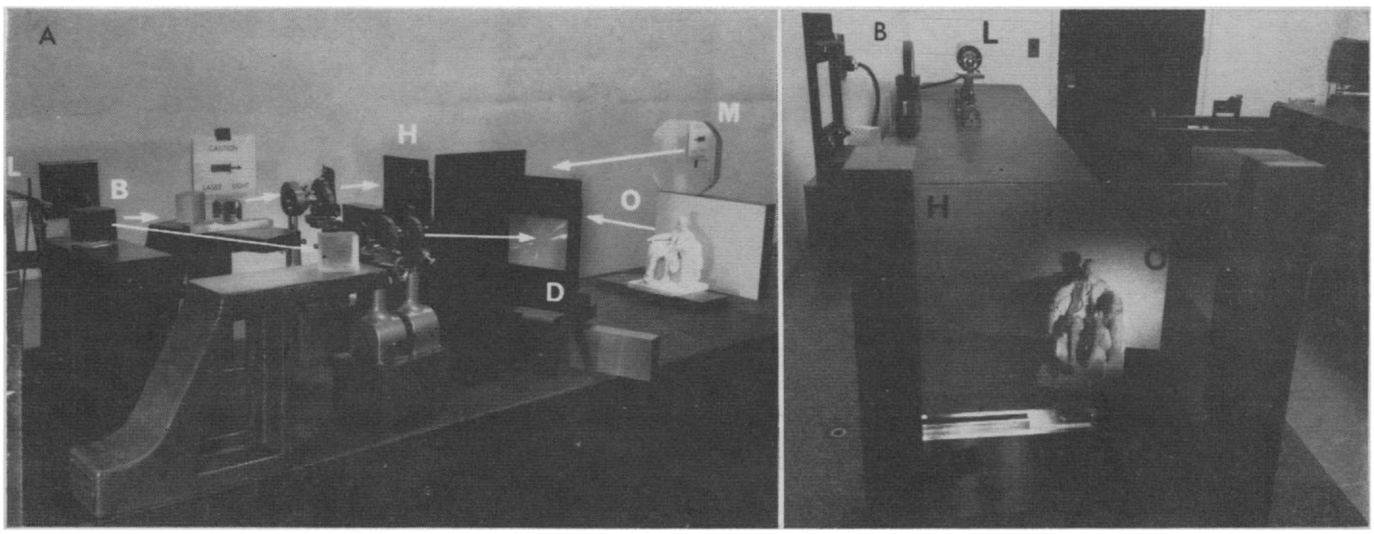


Fig 2. (A) Experimental arrangement for the recording of a three-dimensional hologram. *L*, laser; *B*, beam-splitting mirror; *M*, reference mirror; *D*, diffusor for diffuse illumination of object *O*; *H*, hologram (photographic plate). (B) View through hologram *H* recorded in arrangement of A. [After (*4*)]

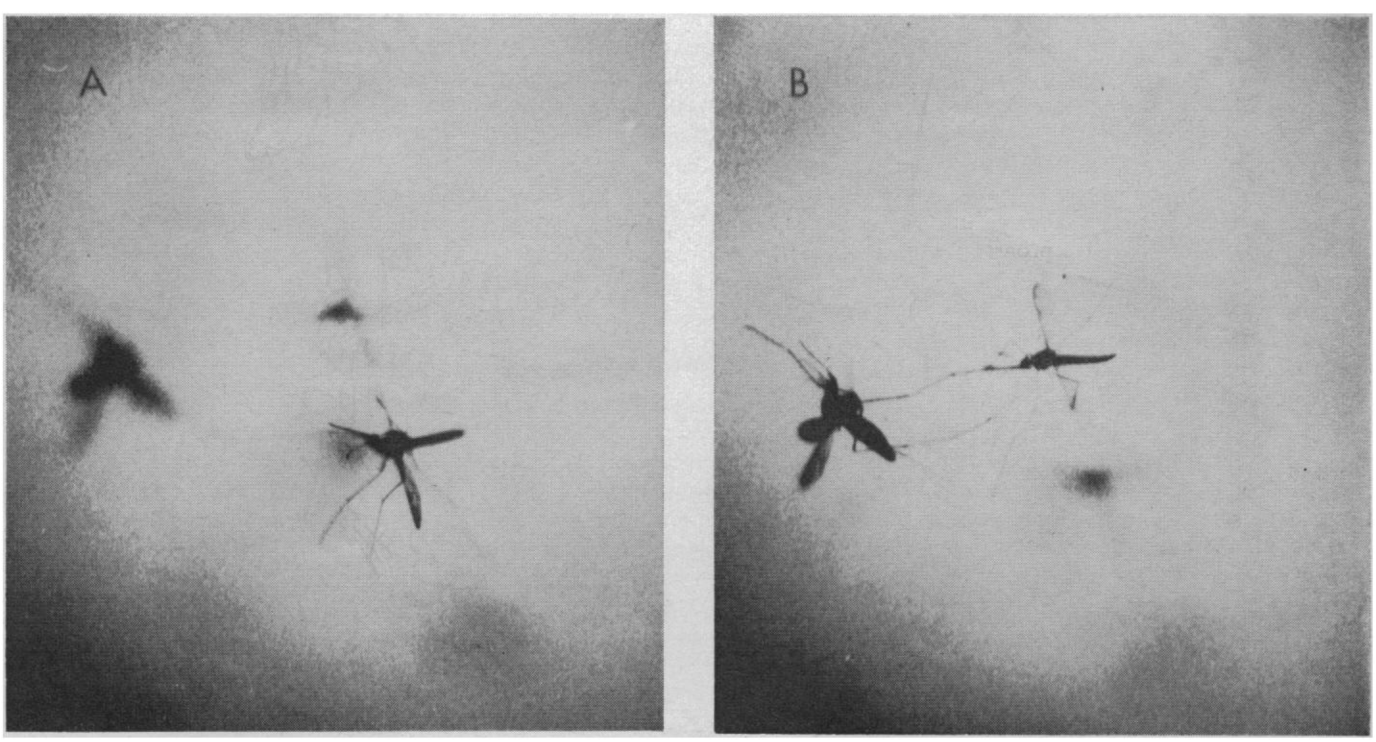


Fig. 3. Helium-neon laser reconstruction of a Q-switched ruby laser-hologram image of a flight of mosquitoes. Pictures A and B differ by the focus of the 60 mm *f*/2 copy camera lens. [Courtesy of R. F. Wuerker and co-workers, TRW Systems, Redondo Beach, California]

used both to illuminate the scene (a three-dimensional object) and to act as the plane reference waves at the top of the figure. After exposure, the photographic plate is developed and fixed; and it thereby becomes the hologram. When the hologram is illuminated with the original reference wave, as in Fig. 1B, a viewer sees the object in three dimensions.

One simple example of a photographically recorded interference pattern which can recreate an image of the original "scene" is a photographically made grating. Such a grating can be made by recording the combination of two sets of coherent plane waves, as shown in Fig. 4A. Wave addition occurs on those horizontal lines of the photographic plate where the crests of wave sets A and B reinforce (marked ++). Wave diminution occurs where the crest of one meets the trough (−) of the other (marked +−). Where addition occurs the plate is more strongly exposed, and parallel striations are thus recorded on the film as a photographic grating. When the grating is illuminated by horizontally traveling plane waves (Fig. 4B), some wave energy passes straight through (the zero-order component), but some wave energy is also deflected (diffracted) both upward and downward (the first-order diffracted components). The downward diffracted set in Fig. 4B proceeds in exactly the direction of the original set B of Fig. 4A, which formed the grating. Accordingly, a viewer at the lower right of Fig. 4B, and hence in the path of these reconstructed waves, would imagine that the source which generated the original set B in Fig. 4A was still located behind the photographic grating (the hologram). The hologram is thus able to "regenerate" a wave progression long after its original source has ceased to exist. Holographic gratings may also be generated by laser light originating from two neighboring "point" sources. When one of the "point" sources is replaced by a more complicated "object," the hologram is still a grating, albeit a somewhat more complicated one. In fact, the hologram now consists of a superposition of gratings, one for each "point" in the object (or scene). An example of this is the lensless Fourier-transform hologram of the word *holography* (4) in Fig. 5.

A second example of a photographically recorded interference pattern which can reconstruct an original image is the interference pattern between a set of plane waves and a set of spheri-

A

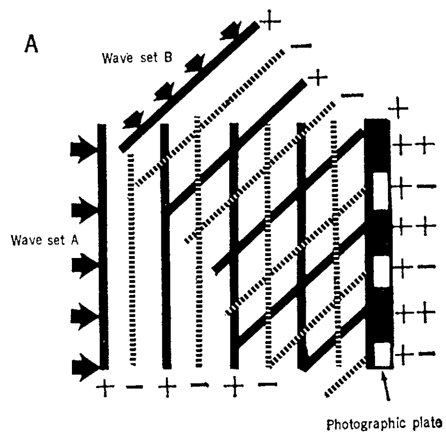
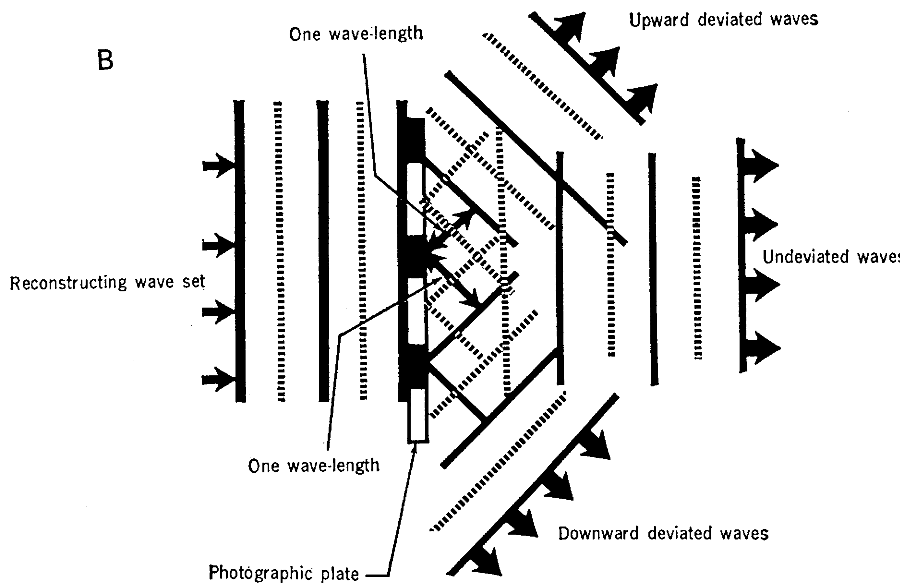


Fig. 4. (A) When two sets of single-wavelength plane waves meet, interference occurs; where wave crests and troughs coincide, wave addition results; and where a crest of one coincides with a trough of the other, wave cancellation occurs. (B) When the line pattern, as recorded in A, is illuminated with the original, horizontally traveling set of plane waves, two off-angle plane wave sets and one undeviated plane wave set result. One of the off-angle sets travels in the same direction in which the original off-angle wave set was traveling. [After (5)]

B



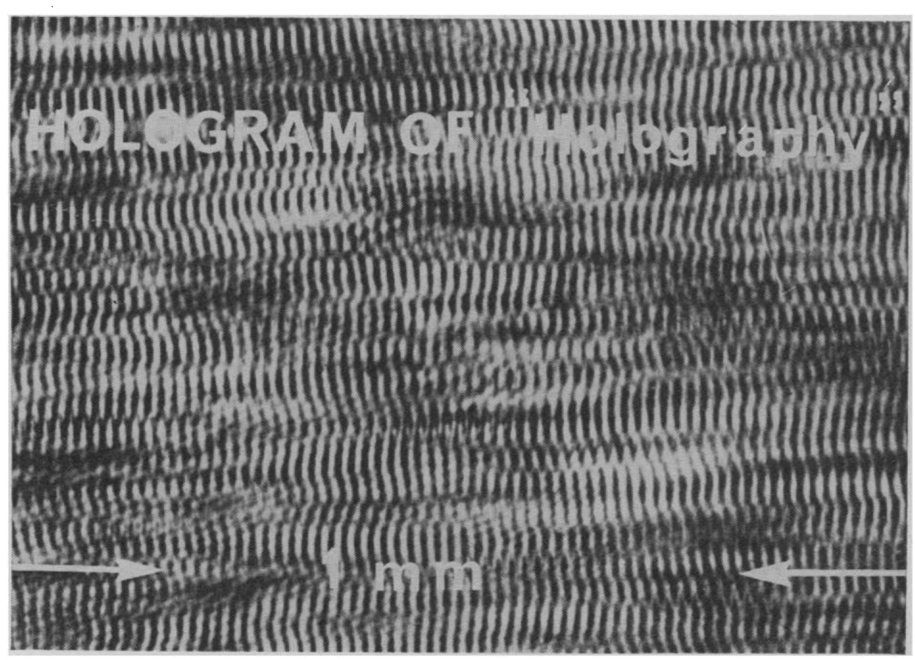
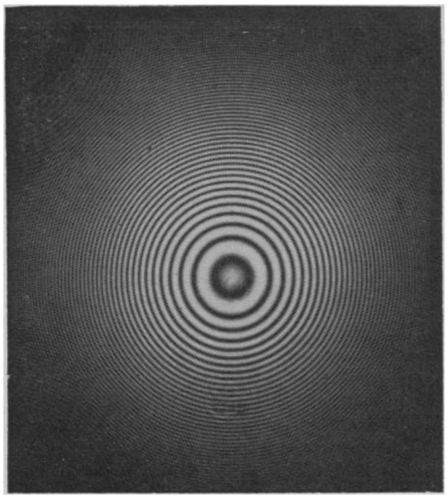


Fig. 5. Hologram of the word *holography* recorded in a lensless Fourier-transform recording arrangement [After G. W. Stroke, "Diffraction Gratings," in *Handbuch der Physik* (Springer, Berlin, 1967) vol. 29]. The interference fringes which characterize holograms recorded with a point "reference" source located near the object have a grating-like structure, and the fringes have a comfortably coarse spacing (about 80 fringes per millimeter), at 600 mm from the object, with the source at about 15 mm from the object.



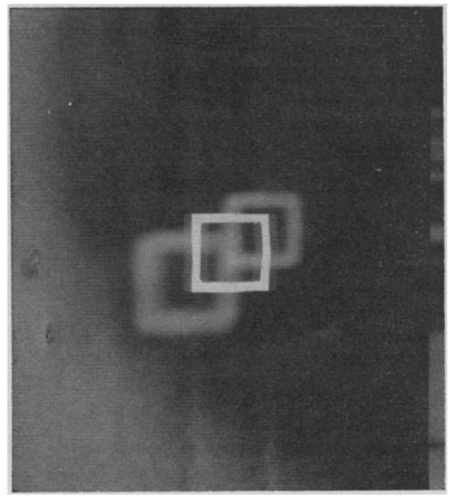


Fig. 6 (left). A photograph of the interference pattern generated by combining coherent plane and spherical waves has a very close resemblance to a zone-plate pattern. Fig. 7 (right). Multiple-image effect produced by the converging and diverging waves generated by a zone plate. For this photo a zone plate 5 cm in diameter was used, made by causing spherical waves and plane waves to interfere on a photographic plate. The object to be imaged is the white square frame shown as the central object. The zone plate was moved off-axis to partially separate the three components. One of the two fainter images is produced by the zone plate's positive lens action, the other by negative lens action. If the zone plate had been offset still farther, the three diffracted components would have been completely separated. [After (*5*)]

cal waves. Again, areas of wave addition and subtraction are generated; but now a circular pattern is formed, and the record is found to be identical to the well-known optical zone plate (*6*). A photographic record of such an interference pattern is shown in Fig. 6. When this circular pattern is illuminated with plane waves, three wave sets will again be generated. Figure 7 illustrates this phenomenon; it shows a photographically made zone plate creating three images of a white square (*7*).

The full two-step zone plate hologram process is shown in Fig. 8. Here a pinhole in the opaque card at the left serves as the "scene" (a point source of spherical waves). At the photographic plate, the spherical waves interfere with the plane reference waves arriving from the left. The upper portion of the circular interference pattern is recorded, and when this photographic zone plate is developed and fixed, and then placed, as shown at the right, in the path of the original plane reference waves, an image (a virtual image) of the original pinhole light source is formed at the conjugate focal point, F_c. A viewer at the upper right thus imagines he sees the original light from the pinhole. (The real image, which appears at the true focal point, F, is not used in the usual viewing of a hologram.)

Imagine that the original scene of Fig. 8 consisted of not one pinhole, but of several point sources of light, each of which was located in a different vertical position and at a different distance from the photographic plate. Then each of these sources would have generated, in conjunction with the plane reference waves, its own zone plate photographic pattern; and upon reillumination, several sets of upward waves would have been generated. Virtual images of each of the original pinholes would have been formed, so that a viewer would imagine that he saw several point sources of light, all fixed in position and each at its original location in space.

In any scene which is illuminated with (laser) light, there are always points which are sources of reflected light. Each reflecting point can be looked upon as a point source of laser light. When a laser reference wave is also present, each source can form, on a properly positioned photographic plate, its own zone plate. The superposition of all of these zone plates constitutes, of course, a very complicated interference pattern, but when this recorded hologram is developed, fixed, and reilluminated, reconstruction will occur (just as in Fig. 8). Light will be diffracted by the superimposed zone plates so as to cause all of the original light sources to appear in their original locations. A fully realistic three-dimensional illusion of the original scene is thus provided.

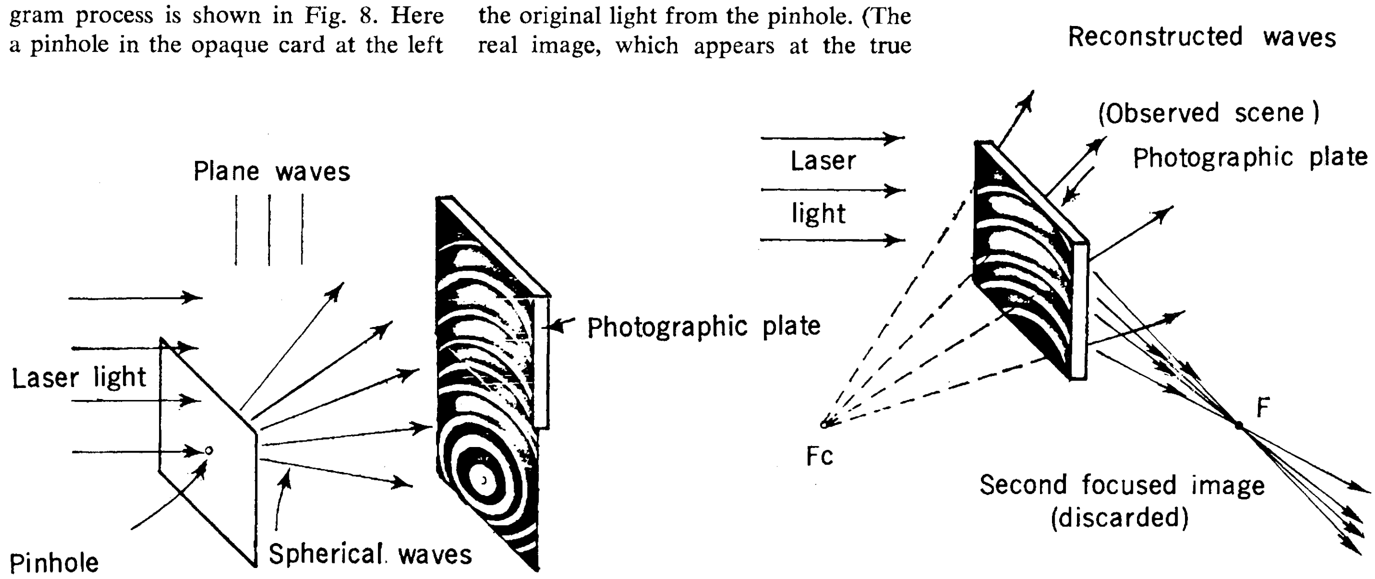


Fig 8. Circular interference fringes, corresponding to a zone plate, are created by the interference pattern formed by plane waves arriving from left and by spherical waves emerging from the pinhole. If a portion of this pattern is recorded on a photographic plate, the resulting hologram, when illuminated, causes waves to be generated, and reconstructs the image as if it came from the original location of the pinhole. [After (*5*)]

Properties of Holograms

Holograms differ from ordinary photographs in several ways. When a photo is taken of a scene a negative is first made, then the dark and light areas of this negative are reversed to form a positive print which portrays the scene as originally seen. Both the positive and the negative versions of the usual hologram will generate the identical three-dimensional illusion. This property is a consequence of the similarity between holograms and zone plates; zone plates perform equally well if their dark (blocking) areas and their bright (transparent) areas are interchanged. A second way in which holograms differ from photographs is in the appearance of the photographic plate. When the usual hologram is held up to the light, it appears to be a uniform gray sheet; hardly any pattern is seen, certainly none which is indicative of the scene recorded, as in a photographic negative.

A further difference between holography and photography is that in holography the original scene can be reconstructed with only a part of the hologram. Figure 9 shows why this is so. Here the zone plate ABCD is shown causing some energy to be brought to a focus at f and some to diverge upward from f_c. But if only the smaller portion A′B′C′D′ were used, some energy would still converge on f and some would diverge from f_c. Because a hologram is a superposition of many zone plates, it behaves in a similar way. Using a small part of the hologram has only the consequence that the resolution is less, and the signal-to-noise level is reduced.

When they made the first laser holograms, Leith and Upatnieks used a prism to cause the reference wave to interfere with the waves from the object (*3*); these holograms are usually referred to as two-beam or offset holograms. In Gabor's original procedure, a single light beam was used; and the light which passed around the object acted as the reference wave. Gabor's single-beam technique can also provide a separation of the twin images if the photographic recording is properly made (*8*); the arrangement in Fig. 8 used such a procedure.

It may be shown (*4*) that the spacing d of the "carrier" interference fringes in a hologram is given by the relation $d = \lambda/2 \sin(\alpha/2)$ where α is the angle of the mean direction of the object beam with respect to the reference beam and λ is the wavelength. Because light wavelengths are so short, the recording on film of a light-wave interference pattern demands film which has a high resolution capability. Most holograms use off-axis reference beams, and the zone spacing at a wide off-axis angle approaches one wavelength of light. At laser wavelengths (neon-helium lasers) this would be a spacing of approximately 1500 lines per millimeter in representative cases. Fortunately, there are special high-resolution films (*9*) which can handle this task.

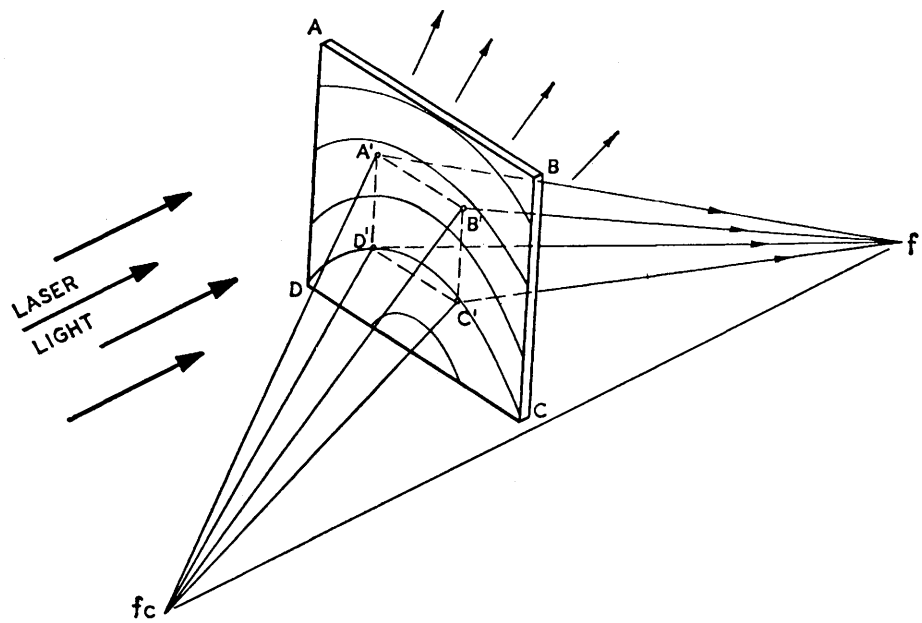


Fig. 9. Only a part of a hologram is necessary to reconstruct a scene in its entirety. [After (*5*)]

A hologram zone plate can act as a lens (Fig. 10) (*7*); photographically made (hologram) zone plates may find application as lightweight lenses in various applications, such as space communication, astronomy, and space exploration. For such uses the zone plates could be photographically fabricated on thin, lightweight plastic sheets which can be stowed in small volumes on launch and later unfurled to full appertura size once the craft has reached outer space. They could be used to concentrate laser communication beams or to act as lightweight photographic lenses (*10*).

Three-Dimensional Realism

The three-dimensional illusion produced by a hologram is quite pronounced, and the viewer quickly realizes that much more information about the scene is furnished by a hologram than by other three-dimensional photo processes, such as stereo photography or 3-D photos using ridged film. In the hologram reconstruction, as we saw in Fig. 3, the viewer can inspect the three-dimensional scene not just from one direction, as in stereo photography, but from many directions and with the ability of focusing sharply on all planes.

The viewer, looking through a holo-

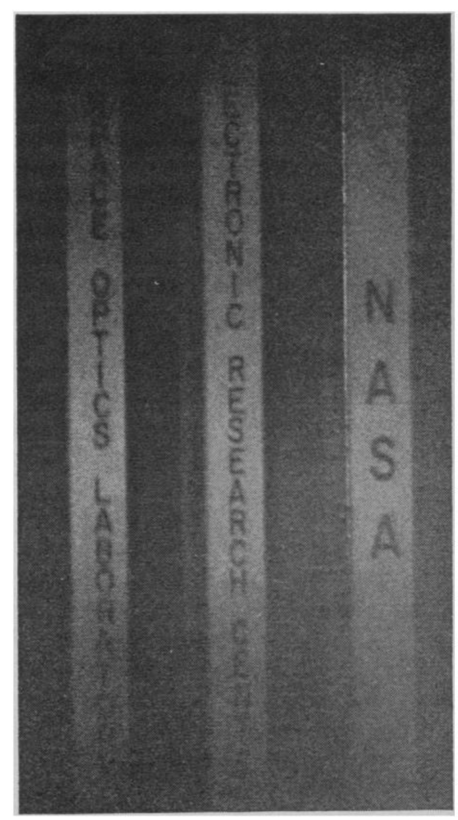


Fig. 10. A photograph taken with a camera using the 5-cm zone plate of Fig. 7 as its only lens. [After (*5*)]

gram, is usually encouraged to move his head sideways or up and down so that he may observe an effect called parallax. In a real scene, more distant objects appear to move with the viewer, whereas closer objects do not. Such effects are very noticeable to a person riding in a train; the nearby telephone poles move past rapidly, but the distant mountains appear to move forward with the traveler. Similarly, the parallax property of holograms constitutes one of their most convincing proofs of realism.

Another proof of the realism of holograms is provided if a lens is included in the recorded scene (*11*). Then, in place of a sideways motion of the viewer, a motion toward or away from the hologram provides the expected enlargement or contraction of objects located behind the lens.

Hologram designers often include cut-glass objects in the scene to be recorded. In the real situation, glints of light are reflected from the cut glass, and these glints appear and disappear as the viewer moves his head. This effect also occurs for the hologram, and is of considerable importance because it illustrates the appearance of specularly reflecting, mirror-like objects when they are illuminated with coherent collimated radiation. This type of appearance characterizes many objects when they are viewed with ultrasonic radiation in accoustical holography.

Another interesting use of lenses in holograms was made in 1966 by Rosen (*12*). In this procedure, now called focused-image holography, a hologram is made of the real image of a group of objects located behind a lens. The photographic plate can even longitudinally straddle the real images of the actual objects; that is, the image of one object can be positioned behind the photographic plate, and the image of another object positioned in front of the hologram plate. When this hologram is developed and properly illuminated, the viewer sees one object behind the hologram plate and another standing out in space in front of the hologram (*13*).

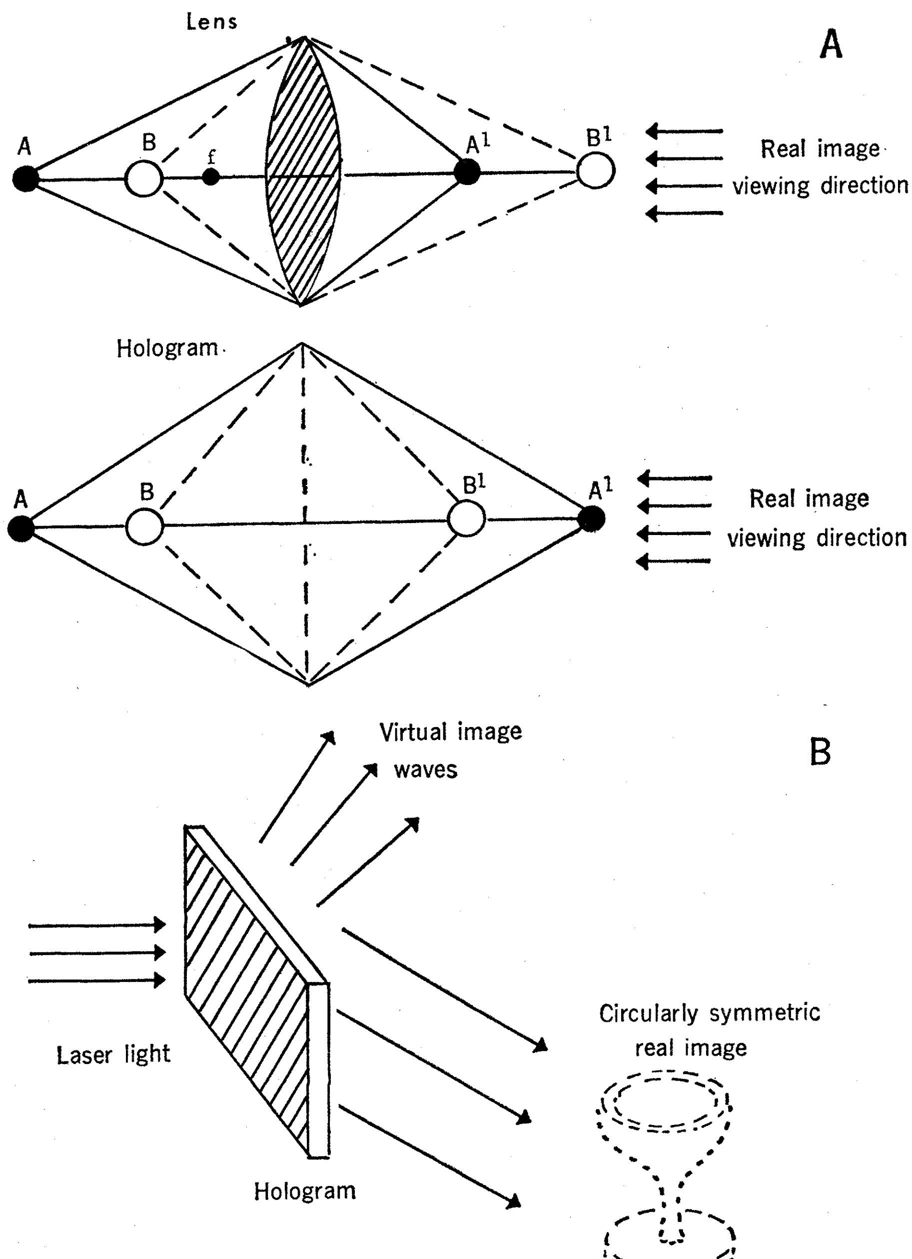


Fig. 11. Pseudoscopy is illustrated by these diagrams. (A) objects which are imaged by a lens retain their original relative positions. When a hologram is made, each object forms its own zone plate and, on reconstruction, the real and virtual images are positioned equidistant from the hologram. Pseudoscopy, or image inversion, thereby occurs. (B) A circularly symmetric image can be made to stand out in front of the hologram very realistically despite the pseudoscopy associated with the real image of a hologram. [After (*5*)]

Pseudoscopy in the Real Image of a Hologram

We saw that hologram zone plates can function as converging lenses and that the real image which they form can be recorded on film, just as the real image from a camera lens is recorded. In a hologram of a scene, the reconstructed real image can also be reviewed by placing a white card at the focal area (*f* in Fig. 8). If the original scene is three-dimensional, the reconstructed real image of the hologram is also three-dimensional, but it differs significantly from the real image which a lens would form of the same three-dimensional scene (Fig. 11). When an object is moved farther to the left of the focal point of a lens, as from B to A (Fig. 11A), the position of its image likewise moves to the left, as from B′ to A′. Objects A′ and B′ in this lens-produced real image thus bear the same relation to a viewer at the right as the actual objects A and B do.

For the holographic real image this is not the case. In the recording process, luminous object A forms its own zone plate, which, when developed and illuminated, forms a real image at the equidistant point A′. Similarly, object B produces its own zone plate, which forms its real image at the equidistant point B′. For the viewer on the right,

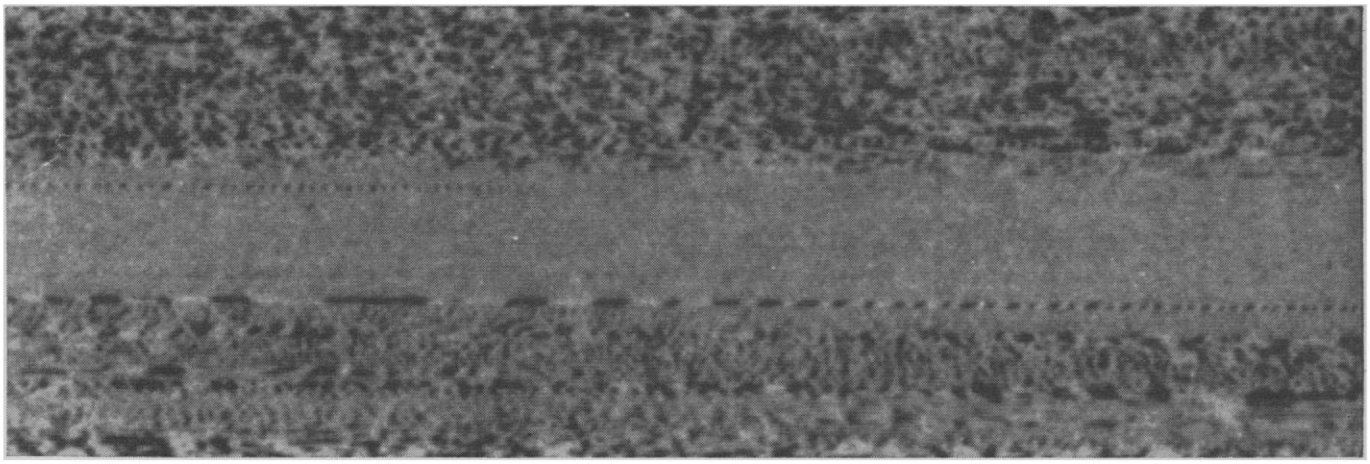


Fig 12. A photographic record from a synthetic aperture radar. As in the case of an optical hologram, when this microwave hologram is illuminated with coherent light, reconstruction of the terrain results. A strongly reflecting object generated the prominent one-dimensional zone plate near the bottom of the central, almost blank, area. [Courtesy of L. J. Cutrona, E. N. Leith, L. J. Porcello, W. E. Vivian (*19*)]

objects originally in the rear thus appear to be in the foreground in this real image, and vice versa. This reversal of forward and back objects has been given the name pseudoscopy; the image is said to be pseudoscopic. Because such images are rather confusing, little attempt has been made to use the real image of a hologram for viewing purposes. In one experiment, however, a circularly symmetrical object (a champagne glass) was used as a hologram subject (*14*). In the reconstruction of this hologram the viewer sees the real image standing out in front of the hologram, as sketched at the right side of Fig. 11B. Because of the symmetry of the champagne glass, the exchange of front for rear is not significant, and the viewer imagines he sees a normal, nonpseudoscopic image.

Such "out-in-space" images can be obtained in other ways, such as by focused-image holography, which we discussed above. Another procedure is to make a second hologram of the pseudoscopic real image of a first hologram. The real image of this second hologram then becomes a "pseudoscopic-pseudoscopic" image (a doubly reversed image), that is, a normal image. In this process, any scene, including unsymmetrical ones, can be used as a subject (*15*).

Holography and TV

Holograms provide the viewer with a very large amount of information about the scene recorded, including its three-dimensional properties. This large information content has unfortunately limited the use of holograms in many interesting applications. Such applications would include three-dimensional movies and three-dimensional television, fields which would obviously benefit from the realism of holograms. The large information content of a hologram is a consequence of the extremely fine fringe detail in the interference pattern. This detail, approximating 1500 lines per millimeter, is a far cry from the capability of present television systems, which employ much coarser line structure. Accordingly, the outlook for using holograms in television is very bleak indeed.

Several methods have been suggested for reducing the information content of a hologram without sacrificing completely some of its valuable properties (*16–18*), but this road is a very difficult one. Television pictures in the United States have approximately 500 vertical lines and 500 horizontal dots. One television picture, which corresponds to one frame of motion-picture film, accordingly has an information content of $(500)^2$, or 250,000 dots. A hologram 200 mm (8 inches) square, with its many superimposed zone plates requires a resolving power of 1500

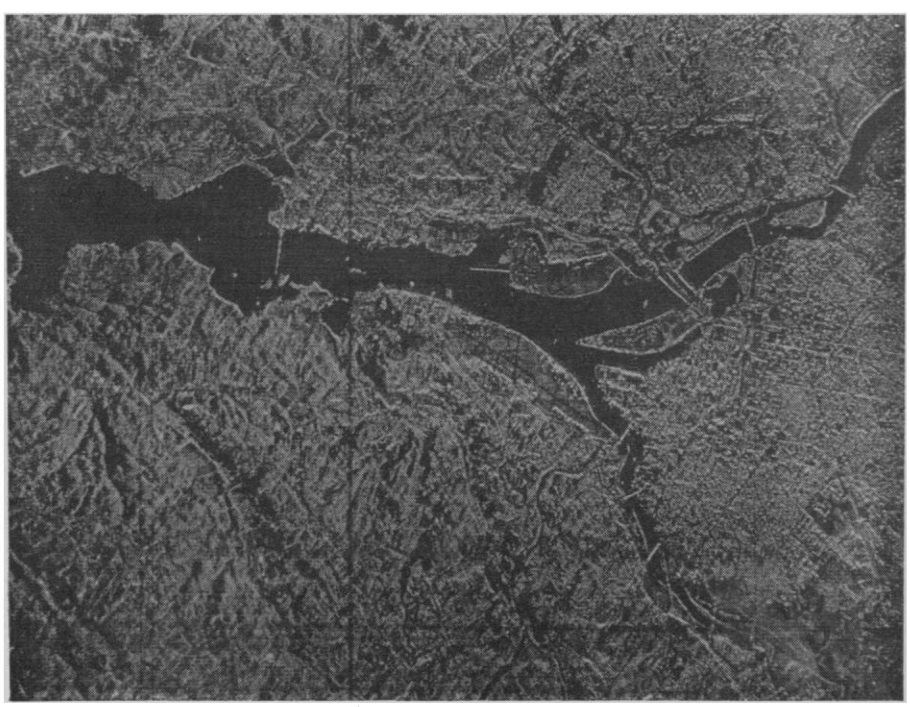


Fig 13. Photographic image of Washington, D.C., extracted by laser light illumination from a photograph of an oscillograph display of a microwave hologram (such as that of Fig. 12) recorded according to the method of (*17*). [Courtesy of L. J. Cutrona *et al.* (*19*), see also (*20–25*)]

fringes (lines) per millimeter; it would have the equivalent of 200 times 1500, or 300,000 vertical lines and 300,000 horizontal dots, with a total information content corresponding to 90 billion dots. The ratio between this potential information content of an 8-inch square hologram and that of a U.S. television picture is thus 360,000 to 1. To reduce the information content of a hologram by a factor that large would be a remarkable accomplishment.

Microwave Holography

Although Gabor's conception of optical holography in 1948 lay almost dormant until 1963 when the University of Michigan researchers Leith, Upatnieks, and Stroke initiated what has now become a very extensive, worldwide development effort on it; another electromagnetic form of holography received wide attention all through the 1950's. The importance of this development, known as synthetic aperture (coherent) radar and pioneered by Cutrona and his group at the University of Michigan (*19*), was recognized quite early.

Actually, the relation of coherent radar to holography was not appreciated until rather recently (*20–22*), but several concepts which were applied first in side-looking radar were later used in holography. Most important of these is the technique in which an offset beam is used (in holography this is referred to as the two-beam recording technique).

Figure 12 is a portion of a coherent radar record (a form of microwave hologram); a strongly reflecting point in the terrain has generated a one-dimensional zone plate pattern (instead of the usual two-dimensional zone plates of optical holograms) which appears near the bottom of the central blank area (*23, 24*). Reconstructed pictures that rival the finest photographs are obtainable with these radars even when clouds or fog obscure a visual view of the countryside (*25*); an example (*19*) is shown in Fig. 13.

Volume Holograms

In 1962 the Soviet physicist Denisyuk had a remarkable idea, that of combining Gabor's holography with Lippmann's color photography (*26*). Lippmann, in 1894, first produced extremely fine-grain photographic emulsions, with silver bromide grains smaller than a wavelength of light. He then put such a plate in a camera, back to front, and backed up the emulsion with mercury as a mirror. The effect was one of the most spectacular in the whole history of optics. The light waves falling in

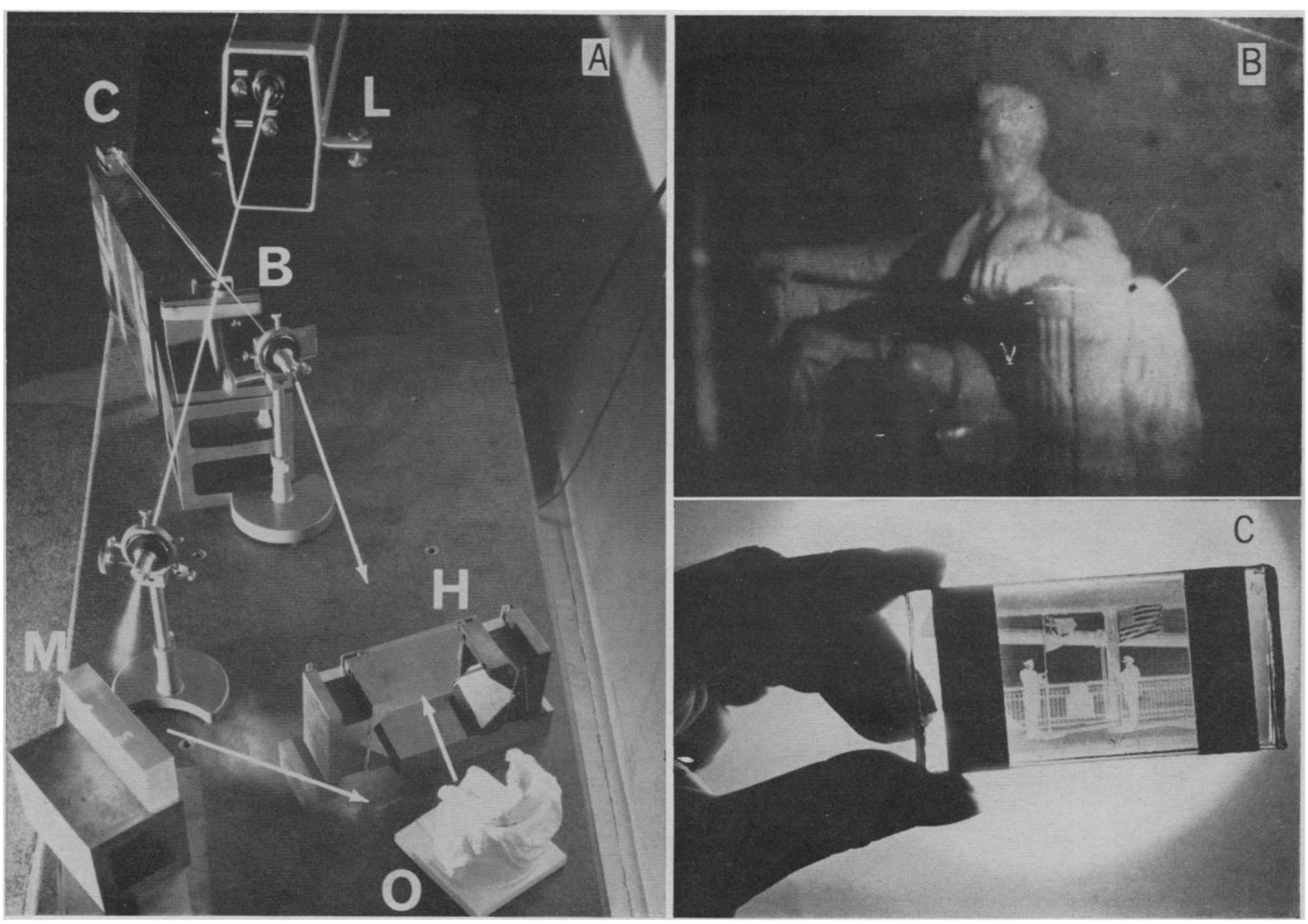


Fig. 14. (A) Original arrangement used by Stroke and Labeyrie in 1965 to record "volume" holograms. The three-dimensional image can be reconstructed with ordinary "white light" illumination (rather than the laser illumination, previously required for viewing of holographic images). *C* is a corner cube reflector; *M* is a mirror; other designations are those of Fig. 2. (B) The image of the model of Lincoln's statue is the first image of this kind obtained. The white-light source was broader than one which would give sharp images [after (*28*)]. (C) A volume hologram which produces a full-color image when illuminated by reflected white light has the appearance of a simple black and white negative when viewed with transmitted light. From an experiment carried out at the Bell Telephone Laboratories, Murray Hill, New Jersey, by L. Lin, K. S. Pennington, G. W. Stroke, and A. E. Labeyrie.

from the front side interfered with the waves reflected from the back and formed a set of standing waves, parallel to the mirror, with maxima spaced by half a wavelength. Very fine silver grains were precipitated in the maxima. Each of these "Lippmann layers" scattered light a little, but their effect reinforced one another only when all these wavelets were in phase, and this occurred only for the original color. That is to say the Lippmann plates selected from white light the original color, and reflected only this to an appreciable extent. Even more surprising, they reproduced faithfully a mixture of pure colors because each color produced its own set of Lippmann layers, and these operated additively, without disturbing one another (*27*). In 1962, Van Heerden drew attention to the immense storage capacity of deep emulsions.

Denisyuk's idea was to combine the Lippmann process with holography, by substituting for the reflected wave a reference wave, falling in from the back of the emulsion. The object wave and the reference wave again form standing waves, but unlike in Lippmann's camera, they are not parallel to the emulsion surface, but form equal angles with the two waves. They produce, as it were, a succession of partial mirrors, which, on illumination by the reference beam alone, reflect in the direction of the original object ray. In other words a "deep" or "volume" hologram is formed, which shows the object in its original spatial position. Moreover, the second image, which was always a disturbance in transmission holograms, vanishes altogether in these "reflection holograms."

Denisyuk had no laser at his disposal; also, his illumination of the object through the plate presented some serious limitations comparable to the original in-line arrangement of transmission holography. Later, Stroke and Labeyrie (*28*) improved the process by illuminating the objects directly while the reference beam remained incident on the back side of the plate. They showed, moreover, that these holograms could be made to reconstruct natural colors when viewed in white light. Figure 14 illustrates this process.

3-D Movies

The problem of providing three-dimensional projected pictures which can be viewed without selective viewing aids, such as polaroid glasses, is an old one. Gabriel Lippmann was the first to approach it by his *photographie intégrale*, the lenticular pictures which one now sees often in shop windows, postcards, and books (*29*). The photographic emulsion is covered with a plastic sheet which is embossed so that it has vertical cylindrical lenticules, each of whose focus is in the emulsion. If a picture of

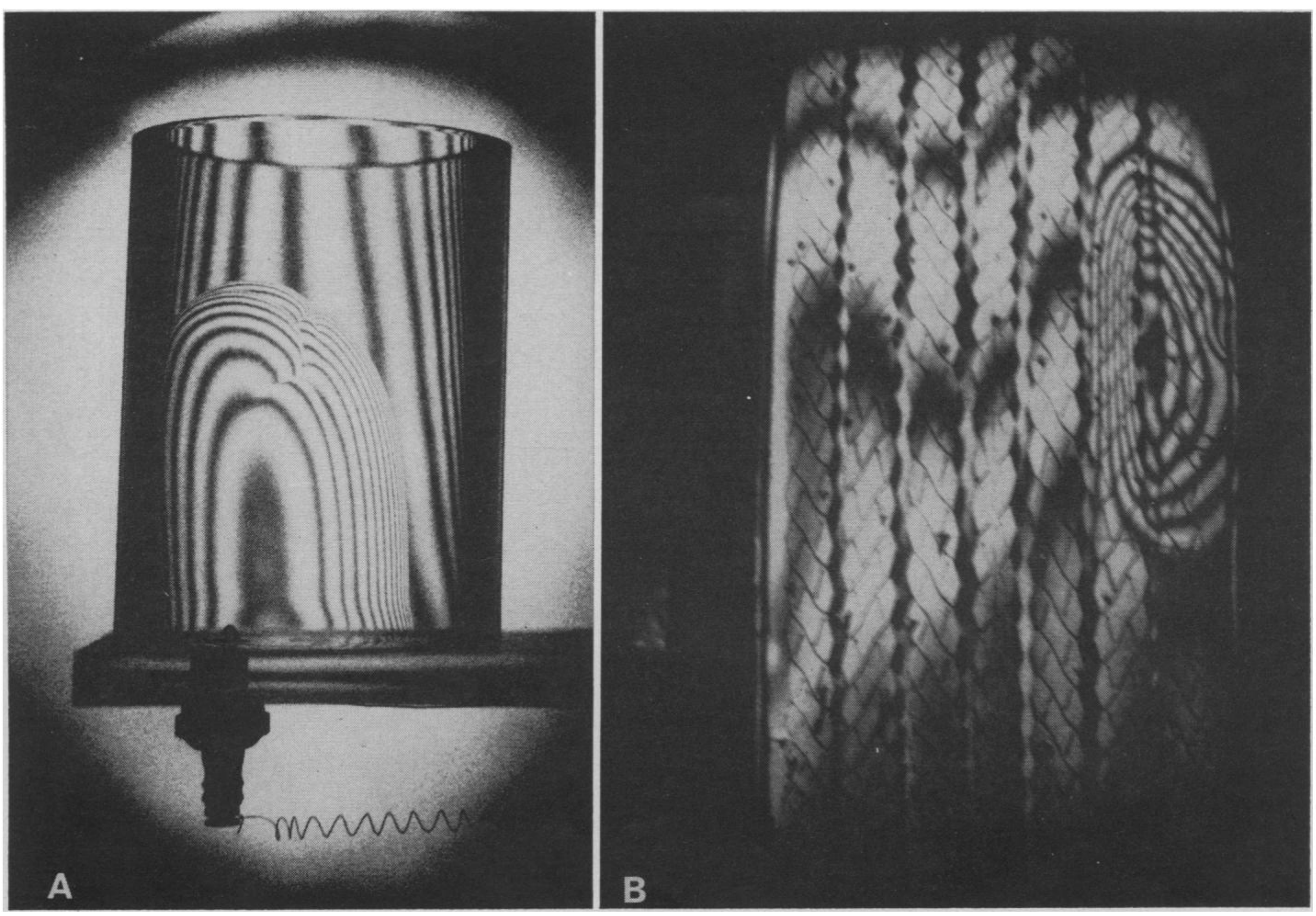


Fig. 15. (A) Reconstruction of a doubly exposed hologram showing interference fringes produced by detonation of an acetylene-air mixture within a Plexiglas cylinder. Also seen are the horizontal fringes due to strain. The original hologram was recorded with radiation from a 0.1-μsec Q-switched ruby laser illuminator (Courtesy R. F. Wuerker and co-workers, TRW Systems, Redondo Beach, California). (B) "Real time" (live) holographic interferogram of a large (8.25×14) tubeless automobile tire showing defect (separation between tread and outer ply of a two-ply bias). Natural creep of normally inflated tire was photographed during two successive states (the original tire state, used to produce hologram, and successive state, existing during observation). [Courtesy Dr. Ralph M. Grant, GC-OPTRONICS, Ann Arbor, Michigan; after (*4*)]

a spatial object is taken through this sheet and this emulsion developed, the object will appear in its original position and size. This is because the "autocollimating" property of the lenticules causes each ray to return in the direction from whence it came.

Recently Gabor proposed that "holographically made" Lippmann lenticular sheets be used for a 3-D projection system (*30*). In this procedure, the viewing screen is a large volume hologram (a Lippmann-Denisyuk hologram), so that the image projected on it from one projector will be seen only from certain viewing zones and the image from a second projector only in other zones. Then when the two projectors illuminate the hologram screen with coherent light, each viewer perceives the proper image in each eye, and the desired 3-D effect results.

Holographic Interferometry

If two successive holograms of the same object are superposed in the same hologram emulsion, an image of the object covered by interference fringes may be reconstructed. These fringes are a direct measure of the topographical changes of the object between the two exposures (*31*). The principle of this type of holographic interferometry is readily explained. Two image-forming wavefront components are reconstructed from the hologram, and any slight difference between the two wavefronts will manifest itself in the form of an interference pattern, which may be photographed. Holographic interferograms permit study of deformations in objects of great complexity; moreover, the objects need not be mirrorlike, but may,

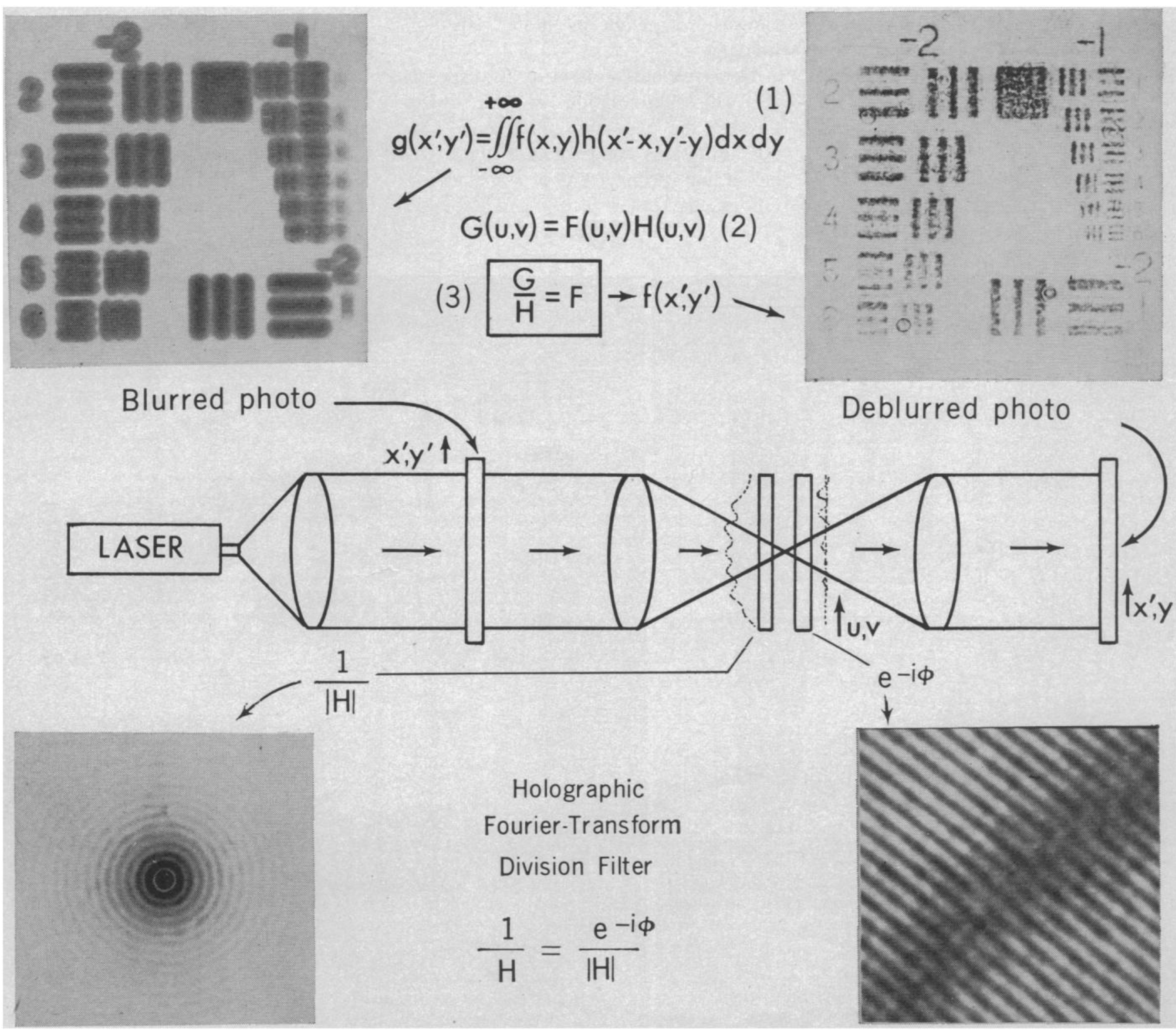


Fig. 16. Holographic deblurring of an image according to the optical computing method (*34, 35*). The original image intensity distribution is represented by $f(x,y)$; the intensity distribution in the blurred photo is $g(x' y')$; and the deblurred intensity distribution is $f(x',y')$. Mathematically, the blurring process can be represented by the convolution integral of $f(x, y)$ with the point-spread function, $h(x'-x, y'-y)$; so that Eq. 1 describes the blurred photo. The convolution integral takes on the form of a product in the Fourier domain (Eq. 2) where G, F, and H are the spatial Fourier transforms of the functions g, f, and h. Equation 3 describes the operation of the deblurring system, which takes place in the Fourier domain. The holographic Fourier-transform division filter represents the function $1/H = |H|^{-1}e^{-i\phi}$ and is made up of two photographic plates; the first contains the amplitude component ($|H|^{-1}$), and the second contains the phase component ($e^{-i\phi}$). An important feature of the method is that the components of the holographic filter may be physically generated from the experimentally obtained point-spread function—the blurred image of a point [after *43*)]. The photographic inserts are previously unpublished experimental results of Stroke and Halioua.

in fact, be perfectly diffusing. The method has already found wide applications in the study of vibrations—for instance in measurements of loudspeakers, sonar transducers, and so forth; two examples are shown in Fig. 15. It could be used for measurements of very small dimensional changes in inertial guidance components, such as gyroscopes, under dynamic conditions or stress deformations.

Computer-Generated Holograms

Considerable interest has been shown in applying the new holographic principles of three-dimensional image storage and reconstruction to digital computer displays and other computer applications. Thus, it has now become possible to generate holograms that are capable of displaying three-dimensional images of objects that never existed in reality.

Methods have been described by Lohmann and Brown for synthesizing holograms by photographically reducing the size of the intensity distribution obtained in a large-scale drawing from a computer-guided plotter (*32*). Digital computation of a hologram will in general be impractical except in simple cases.

Gabor and Stroke have described a method for synthesizing "computer-generated" holograms directly by holography (*33*). One synthesized hologram was recorded by summing successively, in the same latent image, the intensities of 450 component holograms, each corresponding to one image point in the scene. Other types of artificial or synthesized holograms, realized either graphically or by interference or by coding, have also been described (*4*).

Holographic Image Deblurring

Holography began with an attempt to sharpen electron micrographs that were blurred by the spherical aberration of electron objectives. This goal has in fact now been met by means of an image-deblurring method first proposed by Stroke in 1957, and more recently perfected by him and his co-workers in the form of "holographic Fourier-transform division." The general principle of the method (*34, 35*) is illustrated in Fig. 16, and its application to the deblurring of electron-beam photographs is shown for the first time here in Fig. 17. This figure shows an enhanced (deblurred) image extracted from a blurred microphotograph from a scanning electron microscope by means of a new extension (*36*) of the holographic Fourier-transform division method first described by Stroke and Zech in 1967

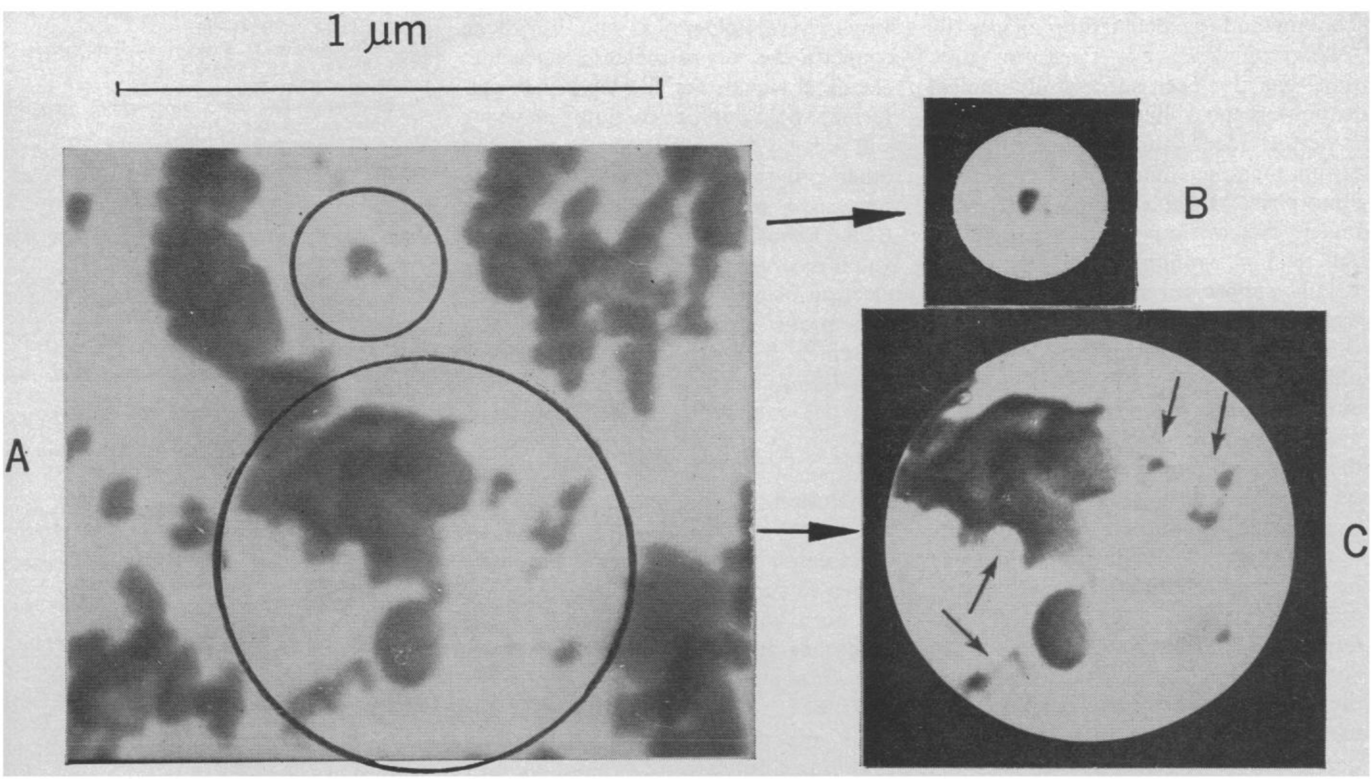


Fig. 17. Holographic resolution enhancement of micrograph from a scanning electron microscope (*36*). (A) Original micrograph of gold-palladium particles on a collodion film, showing maximum resolution (200Å) attainable under normal operating conditions with the instrument used (Materials Analysis Co. MAC SX-II scanning electron microscope; magnification, × 50,000; voltage, 25 kv). (B and C) Holographically sharpened images extracted from (A) by the method of Stroke and Halioua (*35*), based on a new extension of the "holographic Fourier-transform division image deblurring method" of Stroke and Zech (*34*). The sharpened images show an increase of resolution by a factor of more than three (to better than 70 Å), as well as associated enhancement of contrast. The small particle image (B) has decreased dimensions, and its separation from the large image is improved. The greatly enhanced contour resolution as well as the revealing of the filamentary structures in (C) would have probably been incorrectly interpreted in the original micrograph. Deblurring by the optical computing method requires as little as 2 seconds, and is thus considerably faster than digital computer processing methods. Moreover, the deblurring is carried out directly from a copy of the original micrograph (see Fig. 16), without the need of any microdensitometer scanning and encoding required in digital computer processing for which computing times from 5 minutes to 1 hour are representative. The validity of the holographic image-deblurring principle and method has now been further verified as a part of still unpublished collaborative work between one of us (G.W.S. with Halioua) and A. V. Crewe of the University of Chicago. In this work we have succeeded in enhancing photographs obtained in the much higher resolution transmission scanning mode (*44*); an improvement of resolution from about 5Å to probably much better than 2.5Å has been attained and has permitted the double-helical structure of a filamentary bacterial virus to be revealed (*45*).

(*34*). Ever since the work of Gabor in 1948 (*2*) it had been clear that atomic-scale resolutions could be obtained in electron microscopy if certain inherent instrumental imperfections could be surmounted by a posteriori methods, variously called "enhancement," "deblurring," "restoration," and "compensation." The original suggestion of Gabor was to first make an electron-beam hologram and then to correct its imperfections by compensation in an optical reconstruction step. This suggestion has in fact again been recently taken up, in view of the enhancement of resolution in electron microscopy by image holography (*37*), notably also following the success in recording actual electron-beam holograms (*38*), but no experimental results of such optical compensations have been reported to date. In the optical method of image deblurring, Stroke and co-workers have now shown that it is possible to extract greatly improved images from the imperfect electron microphotographs themselves. The method of deblurring images by "holographic Fourier-transform division" has also been successfully applied to photographs blurred by motion and imperfect focus, and it may be applied to photographs blurred by vibrations, atmospheric turbulence, and by other image system imperfections (such as spherical aberration) which cannot be readily suppressed by instrumental design and realization. In all cases, the deblurring starts from an "ordinary" photograph, such as that taken by an amateur with a conventional photographic camera. The implementation of the holographic image deblurring method requires very great photographic care, but in its simplest description, the optical image deblurring methods may be compared to electrical signal filtering methods, such as those used in high-fidelity sound reproduction, where "compensation" at various ranges of the sound-frequency spectrum is used to display the music in a form more acceptable to an informed listener (*4*, *39*).

Holograms for Video Storage

Perhaps the area where the most extensive use of holograms is likely to occur in the near future is in the replacement of magnetic tapes or photographic films by hologram films for video playback purposes (*40*). Such hologram films have the advantage that they can be made small and inexpensive, and, because they are holograms, their information content is highly redundant, so that scratches or other damage which would seriously degrade the final picture in a film or tape system do not affect the holographically reconstructed TV picture because a small portion of a hologram can reproduce the entire hologram scene. In this procedure, the hologram process is employed merely for reasons of economy and reliability, not for exploiting the three-dimensional capability of holography. The original color frames of the movie are converted into transparent, phase holograms, which are equivalent to intensity holograms; and from these an embossed master can be made from which many pressed copies can then be reproduced on inexpensive vinyl material. Cartridges of these recorded vinyl tapes are inserted in a suitcase-size device attached to the television set, and the reconstructions are shown as a movie on the set's screen. Inside the attachment, a laser reconstructs the vinyl tape's holograms, and a vidicon converts the reconstructed images into electrical signals for display. Once perfected, holographic cassette playback will display recorded educational and other programs on ordinary television sets, in a manner comparable to the CBS Laboratories' EVR (electronic video recording) system (*41*). By using electron beam recording, the EVR system packs imaging information with extremely high density on conventional film emulsions, in frames requiring only 2.3×3.1 mm^2 per video frame.

Conclusion

Research on holography has now grown to such dimensions that we have not been able to mention each of the numerous authors who have made significant contributions to it. Investigators from Bell Telephone Laboratories, the RCA, Xerox, and Westinghouse laboratories, Conductron Corporation, GC-Optronics, IBM, TRW Systems, the University of Michigan, and Stanford University have made particularly significant early contributions in the United States. Especially notable were the efforts of R. J. Collier, L. Lin, K. S. Pennington, D. Ansley, L. Siebert, R. M. Grant, A. Lohmann, R. F. Wuerker, K. Stetson, R. Powell, J. Goodman, and their co-workers, in addition to those already mentioned, among many others. Early work in many parts of the world also includes that in France by S. Lowenthal, G. Nomarski, and J. Viénot; in Germany by H. Nassenstein; in Great Britain by J. M. Burch; in Japan by J. Tsujiuchi and T. Tsuruta; and in the Soviet Union by Yu. Y. N. Denisyuk, I. Nalimov, and L. M. Soroko. For a fuller account of these developments, see (*42*) and other references.

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A Gorilla-Sized Ape from the Miocene of India

A newly recognized association of fragments makes possible fuller reconstruction of a fossil ape.

E. L. Simons and David Pilbeam

Isolated teeth and parts of upper and lower jaws of *Dryopithecus indicus,* separately found in India between 1915 and 1950, provide the fullest knowledge yet available on the dental and facial anatomy of any extinct Eurasian great ape. These remains represent a large, robust ape species that in molar length, breadth, and mandibular thickness at M_1 exceeds these values in all chimpanzees examined. The palate and mandible principally discussed here contain relatively large, projecting canines, such as one would expect to find in a male. Other large ape jaws discovered in the area have smaller canines, as would be appropriate for female of *D. indicus*. The lower jaw and palate described here emphasize the differences between early hominids and this ape.

The earliest hominid, *Ramapithecus punjabicus*, occurs at Haritalyangar, in northern India, at the same general levels, but seldom at the same sites, as *D. indicus*. The reasons for believing that *Ramapithecus* is a "dental" hominid will not be outlined here, since they have already been dealt with in a number of papers (*1*). The suggestion has occasionally been made that specimens of *Ramapithecus* might actually represent female apes, thus accounting for their small canines and incisors. Nevertheless, the front teeth of *Ramapithecus* are smaller, relative to molar size, than are those of the smallest female pygmy chimpanzees (*2*). Each specimen of *Ramapithecus* from northern India represents a very small hominoid, smaller than the specimens which appear to be female *D. indicus*. If facial and dental proportions corresponded to body size in approximately the manner seen in present-day African apes, then *Ramapithecus*, or at least those from Haritalyangar, would have been approximately the size of a female pygmy chimpanzee. As has already been stated, both presumed sexes of *D. indicus* are nearly gorilla-sized. In consequence, the diminutive canines of *Ramapithecus* cannot be interpreted as those of a female of a contemporary, sexually dimorphic, pongid species. *Ramapithecus punjabicus*, *D. indicus*, and possibly a gibbon-like form are the best-known hominoids occurring in the section of rocks exposed at Haritalyangar. Monkeys are absent. Such possible sympatry probably implies that the larger hominoids were at least as ecologically and behaviorally distinct as chimpanzee and gorilla are today, where their ranges overlap.

Dryopithecus indicus has been a much more poorly understood animal than *Ramapithecus*. Because of the associations of jaw parts discussed here, the dentition and face of *D. indicus* is now better known anatomically than is that of any other Eurasian fossil great ape. The species contributes significantly to our understanding of ape and hominid evolution in Asia, and perhaps in other parts of the world as well. *Dryopithecus indicus* is a reasonably distinctive species. The teeth are unusually large and broad for the genus. When unworn, the central fovea of tooth crowns are relatively restricted, and the outer sides of the tooth cusps belly outward toward the alveolar border. Some finds referable to this species, from sites in the Himalayan foothills other than Haritalyangar, suggest that certain individuals may have rivaled large mountain gorillas in the size of their teeth and jaws. The molars of this species show considerable crown height compared to the height of individual cusps, and the crowns of the cheek teeth show less crenulation than is usual among hominoids, including *Gorilla gorilla*. Unlike most African Tertiary great apes, and some other Eurasian ape species of approximately the same age, there are no cingula on the upper or lower molars. The taxonomic significance of this is not entirely clear. Occurrence of the cingulum is a variable character among modern African pongids. The known sample of *D. indicus* is not large enough to allow the deduction that cingula are always absent in this species. In any case, reduction of molar cingula is a trend seen through time among all Hominoidea. Furthermore, in spite of the gorilla- and chimpanzee-like features of *D. indicus*, it is only fair to say that retention of these cingula is more characteristic of living gorillas than of the other present-day higher primates. Otherwise the teeth and jaws of this species are remarkably gorilla-like.

Dryopithecus indicus shows several additional species distinctions. Despite large canines, confirmed in a number of fossil finds, the molar cusps of this

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