Bibliography on Holograms—II

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In Bibliography on Holograms—I(April 1966 issue of the Journal*), R. P. Chambers and J. S. Courtney-Pratt, Bell Telephone Laboratories, Inc., Murray Hill, N. J. 07971, included a list of about 180 papers on holograms. This present compilation contains about 140 more papers on holograms, most of which have been published in 1966. As before, authors, titles and sources are listed, and within each year the papers are placed by first author in alphabetical order.*

Abstracts are also given for almost all these papers in the same order as the papers are listed in the bibliography. Where they existed, author abstracts are utilized. When a paper was shorter than one page, the whole article is reproduced. Elsewhere the compilers of the bibliography have extracted an introductory section from the paper or have appended their own brief comments.

In this Bibliography papers on spatial filtering or other optical signal processing are not included unless they make specific use or mention of holograms.

Footnote references in brackets can refer to either this second bibliography, or the first Bibliography printed in the April Journal.

This second Bibliography was submitted to the Journal *on June 2, 1966.*

Introduction (*Repeated from April* Journal, *p. 373.*)

An ordinary photograph is a record of the intensity distribution of the light in an image of an object. A hologram is a record of the intensity distribution and also of the relative phase of the light from an object. The phase information is captured by recording the pattern of interference between the light from the object and a coherent reference beam. As all of the information in the light beams leaving the object has been recorded, it is in principle possible to reconstruct similar light beams and so to produce a realistic three-dimensional image of the object. In practice, it has been shown that such three-dimensional images can be viewed directly; sequences of images, all recorded on the one holographic plate, can be exhibited; image magnification can be achieved by change of wavelength; or the information can be further processed for special effects.

66*1 "Information processing," a brief account of a meeting of the OSA Technical Group on Information Processing, *Appl. Optics, 5:* 456, 1966.

66*2 "Lasers," *Encyclopaedia Britannica 1966 Yearbook* (for 1965), Encyclopaedia Britannica, Inc., Chicago, 1966, 615, 277.

66*3 "Two-color pictures (red and blue)," *Jour. SMPTE, 75:* 48, 1966.

66*4 "Pure light for practical pictures," *Time, 87:* 60, Mar. 18, 1966.

66*5 "Lensless photography in two colors," *Ind. Research, 8:* 89, Jan. 1966.

66*6 "Advances in laser pictures," *Ind. Electronics, 4:* 32, Jan. 1966.

66*7 "Holography takes off," *Laser Focus*, 2, Mar. 15, 1966. (Title only.)

66*8 "Holograms will speed space communications," *Laser Focus*, 3–4, Mar. 15, 1966.

66*9 "Data storage via color holograms," *Laser Focus*, 4, Mar. 15, 1966.

66*10 "Holographic reader nears completion," *Laser Focus*, 4, Mar. 15, 1966.

66*11 "Holography could be next 'revolution' in show business," *Laser Focus*, 4–5, Mar. 15, 1966.

66*12 "Laser disdrometer market blooms," *Laser Focus*, 5, Mar. 15, 1966.

66*13 "Laser holography makes photometric measurements," *Laser Focus*, 5–6, Mar. 15, 1966.

66*14 "3-D laser holographic technique uses thermoplastic medium," *Laser Focus*, 8–9, Mar. 15, 1966.

66*15 "Holograms used to achieve 'hidden view' effect," *Laser Focus*, 9, Mar. 15, 1966.

66*16 "AF checks on holographic image storage," *Laser Focus*, 12, Mar. 15, 1966.

66*17 "How one laser-oriented company applies laser holography," *Laser Focus*, 4–5, Apr. 1, 1966.

66*18 "3-D multicolor holographic viewing—without lasers," *Laser Focus*, 5–6, Apr. 1, 1966.

66*19 "A hologram records the distortion," *New Scientist, 29:* 621, Mar. 10, 1966.

66*20 "Time-lapse laser interferometry," *New Scientist, 29:* 777, Mar. 24, 1966.

66*21 "Laser light 'freezes' stress and vibration," *New Scientist, 29:* 475, Feb. 24, 1966.

66*22 "Holography shows up shock waves," *New Scientist, 30:* 20, Apr. 7, 1966.

66*23 "Multicolor holograms viewed with white light," *Bell Labs. Record*, 103, Mar. 1966.

66*24 "Bell Labs scientists developing new dimensions in holography," *Bell Labs News*, 2, May 2, 1966.

66*25 "First laser hologram mirror described," *Laser Focus*, 8–9, Apr. 15, 1966.

66*26 "Depth inspection by laser holography," *Sci. Jour., 2:* 12, Jan. 1966.

66*27 "Two colour picture produced from holograph," *Sci. Jour., 2:* 18, Jan. 1966.

66B1 R. E. Brooks, L. O. Heflinger and R. F. Wuerker, "Pulsed laser holograms," Advance Program, 1966 Quantum Electronics Conference, Phoenix, p. 44.

66B2 J. M. Burch and A. E. Ennos, "Interferometry with reconstructed wavefronts," Program, Opt. Soc. Am., Mar. 1966 Meeting, pp. 11–12.

66B3 J. M. Burch, A. E. Ennos and R. J. Wilton, "Dual- and multiple-beam interferometry by wavefront reconstruction," *Nature, 209:* 1015–1016, 1966.

66B4 R. A. Becker, "Comments on 'Some curious properties of holograms'," *Proc. IEEE, 54:* 716, 1966.

See 65K1, 66H7 and 66K6.

66B5 Joan Blum, "Holography, the picture looks good," *Electronics*, 139–143, Apr. 18, 1966.

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66H3 L. O. Heflinger, R. F. Wuerker and R. E. Brooks, "Holographic interferometry," *J. Appl. Phys.*, *37:* 642–649, 1966.

66H4 O. S. Heavens, "Recent applications of lasers," *Brit. J. Appl. Phys.*, *17:* 287–309, 1966. Pages 298–299 deal with holograms.

66H5 K. A. Haines and B. P. Hildebrand, "Surface-deformation measurement using the wavefront reconstruction technique," *Appl. Optics*, *5:* 595–602, 1966.

66H6 Franklin S. Harris, Jr., George C. Sherman and Bruce H. Billings, "Copying holograms," *Appl. Optics*, *5:* 665–666, 1966.

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See 65K1, 66B4 and 66K6.

66H8 Carl W. Helstrom, "Image luminance and ray tracing in holography," *J. Opt. Soc. Am.*, *56:* 433–441, 1966.

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66K3 Winston E. Kock, "Hologram television," *Proc. IEEE*, *54:* 331, 1966.

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66L7 Emmett N. Leith and Juris Upatnieks, "Holographic imagery through diffusing media," *J. Opt. Soc. Am.*, *56:* 523, 1966.

66L8 E. N. Leith, A. Kozma, J. Upatnieks, N. Massey and J. Marks, "Holographic recording on three-dimensional media," Program, Opt. Soc. Am., Mar. 1966 Meeting, p. 6.

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66N3 E. G. Nassimbene and R. M. Ross, "3-D holograms," *IBM Tech. Disclosure Bull.*, *8:* 1403, 1966.

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66R1 A. K. Rigler and T. P. Vogl, "The dispersive properties of photographically recorded interferences," Program, Opt. Soc. Am., Mar. 1966 Meeting, p. 33.

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66*1 "Information processing," a brief account of a meeting of the OSA Technical Group on Information Processing, *Appl. Optics*, *5:* 456, 1966.

The meeting started with a member asking George Stroke to elaborate on *noncoherent holography* and quickly moved into a fast-pace discussion with many questions, comments, and interruptions. The participants debated various contributions by prominent workers in the field. Most of the important contributors to holography and coherence theory were present.

The temperament of the group was such that holography became the subject of major conversation. Questions such as "Who has achieved the highest resolution in a holographic system?" were asked. The smallest resolvable detail in the holographic reconstruction was reported to be on the order of 1 or 2 μ. Other questions concerned the nature of the photographic films used and the limit of magnification achieved by various workers.

The meeting was dominated by the 6 to 12 people most active in the field, hence the feeling of some attendees that potentially important applications of holography were submerged because of company proprietary positions and/or government classification. Some, although very few, comments were made on other technologies and techniques appropriate to information processing in optics.

66*2 "Lasers," *Encyclopaedia Britannica 1966 Yearbook* (for 1965), Encyclopaedia Britannica, Inc., Chicago, 1966, pp. 615, 277.

On the fifth anniversary of the invention of the laser, significant progress could be discerned in the production of high power and a wide range of frequencies. Many new materials and techniques were being exploited to permit these gains. In 1965, laser research seemed to be involved in a race to achieve the most powerful, most efficient, continuously operating laser. From week to week, power outputs doubled and tripled. By the year's end a laser containing a mixture of carbon dioxide, nitrogen and helium produced 183 watts of continuous power. In solid-state lasers 42 watts of continuous power were produced with an yttrium-aluminum-garnet device. Pulsed outputs with megawatts of peak power became routine.

While electronic research scientists were delighted with the laser, with the exception of some special welding equipment, few practical operating laser systems were produced. However, some of the potential uses were suggested by several significant accomplishments: a specific chemical product, polystyrene, was created by irradiating a sample of styrene monomer with a pulsed laser beam; at another laboratory, three-dimensional images, called holograms, were achieved with the help of a technique known as holography. In holography, light reflected from an object forms an interference pattern on film when combined with a reference source of light. The pattern bears no resemblance to the object. But when the film is developed and the beam of a laser is passed through it, the object is reconstructed in three dimensions at the focal point. Motion pictures were simulated by taking a series of such holograms at slow speeds and then projecting the images rapidly. The images are truly three dimensional; if the observer moves, he changes his relative field of view, just as when observing a real object.

A spectacular article in *Scientific American* (June 1965) described a three-dimensional photographic process using coherent laser light. The principle itself is not new; for example, the Fresnel diffraction pattern of an illuminated pinhole (the zone plate) and the Fraunhofer diffraction spectra of a grating will (if suitably illuminated) reproduce the pinhole and the grating respectively as their own diffraction patterns. (This two-way process is called Fourier transformation in mathematics, and has been used to form pictures of the arrangements of atoms in a crystal by using templates of x-ray diffraction patterns as optical gratings.) The new process uses wide laser beams and produces the transform (called a hologram) on a photographic plate as an interference pattern between a direct light beam and a beam reflected from the object. The patterns thus can act as a collection of superposed zone plates (one for every point on the object) and will reproduce the points (without the intervention of any lens) as a real image of the whole object when laser light shines through the pattern onto a screen. Remarkably, when the observer looks through the pattern at the beam the virtual image appears three dimensional; application to television was predicted.

66*3 "Two-color pictures (red and blue)," *Journal SMPTE, 75:* 48, 1966.

Two-color pictures (red and blue), produced by lensless photography (hologram), have been achieved at Bell Telephone Laboratories by use of two different lasers as the source of the coherent light. Although holograms with black and a single color have been made before, it is believed that the Bell experiments are the first to have resulted in a two-color picture from a hologram. A hologram is a record of the pattern of light waves reflected from an object as that pattern exists on a plane in space at a particular moment. The hologram records not only the brightness at each point on the object, but all the information that can be conveyed by light scattered and reflected from the object. Although the hologram looks like a mass of gray swirling lines, it can reproduce an image of the original object, if the plate is illuminated with a beam.

To produce the two-color pictures a red light from a helium–neon laser and a blue light from an argon laser are combined into a single beam of bluish-pink. The beam is split into two parts. One part is scattered directly from the object or color transparency onto a photographic plate; the other part is reflected from a mirror to the same photographic plate. The two beams striking the plate form interference patterns throughout the emulsion. When the original red and blue beams are shown on the completed holograms, a single, two-color image emerges.

66*4 "Pure light for practical pictures," *Time, 87:* 60, Mar. 18, 1966.

From repairing damaged retinas in the human eye to burning precision holes in industrial diamonds, the list of uses for laser light has grown steadily since the fierce, pure beams were first projected less than ten years ago. A recent application may yet prove to be one of the most practical of all. With lasers (for "light amplification by stimulated emission of radiation") to help them take their pictures, Professor George Stroke and his associates at the University of Michigan are perfecting the techniques of holography—three-dimensional photography without the use of a lens.

Holography produces no familiar photographic negative or print. But when light is directed upon a holographic negative—or hologram—its smudgy and apparently meaningless patterns of concentric circles and parallel lines become a window through which a viewer sees the scene that was photographed. By moving his head from side to side, he can look through that window at different angles and change the perspective of the three-dimensional view; he can look around an object in the foreground to see what is behind it, just as if he were examining the actual scene.

The basic principles of holography were worked out twenty years ago by British physicist Dennis Gabor, but they could not be put to use effectively without the peculiar light that lasers now provide. Unlike "white" light from the sun or an electric light bulb, which radiates in all directions and consists of a whole spectrum of colors, light waves from a laser are highly disciplined or "coherent." They are of only one color—which means that they are all of the same frequency. And they all emerge from the laser in step—in phase with each other and traveling along precisely parallel lines.

To produce a hologram, light from a laser is split into two beams, one of which is directed by a mirror onto a sheet of photographic film. The other beam is used to illuminate the subject. When the laser light hits the subject, it is scattered by the irregular surface and reflected back toward the film. As a result, many of the reflected light waves are jumbled and out of phase both with each other and with the light from the undisturbed beam reflected by the mirror. When the light waves from subject and mirror are reunited at the surface of the film, they interfere with each other in strange patterns of bright and dark areas that are recorded on the film. "In the hologram," says Stroke, "the light waves are stored in a manner similar to the way a musical tone is stored in a piano string. It is there, but it is not released until the string is plucked."

To pluck a hologram and release its light waves, a laser beam is passed through it. As the laser beam hits the hologram's interference pattern, it is diffracted into light waves that duplicate those that were reflected from the subject. The viewer sees the subject of the picture in three dimensions, apparently suspended behind the hologram at the same distance it was from the sheet of film.

Though holography is the subject of intense research in commercial and university laboratories across the country, its practical use has been limited by two handicaps: holograms have displayed their pictures in only one color, the color of the original laser beam, and viewing the picture has also required laser light, which is not only expensive and difficult to handle but can cause serious eye injury as well. Stroke has apparently eliminated both these difficulties. At a meeting of the Optical Society of America in Washington this week, he reported that he and a student, Antoine Labeyrie, have produced holograms that can be seen with ordinary light and show their images in true colors. "The amazing thing," says Stroke, "is that no one had gone to work on eliminating these problems. It was widely assumed that it could not be done."

Stroke went to work on the problem last year, and in December decided to apply the principles of a photographic process that won Gabriel Lippmann a Nobel Prize in 1908. By changing the position of the holography mirror, Stroke directed the undisturbed laser light to the back, rather than the front, of a sheet of film. As the beam passed through the film, it met the scattered light reflected from the subject coming through in the opposite direction. The new arrangement had the effect of producing layers of interference patterns in the emulsion of the film. When a beam of ordinary white light was directed at the developed film, these layers filtered out all its components except the color of the laser beam used to illuminate the subject. Thus only waves of this frequency were reflected back to the viewer as a single-color, three-dimensional image.

Last month, with the aid of scientists at the Bell Telephone Laboratories, Stroke began using overlapping red and blue laser beams to illuminate his holography subjects. The combined beams produced even more complex layers of interference patterns in the emulsion of the film and added a new facet to the hologram. In addition to carrying information about the intensity and phase of the light reflected from the subject, it now contained full color information—even though the hologram itself was made on black-and-white film. When ordinary white light was reflected from the new hologram, two colors—red and blue—reached the viewer's eyes in varying combinations that produced a multicolor image.

Though there are many technical problems still to be solved before holograms come into widespread use, the University of Michigan development should speed the transition of holography from a laboratory curiosity to a valuable industrial and scientific tool. Stroke also sees it as a living-room entertainment medium. His new holograms can be framed and hung on the wall, where standard illumination will transform them into windows revealing three-dimensional scenes. Though motion pictures and television present more difficult technical problems, holography may eventually be used to present them in three dimensions and in full color. "In our field," says Stroke, "this breakthrough is the equivalent of a successful Apollo shot. We asked for the moon and we got it."

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66*5 "Lensless photography in two colors," *Ind. Research, 8:* 89, Jan. 1966.

A new lensless technique that takes three-dimensional pictures in two colors has been developed at Bell Telephone Laboratories. Keith S. Pennington and Lawrence H. Lin have used "captured" light waves in a hologram to produce photographs in red and blue. Pennington and Lin said that holograms can be made to store information in many colors and are promising in x-ray microscopy because they can be magnified while x-rays cannot.

Holograms are a record of light-wave patterns reflected from an object as that pattern exists on a plane in space at a particular moment. They record not only brightness at each point on the object but also three dimensions, parallax and—in the Bell method—color. The scientists achieved the two-color pictures by using two different lasers as the coherent light sources. They explained that a red light from a helium-neon laser and blue light from an argon laser combine into one bluish-pink beam. The beam is split—one part scatters directly from the object or color transparency to the photographic plate, and the other part reflects from a mirror and then onto the plate. The two beams striking the plate form interference patterns throughout the emulsion. The mass of gray swirling lines on the hologram can provide an image of the original object if the plate is illuminated with a laser beam.

66*6 "Advances in laser pictures," *Ind. Electronics, 4:* 32, Jan. 1966.

Two new advances in holography—a means of producing visible images—have been announced by the Westinghouse Research Laboratories, U.S.A.

Holography is the science of producing images with the pure coherent light emitted by a laser, the images being formed by a specially exposed photograph (negative) called a hologram. When seen under ordinary light, a hologram is only a meaningless, grayish mottled surface; but when it is illuminated by laser light or another pure color source, a three-dimensional image having height, width and depth springs into view. As it hangs suspended in space, the image is so lifelike that one can look around it, just as if it were the real object.

A hologram is made by photographing an object illuminated with light from a laser. It is done in such a way that both the light reflected from the object and the light coming directly from the laser beam are recorded together on a photographic emulsion. Then, when viewed by the same kind of light, a three-dimensional picture of the original object is reconstructed. Holograms have usually been made on specially sensitized 4 by 5-in. glass plates, but the largest known holograms are 5 in. wide and more than 3 ft long; they are made directly on commercially available photographic film.

The new Westinghouse holograms "see" more than halfway around an object, and in principle, they will enable anyone to look at all four sides of an image, that is, throughout a complete circle of 360 degrees.

The second advance reported is the development of the first hologram mirror. Previously, hologram images could be seen only by looking through a photographic film or plate. The hologram mirror generates equally clear and bright three-dimensional pictures by reflecting the laser viewing beam from the surface of the hologram. A hologram mirror is made by depositing an extremely thin layer of aluminum on the surface of a conventional hologram. This acts as a reflecting surface that duplicates the microscopic pattern of the photographic film.

The hologram mirror makes possible the large-scale duplication of holograms. This would be done by replication, a technique in which a detailed surface is duplicated time and time again simply by bringing a new surface into contact with the original.

Because they are so new, holograms have not yet reached the stage of commercial production. There is speculation about their possible use in three-dimensional displays, in machines that can recognize the shapes of printed words and letters and, eventually, in 3-D films and television.

66*8 "Holograms will speed space communications," *Laser Focus*, 3–4, Mar. 15, 1966.

1. In the not too far distant future, laser-produced holograms might be able to reduce significantly the time needed to transmit data from satellites to earth. This is the opinion of Gene T. Vacca, chief of the Instrumentation and Data Processing Branch of NASA, who did not amplify his remark but did indicate that photographs transmitted during the recent Mariner satellite experiment took eight hours to receive—a prohibitive amount of time.

2. In support of this conclusion were comments made by engineers from Electro-Optical Systems, Inc., at the Winter Convention on Aerospace and Electronics Systems in California. According to EOS, at the present state-of-the-art a space-to-earth optical communications system could be built which would have a data rate of 16,000 bits per second with a 10-dB noise figure. They would use a sun-pumped neodymium laser transmitter which could produce 0.2 watt in a single mode at 1.06 μ.

3. Furthermore, the EOS engineers believe that by 1975, a laser transmitter operating in the 1 to 10μ range should be available with up to 10 watts output in a single mode. By then, they figure, pointing accuracies should be attainable corresponding to aperture diameters of one meter at one micron. Assuming a detector quantum efficiency of 0.9 and an overall transmission efficiency of 0.4, the data rate would be about 9,000 million bits a second!

[These comments need to be interpreted with caution. The use of holography could not increase the bit rate (or rate of transmission of data bits), although much empty data is sent in conventional pictures, and image processing and/or holography may well allow more efficient coding of the useful information in a picture.

Paragraphs 2 and 3 are not directly concerned with holography but with estimates of possible improvements in power and efficiency of transmission of data (of any kind).]

66*9 "Data storage via color holograms," *Laser Focus*, 4, Mar. 15, 1966.

As we indicated in our issue of December 1, 1965, (pp. 9 and 10), scientists at Bell Telephone Laboratories have found that holograms can be made to store information in many colors. They now report that data can be stored in holograms by varying color as well as by varying exposure angles—that is, different-color laser beams activate different depths of the holographic emulsion of color film.

Data recorded in this way can later be seen through appropriately colored laser light without interfering with information photographed in other colors. BTL feels that the application in the telephone business—where names and numbers are a way of life—is obvious.

Electro-Optical Systems, Inc., is also working on holographic information storage. From results to date, the company sees great potential in processing data by coherent optical techniques.

66*10 "Holographic reader nears completion," *Laser Focus*, 4, Mar. 15, 1966.

A brief news item in our July 1, 1965 issue (p. 12) announced that a potentially important device—a holographic reader—was under development by General Electric. We have recently learned that this project—under the direction of C.Q. Lemmond of GE's Research and Development Center—has progressed considerably and is nearing completion.

In this application, a hologram is made from the light patterns of certain words or series of words contained on microfilm. When developed, the hologram is used as a spatial filter that will permit light to shine through only where the original shapes or patterns appear. In this manner the hologram can be used as a high-speed reader, scanning huge amounts of printed material to find shapes or patterns similar to those recorded from the microfilm. A prototype model is expected to be completed soon which will probably be used to read microfilm and for other similar applications, including such tasks as computer read-in.

According to GE, as many as 100 characters can be recorded on a single hologram, allowing recognition of complex word or number patterns. Unlike ordinary photographic techniques that permit one exposure per piece of film, many documents can be recorded on a single hologram by varying the angle of the exposure. Thus, it is possible to read out by varying the viewing angle in the same way. This technique will greatly condense the space needed for information storage.

66*11 "Holography could be next 'revolution' in show business," *Laser Focus*, 4–5, Mar. 15, 1966.

Holography is a fascinating as well as useful technology. Just watch the crowd gather at even the most primitive demonstration of the technique! But will it ever become a medium for entertainment?

With the development of both holographic motion picture and color reconstructions coming at a rapid pace, the day might not be far off when the moguls of television and the silver screen will be faced with a decision of whether or not to go "full 3-D" via laser-produced holograms and unsubstantial, but very real "solid" images. At any rate, there are many difficulties to be surmounted before the entertainment potential of holography can be realized.

Take holographic television. Theoretically, holograms can be televised. However, transmission of holograms would require frequencies much higher than those now used—the first practical demonstration might have to await development of an appropriate laser communication system. Furthermore, existing TV receivers could not be made compatible with the technique; thus, completely new sets would have to be purchased by the public to tune in the broadcasts. Remember all the fuss about color and UHF compatibility? This gigantic new step would not be welcomed by either the FCC or the broadcasting industry and, therefore, would not be as easily overcome.

On the other hand, holographic motion pictures are somewhat more feasible, although there is the hairy problem of how to make the image sufficiently large for proper viewing. To date, the largest reconstructions reported have been made by Westinghouse Electric Corporation, but the image size was only 3 ft long and 5 in. high—hardly big enough to accommodate an audience of any size. And this factor is important because holograms cannot be projected on flat screens and still retain their three-dimensional qualities.

Safety is another problem that must be overcome. Techniques involving pulsed lasers are not only exacting, they require a high light energy to illuminate a large scene; this could be harmful to the observer's eyes. Unfortunately, lower-powered techniques require that the objects being photographed remain stationary—a factor which greatly limits that usefulness of the holographic approach in commercial applications.

There is one other "entertainment" application for holography—in the advertising business. Could you picture a Chevrolet hanging over Times Square in all its full-color, three-dimensional glory?

66*12 "Laser disdrometer market blooms," *Laser Focus*, 5, Mar. 15, 1966.

In October 1965, Technical Operations, Inc. announced the commercial availability of its Laser Fog Disdrometer. In a recent interview, Stanley Hyle, director of information for TOI, told us that "the company has been beseiged with 400 or so letters from a wide cross-section of industrial and scientific organizations for further information on the instrument." Basically, the laser disdrometer measures the size, distribution and relative positions of both large and small particles suspended in a sample volume and provides a total permanent record of the event. (A complete description of the device and its operation was given in [65*7].

TOI expected the instrument would sell well to a comparatively small and specialized market. Thus, the company was astonished at the tremendous response indicating that the size and—perhaps more importantly—the character of the market was considerably different than had been calculated. Apparently, many engineers and scientists have long had a problem in measuring and studying atmospheres.

Here are a few examples of user applications: monitoring turbulent flow in fluidized beds, controlling air pollution, studying dynamic aerosol problems, analyzing lubrication systems, viewing the interior of steam turbines, inspecting cloud chambers used in nuclear physics, analyzing fog droplets to detect growth and decay, and controlling and analyzing medicinal aerosols.

In the case of air pollution control, the laser disdrometer via its holographic display yields an accurate three-dimensional record of air volumes. In the past, large particles in such volumes have been difficult to sample with good statistical reliability.

It should be possible to "holograph" through gas pipelines to get a clear picture of the central oil fog distribution. Also, holographing through the window of a steam turbine would show those particles which are too large to flow in streamlines and therefore are hitting the turbine blades.

Present techniques for inspecting cloud chambers involve three cameras which photograph the atomic particles' tracks and a computer which reconstructs the information in a volume configuration. Holographic techniques make this a simple, one-step procedure.

TOI admits that the instrument has two weaknesses: both the lasers and the film need improving. Two lasers are employed in the system: a *Q*-switched ruby laser to record the hologram, and a continuous-wave He–Ne laser to reconstruct the image. What is needed are improved, sturdier, optical-quality lasers. Also, a film is needed which has better optical homogeneity of backing—that is, light-absorbing coatings—and higher resolution than has been obtained with Kodak SO 243 serial film.

The initial model has been so enthusiastically received that TOI plans to build a family of three Laser Fog Disrometers which will be introduced a little later in the year. The price range will be $30,000 to $60,000, depending on supplementary equipment needed.

TOI plans to offer the first system of optical and mechanical devices required for making hologram plates. Their initial use likely will be in laboratory research. The company also intends to try the basic disdrometer process for photographing cloud sections for rainmaking experiments.

66*13 "Laser holography makes photometric measurements," *Laser Focus*, 5–6, Mar. 15, 1966.

A joint patent has been taken out by the National Physical Laboratory (NPL) and the Atomic Weapons Research Establishment, both in Britain, on an experimental technique NPL has developed for carrying out interferometric measurements on rough surfaces using laser holography. Until now, it has been necessary that surfaces used for measurements of this type be highly polished. According to NPL, the same process can be used for the measurement of vibration patterns on surfaces (a process already worked out by University of Michigan researchers),[1] the examination of the inside of tubes and in observations through imperfect windows. Further work is expected to extend considerably the technique and field of application.

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[1] [65*12]

66*14 "3-D Laser holographic technique uses thermoplastic medium," *Laser Focus*, 8–9, Mar. 15, 1966.

Three-dimensional holographic images can now be made using a xerographic thermoplastic process according to John C. Urbach and Reinhard W. Meier, Xerox Corporation scientists. Details of their work were presented in a paper they gave before the 50th anniversary meeting of the Optical Society of America being held as this issue goes to press [66U1].

To understand the new development, it is necessary to present a brief review of the basic holographic process. Unlike a photograph, a hologram is actually a recording that must be reconstructed to be viewed. When looked at under ordinary ambient lighting conditions, only a meaningless pattern can be seen. However, when illuminated with a laser beam, the hologram produces the scene recorded on it with three-dimensional reality.

Holograms are made by a unique method of photographic exposure that does away with the camera lens. The subject is illuminated with coherent light, usually from a laser, which is reflected back to the recording plate. At the same time, a mirror arrangement reflects some of the laser's light directly onto the plate at an oblique angle. Together with the light reflected from the subject, it creates a pattern which is captured by the plate. In effect, the multiple wavefronts of laser light that would reach a viewer's eyes if he stood at the plate and looked at the subject are photographically "frozen" on the plate.

Until now, holograms have usually been made on conventional photographic plates. These are developed chemically, just like a snapshot. Like any photographic film, such plates form their images with grains of metallic silver.

The new method developed by Xerox makes it possible to develop a hologram immediately, without using chemicals. Such a hologram is "cleaner," that is, it is free of the grain pattern inherent in the photographic plate. In addition, it is possible that the thermoplastic hologram can be duplicated by a simple mechanical pressing technique. Such a technique would result in better quality than current methods for copying a hologram made on a conventional photographic plate.

Xerography is based on the use of a photoconductor, a material that acts as an electrical insulator in darkness but serves as a conductor of electricity in the presence of light. To make a xerographic hologram, transparent photoconductive material is coated onto a special kind of clear glass plate that can conduct electricity. Then, the plate is covered with a thin layer of transparent thermoplastic material.

To record a hologram, the plastic outer surface of the special xerographic plate is first given a positive charge. This simultaneously induces a negative charge throughout the area where the photoconductor meets the glass base. The plate is then exposed to the laser light reflected from the subject. This exposure causes negative charges to migrate up through the photoconductor at each point struck by the laser light. They come to rest within the photoconductor at the boundary with the plastic. Wherever light fails to strike the plate, there is no such migration of negative charge. The plate is then recharged, removing further sensitivity to light.

Finally, the plate is developed. This is done by simply heating the plastic surface until it begins to soften. Areas carrying positive charge flow downward, attracted by the negative charges in the boundary layer. The resulting deformation is made permanent as the plastic cools and hardens. When a laser beam is directed through the plate, the light-deflecting properties of this deformation pattern shape the beam so that it creates an image of the original object.

Urbach and Meier expect the xerographic hologram to find applications wherever simple and rapid processing, duplication, and low scattered-light levels are important.

66*15 "Holograms used to achieve 'hidden view' effect," *Laser Focus*, 9, Mar. 15, 1966.

Emmett Leith and his associates at the University of Michigan's Institute of Science and Technology have discovered another intriguing property of holograms—the "hidden view" effect. The effect is achieved as follows: First, a frosted glass, similar to that used in ordinary bathroom window, was put around an object and a hologram was made of the scene. When developed, the hologram showed only the frosted glass. However, when a reconstruction from the hologram was superimposed over the glass and the area was bathed in laser light, the interference patterns of the hologram and the plate cancelled each other, permitting a view of the object behind.

This phenomena—which could be tagged the "disappearing glass plate" effect—occurs only when the same glass used in making the hologram is used in the superimposition. Thus, it is a virtually detection-proof means of carrying supersecret photographs and plans—that is, the hologram would be sent by one carrier, the glass by another. According to Mr. Leith, the military has already shown some interest in the device.

66*16 "AF checks on holographic image storage," *Laser Focus*, 12, Mar. 15, 1966.

A photographic image data-storage unit has been supplied to Wright Patterson AFB which is capable of storing a hundred 35mm, three-dimensional images on a single one-inch-square potassium bromide crystal. Images are produced by holography using a He–Ne laser. Work will be carried out to increase the read-in rate and improve storage capabilities to a thousand images. The crystal element has a storage capability of a million bits per half inch square.

66*17 "How one laser-oriented company applies laser holography," *Laser Focus*, 4–5, Apr. 1, 1966.

Perkin-Elmer Corporation has provided information on how it is applying holography within its engineering and scientific laboratories. Basically, these applications fall into four major areas: reconstruction of images from microwave holograms; holographic techniques for optical matched filtering; real-time hologram reconstruction; and holographic metrology. A brief description of each activity follows.

Perkin-Elmer is building optical systems whose purpose is to reconstruct images of the earth from microwave holograms. As has been recently disclosed by research workers at the University of Michigan (AGARD Symposium, Paris, September 1965), one of the prime military reconnaisance applications of holography is in the field of airborne mapping radars. In this application, a microwave hologram is made of the earth by means of a coherent radar and is recorded on photographic film. An optical system is then utilized to reconstruct a visible image of the ground from this hologram. Such optical hologram processors of high quality require extreme sophistication in both design and manufacture. The company has produced a high-resolution optical system for reconstructing microwave holograms. It is also a major manufacturer of optics for coherent radar optical processors for military tactical reconnaissance aircraft.

The company is using an optical system capable of producing holograms of particular objects. These holograms can be utilized as two-dimensional, optically matched filters to locate specific objects in aerial photographs. Another illustration of the application of this technique is the automatic location of chromosomes on microscope slides. This demonstration is the first step toward automating genetic studies.

Research in real-time holographic reconstruction is another active field of the company. Instantaneous, two-dimensional light modulators that are now in the research stage will eventually permit the remote real-time viewing of holographic images. Such devices will also permit the instantaneous reconstruction of visible images from holograms produced using nonvisible wavelengths, such as microwave and infrared.

Holographic metrology is also being explored. The major use is in the manufacture of precision optics. Here, advantage is taken of the fact that visible wavelength holograms furnish information on the dimensions of an object with an accuracy of a fraction of a wavelength of light. Minute changes in the surface contours of optical components can be detected either after further "figuring" of the component or when the component is subject to mechanical or thermal stress. Thus, it is expected that holography will materially aid in both the manufacture and test of precision optical components.

66*18 "3-D multicolor holographic viewing—without lasers," *Laser Focus*, 5–6, Apr. 1, 1966.

Until recently, hologram images could be viewed only by using a coherent light source, such as one or more lasers, for illumination. Now, however, scientists have found that three-dimensional multicolor reconstructions can be seen by shining ordinary white light—from the sun or a flashlight—on a hologram!

This observation was made by L. H. Lin and K. S. Pennington, of Bell Telephone Laboratories, and G. W. Stroke and A. E. Labeyrie, of the University of Michigan, using a modified optical setup conventionally used to make holograms. Although lasers are still needed to make the holograms, it is now possible for even white light to sift through the interference patterns formed on the emulsion of the hologram photographic plate and select the information that gives the eyes an impression of depth, shape and color.

As reported in the Dec. 15, 1965 issue (pp. 13 and 14),[1] multicolor holograms are made by combining two or more laser beams of different colors to form a single beam. This beam, in turn, is split into an object beam, which shines on the object, and a reference beam, which shines directly on the photographic plate. The pattern formed by the object beam interfering with the reference beam is recorded in the emulsion of the plate. Reconstruction of the image is achieved by shining the original laser beams on the hologram.

Emulsions used on a photographic plate are much thicker than the wavelength of light. When the reference beam and the object beam used in making a hologram interfere with each other in the emulsion, many interference surfaces are formed. Previous methods of making holograms used an angle of from 30 to 90 degrees between the two beams. Although both the amplitude and direction of the light waves were recorded on the hologram, the spacing between the interference surfaces was such that only a limited number of surfaces could be formed. Because of this, the same laser light sources had to be used to reconstruct the image in multicolor. By increasing the angle of the object and reference beams to 160 degrees, for example, the BTL and University of Michigan scientists were able to space the interference surfaces in the emulsion closer together and make room for many more surfaces. This greater number of interference surfaces records enough color information to produce a high-quality, multicolor, three-dimensional image when ordinary white light is shone on the hologram.

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[1] [65*1]

66*19 "A hologram records the distortion," *New Scientist*, *29:* 621, Mar. 10, 1966.

A method of detecting and analyzing distortions in an engineering component that avoids the need to make physical contact with the component is being developed at the National Physical Laboratory, Teddington, Middlesex, England. It is an application of "image reconstruction" (wavefront reconstruction), a photographic technique using laser light.[1]

J. M. Burch, A. E. Ennos and R. J. Wilton report a series of image reconstruction experiments on a U-section girder distorted by compression, in the current issue of *Nature*.[2] In their experimental arrangement, light from a helium-neon gas laser is allowed to strike both a photographic plate and the U-girder. Light is reflected from the U-girder, but by the time it reaches the photographic plate, it is out of step with the light which fell directly on the plate from the laser.

The fact that the reflected light is out of step is the basis of holography. An interference pattern (or hologram) is formed between the direct and reflected beams and is recorded by the photographic plate. Simply by shining laser light through the photographic record of the interference pattern, a lifelike reconstruction of the original object can be made.

Dr. Burch and his co-workers realized that an extension of this idea would enable them to see the effects of applying stress to a piece of material. By illuminating a girder under stress with coherent (laser) light beamed through the hologram of the unstrained girder, a set of interference fringes can be superimposed on the girder itself. A permanent record (hologram) was obtained by applying this technique to the U-girder. The girder was clamped across its middle and the clamps were tightened so that the trough was under compression. The permanent record of the superimposed sets of fringes was obtained simply by exposing the photographic plate first to the hologram from the unstressed girder and then to a hologram from the stressed girder.

The interference pattern obtained by using two superimposed holograms is fairly crude—the bright fringes are very wide and rather diffuse. A method investigated by these research workers to improve the clarity of the interference pattern has met with some success. Here, the stress on the girder is increased in a number of equal steps, and at each stage a new hologram is superimposed on the photographic plate. If the girder distorts by equal amounts for equal increments of stress, as it should if it behaves elastically, the image quality of the interference pattern is greatly improved. Five equal increments of stress were applied to the beam and the series of holograms was recorded on one plate.

To produce such an interference pattern requires that the equal increments of stress produce equal amounts of distortion. If this were not true in parts of a structure, then this lack of elasticity in behavior would show up on the hologram. The method can therefore be used to show up weaknesses in structures and any stresses produced by thermal expansion when the structure is warmed.

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1. [66G2]   2. [66B3]

66*20 "Time-lapse laser interferometry," *New Scientist, 29:* 777, Mar. 24, 1966.

There is currently a spurt of interest in the application of laser holography, the technique in which a pattern of light and dark bands on a photographic plate is used to preserve a complete three-dimensional representation of a scene (see "Holography, or 'the whole picture'," by Dennis Gabor).[1] The latest development is a new form of interferometry (the technique of measuring small distances, or small changes in the density of a transparent medium, directly in wavelengths of light); variants of the new "holographic interferometry" have been invented simultaneously at the National Physical Laboratory, Teddington, England (see "Science in Industry," March 10), the University of Michigan, Bell Telephone Laboratories and TRW Systems, Redondo Beach, California.

The TRW team, L. O. Heflinger, R. F. Wuerker and R. E. Brooks, have demonstrated their method by obtaining interference-fringe pictures of, among other things, the variations in gas density around a bullet moving at Mach 2.5. The first step is to make a hologram of the background against which the bullet will be seen: this is done by letting two beams of coherent light fall onto a photographic plate simultaneously, from the background and from a "reference" source. The resulting hologram is simply a set of parallel fringes, since the beams are both taken, by different routes, from the same laser light source. Next, the same photographic plate is used again in exactly the same way except for the presence of the rifle bullet and the shock wave it generates.

To obtain the photograph, the reference beam is shone as before onto the (now developed) plate carrying the superimposed holograms of the background and of the shock wave, and a photograph is taken, in the usual way, through the hologram plate. In effect, the camera sees the shock wave and the background simultaneously, and records interference fringes revealing the extent to which the compressed gas delays the light passing through it.

In fact, the photograph was produced by a more advanced technique than this. The background contained a ground-glass screen, so that light traveled through the shock wave to the hologram plate in a range of directions. The shock wave could be reconstructed by photographing the hologram from a similarly wide range of directions.[2]

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1. [66G2]   2. [66H3]

66*21 "Laser light 'freezes' stress and vibration," *New Scientist, 29:* 475, Feb. 24, 1966.

One application for holography, the lensless photographic technique that uses laser light, may lie in the nondestructive testing of engineering parts. E. N. Leith of the University of Michigan, Ann Arbor, who collaborated with Juris Upatnieks in developing laser holography (see also [66G2]), has found it possible to measure vibrations and stresses too complex to measure by other means.

His technique is to use holography's immense capacity for resolving detail in a photograph—ten times better or more than the best lens can achieve. The microscopic movements occasioned by vibration or stress, which normally in an interferometric process would perturb the fringes and so destroy the image, can be resolved on a hologram (laser photograph) to give an accurate measure of the amount of movement (*Iron Age, 197:* No. 4, [66M3]).

Another technique Leith and his colleagues are investigating is that of taking a hologram before and after stressing a part. The interference fringes indicating differences in shape or size between the two holograms then become a direct measure of the amount of distortion.

Another American research laboratory, the Carson Laboratories of Bristol, Connecticut, has proposed a laser curve follower to record the contours of a component. An analog-to-digital conversion would translate the image thus generated into coordinates that could be fed to a computer.

66*22 "Holography shows up shock waves," *New Scientist, 30:* 20, Apr. 7, 1966.

Holography, or image reconstruction, is rapidly becoming a technique which can be applied in very widely dispersed branches of technology. A recent extension of this technique is in the study of fluid behavior in work done by L. H. Tanner of the Department of Aeronautical Engineering at the Queen's University, Belfast, Northern Ireland.

A hologram is produced by shining light from a source, such as a laser or very fine slit, onto an object and also onto a photographic plate. Because the light reflected from the object has to travel farther to get to the photographic plate than the direct beam, it falls out of step. The result is an interference pattern which is recorded by the photographic plate.

In this record, or hologram, all the information on the object's size and position in space is stored and can be "read out" simply by shining coherent light (light in step) through the record. The image reconstructed from the hologram is three-dimensional.

The adaption of this technique to fluid mechanics depends on the fact that there are shock waves in a moving fluid.[1] The existence of these waves compresses the fluid in some regions and in these regions, the refractive index is changed slightly from that of the uncompressed fluid. This is a commonly seen phenomeon—the shimmering layers seen above a hot object are layers of air of different densities and refractive indices.

Because of this slight change in refractive index, any light traveling through the more dense part of the fluid will be slowed down more than light going through the less dense part—and so falls out of step. In applying this technique, two streams of gas were allowed to flow from each nozzle—holograms being obtained in the "flow" and "no-flow" conditions.[2]

From these holograms it is possible to obtain schlieren and shadow photographs—an advantage which means that it is unnecessary to decide in advance which type of photograph would yield most information. The only limitation of this method at present is that it requires high-resolution photographic plates, which necessitates a long exposure time—a condition difficult to satisfy when dealing with rapidly changing conditions.

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1. [66T3]   2. [66*20]

66*23 "Multicolor holograms viewed with white light," *Bell Labs. Record*, 103, Mar. 1966.

Three-dimensional multicolor images can now be seen by shining ordinary white light—from the sun or a flashlight—on a hologram. Previously, hologram images could be viewed only by using one or more laser beams for illumination.

L. H. Lin and K. S. Pennington of the Electron Tube and Optical Device Department and G. W. Stroke and A. E. Labeyrie of the University of Michigan modified the optical setup conventionally used to make holograms. Although lasers are still needed to make the holograms, it is now possible for even white light to sift through the interference patterns formed on the emulsion of the hologram photographic plate and select the information that gives our eyes the impression of depth, shape and color.

Multicolor holograms[1] are made by combining two or more laser beams of different colors to form a single beam. The beam, in turn, is split into an object beam, which shines on the object, and a reference beam, which shines directly on the photographic plate. The pattern formed by the object beam interfering with the reference beam is recorded in the emulsion of the plate. The image is reconstructed by shining the original laser beams on the hologram.

The emulsion of a photographic plate is much thicker than the wavelength of light. When the reference beam and the object beam are used in making a hologram interfere with each other in the emulsion, many interference surfaces are formed. Previous methods of making holograms used an angle of from 30 to 90 degrees between the two beams. The amplitude and direction of the light waves were recorded on the hologram, but the spacing between the interference surfaces was such that only a limited number of surfaces could be formed.

Because of this, the same laser light sources had to be used to reconstruct the image in multicolor. By increasing the angle of the object and reference beams to 160 degrees, for example, the Bell Labs and University of Michigan scientists were able to space the interference surfaces in the emulsion closer together and make room for many more surfaces. This greater number of interference surfaces records enough color information to produce a high-quality, multicolor, three-dimensional image when ordinary white light is shone on the hologram.

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[1] [65P6]

66*24 "Bell Labs scientists developing new dimensions in holography," *Bell Labs News*, 2, May 2, 1966.

A hologram of an object is a unique photographic recording containing much more information about the object than is possible with a conventional photograph. Until recently, hologram images could be viewed only by using one or more laser beams for illumination. Now three-dimensional multicolor images can be seen by shining ordinary white light—from the sun or a flashlight—on a hologram.

Lawrence H. Lin and Keith S. Pennington of BTL's Optical Information-Processing Device Group collaborated with G. W. Stroke and A. E. Labeyrie of the University of Michigan in developing the method.

Scientists at Bell Labs are interested in applying hologram techniques to the storage and retrieval of information for switching, information services and other communications purposes. The hologram promises to condense greatly the space needed for storing this kind of information, and to make the information more readily accessible.

In another area, BTL scientists have transmitted simple black-and-white holograms over television in the laboratory to study new ways of achieving more efficient transmission of signals over TV systems. Although the technique used here is a long way from perfection, it may well be the first step toward providing three-dimensional television or Picturephone service.

One of the most important properties of a hologram is its ability to reproduce a three-dimensional image—one that "floats" in mid-air and is practically indistinguishable from the real object itself.

In making a hologram, coherent light (contains light waves of nearly the same wavelength), such as provided by a laser, illuminates the hologram directly. A second wave illuminates the object, reflects from it, strikes the hologram and "interferes" with the first wave. This interference phenomenon is three-dimensional: it takes place not only on the surface of the photosensitive emulsion but also through its thickness. (The emulsion of a photographic plate is much thicker than the wavelength of light.)

However, the resultant visual pattern does not resemble the original subject. It's a combination of lines, specks and swirls and may, at times, look like an out-of-focus fingerprint or a smudged photographic plate. Depending on how the original hologram was made, the image can be reconstructed by shining a laser beam or ordinary white light on the hologram.

In either case, a realistic image of the original object will appear to be floating in mid-air. The image may appear in front of the hologram or behind it, and is "framed" by the edges of the hologram plate.

Using the same techniques, a multicolor picture can be made from a hologram. Here, in making the hologram, different colors of laser light are used and combined into one beam. The resultant image will be in two colors.

66*25 "First laser hologram mirror described," *Laser Focus*, 8–9, Apr. 15, 1966.

Last October during the annual meeting of the Optical Society of America in Philadelphia, Westinghouse physicists T. P. Vogl and A. K. Rigler[1] reported on a hologram mirror—the first of its kind. Previously, hologram images could be seen only by looking *through* a photographic film or plate. Through use of the hologram mirror, however, equally clear and bright three-dimensional pictures can be generated by reflecting the laser viewing beam from the surface of the hologram.

A hologram mirror is made by depositing an extremely thin layer of aluminum on the surface of a conventional hologram. The aluminum layer acts as a reflecting surface that duplicates the microscopic pattern of the photographic film. Development of the hologram mirror opens up the possibility of large-scale duplication of holograms. This process would involve replication—a technique in which a detailed surface is duplicated time and time again simply by bringing a new surface into contact with the original.

Vogl and Rigler also exhibited the largest known holograms—5 in. wide and more than 3 ft long. Unlike conventional holograms which are usually made on specially sensitized 4 by 5 in. or 8 by 10 in. glass plates or special 35mm and 4 by 5 in. film developed for astronomical or spectrographic work, the Westinghouse holograms are made directly on commercially available photographic film.

According to Westinghouse, its new holograms permit a viewer to "see" more than halfway around an object from either side. In principle, then, they will enable anyone to look at all four sides of an image—that is, throughout a complete viewing circle of 360 degrees.

Westinghouse speculates that holograms might possibly be used in three-dimensional displays, in machines that can recognize the shapes of printed words and letters, and, eventually, in three-dimensional motion pictures and television. It could be that these two new Westinghouse developments constitute a giant step toward larger and less expensive holograms than those in use today.

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[1] [65V2]

66*26 "Depth inspection by laser holography," *Sci. Jour.*, *2:* 12, Jan. 1966.

A completely new concept in nondestructive testing, built up around laser holography, was described at a recent symposium in Dayton, Ohio. The research itself is being carried out at the University of Michigan.

Holographs obtained with coherent laser light are photographic records of the complex interference pattern between the incident light and the light reflected from an object. Each point of the pattern contains information relating both to the phase and amplitude of the light reflected from the whole surface of the object. Although the holograph itself is completely unintelligible, by irradiating it with laser light a three dimensional reconstructed image can be made to appear with all the perspective and parallax of the original object.

As an aid to inspection, the technique is being used to study the standing wave patterns of vibrating surfaces by direct observation of the contours of equal displacement. A second application has even wider possibilities. When a deformed surface is lined up exactly with the image formed from a holograph obtained with the undeformed surface, interference is again detected. This time, the pattern of fringes is a complete record of the amount of microdeformation the object has undergone since the holograph was obtained. It could be used to study the significance of individual defects in a service environment. As a variant of this technique, modifications within a translucent material have been detected non-destructively by comparing successive holographs of an object placed behind it.

Holography also shows promise of extending the resolution obtainable with x-ray microscopy and, probably of greater practical interest, of even providing a three dimensional record of internal defects with ultrasonics.

66*27 "Two colour picture produced from holograph," *Sci. Jour.*, *2:* 18, Jan. 1966.

A two colour picture in red and blue has been produced from a holograph—a visual record, made without the aid of lenses, in which light waves are "caught" direct on a photographic plate. The holograph records not only the brightness at each point on the object—as a photograph does—but all the information that can be conveyed by light scattered and reflected from the object. This includes perspective, parallax and, in this case, colour. Laser light is used to reconstitute the image from the holograph.

Working at Bell Telephone Laboratories in New York, Drs. Keith S. Pennington and Lawrence H. Lin achieved the two colour pictures by using two different lasers as the source of the coherent light required to make the holograph. The red light from a helium-neon laser and the blue light from an argon laser were combined into a single beam of bluish pink. The beam was split into two parts, one part being scattered direct from the object or colour transparency on to a photographic plate, the other being reflected from a mirror to the same photographic plate. The two beams were made to strike the plate and form interference patterns throughout the emulsion of the plate. When the original red and blue laser beams were shone on the completed holographs, a single, two colour image emerged.

Pennington and Lin say that holographs can be made to store information in many more colours. Besides their potential for three dimensional photography, their unusual storage capacity could make holographs useful in memory systems for data processing. They may also hold promise for x-ray microscopy—holographs provide a means for magnifying without lens while x-rays cannot be optically focused.

66B1 R. E. Brooks, L. O. Heflinger and R. F. Wuerker, "Pulsed laser holograms," Advance Program, 1966 Quantum Electronics Conference, Phoenix, p. 44.

Holograms can record and reconstruct "completely" light waves scattered from a laser-illuminated object. A single hologram record can provide shadowgraph and schlieren information; can be used for interferometric measurements; and can provide direct imaging of the object with the ability to focus at different locations in the scene with different *f*/numbers and magnifications. The pulsed laser hologram is particularly useful with high-speed objects; it effectively "freezes" any motion, permitting leisurely examinations.

66B2 J. M. Burch and A. E. Ennos, "Interferometry with reconstructed wavefronts," Program, Opt. Soc. Am., Mar. 1966 Meeting, pp. 11–12.

Hologram techniques make it possible to record and to reproduce subsequently the phase information contained in a traveling light wave. In hologram interferometry[1–4] at least one of the interfering beams has been stored in this manner, and comparison can be made, for example, between samples of the same beam taken at different epochs. In many arrangements the wavefront reconstructed by diffraction at the hologram interferes with another wavefront transmitted through the hologram, and "live" two-beam fringes are obtained. Alternatively, "frozen" two-beam or even multiple-beam[2] patterns are obtained merely by recording double or multiple exposures on the same photographic plate. White light fringes can sometimes be obtained by using a "direct image" hologram in a compensated system. Hologram interferometry can be used to cancel unwanted aberration or to extract more information from a wind-tunnel interferogram,[5] but perhaps its most striking application is in detecting the deformation, whether gradual, sudden or vibratory,[1] of an irregular or diffusely reflecting surface, e.g., of an engineering structure. Alternatively, if the surface finish and obliquity of illumination are sufficient to ensure specular reflection, several separately machined components can be compared interferometrically against a master.[2]

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1. [65P8]   2. [65B4]   3. [65C3]
4. [65S3]   5. [65H6]

66B3 J. M. Burch, A. E. Ennos and R. J. Wilton, "Dual- and multiple-beam interferometry by wavefront reconstruction," *Nature*, *209:* pp. 1015–1016, 1966.

The formation of optical images by wavefront reconstruction as originated by Gabor[1] and more recently extended by Leith and Upatnieks[2] has made it possible to perform interferometry with light reflected or scattered from an irregular three-dimensional object.[3] Some of the possibilities of this method have been discussed in a previous publication,[4] and more recently Stetson and Powell,[5] Collier, Doherty and Pennington[6] and Brooks, Heflinger and Wuerker[7] have demonstrated several potential applications. This communication reports the successful achievement of multiple-beam as well as two-beam interferometry from the surfaces of standard engineering components. It would seem that many problems involving dilatation of a structure may be investigated in this way.

The principle of the method consists of recording the hologram of an object using coherent laser light, and afterward replacing the processed hologram plate in its original position in the same apparatus. One then sees the reconstructed image of the object superimposed on the object itself. Any slight change in the surface contours produced, for example, by mechanical strain or thermal expansion will give rise to interference effects between corresponding points on the object and its holographic image, and fringes will be seen to cross the surface.

An experimental arrangement was used to produce holographic recording of a piece of steel channel-section girder, and to demonstrate interference effects on distorting it. Coherent light from a helium–neon gas laser was directed through a microscope objective, which diverged the beam through a suitable angle so that the object was illuminated obliquely. The photographic plate received an undisturbed spherical wave, together with light scattered from the rough surface of the girder. The resultant hologram contained sufficient information to reconstruct a three-dimensional image of the girder in exactly the same position as the original.

The appearance of the girder after it had been clamped across its webs was viewed through the replaced hologram. Two-beam interference fringes were formed over the surface, their contrast being governed by the relative brightness of the object and reconstructed image, and their number and position on the degree of distortion. The angles of illumination and viewing also had to be taken into account for a quantitative assessment.

For a permanent fringe record it is unnecessary to form "live" fringes between the object and its recorded image. Instead, a double hologram may be made by exposing the photographic plate twice, once with the girder unclamped, and a second time with it clamped. The fringes are now "frozen" into the photographic recording, and the object, together with the fringes covering it, may be reconstructed without special re-positioning in the apparatus. In fact, it is no longer necessary to use highly coherent light for the purpose, a divergent beam of monochromatic light, for example, from a filtered mercury lamp being sufficient.

An extension of the method of frozen fringes makes it possible to observe multiple-beam interference. Here a multiple-exposure hologram is made with equal increments of strain between exposures. A reconstruction from a five-exposure hologram of the girder was made. In this experiment the strain was obtained by welding vertical steel bars to the sides of the girder and connecting their upper ends with a long threaded bolt equipped with a wing nut and self-aligning washers. Equal turns of the nut then resulted in equal increments of strain in all parts of the structure. The fringe pattern obtained was a sharpened version of the two-beam interference pattern which would have resulted from a single-strain increment. Three subsidiary interference maxima were also present between each sharp fringe. With further exposures the main fringes sharpened still further and the subsidiary maxima became weaker. It is also possible to suppress these maxima by an apodization procedure involving only the duration of each exposure.

Sharp multiple-beam effects are obtained only when each individual point on the surface of the object is displaced by equal amounts between exposures. To produce a photograph illustrating the experiment just described, it was assumed that the structure behaved perfectly elastically, which was borne out in the result. However, if (owing to overstress, for example), Hooke's law had not been obeyed, the fringes would no longer have been sharp. It is therefore possible that this method could be used to detect weak spots in an engineering component.

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1. [49G1] 2. [64L1] 3. [65P8]
4. [65B4] 5. [65S3] 6. [65C3]
7. [65B1]

66B4 R. A. Becker, "Comments on 'Some curious properties of holograms'," *Proc. IEEE, 54:* 716, 1966.

See 65K1, 66H7 and 66K6.

Attention is drawn to the correspondence of Kock and Rendeiro.[1] The "curious" properties of holograms are not curious at all, but are exactly what one should expect. What apparently has not been realized by them is that [in their Figs. 1 and 2] they were switching their observation from the real to the virtual image (or conversely) of the hologram. The real and the virtual images are inverted and reversed with respect to one another.[5,6] [In their third figure] the authors are not switching from one type of image to another, but are merely observing the "expected inversion" of one of the images.

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1. [65K1] 5. [64L1] 6. [65S9]

66B5 Joan Blum, "Holography, the picture looks good," *Electronics*, 139–143, Apr. 18, 1966.

Holography has come a long way since Dennis Gabor of the Imperial College of Science and Technology in London used nearly coherent light to record phase and intensity data about an object on a photographic film or plate—a hologram—and then reconstructed the object's image in space. In the last few years holography has become a discipline with a research budget of $10 million to $20 million, spread over about 100 laboratories.

Although there are no commercial applications yet, possiblities range from three-dimensional color television to pattern recognition.

Research has already produced several breakthroughs:

The use of ordinary white light, rather than coherent light, to reconstruct holographic images.

Multicolor holograms.

Hologram motion pictures, made from multiple exposures stored on the same photographic plate.

Excellent quality holographic images of complex objects constructed with ordinary, incoherent light.

Holographic contour maps.

A holographic vibration analysis technique.

180° and 360° holograms.

Synthetic, computer-generated holograms, for which no physical object is required.

Interest in holography revived with the development of the laser. Research is being done, for the most part by private industry, but an estimated one-fourth of the research funds come from government agencies such as the National Science Foundation.

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66C1 W. H. Carter and A. A. Dougal, "High-quality three-dimensional records of microscope specimens on single microholograms utilizing gas laser illumination," Advance Program, 1966 Quantum Electronics Conference, Phoenix, p. 44.

This paper reports on findings in recent studies employing Gabor's technique for reconstructing wavefronts to make three-dimensional records of microscope specimens on single photographic negatives. Reconstruction utilizing unique arrangements show high-quality bright-field and polarizing images.

66C2 R. J. Collier and K. S. Pennington, "Ghost imaging by holograms formed in the near field," *Appl. Physics Letters, 8:* 44–46, 1966.

The hologram-generated ghost images predicted by Van Heerden[1] have recently been observed by Stroke et al.[2] for the case where a subject transparency is illuminated by collimated laser light and by Pennington and Collier[3] for the case where the transparency is illuminated by diffuse laser light. The present letter reports ghost imaging of solid objects, without the use of Fourier transforming lenses, so that the hologram plate is in the near field of the subject scene.

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1. [63V1] 2. [65S16] 3. [66P1]

66C3 Michael Coady, "Laser hologram systems due for fast-moving-particle study," *Electronic News*, 26, Mar. 23, 1966.

Technical Operations, Inc., will market three laser-hologram camera systems within 90 days. They will cost from $30,000 to $65,000. The potential dollar value of the market for these devices is not known. But it is expected to grow rapidly, as needs develop to measure the volume of particles in air-pollution control and bomb-blast particle-size evaluation programs. Other expected applications for the three-dimensional measuring systems include particle sizing; aerosol decay studies; nondestructive testing of jet nozzles; rain and precipitation studies; and cavitation studies in fluids and in environmental control systems.

The main components of the system include a 10-MW peak power, Q-switched laser; digitally controlled power supply; laser collimator; and camera and hologram reconstructing equipment with visual and photographic readouts.

Tech/Ops installed two hologram systems during the summers of 1964 and 1965 at Otis Air Force Base for measurement of naturally occurring fog by the AF Cambridge Research Laboratories.

A hologram camera and reconstruction system was developed and installed at Edgewood Arsenal, Md., for assessment of explosively generated aerosols under contract to the Army Chemical Corps research and development laboratories.

In a typical operation, particles in the air drift between the laser illuminator and the camera. Every 2 sec a Q-switched laser emits a burst of coherent light lasting 20 μsec. During this instant, a photographic film records a hologram of all particles illuminated. When the hologram negative is illuminated by another laser, the entire scene is reconstructed in full three-dimensional form. An observer can view the scene from any number of angles, and can even see particles or droplets hidden behind others. A particle may be measured anywhere inside the 3-D image by conventional optical measuring devices.

Other advantages cited are that hologram camera systems have at least fifty times the depth of field of ordinary imaging systems, because the object need not be in focus to be recorded. And because the cameras do not have to be focused, they can be operated remotely in contaminated and dangerous areas by untrained personnel.

The particle-size analysis technique for dynamic aerosols can also record a large volume of particles, in situ, without disturbing the velocity of particles being measured.

When using holograms to study rain droplets, a Q-switched laser "photographs" the raindrops as they fall. The reconstructed hologram is displayed on a TV monitor. As the hologram negative is moved along the scanner carriage, different droplets come into focus. The technique makes it possible to measure the diameter and distribution of particles as they existed in the original volume.

Classical methods of particle-size analysis include filtering, electrostatic precipitation, thermal collection, light-scattering particle counters and inertial collectors. The accuracy of these methods depends in part on knowledge of the variations in velocity particles during the sampling procedure.

[Reprinted from Electronic News.]

66C4 W. H. Carter, P. D. Engeling and A. A. Dougal, "Polarization selection for reconstructed wavefronts and applications to polarizing microholography," *IEEE J. Quantum Electronics, 2:* 44–46, 1966.

This article reports a phenomenon allowing the phase reference beam of the "two-beam, carrier-frequency" holography method of Leith and Upatnieks to be used as a polarization reference as well. A technique for utilizing this for selecting and recording a particular linearly polarized component of the image-carrying beam is described and applied to a unique arrangement for microholography. The waves reconstructed by the technique are described mathematically and compared to waves passed by a polarizing microscope. Experimental confirmation of these observations is presented.

66C5 V. J. Corcoran, R. W. Herron, Jr., and J. G. Jaramillo, "Generation of a hologram from a moving target," *Appl. Optics, 5:* 668–669, 1966.

In ordinary, three-dimensional holography, the reflecting object must remain stationary to less than about one eighth the wavelength of the illuminating light for the duration of the exposure.[1] A technique for circumventing this requirement has recently been suggested. It requires that the reference beam be changed effectively to correspond to the motion of the object during the exposure. A method for demonstrating the principle of the moving target hologram is described below.

By using a modified Michelson interferometer the change in path length of the reference is made identical to the change in path length for the target, which in this case is a mirror. This is possible by reflecting the reference beam from the same mirror that is used as a target.

The laser light (6328 Å) is divided by a beam-splitter into a reference beam and an illuminating beam incident on the target mirror. The reference beam is reflected also from the target mirror, which is mounted on a motor-driven, precision translation stage. Motion of the target is compensated for by a change in the path of the reference beam. The two beams are then brought together in a plane in which a photographic plate may be placed. The translating stage is moved at an average rate

$$\bar{v} \geq (\lambda/8)(1/T)$$

where T is the exposure time. For an exposure time of 1 sec, without motion of the mirror, the familiar interferometer rings, which are a hologram of a mirror, are clearly stationary. Under the ordinary conditions of moving the illuminated object relative to the photographic plate, the hologram would be washed out by the integration time of the film exposure. When the mirror that is common to the reference beam and the illuminating beam is rotated during the exposure of the photograph, the difference between the illuminating beam and the reference beam paths is found to be a function of time, and the interferometer rings are not visible.

The results described here help to verify in an elementary manner the possibility of obtaining holograms from moving targets. Although considerable difficulty may be encountered, it is expected that the use of nonmechanical, effective-path-length corrections should increase the versatility of the moving-target hologram.

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1. [64L1]

66D1 D. J. De Bitetto, "On the use of moving scatterers in conventional holography," *Appl. Physics Letters*, *8:* 78–80, 1966.

It has recently been reported[1] that multidirectional illumination holograms can successfully be recorded in a conventional Leith-Upatnieks 2-beam technique[2] by illumination of the stationary objects through a moving scatterer while maintaining a stationary coherent background. However, experiments herein described indicate that such a dynamic recording procedure is in general disastrous to the recording. The present results are not in contradiction to a very recent paper[3] in which a moving diffuser is also employed. Despite the apparent similarity, this recent work employs a substantially different experimental technique similar to that used in the well-known wavefront folding interferometer.[4] In this technique, the image pattern must be rendered incoherent, for which the insertion of a moving diffuser is known to suffice.[5]

Three simple types of diffuser motion have been investigated: oscillatory, constant-speed rotational and uniform rectilinear motion. All attempts to make conventional 2-beam Fresnel-type holograms under these dynamic conditions were immediately preceded by successful (control) exposures in the identical test setup, but in its static condition. Only the first two types, interrupted and uninterrupted motion, are described in detail.

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1. [65S11, 65S7] 2. [64L1] 3. [65S14]
4. [65M9, Chap. 4] 5. [65M9, p. 109]

66D2 John B. DeVelis, George B. Parrent, Jr., and Brian J. Thompson, "Image reconstruction with Fraunhofer holograms," *J. Opt. Soc. Am.*, *56:* 423–427, 1966.

The holograms considered are formed from opaque or transparent diffracting objects which are contained in an aperture illuminated with a coherent, collimated, quasimonochromatic beam of light. It has been shown that the intensity distribution in the near-field of the aperture, but in the far-field of the individual objects which are contained in the aperture, is given by a function whose essential term represents the interference between the Fraunhofer diffraction pattern from the object and the coherent background. The hologram thus formed is referred to as a Fraunhofer or far-field hologram because of the imposed condition. The reconstruction, which is accomplished by placing the recorded hologram in another coherent collimated quasimonochromatic beam and again going to the far-field of the individual objects, yields an intensity which is essentially the original object distribution. In the far-field region of the individual objects for which this result is valid, the reconstruction is seen to be devoid of the evidence of a virtual image. One advantage of this particular method is that the virtual image which appears in the conventional (Fresnel) hologram method creates no problem here since it reduces to a constant for the far-field approximation.

66D3 Yu. N. Denisyuk, "Complete illusion of reality of photographic images," (in Russian), *Zhur. Nauchnoi I Prikladnoi Foto. I Kinema.*, *11:* No. 1, 46–56, 1966.

The task of producing photographs with complete illusion of the reality of the image is considered. For such an illusion, it is necessary to recreate the wave field of radiation scattered by the object. The photograph itself must also reproduce the optical properties of the object. Existing photographic methods that solve this problem to any degree are analyzed. It is shown that the phenomena underlying the Gabor hologram method and the Lippman interferential color photography method are special cases of a more general phenomenon: reproduction of optical properties of an object by volume photography of the standing wave picture. The validity of the predicted phenomenon is substantiated theoretically and experimentally confirmed. In the course of the experiment, photographic copies of convex mirrors are obtained whose optical power matches that of the original, as well as photographs of an arbitrary object, the scale of an object-micrometer. The influence of source dimensions on the resolving power of photography by this method is discussed.

66E1 L. H. Enloe, J. A. Murphy and C. B. Rubinstein, "Hologram transmission via television," *B.S.T.J.*, *45:* 335–339, 1966.

Holography, or wavefront reconstruction photography, was first demonstrated by Gabor[1,2,3] over fifteen years ago, and it has been the subject of increased investigation over the last five years since the advent of lasers. Possible applications of holography suggest themselves in the fields of three-dimensional and multicolor television.[4] Furthermore, the statistics and redundancy of the hologram of an image may be deliberately made quite different from those of the original image. This has obvious possibilities in encoding schemes for television transmission in general. In this communication we report a first experimental step in this direction, namely the successful transmission via television of a Fresnel type of hologram in which the original object was a transparency.

In conventional two-dimensional hologram construction a transparency is illuminated from behind by a monochromatic, spatially coherent light wave which then impinges on a photographic plate. This interferes with a reference or carrier wave derived from the same source that strikes the plate at an angle. A record, or hologram, is thus made of both the amplitude and phase of the light transmitted by the transparency. Reconstruction may be achieved by illuminating the hologram with a monochromatic, spatially coherent light wave. This results in the production of a real image, a virtual image and a direct wave. Most experimenters in the field have used relatively large angles between the reference and object beams, and the recording has been done on Kodak Spectroscopic plates with 649F emulsion. In the television experiment described here, the limited resolution of the equipment required the use of angles of less than one degree between the object and reference beams, and would severely limit three-dimensional and multicolor capabilities. The use of these small angles raised the problem of reconstructing the real image without interference from either the direct wave or the virtual image. This was solved by the use of a Fourier transform method which is described in the discussion of the reconstruction process. All recordings were on Polaroid Type 55 P/N film.

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1. [48G1] 2. [49G1] 3. [51G1]
4. [65L9]

66E2 J. Richard Elliott, Jr., "Laser's edge—it's cutting into commercial markets with the speed of light," *Barron's Business and Financial Weekly*, 3, 10, 17–19, 21–23, Apr. 4, 1966. Holography is mentioned on pp. 19 and 21.

The most promising innovation for data-processing is the dramatic development in recent years of a relatively ancient science: holography. A British scientist, Dennis Gabor, worked out the holography concept twenty years ago—making it four times as old as the laser. But its application had to wait for Dr. Townes' invention and Dr. Maiman's first working coherent-light device in 1960.

Essentially, what holography does is to record on film (using no lens, but doing so literally with mirrors) a fully rounded image of an object in a confusing pattern of smudges and concentric circles which a laser beam can then transform into a three-dimensional picture. Talk of late that the technology will transform the motion-picture and TV industry is premature, to say the least; theory aside, the technical problems in any such applications seem all but insoluble.

On the other hand, the hologram may well transform data-storage. By permitting the optical recording on film or discs of bits of information through, in effect, superimposing a spot from one coherent-light frequency upon another, and another —to an almost infinite extent—it could revolutionize computer memory systems. What's more, the same techniques can be used to record as many as 100 printed documents on a single piece of microfilm; unintelligible to the unaided eye, such a record yields any of the data required by simply beaming upon it the appropriate laser-light frequency.

66F1 A. A. Friesem and J. S. Zelenka, "Effect of nonlinearities in optical data processing," Program, Opt. Soc. Am., Mar. 1966 Meeting, p. 12.

A study of the effects of photographic nonlinearities in optical data processing is reported. Particular emphasis is placed on holography using the two-beam interferometry technique. A phenomenological model which provides the mathematical formulation for describing the effects of nonlinearities is described. The model includes a zero-memory nonlinearity which represents experimentally derived transmittance–exposure curves for various photographic emulsions. An analysis of this model reveals many interesting phenomena which are supported experimentally. In particular, the nonlinearity of the film generates false targets, causes weak-signal suppression, and can introduce additional noise as a result of spectral folding. Experimental results, verifying the analysis, are presented. These include representative samples of transmission–exposure characteristics of various photographic plates and films, and photographs of hologram reconstructions depicting increased noise and false targets with progressively increasing nonlinearity levels.

66G1 M. Parker Givens and William J. Siemens-Wapniarski, "The experimental production of synthetic holograms," Program, Opt. Soc. Am., Mar. 1966 Meeting, p. 7.

By multiple exposure of a photographic plate to a pattern of Newton's rings the authors have produced holograms which reconstruct a predetermined pattern such as the letter *E*. This method of synthesis makes the interpretation of holograms as a collection of zone plates apparent. Three-dimensional reconstructions have also been achieved from these synthetic holograms.

66G2 Dennis Gabor, "Holography, or the 'whole picture'," *New Scientist, 29:* 74–78, Jan. 13, 1966.

An eighteen-year-old idea of the author for reconstructing all the information present in the light from an object now comes to remarkable fruition when implemented with laser light. By this means one can take photographs without lenses and record information down to the limit set by the grain-size of the film.

66H2 B. P. Hildebrand and K. A. Haines, "Contour generation by wavefront reconstruction," Program, Opt. Soc. Am., Mar. 1966 Meeting, p. 7.

The wavefront reconstruction technique, first proposed by Gabor and later refined by E. N. Leith and J. Upatnieks, provides a method for the storage of three-dimensional information on a two-dimensional storage medium. The information so recorded may be retrieved by illuminating the storage surface with a coherent beam of light, whereupon a complete three-dimensional image of the recorded scene or object is reconstructed. A possible future application for this recording process is in the three-dimensional mapping of terrain. Another application might be the cross-section tracing of models for certain manufactured products. In such an application, the addition of constant altitude contour lines would be desirable. The generation of such contours is the subject of this paper. The analysis performed in the paper shows that there are two possible methods for obtaining a contoured reconstruction. The first method requires that the object be illuminated by two collimated beams separated by a small angle, 2θ, with the hologram plate placed at 90° to the illuminating beams. In this case the depth separation of the adjacent contours is $\lambda/2 \sin \theta$. The second method requires two frequencies in the illuminating beam. The depth separation between contours is $\lambda^2/\Delta\lambda$, where $\Delta\lambda$ is the wavelength separation of the two frequencies. Both these methods have certain advantages and disadvantages which are fully explored in the paper. Experimental results illustrating both methods are given.

66H3 L. O. Heflinger, R. F. Wuerker and R. E. Brooks, "Holographic interferometry," *J. Appl. Phys., 37:* 642–649, 1966.

A new method of interferometry, based upon holographic photography, is described. The interferometer uses a common optical path in which beam separation is achieved by two exposures separated in time. Its significant advantages are (1) accurate alignment and precision optical elements are not required, (2) differential interferometry, used to measure small changes in either optical path or position of complex subjects, is easily performed, (3) a complete three-dimensional record of the interference phenomena is obtained, permitting post-exposure focusing and examination from various directions and (4) the technique is well-suited to the recording of transient as well as stationary phenomena. Experimental examples of its use with aerodynamic phenomena are given.

66H4 O. S. Heavens, "Recent applications of lasers," *Brit. J. Appl. Phys., 17:* 287–309, 1966. Pages 298–299 deal with holograms.

In the field of holography (Gabor 1948, 1949) the arrival of the laser source has provided a decisive impulse. Realization of the potentialities of this method of image reconstruction proved very difficult when no powerful coherent sources were available. (The technique may be thought of as an optical counterpart of the usual RF techniques, in which difference frequencies are handled by the use of a local oscillator.) The photographic plate records, as a combined mixer and recorder, the difference terms arising from the combination of the scattered waves from the object and the reference wave. In the reconstruction process, a reference beam is passed through the hologram and both virtual and real reconstructed images may be seen. In order that three-dimensional reconstruction may be obtained, the coherence length associated with the illuminating and reference beams must be larger than the depth of object to be reproduced. With He–Ne gas lasers operating in single mode, the associated coherence lengths are adequate for this purpose. The main contribution of the laser in this field is that it enables holograms to be recorded in short exposure times, so that reproduction of moving objects becomes possible. Thus, provided that the movement of the object during the exposure time does not exceed approximately $\lambda/10$, a good record may be obtained. Incoherent sources are unsuitable not only because the short coherence length prevents three-dimensional imaging but also because the low brightness necessitates long exposure times.

[Reprinted by permission of The Institute of Physics and The Physical Society.]

66H5 K. A. Haines and B. P. Hildebrand, "Surface-deformation measurement using the wavefront reconstruction technique," *Appl. Optics, 5:* 595–602, 1966.

Among the most modern and sophisticated techniques of surface deformation analysis, is the moiré fringe technique of stress and strain analysis. This technique has a great deal in common with the method demonstrated in this paper.[1] This new method, which measures minute deformations of arbitrary three-dimensional objects, such as might occur due to applied stress, is an application of the wavefront reconstruction technique, as developed by

Leith and Upatnieks, to the interferometry of three-dimensional diffusely reflecting objects. Both techniques provide visual displays on which localized concentration of stress may be observed directly. However, the moiré technique has three serious shortcomings, none of which exists with the technique presented in this paper. These are: (a) the method is restricted to two-dimensional models, (b) a model of the actual object is required and (c) sensitivity is not high.

The object can be a complex three-dimensional diffusely reflecting object, and the displacements can be measured down to a fraction of a wavelength of light if desired. The new technique presented here has at least one other advantage. The object under investigation need not be modified or handled in any way, nor is it necessary to place any film or other apparatus on, or close to, the object.

The basic optical development that makes all this possible is known as the wavefront reconstruction technique. This technique, first proposed by Gabor,[2] has been improved by Leith and Upatnieks[3] to the point where three-dimensional images of arbitrarily shaped objects may be recorded. The usefulness of this property as a means of recording transient phenomena and then using the recording to perform interferometric measurements was first suggested by Horman.[4] A related technique for vibration measurement was used by Powell and Stetson.[5] These images are identical in appearance to the real object; the identity is so exact that the image and the object may be compared in an interferometer. Accordingly, the object may be strained and the surface deformation measured just as polished mirrors, prisms or optical flats are presently tested. The distinction is that now any three-dimensional object, not necessarily specularly reflecting, may be tested to the same degree of precision.

A detailed theory for the interpretation of the interference phenomena observed in terms of the translations and rotations undergone by a point on the object is presented. Experimental results verifying the method and the theory are shown.

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1. [66H1] 2. [49G1, 51G1]
3. [64L1] 4. [65H7] 5. [65P9]

66H6 Franklin S. Harris, Jr., George C. Sherman and Bruce H. Billings, "Copying holograms," *Appl. Optics, 5:* 665–666, 1966.

The making of holograms has attracted much attention since laser light has been applied to the problem.[1] Though holograms have been copied successfully also at the University of Michigan,[2] Sperry Gryscope Company,[3] Stanford University,[4] Institut d'Optique[5] and elsewhere, a simple statement of the problems that arise in photographic copying is not readily available. A procedure such as the one outlined below enables an interested person to make good copies of holograms when certain critical conditions are encountered.

In a typical hologram the fringes on the film that carry the information are on the order of microns in separation. These fringes have an intensity gradient that, in the viewing process, eliminates effectively images beyond the first order. Accordingly, it is necessary to have resolution on the order of 1000 lines/mm to make a good copy. A copying device that uses lenses to image the hologram on a film will not have the required resolution. In addition, the hologram fringes have finite thickness and must be oriented with respect to the copying or viewing light beam so that there is no shadowing or venetian blind effect. This venetian blind effect was pointed out to us by the Stanford Electronics Laboratory.[4] In order to meet these conditions, contact printing was employed, with the hologram and copying film held as close together as possible by means of a vacuum printing frame. Because of the small spacing between hologram fringes, the permissible distance to copying film must be small to avoid loss of resolution by diffraction. It is interesting to note that a very contrasty hologram with higher order images can theoretically be improved by this copying technique. The ratio of high-order to first-order image intensities can be much reduced. The reduction of contrast of the fringes in the copy will produce an improved sinusoidal variation of transmitted light. The sinusoidal grating has only one diffraction order. Successive copies will, however, degenerate since each copy will be more blurred than the previous one.

Two holograms were copied: one, a 649F plate of a chessboard scene[6] made at the University of Michigan; and the other, a 91.5 cm-long SO-243 film of a scene with two horse statues seen through a variation in view of 180° made at Westinghouse Research Laboratories.[7] The procedure adopted finally that produced acceptable hologram copies is given below, with some comments.

The copy film used was Eastman Kodak Spectroscopic type 649-GH, which is sensitive out to the green. Type 649-F red sensitive is necessary for making original holograms with red laser light. This material has a resolution better than 2500 lines/mm.[4,8,9] The emulsion is available on both plates and film. Also usable for original holograms are Kodak Special High Definition Aerial Film SO-243 with resolution about one-fifth that of type 649, but 200 to 300 times as sensitive at 6328 Å. Kodak Spectroscopic Plate, type V, has marginal resolution and Kodak High Contrast Copy can be used.[10] We used only type 649-GH because it has the highest available resolution.

The light source should subtend only a small angle. We found that a tungsten Colight Printing Lamp (Colwell Litho Products, Inc.) of 1.25 cm diam, used at a distance of 1 m, was satisfactory. A stopped-down, high-pressure, mercury lamp AH-6 and a 300-W, zirconium concentrated-arc lamp were used successfully also. The speed of type 649 is extremely slow, with an ASA of 0.003 for F sensitizing.[8] A typical exposure with the Colight was 5 min in copying from the Michigan plate and 10 min from a Westinghouse film.

The distance between the hologram and copying emulsions is very critical. The separation of the fringes on the holograms was calculated from the angle between the image and reference beams and was verified by measurement with a microscope to be 1.6 μ on the University of Michigan hologram and 3.2 μ on the Westinghouse hologram. Thus, the fringes will be obscured by diffraction a very small distance from the hologram. A Robertson vacuum printing frame at 1 atm was used to hold the emulsion of the original in close physical contact with the emulsion of the copying film. The separation between emulsions was estimated theoretically to be 30 μ, by considering the ultimate pumping speed from two, plane-parallel sheets with typical outgassing. We found that with this spacing we were able to copy the University of Michigan hologram with some loss of resolution and the Westinghouse hologram nearly perfectly. When the copying was performed, using the frame without applying the vacuum, both holograms were copied, but with further reduction in resolution—particularly in the University of Michigan hologram. When a piece of clear photographic film of 140 μ thickness was inserted between the two emulsions, the Westinghouse hologram was again copied with further loss of resolution, while the University of Michigan hologram was not copied at all. In this case both copy films exhibited a series of light and dark circular rings centered about the laser used to view the images.

A directional effect was observed also. In printing, the light should come from a similar direction, with respect to the hologram, as did the incident light in the original. Best results for the glass-plate hologram were obtained by having the printing light source in a direction midway between the viewing laser source direction and virtual image direction. When the angular orientation of the source was reversed, no image could be seen in the copy. This has been called a venetian blind effect by the Stanford University group who brought it to our attention.[4] Because of the fine spacing of the fringes and the emulsion thickness, the light must go in depth parallel to the channels between fringes, as with a venetian blind.

The film processing is not critical. Type 649-GH was developed either in D-19 for 5 min or in D-8 for 2 min. Kodak High Resolution Plate Developer can be used.[9]

For viewing, a laser light source is diverged by a suitable positive or negative lens to cover the hologram. Any point source can be used but, the more monochromatic the source, the better the image reconstruction.

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1. [63L2]
2. G. W. Stroke (private communication).
3. B. J. Howell (private communication).
4. W. H. Huntley, Jr., and J. W. Goodman (private communication).
5. G. Nomarski (private communication).
6. [65L3] 7. [65V2] 8. [65L15]
9. [65*18] 10. [65J1]

66H7 T. S. Huang, "Comments on 'Some curious properties of holograms'," *Proc. IEEE, 54:* 716, 1966.

See 65K1, 66B4 and 66K6.

In a recent correspondence,[1] Kock and Rendeiro reported certain properties of holograms. In particular, they described the inversion or noninversion of reconstructed images when a hologram is rotated 180° in various ways. The purpose of the present letter is to explain these properties for the Fourier-transform holograms.[2,3]

Let the brightness of the original image as a function of spatial coordinates be $f(-x, -y)$, and let the Fourier transform of $f(-x, -y)$ be $F(u,v)$. The Fourier-transform hologram records, except for some scale factors, the function

$$H(u,v) = |F(u,v) + Be^{iau}|^2 \qquad (1)$$

where the term Be^{iau} represents the carrier beam (B and a are real constants). Equation (1) can be written as

$$H(u,v) = |F(u,v)|^2 + B^2 + BF(u,v)e^{-iau} + BF^*(u,v)e^{iau} \qquad (2)$$

where * denotes complex conjugation.

When the hologram is illuminated by a collimated laser beam, there are two reconstructed images. Let us concentrate on the reconstructed image associated with the factor e^{-iau}. For the unrotated hologram $H(u,v)$, this image will be the Fourier transform of $BF(u,v)e^{-iau}$, viz., $Bf(x + a, y)$, which is $Bf(x, y)$ shifted to $x = -a$.

Let the positions of the laser and the observer remain unchanged, and let the u and v axes in the hologram plane and the x and y axes in the reconstructed image plane be fixed in space. We also assume that the x and u axes are horizontal and the y and v axes are vertical. Then a rotation of the hologram by 180° about a vertical axis will change the function $H(u, v)$ to $H(-u, v)$. The term in $H(-u,v)$ which contains the factor e^{-iau} is $BF^*(-u, v)e^{-iau}$. The reconstructed image due to this term is its Fourier transform $Bf(x + a, -y)$, which is $Bf(x, -y)$ shifted to $x = -a$. The image $f(x, -y)$ is clearly the image $f(x, y)$ inverted in the y-direction.

A 180° rotation of a hologram about an axis perpendicular to the plane of the hologram will change $H(u, v)$ to $H(-u, -v)$. The term in $H(-u, -v)$ that contains the factor e^{-iau} is $BF^*(-u, v)$ whose Fourier transform is $Bf(x + a, y)$. Therefore, in this case the reconstructed image is not inverted.

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1. [65K1] 2. [62L1] 3. [64S3]

66H8 Carl W. Helstrom, "Image luminance and ray tracing in holography," *J. Opt. Soc. Am.*, *56:* 433–441, 1966.

Image formation in holography is treated by means of the Fresnel-Kirchhoff diffraction formula. The luminance of an image formed by paraxial rays is calculated, and its dependence on the resolution loss in the photographic film is evaluated. It is estimated that at most 1/16 of the light striking the hologram goes into each image. When a hologram is viewed, a glow is observed to surround the source of coherent light. It can be attributed to two causes, the granularity of the photographic emulsion and random interference between waves reflected from pairs of points on the object when the hologram is recorded. The luminance of each of the components of the glow is calculated. Ray-tracing equations are presented, and formulas are derived for locating the foci of the astigmatic pencils of rays emitted by the hologram when coherent light is incident.

66H9 T. S. Huang and B. Prasada, "Considerations on the generation and processing of holograms by digital computers," *MIT Res. Lab. of Elec. Quart. Prog. Rep. No. 81*, 199–205, April 15, 1966.

Holography and other coherent optical processing schemes have aroused considerable interest among those working in the field of television bandwidth compression and image processing. These new techniques have made possible relatively simple ways of obtaining the Fourier transforms of two-dimensional functions and operating on them in the frequency domain.

Holography provides an alternative description of pictures, which might be more amenable to bandwidth compression. To investigate this possibility, it is desirable to measure various statistics of the hologram, and to try various operations on it to see what their effects would be on the reconstructed pictures.

The types of processing that one can do by using coherent optics are rather limited. If one can get the hologram into a digital computer, however, or generate the hologram in the computer in the first place, then the number of possible operations one can do on the hologram is almost unlimited. The reconstruction of the picture from the processed hologram can be done either on the computer or by coherent optics (after having first obtained a transparency of the hologram from the computer).

66K2 Frederick C. Klein, "Laser photography," *The Wall Street Journal*, 1, 12, Mar. 7, 1966.

Televison and motion pictures in true three dimension. Cheaper data processing. Faster transmission of pictures from outer space. A new tool for intelligence agencies handling secret photographs. All these and more are distinct possibilities as a result of a new and rapidly growing science called holography, a process hailed by many scientists as the most important photographic event since the invention of photography itself more than 100 years ago. Already, after only a few years of its development, major universities and companies with an interest in photography, electronics and communications have launched extensive research on it, and a few commercial products actually are appearing.

The key to holography is that seemingly magical device, the laser, which produces a "pure" single-color light not ordinarily obtainable from other light sources. Holography amounts to photographing objects by the light of a laser. The use of laser light enables scientists to capture on film special patterns of light reflected from an object. Holography uses no lens and the exposed film, called a hologram, bears no resemblance to an ordinary photograph; rather, it usually appears to be a meaningless gray mass of concentric circles. But when a viewer looks through the film into the light of a laser, a three-dimensional image of the original object suddenly springs into view, floating in mid-air behind the film.

Perhaps even more startling, the viewer can move his head to, say, the left, and his view changes just as though he were changing his angle of viewing the original object. This, of course, is impossible with an ordinary photograph; there, the angle of view of the image is always the same, no matter from where a person looks at the photograph.

Scientists are quick to point out that these strange properties of a hologram are possible only under certain conditions, and some substantial problems have to be overcome before holography can be adapted for television and motion pictures. Yet, the process has a wide range of other applications of immediate scientific and commercial interest, applications that have little to do with three-dimensional imagery.

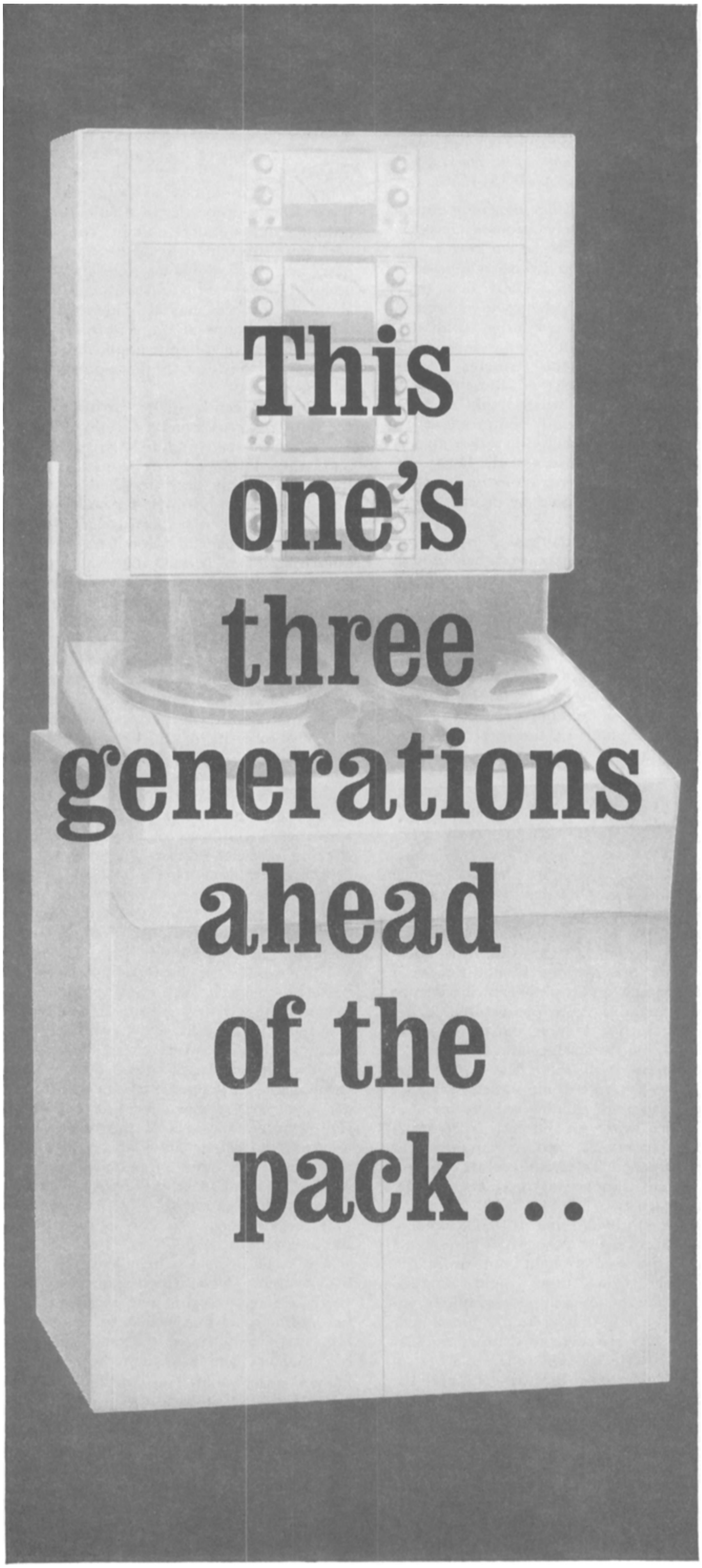
Holograms can be made, for instance, of the light patterns from a certain word or series of words contained on microfilm and, when developed, can be used as filters that will permit light to shine through only where these words appear. Such a hologram can then be used on high-speed readers or scanners for computers, scanning huge amounts of printed material to select the material that is wanted. Other potential uses range from information storage to materials testing.

The fascination of holography is that it records on film and then reproduces the total light patterns reflected from an object. Ordinary photography misses a great many of these patterns; it records only the intensity of the light—variations in brightness—reflected from an object. An ordinary black-and-white picture is nothing more than shadings of black through gray to white, corresponding to the variations in intensity of light bounced to the film by the objects being photographed. If one object is a foot behind the other, but both reflect the same amount of light, the film records them equally. Thus, conventional photography produces only two-dimensional pictures.

Holography, by contrast, records wave patterns as well as intensity patterns. When light strikes a point on a subject, it is reflected back from the point in ever-expanding concentric rings, somewhat like the rings of waves caused by a pebble thrown into a pool. An object such as a car has innumerable reflection points so that innumerable sets of the wave rings are reflected off it; an analogy might be throwing a shovelful of pebbles into the pool. Taken all together, these reflections make up an extremely complex pattern that is distinctive to the object being illuminated.

The basic principles of holography date back as much as two decades, but for many years researchers could not overcome one big obstacle. If one wants to record on film wave patterns of reflected light, he has to start out with light waves of a known, orderly pattern. The light needed is known as "coherent" light; its waves are all of the same length and they pour forth all "in step," that is, trough matches trough, peak matches peak, somewhat like a platoon of soldiers all of the same size parading along.

An ordinary light bulb does not produce this orderly light but rather sends out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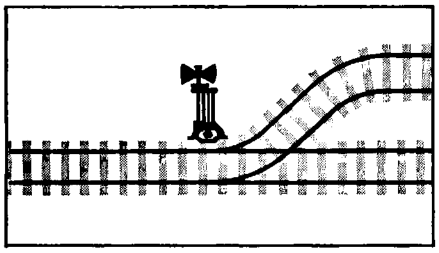

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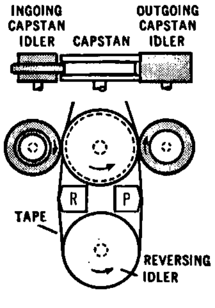

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jumbled light waves of many different lengths, scattering helter-skelter in all directions.

66K3 Winston E. Kock, "Hologram television," *Proc. IEEE, 54:* 331, 1966.

The surprising three-dimensional effects obtained with the hologram process of Gabor[1] had led many to speculate on its possible use in television. As pointed out by Leith and co-workers,[2] the "pictures have a realism unattainable by any other known means. The three-dimensional effect is obtained without the need for a stereo pair of pictures, and without the need for any devices such as polaroid glasses. In addition, all the visual properties of the original scene, such as parallax between near and far objects in the scene, and a change of perspective as a function of the observer's viewing position, are present."

In the same paper,[2] some of the problems involved in applying holograms to television are discussed, and the photography, by holograms, of a television stage scene is examined. It is shown that for the particular example chosen, the usual television bandwidth of 4.5 Mc/s would have to be increased by a factor greater than 30 000, that is, to 1.5×10^{11} c/s. It is the purpose of this correspondence to suggest certain procedures which may permit television holograms to be transmitted within reasonable bandwidths.

Although Leith and his co-workers note that[2] "the number of samples required to transmit a hologram is of the same order as the number of resolvable elements in the scene," they point out that "the resolution under discussion is the aperture-limited resolution as determined by the aperture of the photosensitive surface" (of the television camera which is recording or transmitting the holograms).

Because holograms can be considered as zone plate lenses,[3] and because their "aperture" dimensions involve many, many wavelengths, they achieve extremely high resolutions. In the television example discussed by Leith,[2] the dimension of the hologram was assumed to be 4 in. and the resulting large number of resolvable elements therefore required a very large transmission bandwidth. U.S. television, on the other hand, provides a resolution of only 525 lines, requiring a bandwidth of only 4.5 Mc/s.

The resolution of an aperture is determined by its dimension in wavelengths. To reduce this resolution (and hence, the transmission bandwidth requirements), one can (a) leave the aperture dimension unchanged and increase the wavelength, or one can (b) leave the wavelength unchanged and reduce the aperture dimension.

In procedure (a) short wavelength microwaves would be used to "illuminate" the scene. The reflected electromagnetic field (after combination with a reference field) would be recorded and transmitted as a microwave hologram. To make a hologram, both amplitude and phase must be recorded. In the microwave case, this can be done by illuminating the area of interest with waves generated by the same coherent source.[4] In this procedure the wavelength would be chosen to yield an aperture-limited resolution of the scene which would correspond to the television resolution desired (e.g., 525 lines).

In procedure (b) the usual laser illumination would be employed, but the aperture would be drastically reduced in size so as to yield the desired low resolution as described in the preceding paragraph. Upon reconstruction of the original wavefield, the resulting detail would again correspond to the television resolution desired.

In process (b) the size of the hologram unfortunately becomes so small that many desirable properties are lost. It is obviously impossible, for example, to observe a parallax effect when viewing an extremely tiny hologram. To avoid this, an array of many small portions of the hologram would be used. The entire hologram would thereby be available for viewing, as through many small apertures in a screen.

To test feasibility of this suggestion, a mask comprising a metal structure having a large number of holes in it was placed over a hologram illuminated with a laser light beam. When the three-dimensional scene came into view, the effect of the mask pattern was quite inconspicuous (much like the effect of a screen door on the view beyond).

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1. [48G1]; [49G1] 2. [65L9] 3. [50R1]
4. The subject of microwave holograms was discussed by the author at the 1965 IEEE Internat'l. Space Elecs. Symp., Miami Beach, Fla.; it is presented in more detail in an internal memo entitled "Microwave and acoustic holograms, Oct. 1965." See also [65D2].

66K4 Adam Kozma and Norman Massey, "Bias level reduction of incoherent holograms," Program, Opt. Soc. Am., Mar. 1966 Meeting, pp. 7–8.

The known techniques for making incoherent holograms succeed for an object containing several points; however, they fail in practice for an object with a great many discrete points or for a complicated object with a continuous intensity distribution. This failure occurs because the incoherent superposition of many randomly spaced intensity patterns produces a large bias level which masks the spatial intensity modulations required to reconstruct the object in the film grain noise. This paper describes a technique for eliminating the bias. By introducing a time modulation of the light in one path of the interferometer, the spatially modulated part of the hologram intensity pattern is also modulated at the time frequency while the bias part is unmodulated. The bias term can then be eliminated by performing a point-by-point time correlation over the hologram plane. This technique is similar to that proposed by Ryle for radio astronomy and by Mertz for spectral line discrimination. The implementation of this technique is discussed, together with two possible methods of performing the time correlation, one using a photocell and a narrow-band filter and one using an electro-optical correlator based on a specially modified image orthicon.

66K5 Herwig Kogelnik, "Fundamentals of holography," Talk given Apr. 20, 1966, at Bell Labs., Murray Hill, N.J.; announced in *IEEE Newsletter, 12:* no. 8, 3, 5, 1966.

This talk surveyed briefly the areas of application of holographic techniques and discussed the fundamental principles of holography and wavefront reconstruction. Topics discussed were the three-dimensional aspects of wavefront reconstruction; the use of a spatial carrier or reference beam; the effect of thick emulsions; and others. The talk was followed by a demonstration of holograms.

66K6 W. E. Kock and J. Rendeiro, "Comments on 'Some curious properties of holograms'," *Proc. IEEE, 54:* 716, 1966. **See 65K1, 66H7 and 66B4.**

Huang has provided in Fourier transform terms a clear and concise explanation of the hologram properties noted. An early explanation by one of us,[8] based on G. W. Stroke's observation[9] that an illuminated hologram produces both converging and diverging sets of waves, is the following:

"When a hologram is rotated by 180° about an axis perpendicular to the plane of the hologram, an observer originally viewing the reconstructed waves now sees the diverging waves. This latter scene was originally inverted, but the rotation of the hologram plate causes it to be turned right side up."

The above is seen to be in full accord with Huang's analysis. Becker's explanation is similar; as to his objection to our referring to these unreported properties as "curious," we point out that Webster defines "curious" as "exciting attention as novel."

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8. W. E. Kock, "Microwave and acoustic holograms," internal memorandum, October 1965; portions of this paper were discussed by the author at the IEEE Intnat'l Space Electronics Symp., Miami Beach, Fla., November 1965.
9. [65S8]

66K7 Adam Kozma, "Photographic recording of spatially modulated coherent light," *J. Opt. Soc. Am., 56:* 428–432, 1966.

Photographic recording of spatially modulated coherent light, such as is encountered in wavefront reconstruction or coherent optical data processing, is described in terms of the amplitude transmittance (T_a) vs. exposure (E) curve of the film. It is proposed that the $T_a - E$ curve is more appropriate for this application than the D-log E curve. The nonlinear effects of recording are analyzed in this context using a nonlinear "circuit" model. A general expression for the resulting amplitude transmittance is derived by use of a Fourier-transform technique. A specific nonlinearity, the error-function limiter, is analyzed in detail to illustrate the effects of the film nonlinearity.

66L2 A. W. Lohmann and D. P. Paris, "Synthesis of binary holograms," Advance Program, 1966 Quantum Electronics Conference, Phoenix, p. 44.


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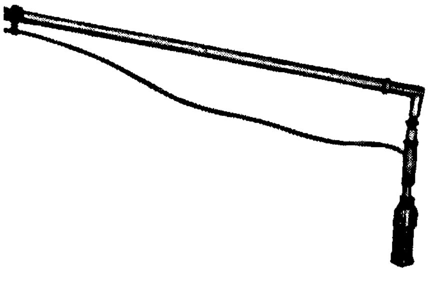

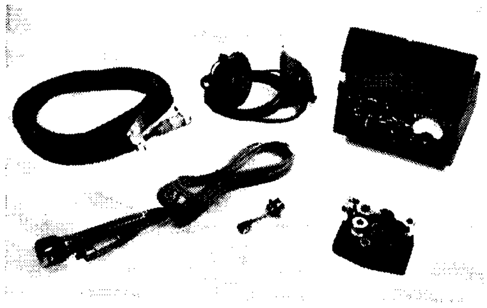

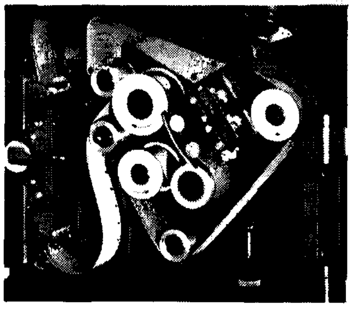


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A computer program, which—with the "mathematical object" as input—guides a plotter drawing a binary pattern, has been developed. This pattern consists of many short parallel lines at proper positions. When reduced in size and recorded on film, such a binary pattern acts essentially like an ordinary hologram. The underlying theory, experimental verification and possible applications will be discussed.

66L3 A. W. Lohmann and D. P. Paris, "Binary image holograms," Program, Opt. Soc. Am., Mar. 1966 Meeting, p. 7.

An image hologram differs from the more common Fresnel and Fraunhofer holograms in the distance of the recording plate from the object (or an image thereof). This distance is zero for an image hologram. Hence, such a hologram is actually the same as an ordinary interferogram, in which the deformations of the interference fringes represent the shape of the wavefront behind the object. Instead of recording the image hologram by means of an interferometer (such as a Mach–Zehnder), we draw the hologram on a large scale and photographically reduce it. In contrast to ordinary holograms, ours contain only black and fully transparent portions. In other words, the transmittance is binary, which facilitates the production. The quality of an image reconstructed from a binary hologram is the same as if obtained from an ordinary gray-tone hologram of comparable dimensions. Our synthetic way of producing an image hologram has the advantage that the object does not have to exist physically. The theory, some experiments and possible applications are discussed.

66L4 L. H. Lin, K. S. Pennington, G. W. Stroke and A. E. Labeyrie, "Multicolor holographic image reconstruction with white-light illumination," *B.S.T.J., 45:* 659–661, 1966.

Color images have been obtained by wavefront reconstruction from a reflection volume hologram illuminated with ordinary white light. The hologram was recorded with coherent light at two wavelengths, 6328 Å and 4880 Å, from helium–neon and argon-ion lasers, respectively.

A simple method of multicolor holography has previously been reported.[1] This method was based upon the formation of volume holograms which were reconstructed by Bragg reflection from the planes formed in the emulsion. The wavefronts were reconstructed by illuminating the hologram with the same laser light used in recording and were observed on transmission through the hologram plate. With beam angles used to give transmission, the Kodak 649F emulsion was not thick enough to form holograms having the angular and spectral selectivities needed for good white-light reconstruction. A simple method for obtaining reflection volume holograms was recently described.[2] It showed that high-quality reconstructions could be obtained in a single color by reflection of white light from the hologram when, in the recording, the reference and subject beams interfered at very large angles (160° to 180°). Reflection holograms of two- and three-dimensional objects form an extension of basic ideas and work by Denisyuk[3] in his generalization of Lippmann color photography[4] and Gabor holography.[5]

The ability to reconstruct multicolor holograms with white-light illumination adds a degree of flexibility to holography; we have now demonstrated the simplicity of obtaining this result. We have recorded reflection holograms both by "projection" and in diffused light, in a single color and in multiple colors. To ensure minimum shrinkage of the emulsion in processing the hologram, we omitted the fixing of the emulsion as suggested by Ives.[6] Any white-light source ranging from flashlight to sunlight can be used to obtain reconstructions. Particularly brilliant multicolor reconstructions were obtained when the light illuminating the subject was focused some distance behind the hologram plane. A similar result was reported in Ref. 2.

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1. [65P5] 2. [66S4] 3. [62D1]
4. G. Lippmann, *J. de Physique, 3:* 97, 1894.
5. [48G1]
6. H. E. Ives, *Astrophys, J., 27:* 325, 1908.

66L5 C. Lanza, "Display device," *IBM Tech. Disclosure Bull., 8:* 1559–1560, 1966.

The display device employs a hologram and a number of individual coherent-light sources to selectively display alphanumeric characters. The hologram is made by reflecting coherent light from an object—which includes the character to be recorded—and a near-by mirror onto a photographic plate.

The various objects or characters to be recorded are placed in different positions, using either two or three dimensions during the recording so that the reflected light falls on the photographic plate from a different direction for each object character. The developed plate, therefore, contains a recording of each character.

Different characters are displayed by selectively energizing different laser sources. The display can be used as a visual display or a recording medium can be employed to produce a printout device.

66L6 A. W. Lohmann, "Crypto-holography," *IBM Tech. Disclosure Bull., 8:* 1402, 1966.

An image can be recorded on a photographic medium in the form of a hologram. When the photographic film is viewed directly, the image does not appear. However, the image can be reconstructed by suitable apparatus. The apparatus used is conventional apparatus for recording the hologram of an object with the exception that a ground glass is inserted between the object and the hologram. The ground glass randomizes the phase of the light being transmitted from the object to the hologram. The only way that an image of the object can be reconstructed is by utilizing apparatus that includes a piece of ground glass that is identical to the first piece of ground glass, but has the light transmitted through it in the opposite direction.

66L7 Emmett N. Leith and Juris Upatnieks, "Holographic imagery through diffusing media," *J. Opt. Soc. Am., 56:* 523, 1966.

By using holographic methods, it is possible to obtain imagery through a diffusing medium, such as ground glass, opal glass or a chunk of translucent mineral matter. In an experimental arrangement, the diffuser is placed between the object and the hologram; the hologram is otherwise made in the usual manner, with a reference beam impinging on the recording plate at some oblique angle.

From the hologram thus produced, the wavefront from the original object cannot be reconstructed by ordinary methods; the hologram reconstructs only that which can be seen from the plane where the hologram was made. Thus, an image of the diffuser is readily reconstructed, but not of the object, since this is obscured by the diffuser.

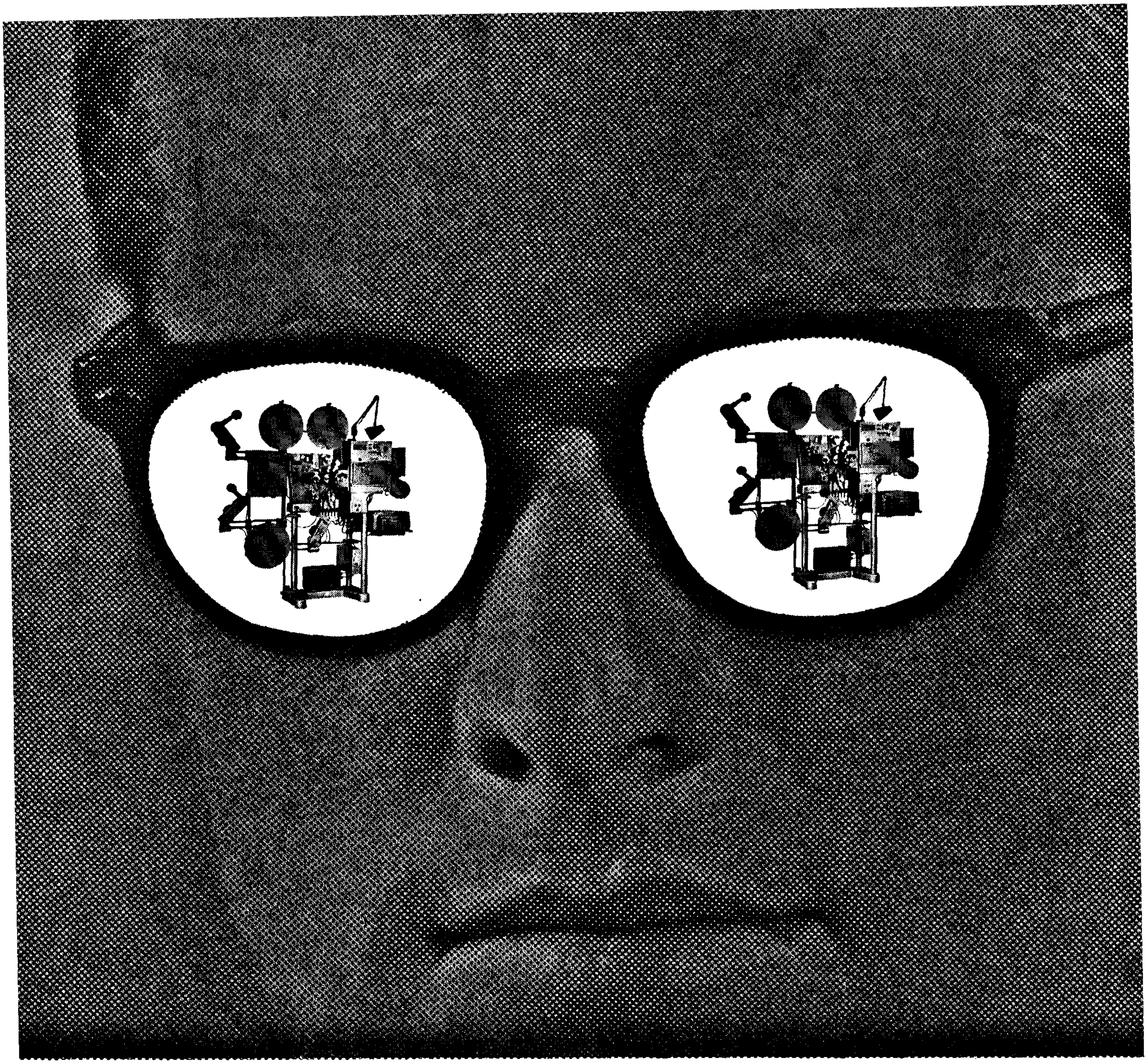
Suppose, however, that in the reconstruction process we place the diffuser in the path of the light emanating from the hologram, in such a position that the diffuser coincides with the hologram-produced real image of the diffuser. When this is done, an image of the original object is produced.

The explanation of the phenomenon is as follows: The diffuser can be regarded as a two-dimensional (or three-dimensional) phase function $e^{i\phi(x,y)}$ where ϕ is a random or noiselike function. The real image is phase conjugate to the object, i.e., has the form $e^{-i\phi(x,y)}$. When the diffuser and its real image superimpose, the phase effects of one are cancelled by those of the other, the diffuser effectively disappears and the original subject, previously obscured by the diffuser, now is clearly produced.

The cancellation is incomplete unless the diffuser is brought into exact coincidence with its reconstructed image. Such alignment is difficult, since there are six degrees of freedom for the diffuser location (three each of translation and rotation). Also, the hologram must be illuminated with a beam having just the right divergence to yield a magnification of unit for the diffuser.

Since the wavefront from the original object can be reconstructed only by using the same diffuser that was used for making the hologram, we have here an interesting coding system.

Of more interest is the possibility of using this system for measuring stresses of other disturbances in translucent (or in general, nonopaque) media, which is a procedure similar to hologram interferometry, as performed by Stetson and Powell[1] and by Hildebrand and Haines.[2] If the diffusing (or translucent) medium has been disturbed between the time the hologram was made and the time when the reconstruction is made, the reconstruction is imperfect, or fails to materialize. This disturbance may be caused by stresses in the diffuser, thermal expansion, change of



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the refractive index through chemical or other means or any other causes of changed optical properties.

Failure of the diffusing material and its image to coincide produces a noiselike pattern instead of an image of the original subject. Thus the signal-to-noise ratio of the reconstruction is a measure of the alteration of the diffusing material.

In a reconstruction that was obtained through a diffuser, the object was transparent lettering; the diffuser was a piece of ground glass. The lettering was recovered with good fidelity. In a further experiment, two pieces of ground glass were used in tandem, with about 1-in separation. Currently, we are attempting to extend the experimental results to much thicker diffusers such as chunks of translucent mineral material.

We have also produced high-quality reconstructions when the diffuser was in the reference beam. This configuration is an example of a type described by van Heerden.[3]

NOTE: In private discussion with K. Pennington of Bell Laboratories, we have learned of similar work carried out by that organization.

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1. [65S2] 2. [66H1] 3. [63V2]

66L8 E. N. Leith, A. Kozma, J. Upatnieks, N. Massey and J. Marks, "Holographic recording on three-dimensional media," Program, Opt. Soc. Am., Mar. 1966 Meeting, p. 6.

When the fringe patterns recorded on a hologram have a spacing comparable to the thickness of the recording medium, the medium must be treated as a volume rather than a surface. The optical properties of such holograms are analyzed. Three cases arise: low-angle reference beam, where the recorded fringes are coarse compared to the medium thickness; high-angle reference beam, where the fringes are fine; and finally, very-high-angle reference beam, in which the reference beam is introduced from the back side of the recording medium, and in which the recorded fringes are nearly normal to the readout beam. Each case has its special properties, and the transition between these cases depends upon the thickness of the medium. Experimental results are given, showing the sensitivity of the reconstructed image to the wavelength and incidence angle of the readout beam. Both the case of uniform fringe contrast throughout the medium and the case of exponential attentuation with depth are considered. An animated hologram has been produced in which successive frames are superimposed on a single hologram by reorienting the hologram between exposures. The images are read out in succession using Bragg angle effects by rotating the hologram in the illuminating beam.

66M1 Reinhard W. Meier, "Cardinal points and the novel imaging properties of a holographic system," *J. Opt. Soc. Am., 56:* 219–223, 1966.

The cardinal points (principal foci, principal planes and nodal points) as well as the focal lengths of a holographic system are established by considering holographic imaging as a projective transformation between object and image space. Expressions for the coordinates of the cardinal points are given in terms of holographic variables, and they are compared with the corresponding expressions for a thin lens. The wavelength ratio between reconstructing and recording light in holography is found to correspond to the refractive index ratio between object and image space in conventional imaging, while the enlargement factor of the hologram has no analog. The peculiar properties of the conjugate image, real or virtual, are discussed and related to the locations of the cardinal points for the conjugate imaging system.

Stigmatic imaging in first-order approximation must by necessity correspond to a projective transformation between object and image space, regardless of the physical nature of the imaging system.[1] Examining the mathematical properties of this transformation, therefore, is a powerful tool for obtaining insight into the properties of imaging without having to refer to any specific technique that might be used for its implementation. A discussion of holographic imaging, then, has to start from this point, and expressing the basic parameters of a projective transformation as a function of the variables in holography pinpoints the analogies and differences between conventional imaging and holography.

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1. [64B1, p. 150]

66M2 Elizabeth Mike, "Holograms move ahead—and in color," *Electronic News, 11:* 1, 29, Apr. 11, 1966.

An animated hologram "movie" and reconstruction in full color using ordinary white light were recently described in new detail during a three-day symposium on electron and laser beam technology sponsored by the University of Michigan and the Institute of Electrical and Electronics Engineers. A technique for overcoming the limitations of incoherent light in making holograms was also reported on.

Two laboratories at the Institute of Science and Technology at the University of Michigan are researching the field: Optics Group of Radar and Optics Laboratory headed by Emmett N. Leith, and Electro Optical Group headed by George W. Stroke.

The hologram is a recording of an interference pattern reflected from an object. From this recording the object image can be reconstructed in three dimensions.

Dennis Gabor reviewed early efforts in holography in 1948 when lack of coherent light prevented any appreciable advances in the field. He pointed to pattern recognition as an important application of holography and said electron microscopy, for which holography was invented, is still waiting exploration but other than that he could not see many commercial applications.

Since the resurgence of interest in holography, due to the development of the laser, the Optics Group at the University of Michigan has conducted a broad research effort in the holography area designed both to enlarge the scope of the field through basic research and to find applications. The research is supported primarily by an Air Force contract.

Dr. Leith emphasized that holography discoveries of the University of Michigan often coincide with those in laboratories in other parts of the country.

An animated hologram and a three-dimensional color hologram are possible because hologram images can be stored in three-dimensional media such as fixed film emulsions or crystals, Dr. Leith said.

The animated hologram is produced from several images (or interference patterns), all of which are diffused over the entirety of a single photographic plate; the plate is rotated slightly for each succeeding recording. The thicker the emulsion, the greater the number of pictures which can be stored in it.

Each image must be recorded and viewed at a particular angle. By changing the angle of each exposure, several holograms can be recorded on one plate provided it is of sufficient emulsion thickness. These holograms can be viewed in succession simply by rotating the plate in a beam of laser light. An important application for this type of holography is data storage. For example, pictures on a 100-ft roll of film could be stored on one hologram plate, a reduction of 1600 times on a two-dimensional basis. The development stems from the University researchers' exploration of the immense storage capabilities of various three-dimensional media. It is an extension of the theory developed by both the Russian scientist Yu. N. Denisyuk, and an American at Polaroid Corp., Peter Van Heerden, which describes how these media store multiple images.

The full color hologram which was described is capable of producing its image in three-dimensional form using ordinary noncoherent white light. A departure from previous holography, in which the ordered wave of coherent light from a laser was required, it follows Denisyuk's work of combining holography with Lippman's photographic process.

Lippman, a French optical and photographic scientist, in 1894 described a process in which color pictures could be produced by using high-resolution black-and-white film. This is done by recording with emulsion interference fringes that selectively reflect different colors when illuminated with white light. The same process is applied in holography using a wavefront or interference recording instead of the photographic negative to produce the three-dimensional color hologram. Thick emulsion aids in making holograms in color.

How to make holograms in incoherent light, again eliminating the necessity for using the coherent light of the laser, was described. Elaborate opto-electronic signal processing methods developed for radar signal correlation were used to provide the ordered light processing required for production of the hologram.

Making contour maps of three-dimensional objects with holograms was described. The precise contours of an object's depth are in effect "painted" onto the holographic image using lasers that

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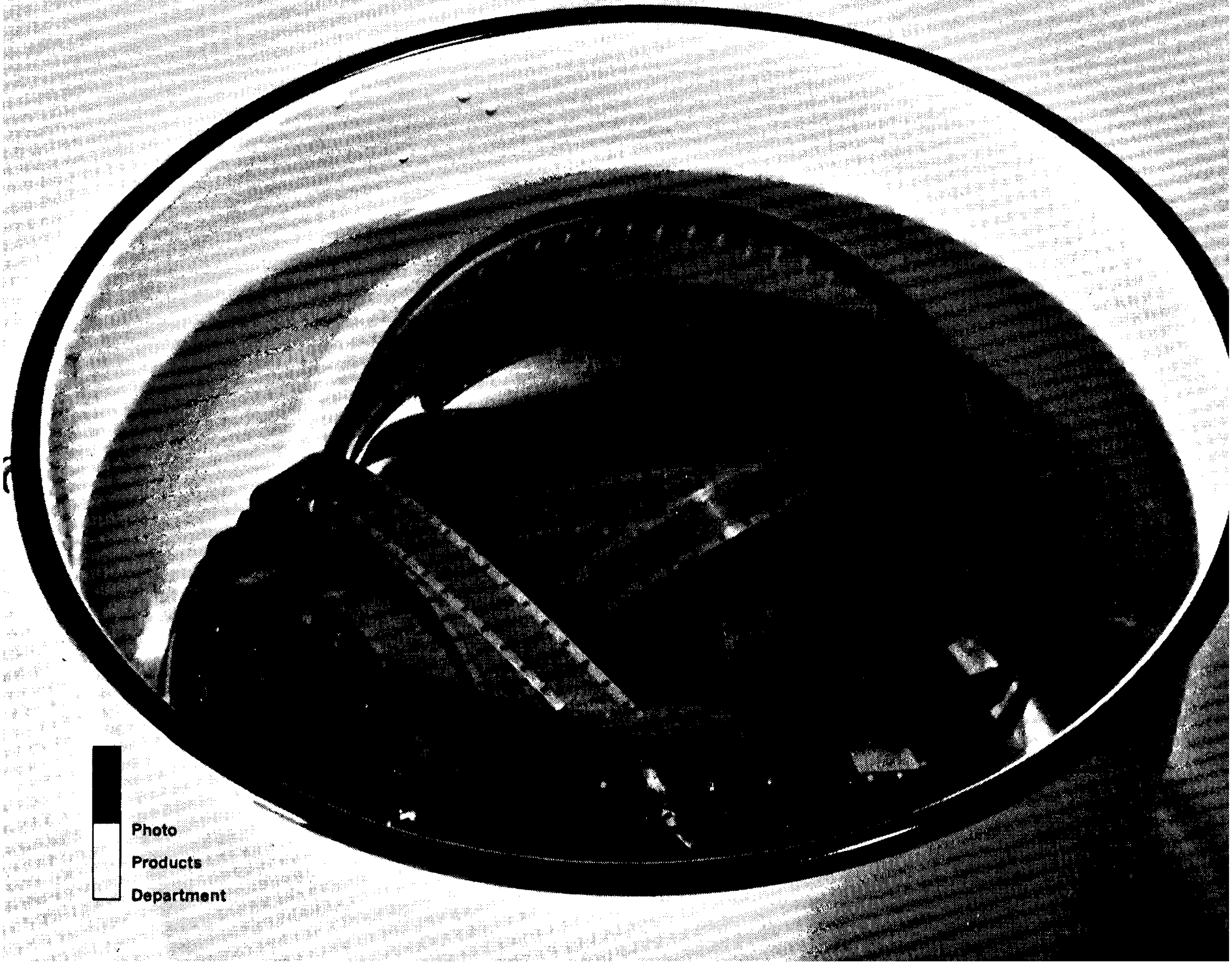

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operate in two frequencies or one laser in different positions. The fringes will then result in a contour of the object. Useful application may be in providing models of complicated three-dimensional objects such as an accurate machine tool.

Holographic images made through opaque glass were among recent findings described by Dr. Leith. He said he could find no immediate application for the process. The diffuser is placed between the object and the hologram is made in the usual manner with a reference beam impinging on the recording plate at some oblique angle. In the reconstruction process, the same diffuser is placed in the path of the light emanating from the hologram.

Professor Stroke reviewed areas of holography introduced since 1963 and stressed holography as a teaching tool.

[Reprinted from Electronic News.]

66M3 T. H. Malim, "Testing blossoms out into color," *Iron Age, 197:* 69–74, Jan. 27, 1966.

If you can see it, you can study it better. Tomorrow's nondestructive testing techniques are coming out of the laboratory now. They promise a new world of pictures and color to make nondestructive testing visual. Liquid crystals, laser holograms, laminographs, thermal images on TV. . . . Tomorrow's metalworking world is about to become visual as nondestructive testing bursts into color. Some of the possibilities are shown in Table I.

[This article is a brief description of the techniques indicated in Table I with about one page on holograms.] Reprinted by SMPTE from *Iron Age* Magazine, January 27, 1966, © 1966, Chilton Co.]

Table I. Testing Takes "Far-Out" Road

Technique	Status	Key Features	Metalworking applications
Liquid crystals	In some use, Commercially, but still largely experimental	Colorless coating undergoes vivid color changes as temperature of stress changes. Also registers presence of certain gases.	Detection of unbonds in honeycomb structures or coatings. Monitoring of approach of critical temperature in machining. Detection of voids or surface defects in welds.
Laser holograms	Experimental	Shows objects or scenes in three dimensions. Possible to show full 360° of three-dimensional object.	Precise study of stress, strain, vibration. Tool for computer-aided design.
Infrared Imaging	Commercial equipment available	Presents thermal information in visual form. Current aims are for faster scanning of active or passive infrared.	Monitoring of components for potential failure by spotting areas hotter or colder than normal. Mapping size, shape, location of inhomogeneities, inclusions, voids in welds, bonded materials, composites.
Color X-Ray	Experimental	Addition of color to conventional radiography to promote resolution, fast reading.	Thickness measurement of very thin foils. Radiography of composite materials or components of varying thickness.
Laminography	Experimental	Radiography of very thin layers of a structure.	Inspection of circuit boards. Examination of thin coatings on base materials for thickness variations, pinholes, inclusions.

66N1 E. G. Nassimbene and R. M. Ross, "Reducing noise in holograms," *IBM Tech. Disclosure Bull., 8:* 1396, 1966.

This method improves a hologram by removing the noise factor due to cross-polarization. In making holograms, a reference beam, usually from a laser, is directed to interfere with diffused, nonpolarized light from an object. The result is captured upon film. An image of the original object can be seen by looking through the film to a virtual image. The latter is formed behind the film plane by wavefront reconstruction. If the hologram is dark, it is difficult to see the image behind it, that is, it is as though an object were viewed through a gray filter. The darker the filter the more difficult it is to see the object through it.

If the reference beam is produced by a gas laser using Brewster angle windows, it is polarized. However, the light which strikes the film from the object is scattered and depolarized. When polarized light is used to cause interference patterns, only light polarized in the same plane causes interference with the reference beam. Light perpendicularly polarized does not. The only part of the light from the object which produces information is that component which is polarized in the same direction as the reference beam. The remaining cross-polarized light does not add information. It does, however, expose the film, thus introducing noise.

A polarizing plate, oriented in the same plane as the reference beam, is placed over the film. The reference beam goes through this plate, and light reflected from the object which is properly oriented passes through, but the remainder is filtered out.

66N2 E. G. Nassimbene, "Panoramic lensless stereoscopic viewing system," *IBM Tech. Disclosure Bull., 8:* 1397–1398, 1966.

This stereoscopic photography system produces panoramic 3-D images viewable without glasses, eliminating the effect which causes the image to appear as though it were being viewed through a distant window. Also, the ordinary narrow angle of view of 30° is widened to 40°. Holograms are used as the recording mechanism. A panoramic 3-D view is achieved by making a hologram, on 16mm frames, of a scene projected by a lens inside a hemisphere, one scene for each eye. When these holograms are viewed by the corresponding eyes, the hemispheres are recreated for each eye just as if the complete hemispheres were physically present. Thus, a complete, panoramic view of any scene can be seen in 3-D by looking directly through a 16mm film strip without glasses.

A characteristic of holograms is that the image formed can be viewed only when illuminated from the same angle as the original reference light. In this system, the right-eye image of one scene can be superimposed upon the left-eye image of the next scene. Thus the same film-strip frame contains two images. The left-eye image is seen by a light beam directed to the left, the right-eye image by a light beam directed to the right by a beam splitter. Three-dimensional panoramic motion-pictures can be made by the proper movement of the film strip.

Each frame may be used for four images. After passing through the beam-splitter, the light beam for the left eye is in a downward direction via a mirror. The light beam for the right eye is in a rightward direction. Pulling the film strip along causes the appropriate separation of right- and left-eye images. If the film strip is turned upside down, two other images can be viewed using these same angles. Thus, the stereo pairs can be obtained by utilizing each frame for four images.

66N3 E. G. Nassimbene and R. M. Ross, "3-D holograms," *IBM Tech. Disclosure Bull., 8:* 1403, 1966.

This device provides a 3-D display of graphic computer output or plotter output. A hologram is made, by a system comprising a laser, a lens, a mirror and a film, of the face of either a dark trace cathode-ray tube or an electrostatic storage and display tube. Either tube receives the computer output and presents an image which can, for example, be part of a sectional drawing, a cross section of a three-dimensional object, a multiaxis plot on x,y,z axes, a mathematical construct, etc. After holographing the film at a plane on the z-axis, the cathode-ray tube is

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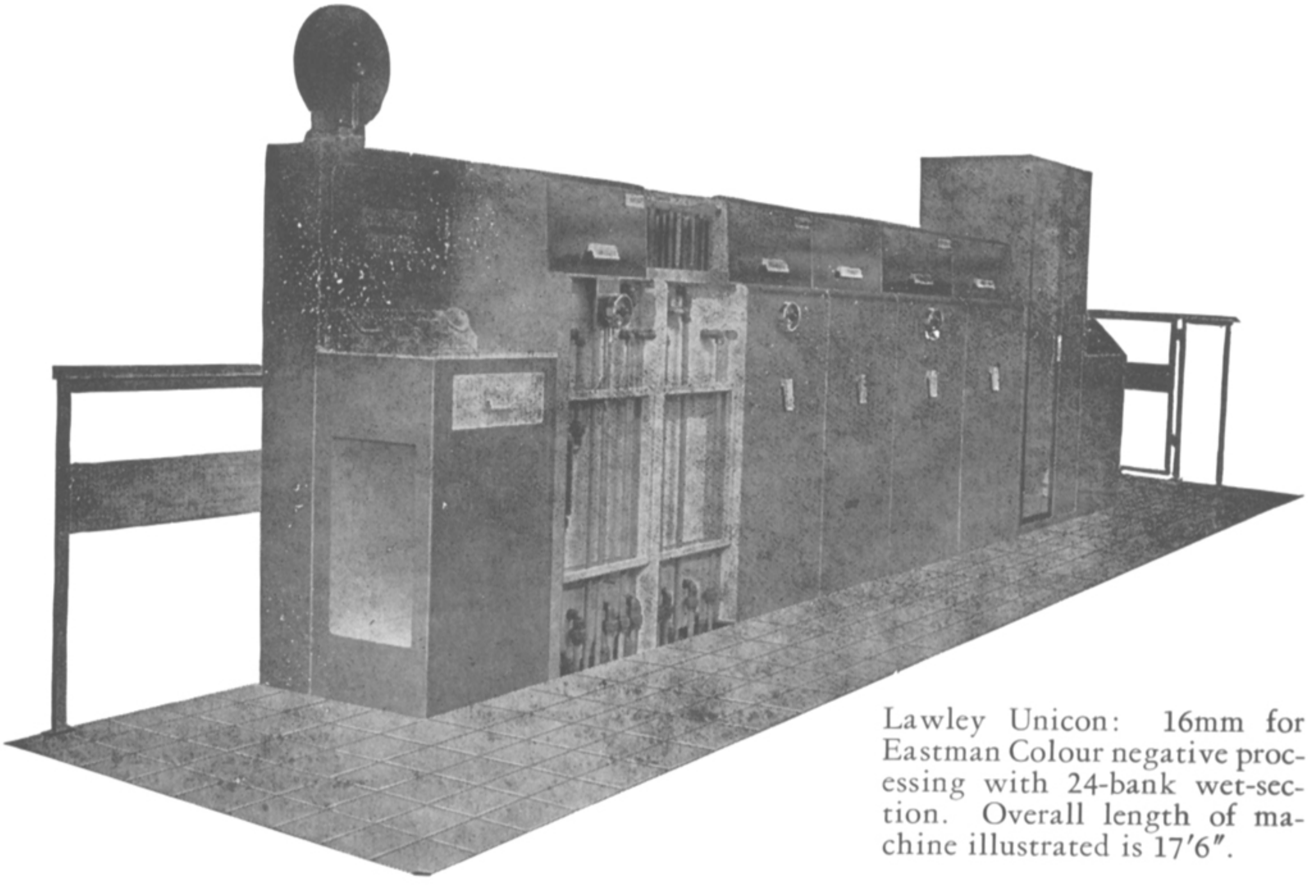

Lawley Unicon: 16mm for Eastman Colour negative processing with 24-bank wet-section. Overall length of machine illustrated is 17'6".

moved a distance corresponding to a distance along the z-axis of the actual object. A new cross-section plane is displayed and another exposure made on the film. After multiple exposures are made at several planes, the film is developed and displayed as a conventional hologram. The image seen appears as a phantom drawing in three dimensions. The cross sections displayed by the cathode-ray tube can be modified by the computer so that partially or completely hidden lines can be completely or partially erased, thereby constructing a more solid 3-D image.

66P2 Kendall Preston, Jr., "Fundamentals of holography," Talk given at a meeting of the N.Y. Chapter of the SPSE, Feb. 16, 1966.

A discussion of the construction of holograms and the problem of reconstructing images from holograms.

66P3 P. J. Peters, "Incoherent holograms with mercury light source," *Appl. Physics Letters*, *8:* 209–210, 1966.

Wavefront reconstructions have been obtained from holograms of an object illuminated with spatially incoherent light from a low-pressure mercury lamp.

The basic idea in making an incoherent hologram is to have each point in the object form its own reference beam. This can be accomplished by splitting the wavefront from each point in the object and causing the two resulting wavefronts to interfere in such a way as to form a Fresnel zone plate. The hologram then consists of the incoherent addition of these zone plates. A number of methods for forming incoherent holograms have been proposed in the literature.[1–5]

A triangular interferometer and afocal lens arrangement was devised by Cochran[5] to produce incoherent holograms. An afocal lens system is placed in the triangular interferometer in such a way that the front and back focal planes of the afocal lens system coincide in a plane in front of the beam-splitter and also at the recording plane. With this arrangement each point in the object gives a zone plate with focal length

$$f = \frac{m^3}{m^4 - 1} z_0 \qquad (1)$$

offset from the optical axis by a distance

$$r = \frac{m}{m^2 + 1} r_0 \qquad (2)$$

where m is the ratio of the focal lengths of the two lenses; z_0 is the axial distance of the point from the front focal plane; and r_0 is the radial distance of the point from the optical axis. In order to separate the real image, virtual image, and d-c background, the object must be located off-axis during the recording of the hologram and the portion of the hologram containing the zone plate centers must be masked off during reconstruction. An important feature of the triangular interferometer is that at the intersection of the recording plane and the optical axis the two wavefronts from each point in the object interfere with zero path difference. In other words, the phase associated with each zone plate adjusts itself so that it has maximum intensity at the point of intersection of the optical axis and the hologram recording plane.

In this experiment a transparency of the letter "C" was illuminated with an 85-W, low-pressure G. E. 85A81PB mercury lamp using a Baird-Atomic interference filter to separate the 5461-Å green line giving a coherence length greater than 1000 wavelengths. Exposures on the order of 10 sec were made on a 649-F plate. Reconstructions were achieved by illuminating the hologram in a collimated laser beam. The image was recorded by exposing Polaroid *P/N* film in the plane where the real image focused.

The reconstruction was made by illuminating an area of approximately 4-mm^2 centered on the optical axis. When the illuminated area was increased, the background noise level increased until eventually the reconstructed image became invisible. The fringe contrast was observed to assume maximum value at the optical axis and to decrease steadily with increasing radial distance from this axis. The radial distance at which the fringe contrast was less than the emulsion grain noise appeared to decrease with increasing object size.

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1. [65L13] 2. [65S14] 3. [63M1]; [63Y1]
4. [65W1] 5. [65C2]

66R1 A. K. Rigler and T. P. Vogl, "The dispersive properties of photographically recorded interferences," Program, Opt. Soc. Am., Mar. 1966 Meeting, p. 33.

As as outgrowth of our investigation of reflection holograms a series of plates were prepared using plane waves from a He–Ne laser as both the object and reference beams. The resulting interference patterns were recorded on 649-F film and exhibited, as expected, diffraction grating properties. The properties of these gratings were investigated and large dispersions were observed. For example, linear dispersion of 0.6 mm/Å for 1-m focal length were measured using the 5770-Å mercury doublet when the included angle between the two recording beams was 120°. These effects can be observed in both transmission and reflection. The results obtained from a series of experiments in which the angle between the two beams was varied will be discussed.

66R2 Harold W. Rose, "Resolution of images reconstructed from copied holograms," Program, Opt. Soc. Am., Mar. 1966 Meeting, p. 12.

The problem of producing copies of a hologram is considered. In particular, the contact printing technique is analyzed in accordance with diffraction theory. The results indicate that image reconstructed from the "copy" will be noisier than those of the original, even though (1) the original and copy emulsions were in "perfect" contact, and (2) the optimum waveshape was used for the contact exposure. Experimental results compare image resolution reconstructed from the copy with that reconstructed from the original.

66R3 F. B. Rotz and A. A. Friesem, "Holograms with nonpseudoscopic real images," *Appl. Physics Letters*, *8:* 146–148, 1966.

The wavefront reconstruction process, first proposed by Gabor[1] and subsequently enhanced by Leith and Upatnieks,[2] produces three-dimensional imagery with a realism unattainable by any other known means. The hologram produces, in its two first-order diffractions, a real and virtual image (complete with all the normal parallax relations encountered in life) which are not preserved in the normal photographic process.

The virtual image is viewed by looking through the hologram as if it were a window. The real image is in a sense more striking, since the observer can "approach" each element of the scene as closely as he wishes. The image, however, has a serious drawback which significantly detracts from its appearance and in fact makes it difficult to observe properly; this difficulty can be roughly described by the statement that the image is pseudoscopic (i.e., shows reversed relief). There are many conflicting visual cues: near objects are obscured by more distant ones, concave surfaces appear convex, etc. Consequently, it is disturbing to view the real image.

We report here a technique for producing holograms having a real aerial image of a three-dimensional scene, in which all the aforementioned visual anomalies are absent. This is done by construction of two holograms in succession,[3] each without the use of lenses. First, a hologram is constructed in the usual manner. This hologram is then illuminated so as to produce the reconstructed real image. This real image is then used as the subject for a second hologram. In our experiment, collimated reference beams were used to maintain unity magnification throughout the process. The two holograms were recorded on Eastman Kodak type 649-F spectroscopic plates.

The second hologram produces a real image in which all the undesirable properties noted above are absent. The entire reconstructed image is suspended in space between the observer and the hologram plate. An observer experiences little difficulty in stereoscopically focusing on this image, and can perceive the original scene in its normal three-dimensional perspective. This is in contrast to the difficulty encountered when attempting to view the pseudoscopic real images of conventional holograms. Despite the two-step process involved, the final reconstructed real image is of high quality and does not exhibit a significant loss of resolution.

Although the above technique is a relatively straightforward extension of existing hologram techniques, it has important implications as far as possible applications are concerned. It presents a method for creating a precise and effective three-dimensional image in space in such a manner that an observer can actually "reach" the scene. The observer is no

longer constrained to look through a window—the hologram plate—at the scene. This feature may be quite significant in the production of extremely realistic visual displays or simulation devices.

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1. [49G1] 2. [64L1] 3. [52R1]

66R4 R. M. Ross, "Making holograms using Brewster's angle," *IBM Tech. Disclosure Bull., 8:* 1404, 1966.

This method of making a hologram gives the observer a greater angle of view of the 3-D object. A higher resolution of the image is also obtained. The hologram is made by placing the object to be recorded quite close to the photographic plate and illuminating it by reflecting plane polarized coherent light from the glass surface of the plate, which is opposite the emulsion. The beam of coherent light is directed toward the plate at an angle which is Brewster's angle for the material involved, i.e., glass/air = 56° 40′. By deviating slightly from Brewster's angle or by rotating the plane of polarization of the coherent light beam, the latter can be made to vary from total reflection to mostly transmission through the glass surface of the plate to the emulsion. In this manner, the optimum light ratio, carrier beam/light from object, is obtained.

66S2 Karl A. Stetson, "Diffraction from surface ripple of aluminized photographic emulsions," Program, Opt. Soc. Am., Mar. 1966 Meeting, p. 12.

The diffraction of light into hologram reconstructions by aluminized 649-F emulsion surfaces has been reported.[1] If it is assumed that the physical mechanism for this diffraction is a set of ripples in the emulsion surface that correspond to the amount of silver developed at each point in the emulsion, then the diffraction process is described by the boundary value problem solutions that have been published.[2] In the case of photographic emulsions, however, the height of the ripples may be assumed to be small and an approximation may be introduced into the formal solution which gives an interesting result. Ripples of a few thousandths of a wavelength height give almost a percent or two of the incident light diffracted into the first order. This indicates that the diffraction of light may be the most practical method of detecting small periodic deformations in metal surfaces.

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1. [65V2]
2. G. W. Stroke (thesis, University of Paris, 1960)

66S3 George W. Stroke, "Three new advances in optical holography," Program, Opt. Soc. Am., Mar. 1966 Meeting, p. 7.

Three new advances yet to be published have now been made in work by the author and his students D. Brumm, A. Funkhouser, A. Labeyrie and R. C. Restrick, in part in collaboration with D. Gabor.[1](1) Holographic interferometry (based on the Gabor and Stroke et al. principle[2] of successively adding intensities in double-exposed and multiple-exposed single holograms): (a) Double-exposed single holograms may be used for two-beam interferometry;[3] (b) Two separately exposed holograms permit one to first "code" an already "invisible" phase object by recording one hologram (even through a random diffuser), and next to "decode" the image with the "decoding" key carried in a second hologram.[4](2) Absence of any "twin-image" separation or of any phase-recording problems in the original Gabor "in-line" holography arrangement has now been demonstrated by us,[5] in contrast with a previously stated widely accepted belief[6] (e.g., statements attributing these properties necessarily to off-axis arrangements, now found to be perfectly equivalent and not different). (3) The Lippmann-Bragg effect in thick holographic emulsions (Denisyuk, 1962[7]) is describable by a simplified "modulated Bragg reflection-layer" theory, which we present, and which has resulted, in particular, in a new type of reflection hologram, yielding color images when illuminated in spectrally incoherent white light.[8]

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1. [66S1] 2. [65G3], see also [65S11]
3. [66S5] 4. [66S7] 5. [66S9]
6. [65L4] 7. [62D1] 8. [66S4]

66S4 G. W. Stroke and A. E. Labeyrie, "White-light reconstruction of holographic images using the Lippmann-Bragg diffraction effect," *Physics Letters, 20:* 368–370, 1966.

An extension of the 1962 Denisyuk method to record reflection holograms in Lippmann emulsions has permitted us to reconstruct monochromatic images with white light (e.g. sun) and demonstrate possibilities of simulating three-dimensional gratings for crystallographic studies.

We have used an arrangement for recording holograms of two- or three-dimensional objects in such a way that illumination of the hologram with ordinary sunlight (or other white light, e.g. from a flashlight) will produce a single-color image of the object by wavefront reconstruction. An example of our method was the reconstruction of the image of a grasshopper which we have obtained with sunlight illumination of such a hologram. The original object in this case was a 24 by 36 mm^2 Kodachrome transparency placed at about 1 in. from the photographic plate (along the z-direction), so as to produce a reflection version of a "projection" hologram[1] by recording in 6328 Å laser light. Reconstructions with three-dimensional objects, both diffusing and specularly reflecting, have been equally successful.

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1. [66S1]

66S5 George W. Stroke and Antoine Labeyrie, "Two-beam interferometry by successive recording of intensities in a single hologram," *Appl. Physics Letters, 8:* 42–44, 1966.

Heretofore in optics, two-beam interferograms of a wavefront scattered by an object have generally been recorded by comparing the scattered wavefront (e.g., reflected, transmitted, or diffracted by an object) to a wavefront simultaneously reflected from a reference mirror, for example in a beam-splitting interferometer, such as that introduced by Michelson and others. More generally, two different wavefronts can thus be added with the aid of beam-splitters or equivalent arrangements. These interferometers permit the complex amplitudes of the two wavefronts to be added, provided the two wavefronts are made to interfere simultaneously.

In this letter we show that two-beam interferograms can be obtained by wavefront reconstruction from a hologram, which was recorded by having a coherent background successively interfere in the same latent image, first with the wave "transmitted" through the object and next with the wave incident on the object, or vice versa. Our method is based on a method which we may call a method of "holographic intensity interferometry," first described by Gabor and Stroke et al.,[1] who showed that successive addition of intensities in a hologram could be made equivalent to a simultaneous addition of complex amplitudes in an interferometer. More precisely we showed that complex amplitudes could be added, of not just two but indeed of several wavefronts, by making each of the wavefronts first interfere in succession (in the latent photographic image) with a same coherent-background reference wave, thus adding in succession the intensities of the individual partial holograms, so as to retrievably store in the resultant hologram the complex addition of the several wavefronts.

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1. [65G3]

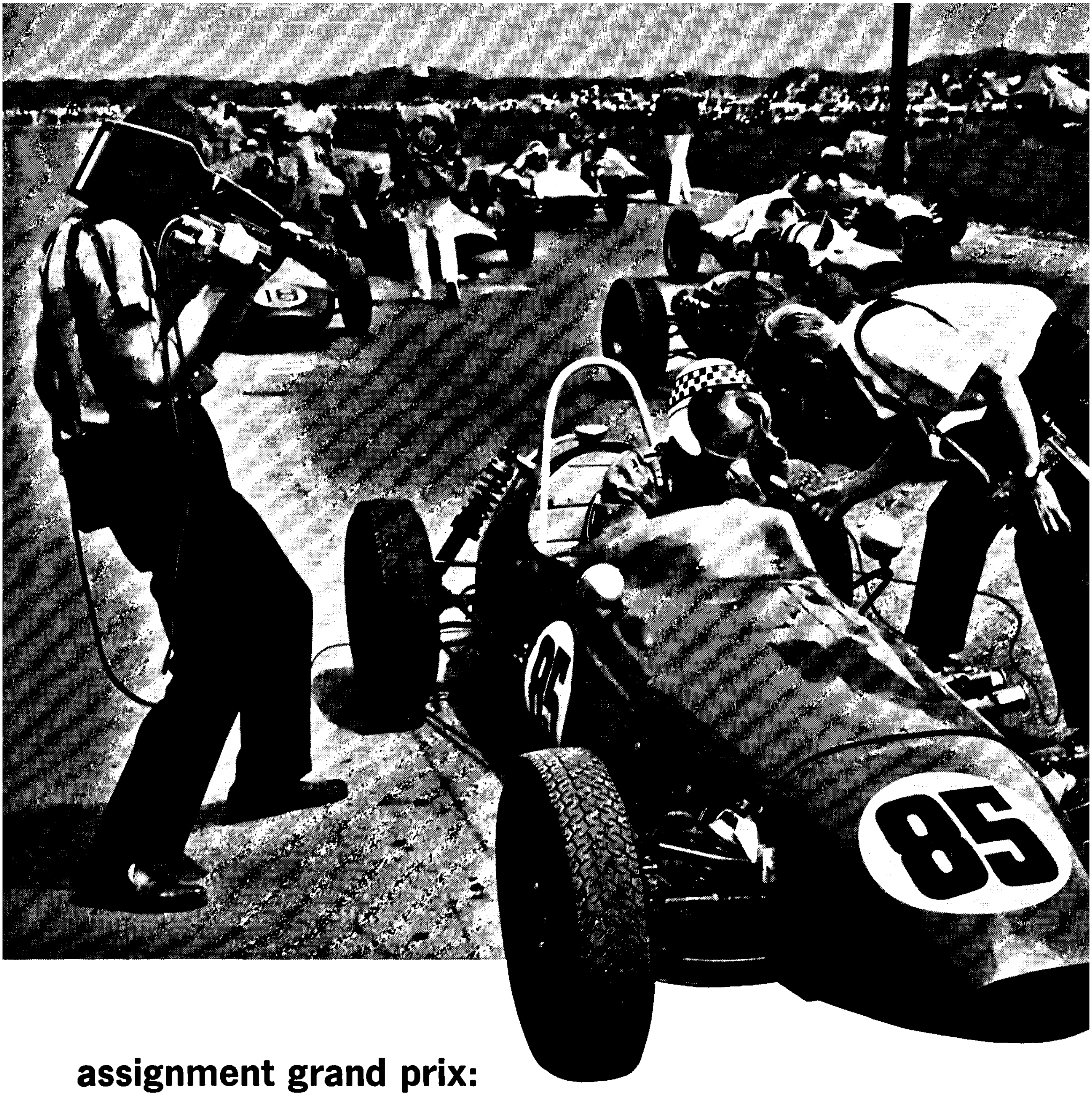
66S6 Alan Serchuk, "Holographic research gaining, economic impact may top TV's," *Electronic News, 11:* 1, 4, Jan. 31, 1966.

Holography is the lensless type of photography or wavefront reconstruction process discovered in 1947 by Dennis Gabor, who visualized its application in electron microscopy, but was hampered by a lack of a coherent light source.

The development of the laser changed that. The laser, the subject, a mirror and a photographic plate are arranged so that part of the laser beam illuminates the subject and is reflected to the plate. Another part of the beam is reflected by the mirror to the plate. Interference patterns form where the beams meet and are recorded on the plate. To view or reconstruct the image, the developed plate must be illuminated by a coherent or nearly coherent light source.

For multiple exposures, the angle of illumination is varied with each exposure. Each succeeding image, however, reduces the resolution of those preceding. The number of images on a single plate, therefore, is limited by the required resolution.

Holography could have an economic impact almost as great as television within a decade. This, at least is the estimate of an observer at GCA Corp., Bedford, Mass. If the number of research teams working in the field is any indication, he may be right. The exact number of researchers is



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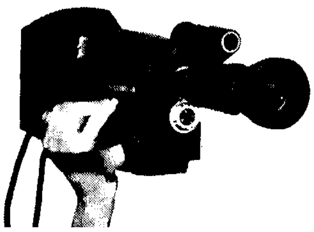

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not known, although one observer believes such work is going on in at least 100 laboratories.

Interest ranges from curiosity—"just keeping abreast of the technology" as one researcher said—to some serious involvement by various government agencies, industrial firms and universities across the country.

Certainly most of the work performed on holography today is still classified as research, although those in the field generally agree that it has passed the laboratory stage. Practical applications still seem some years away—five to ten years by most estimates—although Conductron Corp., Ann Arbor, Mich., is preparing to market holograms and viewing systems.

Holography may lead to three-dimensional motion pictures and television, better aerial photographs and x-rays, but none of these are now feasible and will not be for a while, according to Emmett N. Leith.

The big news in holography, however, appears to be character recognition. Gerald Parker, physicist for Electro-Optical Systems, Inc., Pasadena, Calif., said EOS looks at optical data processing as having "the greatest commercial potential in the field."

[Reprinted from Electronic News.]

66S7 G. W. Stroke and A. E. Labeyrie, "Interferometric reconstruction of phase objects using diffuse coding and two holograms," *Physics Letters, 20:* 157–158, 1966.

In contrast with previously described multiply-exposed single holograms, used for interferometry according to a principle first described by Gabor, Stroke, Restrick, Funkhouser and Brumm, interferometric image coding and decoding may be accomplished in diffuse light with two separately recorded holograms.

66S8 Erich Spitz and Alain Werts, "Reconstruction in three-dimensional space of the curve traced by a moving luminous point," *Compt. Rend., 262:* Series B, 758–760, 1966.

On sait qu'une plaque photographique sur laquelle on a enregistré le réseau d'interférences produit par l'onde diffusée issue d'un objet et une onde de référence provenant de la même source lumineuse cohérente, contient l'information sur l'amplitude et la phase de l'onde diffusée.

Cette plaque appelée hologramme permet de reconstituer l'objet en trois dimensions. En particulier, si l'objet est un point lumineux, la projection de son hologramme permet de reconstituer la position initiale du point dans l'espace.

Nous montrons ici qu'en déplaçant ce point lumineux pendant l'exposition de la plaque, on peut reconstituer la courbe correspondant à toutes les positions du point lumineux.

66S9 G. W. Stroke, D. Brumm, A. Funkhouser, A. Labeyrie and R. C. Restrick, "On the absence of phase-recording or 'twin-image' separation problems in 'Gabor' (in-line) holography," *Brit. J. Appl. Phys., 17:* 497–500, 1966.

In contrast with a general belief which followed Gabor's wavefront-reconstruction imaging work in 1948, the original Gabor "in-line" hologram recording scheme is shown to produce perfectly separable "twin images," without any phase-recording problems, notably in high-resolution imaging and with diffused illumination.

66S10 E. P. Supertzi and A. K. Rigler, "Wide-angle holography," *J. Opt. Soc. Am., 56:* 524–525, 1966.

The literature on holography[1,2] has emphasized the three-dimensional nature of the image. However, over the small area of the conventional 4 by 5-in. photographic plate, or sheet of film, only a small angle is subtended at the scene. This note expands the art of holography by pointing out the ease with which target angles of more than 180° may be recorded in the laboratory.

Our hologram was recorded on Kodak type SO-243 special high-definition aerial film which is available in strips 5 in. wide. The vacuum film holder is a semicircular cylinder of porous bronze with a 12-in. radius and 5-in. height. This cylinder is set in a hollow frame which is connected to the house vacuum.

The scene to be recorded (a pair of figurines 2 in. tall) was placed near the center of the cylinder and illuminated by a diverging beam from a He–Ne laser. To produce a reference beam, a spherical mirror was placed near the scene in the laser beam. This mirror was made by polishing a 1000-ml round-bottom flask. This concentric scheme keeps the angle between the reference and object beams fairly small so that film of extreme resolution capability is not required.

[Figure 1] is a photograph of the apparatus. [Figure 2] is a composite of photographs of the virtual image, as different sections of the hologram are viewed. Portions of the scene are not illuminated directly by the beam from the laser but are lighted by a reflection from the globe. This low-intensity illumination can be enhanced by using plane mirrors for backlighting rather than relying on the reference mirror.

This technique may be extended further so that the scene may be viewed in reconstruction over a large solid angle, thus helping to open up the application of holography to large display or training devices.[3]

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1. [64L1] 2. [65L3] 3. [65V2]

66S11 J. B. Story, G. S. Ballard and R. H. Gibbons, "Schlieren photographs from holograms," *J. Appl. Phys., 37:* 2183–2184, 1966.

The use of holograms in making Schlieren photographs, as suggested by Horman,[1] has been accomplished by using the carrier-beam hologram method of Leith and Upatnicks.[2] The Schlieren method used was essentially that of Dodd,[3] who used a pinhole rather than a first knife edge, and an opaque dot on a glass plate instead of a second knife edge. For the purposes of this experiment, the pinhole was omitted and the laser brought to a point focus. This resulted in an unsophisticated apparatus that was satisfactory for demonstrating the principle involved, but gave pictures of poor quality.

The portion of the apparatus that was used for making the hologram is shown [in Fig. 1]. The wedge deviated one portion of the parallel beam such that it overlapped another portion of the beam that had passed through the Schlieren field. When the hologram was viewed, the Schlieren head was moved to produce a converging light beam. This arrangement caused the light that would have been associated with the virtual image of the Schlieren field to be brought to a point focus and subsequently to form a real image of the Schlieren field. The reconstruction could have been made using a knife edge instead of a dot at the point focus.[4]

Small dots of ink of known diameter were placed on the glass plate at the point focus to block out the major portion of the light that was not deviated in the Schlieren field. The film used in making the holograms was Kodak contrast process panchromatic film (resolution 136-225 lines/mm) instead of the more commonly used Kodak 649F (resolution >2000 lines/mm).

The object viewed in the Schlieren field was a hot soldering iron. The reconstruction of the Schlieren field without using a dot is shown in [Fig. 3]. When a series of dots of varying size were introduced at the point focus, a series of different Schlieren presentations were obtained [Figs. 4, 5, and 6]. Additional presentations were obtained when the dot was placed slightly off-center [Fig. 7].

The advantages of the use of holograms in making Schlieren photographs are obvious. A transient phenomenon can be captured in hologram form, and a maximum amount of information can be extracted from it by making a series of reconstructions using a variety of adjustments, including the viewing of Schlieren fields separated in depth.

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1. [65H7] 2. [63L2]
3. Jack G. Dodd, in *The Microscope and Crystal Front*, (to be published).
4. Richard T. Goddard and Arthur J. Wennerstrom, *AF Res. Rev., IV:* No. 8, 7–9, October 1965 (unpublished).

66T1 Patrick Tollin, Peter Main, Michael G. Rossmann, George W. Stroke and Robert C. Restrick, "Holography and its crystallographic equivalent," *Nature, 209:* 603–604, 1966.

Recent advances in holography[1] have made apparent certain formal relationships between optical image synthesis, on the one hand, and the heavy atom technique in x-ray crystallography, on the other. Bragg[2] has already qualitatively indicated this analogy. An exact correspondence between the two processes has become clear only since the following two developments: (1) Fourier transform holography for extended sources;[3] (2) the Ramachandran and Raman[4] α-synthesis to deconvolute the Patterson function when the structure is partially known.

In the case of holography, we perform an interference experiment between the known and unknown extended objects

$T_P(\xi)$ and $T_Q(\xi)$, where these symbols define the complex amplitude transmission of the electric field vector distribution on illumination by a wave of unit amplitude. Thus the complex amplitude distribution at point x on the hologram will be $A(x) = t_P(x) + t_Q(x)e^{2\pi i a\cdot x}$, where $t_P(x)$ and $t_Q(x)$ are the spatial Fourier transforms of $T_P(\xi)$ and $T_Q(\xi)$ and a is the separation of $T_P(\xi)$ and $T_Q(\xi)$, that is,

$$t(x) = \int T(\xi)e^{2\pi i x\cdot\xi}d\xi$$

where the integral is taken over the surface of the source. The intensity $H(x)$ recorded on the hologram at point x will then be

$$\begin{aligned} H(x) &= A(x)\cdot A^*(x) \\ &= |t_P(x)|^2 + |t_Q(x)|^2 \\ &+ t_P(x)\cdot t_Q^*(x)e^{-2\pi i a\cdot x} \\ &+ t_P^*(x)\cdot t_Q(x)e^{2\pi i a\cdot x} \end{aligned}$$

It was shown by Stroke et al.[3] that a Fourier transformation would permit the reconstruction of the unknown object, $T_Q(\xi)$, provided the hologram were illuminated by the same object $T_P(\xi)$ and that the Fourier transform of the product $t_P(x)t_P^*(x)$ be a delta function. Further, if it is desired to remove the two centrosymmetrically related images, it is necessary that $t_P(x)t_P(x)$ is not a delta function. It follows that the reconstructed object will be formed by the transform of

$$\begin{aligned} &t_P(x)|t_P(x)|^2 + t_P(x)|t_Q(x)|^2 + \\ &{}_P(x)\cdot t_P(x)t_Q^*(x)e^{-2\pi i a\cdot x} + \\ &\qquad t_P(x)\cdot t_P^*(x)t_Q(x)e^{2\pi i a\cdot x} \qquad (1) \end{aligned}$$

In the case of a partially known crystallographic structure we observe the interference effect between the known and unknown parts of the structure. The complex amplitude F_H of the resultant wave will then be

$$F_H = F_P + F_Q$$

where F_P is the structure factor of the known part and F_Q that of the unknown part, at the same reciprocal lattice point. Thus the intensities recorded will be:

$$F_HF_H^* = F_PF_P^* + F_QF_Q^* + F_PF_Q^* + F_P^*F_Q$$

The Ramachandran and Raman α-synthesis reconstructs the crystal structure by taking the Fourier transform of $F_P|F_H|^2$, that is,

$$F_P|F_P|^2 + F_P|F_Q|^2 + F_P^2F_Q^* + |F_P|^2F_Q \qquad (2)$$

which is identical in form to (1). If we consider the noncentrosymmetric case we require the condition that $F_PF_P \neq F_PF_P^*$. That is, we must have a noncentric configuration in the part of the structure that is known. A measure of this can be given by the Fourier transform of F_P^3 (ref. 5). The need for this condition arises from the superposition of the enantiomorphic structures in the crystallographic case. In contrast these two images are separated in holography owing to the physical separation of T_P and T_Q in the recording of the hologram. In the centrosymmetric crystal structure the two overlapping images coincide.

A second-order improvement on the α-synthesis is produced by the β-synthesis[4] in which $|F_H|^2/F_P^*$ replaces $F_P\cdot|F_H|^2$ as coefficients. While this is easy to achieve in crystallography it may present greater difficulties in optics.

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1. [65G1]; [65S7]; [64S3]
2. [50B1] 3. [65S16]; [65S15]
4. G. N. Ramachandran and S. Raman, *Acta Cryst., 12:* 957 (1959).
5. A. L. Patterson, *Acta Cryst., 2:* 339 (1949).

66T2 G. Tricoles and E. L. Rope, "Wavefront reconstruction with centimeter waves," Program, Opt. Soc. Am., Mar. 1966 Meeting, p. 12.

A description is given of wavefront reconstructions which were made with electromagnetic waves of centimeter wavelengths. The objects were a metallic strip and a hollow, dielectric, hemicylinder. Diffraction patterns are given for these objects illuminated with nearly plane waves. Microwave analogs of holograms are described. The configurations of the hologram analogs were determined with three different techniques corresponding to known optical methods.[1–3] Wavefront reconstructions were made by illuminating the analogs with a microwave beam. These reconstructions are compared with the fields diffracted by the objects. Some results are given for laser beam illumination of photographically reduced analogs.

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1. [49G1] 2. [62L1] 3. [65H4]

66T3 L. H. Tanner, "Some applications of holography in fluid mechanics," *J. Sci. Instr., 43:* 81–83, 1966.

The methods of wavefront reconstruction or holography discovered by Gabor and developed by Leith and Upatnieks greatly increase the amount of information which may be recorded on a single photographic plate. Holography often requires the use of slow, high-resolution plates and at first sight might seem unsuitable for use in aerodynamics, in which we are usually concerned with rapidly changing phase objects. The present paper shows, however, that for some purposes the spatial frequencies required are low enough to record on fast plates. A single hologram can be produced which can be viewed at leisure by all the normal visualization methods. Some experimental results are given.

66T4 L. H. Tanner, "The application of lasers to time-resolved flow visualization," *J. Sci. Instr., 43:* 125, 1966.

The method of streak photography is often used for the visualization of transient flows, but a very bright, narrow, flat beam of light is required, usually produced by an illuminated slit. With conventional light sources it is difficult to get enough light through, and Johannesen and Zienkiewicz[1] have shown that this results in restrictions on the space and time resolution. The difficulties cease to exist if coherent light from a gas laser is used, and the space and time resolution may be very much improved.

Suppose we wish to produce a beam 10 cm long, to pass through a shock tube or wind tunnel 10 cm wide, and that we have a laser producing a parallel beam of 1 mm radius. We could, for example, use the following optical elements:

(1) a concave lens, 50 cm focal length, which spreads the beam to a radius of 3 mm at a point 100 cm from the lens;

(2) a cylindrical concave lens of 2.3 cm focal length, 27.3 cm from lens (1): this spreads the beam in one direction only, to a half-width of 5 cm at the point 100 cm from lens (1);

(3) a collimating lens or mirror of 75 cm focal length, placed 100 cm from lens (1).

The focal planes of the collimating lens and of the cylindrical lens coincide so that the resulting beam is parallel, 10 cm long, as required. In the perpendicular direction the focal plane of lens (1) is 150 cm from the collimating lens. The beam will be brought approximately to a focus 150 cm on the far side of this lens, and this is where we place the shock tube.

The thickness of the beam passing through the shock tube may be calculated from the relations for propagation of a Gaussian beam given, for example, by Kogelnik.[2] For the example given, the "waist" half-width at the shock tube centerline is 0.010 cm while at the walls it is greater by a factor $\sqrt{2}$. This thickness compares very favorably with that obtained with conventional sources.

On the camera side we require only an optical system producing a suitable magnification. Suppose this is one-third; then the area of image is 0.022 cm^2. Now a suitable photographic plate requires an energy of 0.1 erg cm^{-2}. Allowing a factor of 5 for light losses in the optics, this means that the energy required is 0.011 erg. If the laser power is P mW, the exposure time required is thus $1.10/P$ μsec. This gives the time resolution of the system and shows that, even with a low-power laser, it is considerably better than can be achieved with conventional light. Still further improvement can be obtained by using a convex cylindrical lens of very short focal length just in front of the photographic plate.

With appropriate optics the end product could be a hologram,[3] an interferogram, a schlieren photograph or a shadowgraph. For example, to obtain an interferogram, a Mach–Zehnder interferometer could be placed between the collimating lenses.

A further possibility is to traverse the light beam repetitively across the width of the shock tube or wind tunnel and use the result as a framing camera. The beam may be traversed by a rotating mirror placed at the focal plane of the collimating lens. The advantages and disadvantages are the same as those of a moving-slit type of focal plane shutter in an ordinary camera. Motion is stopped, so the system could be used, even with a low-power laser, for observation of turbulent flows. Distortion of moving objects would, however, appear. Thus the system would be most useful for wind tunnels in which the flow, though turbulent, is pseudosteady.

The author hopes soon to produce a more comprehensive paper giving experimental results together with a more complete description of the optical requirements.

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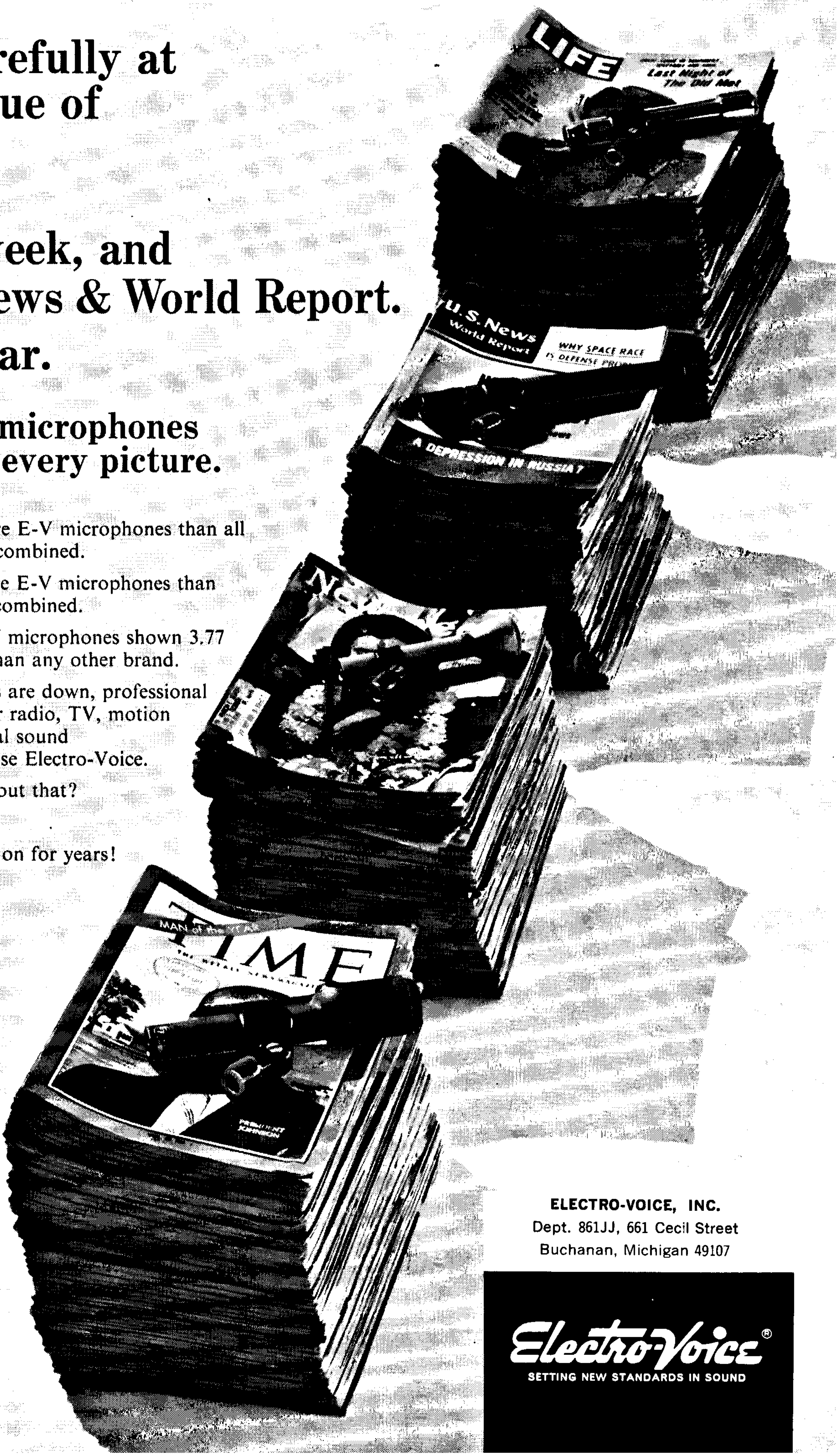

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1. N. H. Johannesen and H. K. Zienkiewicz, *Aeronautical Res. Coun. Rep. No. 26*, p. 634.
2. H. Kogelnik, *B.S.T.J.*, *44:* 455–94, 1965.
3. [66T3]

66T5 G. Leonard Tyler, "The bistatic, continuous-wave radar method for the study of planetary surfaces," *J. Geophys. Res. 71:* 1559–1567, 1966.

A method is described for radar mapping of the surface of a planet. It is based on the use of a bistatic, continuous-wave mode of radar operation between the earth and a spacecraft orbiting or flying by the planet. The interference pattern resulting from a plane wave illuminating the planet and the fields scattered by the planet is analyzed. It is shown that the power in this pattern contains components corresponding to a linear superposition of the elementary wavelets scattered by the surface, multiplied by a phasor. The conditions under which the elementary wavelets may be recovered from a measurement of the interference pattern are given. Matched filter detection is then used to recover the amplitude of the local currents on the surface associated with each wavelet. The response to a point scatterer is calculated. Resolutions of a few wavelengths in range and azimuth can theoretically be obtained. Analogous applications to other geophysical problems are suggested.

This paper presents a novel method for obtaining radar maps—i.e., radar brightness distributions—of other planets and the moon by means of a bistatic, continuous-wave mode of radar operation between an orbiting space vehicle and an earth station. The technique is a simple extension of "wavefront reconstruction" introduced by *Gabor* [1948] for microscopy, except that now an orbiter is used to sample the radio-frequency interference pattern formed by an illuminating wave and the fields scattered by a planet. For high signal-to-noise ratios, these maps will have a resolution of a few to a few hundred wavelengths; for very low signal-to-noise ratios, resolutions of several thousand wavelengths can be achieved. Such maps will provide detailed information on the structure and composition of planetary surfaces—information that has not previously been obtained and that cannot be obtained by optical observations alone. Radar maps of Venus, for example, would apparently provide one of the few means, other than direct exploration, for studying the surface.

66U1 John C. Urbach and Reinhard W. Meier, "Characteristics of thermoplastic xerographic holograms," Program, Opt. Soc. Am., Mar. 1966 Meeting, p. 7.

Successful reconstructions from phase holograms recorded on thermoplastic xerographic materials are reported. The thermoplastic-overcoated photoconductor configuration has characteristics that make it particularly suitable for holographic use. Holograms of this type have been recorded with carrier frequencies as high as 1000 cycles/mm. The bandwidth limitations and noise characteristics of thermoplastic xerography have been examined in the holographic context, and it has been found that under certain conditions the grainless nature of thermoplastic holograms can lead to a very low level of scattered background light in the reconstructed images.

66U2 J. Upatnieks, A. Vander Lugt and E. Leith, "Correction of lens aberrations by means of holograms," *Appl. Optics*, *5:* 589–593, 1966.

Holograms are made of a wavefront emerging from a lens having spherical aberration. The hologram, when used in combination with the lens, serves as a corrector plate for the lens. Experimental results are given, followed by a third-order analysis.

66U3 John C. Urbach and Reinhard W. Meier, "Thermoplastic xerographic holography," *Appl. Optics*, *5:* 666–667, 1966.

It has been demonstrated by Rogers[1] and more recently by Cathey[2] that it is possible to make phase holograms, i.e., holograms in which the recorded information alters the phase rather than the amplitude of the reconstruction wavefront. Such phase holograms have been made previously from conventional silver holograms by bleaching the silver and utilizing the phase differences introduced by gelatin swelling and/or refractive index changes. We wish to report the making of phase holograms by means of thermoplastic xerography, an electrophotographic process in which a phase image results from the electrostatically induced deformation of a dielectric surface.

Of the several variants of thermoplastic xerography, it was decided to use an organic photoconductor overcoated with an insulating thermoplastic and operated in the charge-expose-recharge mode. This configuration has been discussed previously in the literature.[3] It was selected because it has a particular characteristic which seems well-suited for holographic recording. This is its quasiresonant sine-wave response, reported earlier by one of us[4] and since investigated in more detail.[5] As a consequence of the hydrodynamic behavior of thin charged fluid layers, analyzed recently by Budd,[6] the deformation of such a thermoplastic proceeds most rapidly in a particular spatial frequency range determined mainly by the thickness and, to a lesser extent, by the applied voltage. Moreover, an input grating pattern whose spatial frequency is near the quasiresonant frequency tends to suppress random deformation, which constitutes a source of noise in both conventional and holographic recording.

Since the use of an off-axis reference beam in holography produces a spatial carrier of nonzero mean frequency that is modulated by the image information,[7] it is evidently desirable to tune the quasiresonant frequency of the thermoplastic recording medium so that it is centered on the holographic carrier frequency. On the basis of experience with conventional imaging, this should result in maximum sensitivity and minimum random deformation noise. Such tuning can be accomplished by adjusting either the thermoplastic layer thickness and voltage of the recording process or the carrier frequency determined by the off-axis angle of the reference beam.

Thermoplastic xerographic holograms were made using 6328 Å light from a helium–neon laser with an output power of 0.8 mW in the TEM$_{00}$mode. In the hologram-recording apparatus, the reference beam point source was located at the same distance from the hologram as the object. This configuration was shown by one of us[8] to be advantageous from the point of view of aberrations. It has also been shown[9–11] to be a configuration capable of achieving optimum resolution in the object space.

The thermoplastic-overcoated photoconductor (on a conductively coated glass substrate) was corona charged, exposed, recharged and then developed by a stream of hot air. For simplicity and ease of comparison of the reconstructed image with the original object, the former reference beam was used to illuminate the hologram, yielding a unit magnification for the true reconstructed image, which, in this case, is a virtual image coincident in position with the original object. Because the recording material described here has no further light sensitivity after the recharge step, inspection development of the hologram in situ is possible and has been used with most of the holograms made thus far.

The original object (a high-contrast MIL STD 150A target) and its reconstructed true image were photographed with the same telescopic camera having a linear magnification factor of approximately six. The mean carrier frequency used in making the hologram was approximately 370 cycles/mm. Successful reconstructions were obtained also from holograms with carrier frequencies of 210, 800 and 1000 cycles/mm. These four carrier frequencies were used with four different sets of samples, each set having a thermoplastic coating of appropriate thickness. The best results, in terms of sensitivity and freedom from scattered background, have been obtained, as expected, in those experiments in which the holographic carrier frequency most closely matched the quasiresonant frequency of the thermoplastic layer.

Holographic recording on thermoplastics, using the quasiresonant mode of operation, has certain interesting and potentially useful characteristics, three of which are as follows:

(1) *Speed of Processing.* A complete cycle of operation, from initial charge to final image, can be carried out in a matter of seconds without moving the recording medium. The process could be automated readily and reduced in time to a small fraction of a second.

(2) *Intrinsic Freedom from Noise.* Optimum choice of process parameters leads to an intrinsically grainless recording process, inherently free from scattered light. In conventional silver halide holography, it can be said that the grain pattern of the emulsion is the basic noise carrier of image information, and that the two-beam interference pattern, which is the carrier of holographic information, should

be regarded as a subcarrier modulating this grain pattern. Thus, an unwanted background of light, scattered from grains, is an unavoidable feature of silver halide holography. In thermoplastic holography, on the other hand, the basic carrier of image information is the deformation pattern itself, which follows the holographic carrier and is inherently smooth and noise-free. Hence, unwanted scattering is not intrinsic, and can be kept to a low level.

(3) *Photographic Speed.* The speed of the particular process used here was such that exposure times for optimum results were about an order of magnitude less than those required for Eastman Type 649F emulsion under comparable conditions. This speed was achieved with a relatively insensitive photoconductor, and could be increased considerably by selecting one with maximum sensitivity for the hologram-recording radiation. At present, this process occupies a position between general-purpose silver halide emulsions and Lippman-type emulsions, both in speed and in maximum carrier frequency.

These characteristics indicate that thermoplastic xerography should prove to be a useful recording medium for those holographic applications where rapid processing, low scattered-light level, or other inherent advantages of this process are important.

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1. [52R1] 2. [65C1]
3. R. W. Gundlach and C. J. Claus, *Photo. Sci. Eng.*, *7:* 14 (1963).
4. J. C. Urbach, Proc. Conf. on Photographic and Spectroscopic Optics, *Japan J. Appl. Phys.*, *4:* Suppl. I, 208 (1965).
5. J. C. Urbach, Paper delivered at SPSE Symposium on Photography in Information Storage and Retrieval, Oct. 1965.
6. H. J. Budd, *J. Appl. Phys.*, *36:* 1613 (1965).
7. [62L1] 8. [65M6] 9. [52E1]
10. [65W1] 11. [65S6]

66V2 Jean-Charles Vienot and Jacques Monneret, "Application of holography to phase contrast and schlieren studies," *Compt. Rend.*, *262:* Series B, 671–673, 1966.

Les perturbasions d'une onde lumineuse sont mises en évidence par restitution holographique après superposition de cette onde, convenablement filtrée, à une onde cohérente de même courbure. Les avantages des techniques classiques de visualisation des détails (contraste de phase, strioscopie) sont associés à ceux de l'holographie: localisation des microdéfauts, faibles variations d'indice, suivant les trois dimensions simultanément.

Les distorsions d'amplitude et de phase subies par une onde coherente traversant un objet microscopique de transparence complexe sont habituellement mises en évidence par modification de l'onde directe (foucaultage, contraste de phase) ou suppression du fond continu (strioscopie), ne laissant subsister que la lumière diffractée par l'objet. Dans un matériau transparent, les défauts d'homogénéité se traduisent par des déphasages locaux, que les techniques d'examen ne permettent pas de localiser en trois dimensions simultanément. Une restitution complète peut être obtenue par holographie: la superposition d'une onde de référence à l'onde diffractée isolée dans un dispositif strioscopique par exemple, donne un

hologramme contenant l'information suivant les trois directions de l'objet.

66V3 V. A. Vitols, "Hologram memory for storing digital data," *IBM Tech. Disclosure Bull.*, *8:* 1581–1583, 1966.

This system enables digital data to be recorded in hologram form. Such recording is at, or near, the theoretical maximum recording density and is read or reproduced from such high-density recording without distortion or loss of data.

In this hologram recording system, object *O* is assumed to be a record sheet or transparency bearing a perforated or printed pattern of the digital data. Object *O* is illuminated by a collimated, coherent light beam from a laser. The light that passes through object *O* is focused by a lens onto a suitable recording medium or hologram plate *H*. Here it combines with a reference beam from prism *P*, illuminated by the same light source, to form a diffraction pattern or hologram of the object upon medium *H*. The distance between object *O* and the focusing lens is one focal length *f*, causing the object to be imaged at infinity. Hence, the quality of the recording is not affected by minor lateral displacements of the recording medium *H*. The latter can, for example, be in the form of a continuous photographic film fed in increments from a reel. The hologram produced by this method is a true Fourier transform of the object, consisting primarily of straight spectral lines arranged in a distinctive grid pattern which is unique to that object.

66W1 D. W. Wilmot, E. R. Schineller and R. W. Heuman, "Hologram illumination with a flashlight," *Proc. IEEE*, *54:* 690–691, 1966.

Although it has been recognized that a hologram image of the reference beam type[1] can be reconstructed with only partially coherent illumination,[2] the simplicity of such reconstruction has not been generally appreciated. In the course of a recent experiment it was noted that a satisfactory reconstruction of a simple hologram could be obtained using a common, two-cell flashlight as a source.

The hologram used for these observations was commercially produced by Jodon Engineering Associates,[3] Ann Arbor, Mich., and contained the image of two battleships and an overhanging cloud. It was constructed on a Kodak 649-F Spectroscopic plate with illumination provided by a He–Ne gas laser; the laser reference beam had been incident on the plate at an angle of about 40° from normal. This hologram is usually viewed with coherent illumination from a gas laser.

The reconstruction in our recent experiments was observed by simply illuminating the hologram plate with the beam from an ordinary flashlight. The quality of the reconstruction was not equivalent to that obtained with laser illumination; however, both real and virtual images were observed and easily recognized. The quality was sufficient for demonstrating the three-dimensional properties of the hologram image.

It should be noted that no additional optics, i.e., lenses or pinholes, were used. The quality of the reconstruction depended on the distance between the hologram and the flashlight, varying from barely recognizable at a few centimeters to easily recognized at a half meter. With the unfiltered flashlight beam, the edges of the object were highly colored and blurred, as would be expected. However, the use of even broadband Wratten filters improved the image considerably. For instance a fairly good image in shades of green was obtained with a No. 64 Wratten filter, and a similar image of somewhat better quality (in red) was obtained with the No. 23A Wratten low-pass filter. With either of these filters, the flashlight provided sufficient illumination for viewing in a partially lighted room. Further image improvement could be obtained by using a No. 72B Wratten filter for which the bandwidth is on the order of 500Å. This filter reduces the illumination considerably and it is necessary to view the hologram in a dark room. In this case, however, the quality of the reconstruction of distinct objects is sufficient to be quite impressive for simple demonstrations of holograms.

These observations are reported as a rather interesting novelty which may be of some value in initial experimental work—it is often easier to obtain a flashlight than a laser!

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1. [63L2]
2. E. N. Leith, private communication, January 19, 1966

65*19 "Photography by Fourier," Eastman Kodak advertisement, *Intern. Sci. Tech.*, 33, May 1965.

Five years hence, most people reading this ad will have seen a hologram. Maybe. We are not sure. The prophecy will come true if some smart apple watching the stunt done with a He–Ne laser, a mirror or two, and a photographic plate will turn to his buddy and say "Hey, Louis, do you suppose this would be any good in our—" and there he goes. It may have happened already. Perkin-Elmer showed holograms at the Physics Show, the Optical Society of America, and the IEEE. Perkin-Elmer has been doing this to drum up trade for their lasers. We for our part are always drumming up trade for photography.

This is peculiar photography, where the photographic record is quite invisible to the naked eye and doesn't really depend on silver density. The photograph, if you want to call it that, is merely a representation of all the phases and amplitudes in a scene or collection of separate scenes. In the reconstruction, which is astonishingly simple and direct, you get a choice between a three-dimensional virtual image or a series of real images in different planes. You can read all about it in *J. Opt. Soc. Am.*,[1]: and accept it intellectually, but it wouldn't hurt to convince your own eyes. Looking at one of these plates, you recall wondering at an early stage in your career what kind of a dance is being executed by a molecule of air in your ear while listening to a full orchestra and chorus. Baron Fourier sure was ahead of his time.

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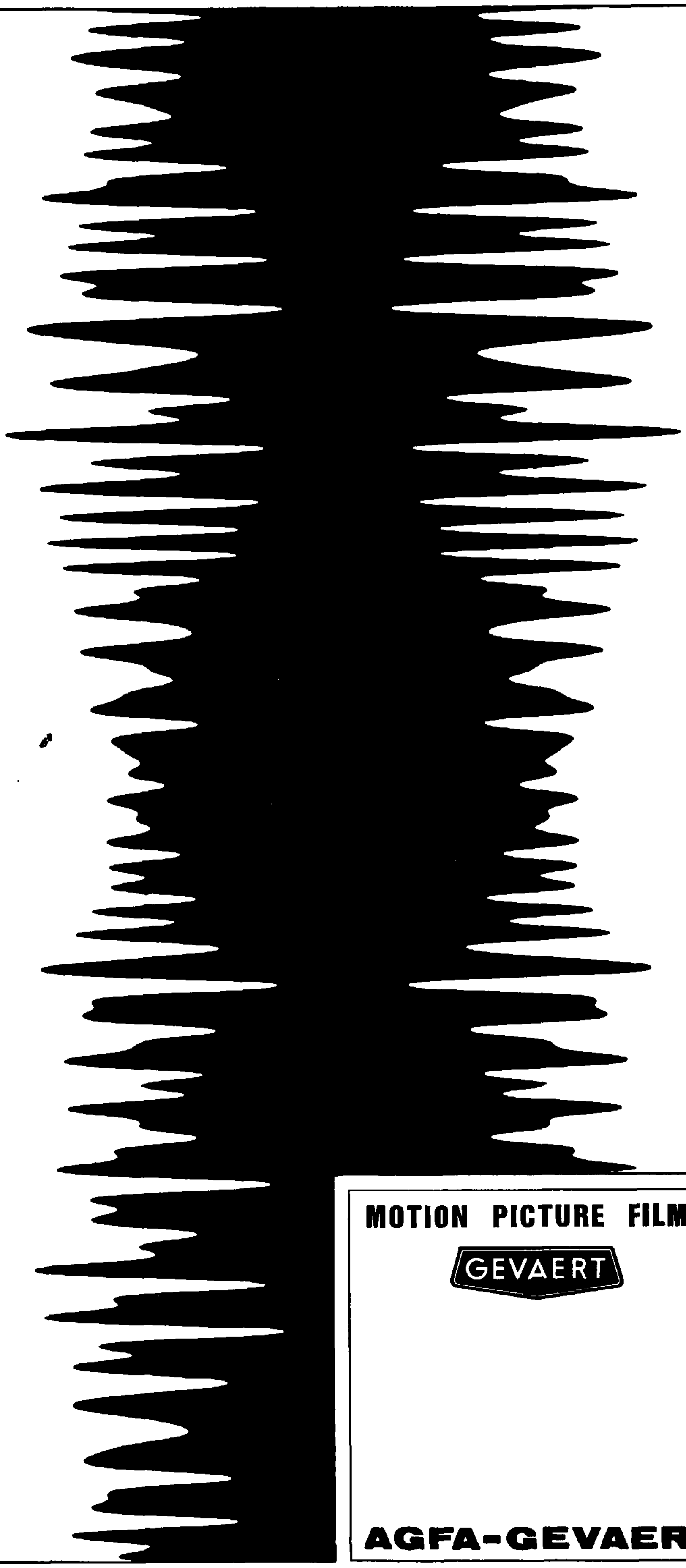
1. [63L2]; [64L1]



65*20 " 'Laser photography' takes 3-D pictures without lenses," Spectra-Physics advertisement, *Intern. Sci. Tech.*, 45, May 1965.

There's a kind of magic about the hologram,[1] even when you know its secret. Your look at it in ordinary light and see merely an exposed photographic negative, with no hint of the fascinating information contained in the grayish random patterns on its surface. But with coherent light you can transform these random patterns into an infinite number of sharp, detailed, virtual or real images in three dimensions.

Holograms are made by exposing a photographic emulsion—without camera or lens—near a subject illuminated by radiation from a highly coherent continuous-wave laser. The result is a Fresnel diffraction pattern capable of reconstructing wavefronts,[2] when placed in a beam of coherent light, to recreate in space a three-dimensional image of the original subject.

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1. [48G1]; [49G1]
2. [62L1]; [63L2]; [64L1]

65*21 "Laser technique photographs droplets," *Ind. Research, 7:* 38, 40, Dec. 1965.

A laser photography technique developed by Technical Operations Inc. for the Air Force provides a new method for taking three-dimensional pictures without lenses. Called a "Laser Fog Disdrometer," the device allows the measurement of such elusive things as droplets in rain, fog and aerosol sprays. It uses a radically different photographic technique in which the size as well as the distribution of particles within the laser beam are recorded simultaneously on film.

Previously, researchers had to study splash patterns on coated glass plates, for example, which did not give an accurate picture of the size, shape and distribution of the droplets.

The device produces a negative, called a hologram, which is a complete record of light waves diffracted from the particles. When the hologram is illuminated by another laser, the entire scene is reconstructed in full three-dimensional form. An observer can view the scene from any angle and can even see particles or droplets hidden behind others.

65*22 "Hologram film took a big step toward utilization—," *Chem. Week, 97:* 112, Aug. 14, 1965.

A big step toward the utilization of holography in data-retrieval systems and three-dimensional displays was taken with the development of a blue-green hologram that employs a continuous-wave ionized argon laser. (The hologram, or lensless camera, permits an observer to actually look behind three-dimensional images.) This is the first time that a gas laser other than helium–neon has been employed in holography. It decreases film exposure time by an order of magnitude. With helium–neon devices, the exposure time is 10 to 15 min. The argon gas laser allows film exposure times of 10 sec.

65*23 "Hologram laser," *Electronics World, 74:* 36, Nov. 1965.

An ionized argon gas laser is the main component of a new light camera that projects three-dimensional images. This unique laser makes hologram film exposures ten times faster than previously possible. The argon oscillator provides radiation in the blue-green portion of the spectrum and thus decreases film exposure times. The laser has a power output of 1 watt, and it permits film exposure times of 10 sec. Times of 10 to 15 min were required with helium–neon lasers used previously. The system was developed by Electro-Optical Systems, Inc.

65*24 "Laser revolution in 3-D photography," *Sci. Digest, 57:* 8–9, Jan. 1965.

When Emmet N. Leith and Juris Upatnieks, two physicists at the Institute of Science and Technology of the University of Michigan at Ann Arbor, want a duplicate of one of their 3-D slides, they simply cut it in half. If they need four copies, they cut it in quarters. The rule is: to multiply, divide. Each piece gives a complete picture, although as the piece grows smaller, details become blurred.

This is just one of the "startling effects" Leith and Upatnieks claim for their pictures taken by laser light. The special nature of laser light enables them to combine information about the shape and shade of an object, as seen in an ordinary photograph, with a sort of radar record of the distance of the various parts. Here are principles involved.

The filament in an ordinary light bulb emits frequencies or colors covering the whole spectrum. Many atoms in neon tubes or sodium vapor lamps emit the same frequency or color, but not in step. A laser emits a single frequency, and what is more, the atoms of the ruby or gas in the laser work in perfect unison, so that wavefronts stream out the end like rows of soldiers on parade.

Leith and Upatnieks bounce laser light from the object to be photographed directly onto film. They need no lens. Part of the beam is also reflected onto the film from a mirror. Light that has bounced from a particular spot on the object will have traveled a different distance to reach the film than the light bounced from the mirror, and the waves may no longer be in step. Or the distance difference may be just equal to one or more wavelengths and the wavefronts will arrive at the film back in step. When the waves arrive in step they will combine their energies into a bright line. When they are out of step, they will cancel each other along a dark line. The final photograph looks like a picture of a calm pond in a summer shower.

Light from every point on the object has reached every point on the film. It hasn't been focused to one point as in ordinary photography. That is why each piece of the film carries all the information to make a complete picture.

The two physicists view their 3-D pictures by shining laser light through the back of a slide and looking down through it at an angle from the front. The image appears behind the transparency. Is an object in the way in the picture? They can simply move to the side and look around it.

Several three-dimensional pictures can be mixed on the same transparency. Different images appear at different viewing angles.

Likewise, photographs of several two-dimensional objects can be combined. To make them visible, the slide is projected on a screen by laser light. As the screen is moved away from the projector, different pictures form and dissolve.

Laboratory table tops will probably be the favorite subjects for a while. Present lasers are so weak they can light only small scenes at long exposures. And it takes a physicist to set everything up.

65*25 "First holographic movies produced by Stanford," *IEEE Stud. Jour., 3:* 41, Nov. 1965.

Three dimensional "living" movies made without lenses by laser light and mirrors have been shown by engineers of Stanford University's Systems Techniques Laboratory.

The laser movie consisted of two "peep-show" films shown in a small black box. The Stanford group's work was supported by the U.S. Air Force.

Although the 35-mm films have no plot and star only some sexless steel balls and a wrist watch, sophisticated viewers have found the two shows more exciting than a Hollywood premiere.

They are not only the first "holographic" motion pictures ever produced, but also the first public demonstration that laser holograms can be made on a continuous strip of film. Most holograms have been made on glass photographic plates.

In addition, a "still" holographic photo on an 8 by 10-in. negative—believed the largest hologram ever made—is being displayed.

The holographic technique, discovered in 1947 by Dennis Gabor at London's Imperial College of Science and Technology, reproduces a scene in space just as an observer sees it rather than as an image on the film surface.

The hologram, or photographic record, bears no resemblance to the scene it records. Instead it looks something like the wavy lines and whorls seen in "watered" silk cloth or moire.

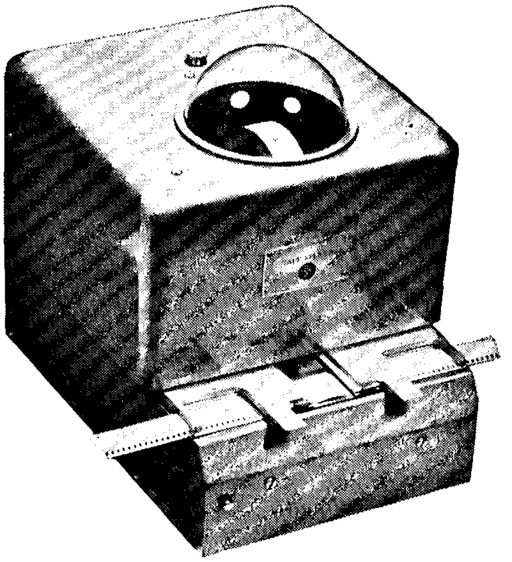
But when laser light is shone through the hologram, the original scene reappears looking real enough to touch.

The reproduction even includes parallax. That is, the viewer can look behind foreground objects to see what's hidden back there.

Much early development work in holograms was done at Stanford by Emeritus Physics Professor Paul Kirkpatrick and his associates, but they were handicapped by the lack of a source of "coherent" light—the laser.

The appearance of the first working laser greatly accelerated development of holograms at Stanford, the University of Michigan, and elsewhere. The Stanford work was largely inspired by successes of the Michigan research.

The hologram movie of rolling steel balls is actually a series of still holograms. Motion



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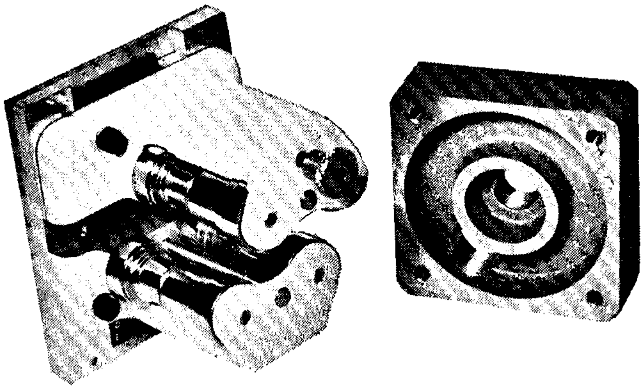

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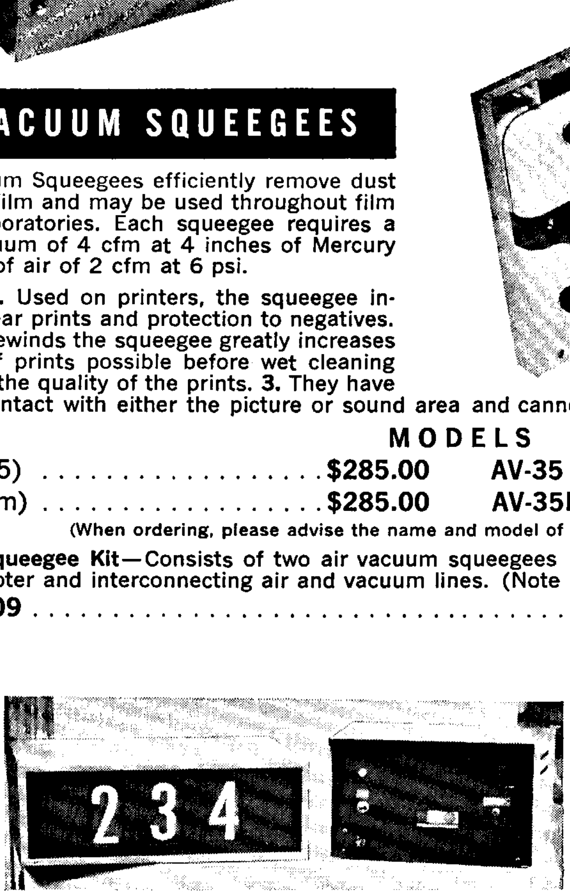

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is produced in the same manner as in animated film cartoons—by rapidly showing a sequence of still pictures. Actual movement of the wrist watch hands was filmed without using animation techniques. But to film faster motion would be much more difficult, and the problems of holographic television are even more awesome.

One of the toughest obstacles to making the hologram movie was to achieve a steady "shooting platform." As little as one-eighth of a light wavelength (about four millionths of an inch) movement is enough to ruin the hologram. Walking, talking—even water running through the building's plumbing can produce earthquake effects under these conditions.

65B3 E. B. Brown, "Modern optics," Reinhold Publishing Corp., New York, 1965, pp. 516–521.

If an object is illuminated by coherent light, it produces, by reflection or by refraction, a spatial distribution of light amplitudes which is characteristic of the object. If an object is illuminated by coherent light, it will give rise to a set of reflected spherical waves, one corresponding to each point of the object. Since the illumination is coherent, each of these waves are mutually coherent, and hence will produce, in a remote region, an interference or diffraction pattern which is determined by the relative location and reflectivity of the various object points. The pattern is characteristic of the object and will be different for different objects.

The same principle applies to transparent or semitransparent objects, where the interference pattern is produced by refraction rather than by reflection.

If this amplitude pattern is recorded in a suitable fashion and the recording is subsequently illuminated by coherent light, the original amplitude distribution (within instrumental limitations) is reproduced, and an image is formed which is similar to the original object.

This is the fundamental principle of the hologram—although, admittedly, highly simplified. The recording of the interference pattern is usually referred to as the hologram. Apparatus for producing holograms, and subsequently producing images from them, have been constructed by a number of experimenters and have produced striking results.

65C5 L. J. Cutrona et al, "Coherent light investigation. Final report," *AD-476-825, Conductron Corp.*, 120 pp., Dec. 1965.

This volume reports, the results of four essentially independent investigations related to applications of coherent optical systems.

In Section 5 (Two Beam Optical Radar), a new optical "radar" technique is presented which may aid in determining range, transverse velocity and rotation of arbitrary diffuse targets. With slight modification, this technique also may become a relatively long range holographic system.

65D3 D. Duffy, "Optical images of microwave illuminated objects," Gen. Elec. Co., Syracuse, N.Y., *Tech. Information Series*, R65ELS-60, Oct. 1965, 15 pp.

Several objects were illuminated with microwave radiation and the microwave diffraction patterns were recorded on photographic film. The photographic transparencies of the diffraction patterns were then illuminated with a helium–neon laser and images of the microwave-illuminated objects were obtained.

65G4 J. W. Goodman, "The role of coherent optics in electrical engineering," *WESCON Tech. Papers, 9:* Part 6, Paper 13.1, 1965, 7 pp.

With the advent of sources of coherent optical radiation, the disciplines of optics and electrical engineering have drawn closer together. Aspects of coherent optics of particular interest to electrical engineers generally fall in two different categories. The first consists of subjects traditionally in the realm of electrical engineering, such as signal generation, modulation, demodulation and propagation. The second consists of topics traditionally in the realm of physical optics, such as spatial filtering of images and wavefront reconstruction. The role of linear filtering concepts in imaging and optical data-processing systems are reviewed and illustrated with examples, including three-dimensional photographs achieved by wavefront reconstruction.

65J3 D. W. Jackson, "Optical devices and techniques," *WESCON Tech. Papers, 9:* Part 6, Paper 13.2, 1965, 4 pp.

The many valuable applications of lasers—such as radar, holography, interferometry—are seriously limited by a number of problems at the present time. It has been the aim of our work to resolve some of these difficulties and expand areas of applications of this very useful tool.

Some of the problems we have studied are: obtaining the required high degree of mechanical stability, detection of movements of less than a micron, restoring a "dirty" laser beam to a diffraction-limited beam, evaluation of cube-corner retroreflectors and noise suppression of gas lasers.

The solutions we have found, as discussed in this paper, improve interferometry and radar systems, and allow successful holography. It is hoped that the examples given indicate some of the approaches that can be taken in solving the problems associated with laser applications.

65L15 Matt Lehmann, "Photography for optical measurements," *WESCON Tech. Papers, 9:* Part 6, Paper 13.3, 1965, 4 pp.

In this paper we examine the various photographic materials available for use with optical data-processing systems and the photochemical techniques essential to realizing the extremely high information-handling capabilities of optical systems. Both the conventional photographic methods and the special approaches developed in our own laboratories to improve precision and control are covered.

Now that a rose is a rose, a few words about one of our primary colors: EASTMAN EKTACHROME Commercial Film.

FILM TALK

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We said *not* to project the original reversal material, but you can visually inspect it, and it will give you some idea of the final result. Generally, however, you'll look at rushes because you'll want to protect your original from loss or damage. For most of your work, you won't need to get your rushes color or intensity timed. A one-light print will do. You'll save money. You'll also be able to more accurately evaluate your lighting.

And this brings us to an important fact about the film. It's inherently flatter than *Kodachrome* II Film, but don't make the mistake of lighting it contrastier. The recommended contrast of key-light-plus-fill-light to fill-light alone should be from 2 or 3 to 1. It should seldom exceed 4 to 1 except where a special effect is desired.

Carry it beyond and you have big problems. An example. You're shooting outdoors in harsh sunlight. You're not using reflectors to lighten key shadow areas. When you look at the rushes, you feel you ought to be giving another half stop exposure. So you get to thinking the film is slower than it's rated (25 Tungsten, 16 Daylight). But add that half stop and you've used up all your overexposure latitude. Your highlights lose detail, and you can't differentiate between light-colored objects. In addition to watching lighting contrast, it's important to be careful about subject contrast as well.

More advice from the factory. As hard as we try for uniformity, there are occasional color differences from emulsion batch to emulsion batch. Naturally, we note any necessary filter corrections. If you're *sure* you'll use only one emulsion for a production, you can forget the filter. But if you use more than one emulsion, save yourself—and your laboratory—a headache. Use the recommended filters.

One laboratory has a further timely suggestion; just that—use one laboratory. Although every processor tries for excellence, one lab's eye for magenta may be another lab's cyan. The key word in color is not "fidelity," as you surely know. It's "pleasing." People (and this includes the mortals who man your laboratory) want skin pinker, grass greener than God gave them to us. The world in winter should always be emerging from a new-fallen snow. The local river must be a rich blue, in spite of the fact that everybody knows it's loaded with detergents. Although we have an uncommon fondness for spectrophotometers, we at Eastman Kodak Company—like you at your camera—are out to please people. Of course, the people that we at Eastman feel most directly responsible for pleasing are you, the cinematographers. That's why we came up with *Eastman Ektachrome* Commercial Film.

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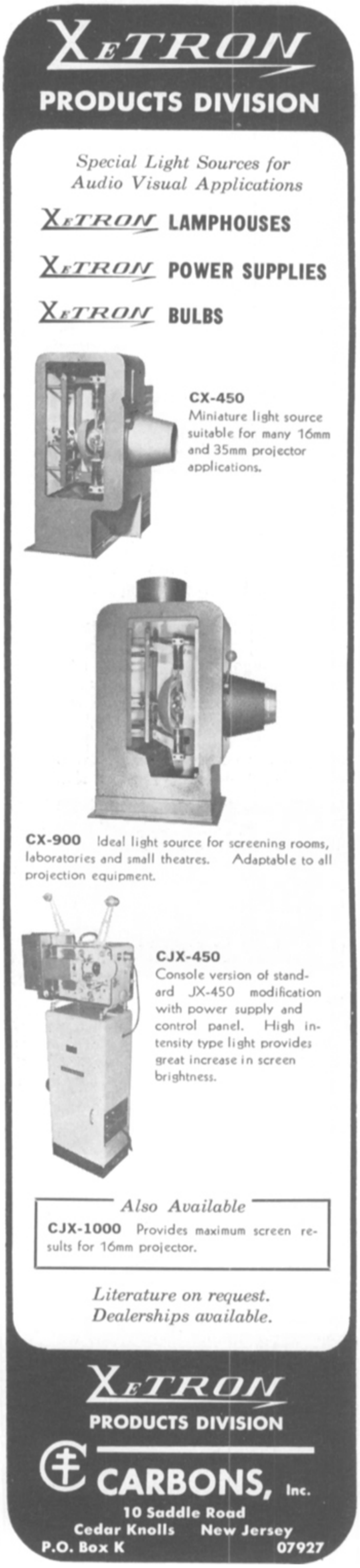

65M10 Jurgen R. Meyer-Arendt, "Optical Instrumentation for the biologist: microscopy," *Appl. Optics, 4:* 1-9, 1965. Holography is discussed on p. 6.

A great variety of optical instruments has been developed for use in biology. The microscope and its many special types are part of them. In this article, a survey is given of the history, development, current status and future outlook of general microscopy, microspectroscopy, interference microscopy and electron and x-ray microscopy.

[After five pages on other techniques the article goes on to holograms as below.]

An apparently fundamental limit to any microscopic image formation is the effect of diffraction. "As long as the numerical aperture governs the resolving power of the microscope," wrote Abbe, "there is no hope that much further progress will be made. Perhaps, some day something may be found to overcome this limit." This "something" has, in fact, been found in the form of the principle of wavefront reconstruction.

Consider a point light source illuminating a point object. The diffraction pattern produced will be a system of concentric rings, not unlike an Airy disk or a zone lens. Now imagine that this pattern is photographed, printed as a lantern slide, and inserted into a light path. It will act there as a zone lens, depicting a point source again as a point image.

Now apply the same principle to a two-point object which, clearly, would produce two Airy disks, that is, two systems of concentric rings which, depending on the distances, would more or less overlap each other. Imaging a point source by means of such a "double-zone lens" would in the image plane give two luminous points.

The same considerations apply to an even more complex object like the letters ABC. Their diffraction pattern would be a rather confusing blur of overlapping lines and fringes. However, reconstruction of such a diffraction pattern will yield the original structure of the object.

Strictly, the term "wavefront reconstruction" implies that an image is rebuilt after the process of image formation has been interrupted somewhere. Since one may start with an artificial mask from which to synthesize an image, without a primary object being present at all, the term "reconstruction" might better be replaced by "optical synthesis." This process has been developed first for, and applied to, crystal analysis. Its great potential for biologic microscopy, however, lies in the fact that it also can be applied to odd-shaped objects. Even three-dimensional holograms have been used for synthesizing an image.

Wavefront reconstruction had been developed originally to compensate for certain aberrations found in, and to increase the resolving power of, the electron microscope; its use for frequencies other than visible light, for instance, for x-ray image formation, might be at least as valuable. Besides, wavefront reconstruction is highly significant from the purely heuristic point of view: it has made possible the separation of the two-component processes that constitute *any* image formation.

It is interesting to see how a satisfactory hologram can be produced with a diffraction beam of relatively low intensity, despite the presence of a high-intensity background of undiffracted light which comes directly from the source, by-passing the object. The reason is that with coherent illumination the amplitudes add and not the intensities. If the intensity of the diffracted, information-carrying beam is only 1% of the intensity of the background beam, its amplitude will be 10%. Considering the two limiting cases of two beams exactly in-phase and out-of-phase, the resultant intensity in the photographic image varies from $(1 + 0.1)^2 = 1.21$ to $(1 - 0.1)^2 = 0.81$, which is a sufficiently high contrast. We see that the phase of the light reaching the emulsion, if accompanied by coherent background radiation, is about that of the background, and little information of importance is lost.

65V3 Jean-Charles Vienot and Jean Bulabois, "Hologram filtering of a complex optical signal—application to improving radar maps," *Rev. Opt. 44:* 621-624, 1965.

La technique de l'holographie dont les principes ont été élaborés par Gabor et développée par différents auteurs est applicable à de nombreux problèmes d' optique cohérente. Rappelons que cette technique consiste à enregistrer photographiquement le phénomène d'interférences entre une onde cohérente jouant le rôle de porteuse et les ondes diffusées par un objet éclairé lui-même en lumière cohérente. Le résultat est un hologramme.

La démodulation permet de restituer les termes d'amplitude et de phase.

Dans la méthode proposée ici, l'hologramme d'un signal pris comme repère à l'intérieur d'une pupille complexe joue le rôle d'un filtre spatial dans un montage à double diffraction. La pupille est du type défini dans le recalage des cartes de radar.

Le repérage, puis la mesure d'un écart en grandeur et en signe entre une carte de référence C_0 et une carte C présentant une partie commune avec C_0 revient à comparer des répartitions de transparences complexes de la forme

$$C(x,y) \exp [i\Phi(x,y)].$$

Les deux opérations sont réalisables : (a) soit par évaluation du degré de corrélation entre C et C_0, l'écart étant mis en évidence par analyse statistique des spectres de C et C_0 comme il a été indiqué ou par filtrage de C par C_0 ; (b) soit en repérant un détail caractéristique r sur C_0 et C.

Dans le cas d'une translation de C par rapport à C_0, OP représente le décalage en grandeur et en direction.

Dans un déplacement plus général (rotation-translation) il est nécessaire de déterminer deux vecteurs définis par les positions relatives de deux régions distinctes. Cette opération est effectuée en filtrant C par l'hologramme de $r \in C_0$.

64C1 G. Cochran, L. Cutrona, A. Ingalls, I. Kay, A. Sabersky et al., "Coherent light investigation, Vol. III," AD-610-082, Conductron Corp., Oct.

1964, 111 pp. Abstracted in *Abstracts of Phot. Sci. Eng. Lit.*, *4:* 392, Oct. 1965.

A new theory is presented for analyzing optical systems in terms of transfer functions and optical systems employed normally with coherent light. Also, the general theory of holograms and complex spatial filters are discussed. The production of 2- and 3-dimensional holograms using coherent light and its implications for synthetic antenna applications, complex filters, matched filters and general filtering systems are described. Practical details on experimental results are also given. Discussions are presented on the use of laser measurements of target acceleration and rotation rates and on the problem of testing large reflective optics.

64C2 Louis J. Cutrona, "Optical computing techniques," *IEEE Spectrum*, *1:* 101–108, Oct. 1964.

The properties of coherent light have found practical application in the performance of many operations on signals. In addition to solving spectral analysis and filtering problems, optical techniques can be used for analog computations.

64D2 D. Duffy, "Optical processing of microwave holograms," Gen. Elec. Co., Ithaca, N.Y., *Tech. Information Series*, DF63ELC54, Jan. 1964, 10 pp.

In Gabor's two-step method of image formation, an image of an object is reconstructed from the diffraction pattern of the object. This program attempted to demonstrate experimentally the feasibility of this technique, using microwaves for the original radiation and light in the reconstruction. Objects were illuminated with 3-cm wavelength radiation and the diffraction patterns were recorded photographically and with an X-Y recorder. No discernible objects were produced, due to limitations in the experimental setup. The technique is believed feasible when better photographic recordings can be obtained.

However, see [65D3]

64H1 Robert D. Heidenreich, "Fundamentals of transmission electron microscopy," Interscience Publishers, a Div. of John Wiley & Sons, Inc., New York, 1964, pp. 135–136.

The interference microscope is a practical development resulting directly from an understanding of the phase change accompanying transmission through a potential film. Gabor[13] proposed an interference microscope using a method of reconstructed wavefronts. The principle of the method requires a point source irradiating an object of arbitrary thickness distribution which introduces a corresponding phase shift in the waves emerging from the object. A screen at distance *L* records the phase shifts as intensity variations producing an interference pattern called a hologram. The hologram is developed as a transmission screen, such as a film, and then placed back in its original position. If it is now viewed looking toward the source with the object removed, the object is "seen" again as reconstructed by the interference pattern. If the object is opaque, the diffraction pattern consists of Fresnel fringes.

Although Haine and Mulvey[14] were able to produce an image in this way, the method is not practical for electrons. First, the transverse coherence length does not allow a sufficiently extensive hologram and second, incoherent scattering adds unwanted background. On the other hand, optical synthesis of a crystal from its x-ray diffraction pattern[15] has been successfully used to simulate an x-ray microscope.

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13. [49G1]   14. [52H1]
15. W. L. Bragg, *The Crystalline State*, *1:* G. Bell and Sons, London, 1949, p. 229.

64M1 L. Mertz, "Another optical Fresnel transformer," *J. Opt. Soc. Am.*, *54:* p. iv, October 1964, Block Associates, Inc., advertisement.

Basically two techniques have previously been used to generate Fresnel transforms (holograms) of images. The first[1] is via Fresnel diffraction; the second[2] is by shadowcasting. The first requires monochromatic coherent illumination. The second does not require either monochromatic or coherent illumination but suffers from diffraction blurring of shadows.

To achieve Fresnel transformation it is necessary to image adjacent source points as adjacent Fresnel zone patterns. The Fresnel pattern blur function can be obtained by aperture synthesis[3] of a lens. The conclusions from this approach lead to the addition of a phase-reversal zone plate[4] in the lens plane. Unfortunately this solution is severely chromatic.

In a new solution which takes the form of a triangular path interferometer[5] a doublet lens is designed to have the same power as the singlet, but with negative chromatic aberration. Chromatic red (R) and blue (B) images of a point source are formed via the path *reflected* by the beam-splitter, and R′ and B′ via the path *transmitted* by the beam-splitter. The image separation and chromaticity are controllable by the positioning of the lenses, and when properly adjusted, achromatic circular fringes in the form of Fresnel zones result. The point source has been imaged as a Fresnel zone pattern. Furthermore, adjacent point sources give adjacent Fresnel pattern images, and thus the output is the Fresnel transform or hologram of the incoherent input.

The particular experiment which I carried out generated on the order of 100 zones, all achromatic and of good contrast. Applications of Fresnel transformation, are numerous and diverse.

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1. [50R1]   2. [61M2]
3. Duffieux, "L'Intégrale de Fourier et ses Applications à l'Optique," Besacon, 1946.
4. Wood, "Physical Optics," Macmillan, 1934.
5. Hariharan & Singh, *J. Opt. Soc. Am.*, *49:* 732, 1959.

64V2 Lloyd F. Varden, "Varden on lensless photography," *Photo Methods Ind.*, 30–31, Jan. 1964.

The Wall Street Journal and *The New York Times* both carried a lengthy article

on December 5 on a method of lensless photography, followed by still another article in the *Times* of December 15. These were based on a paper by Leith and Upatnieks.[1] The lensless aspect of the method and its future possibilities were stressed in the newspaper accounts, although the paper itself has only one short paragraph on these topics, and they are not even mentioned in the authors' abstract of the paper.

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1. [63L2]
See [63*1]; [63O1]; [63D3].

64V3 A. Vander Lugt, "Signal detection by complex spatial filtering," *IEEE Trans. on Information Theory IT-10*, 139–145, 1964.

In the past, spatial filtering in coherent optical systems has been limited by the inability to realize practically a general complex filter. This paper describes a technique for realizing such a filter, and gives an application of spatial filtering to the problem of detecting isolated signals in a variety of noise backgrounds. The experimental results obtained to date indicate that this technique provides an excellent two-dimensional filtering capability that will play a key role in such problems as shape recognition and signal detection.
[This paper is not on holograms specifically but many of the ideas are basic to holography.]

63D3 Jacob Deschin, "No-lens pictures," *The New York Times*, Sect. 2, 29, Dec. 15, 1963.

A photographic process just announced by two research engineers of the University of Michigan Institute of Science and Technology uses light alone to make pictures without the aid of a lens.

The method is still confined to laboratory demonstration, although its developers believe there are wide areas of practical use in medical laboratories, in the design of X-ray cameras and wherever microscopes are used. In these applications, the inventors see the advantage of sharper images than are now being obtained. Another field is in the construction of lensless photographic enlargers.

The system is not likely to revolutionize either amateur photography or the broad range of general professional photography, but the unconventional application of photographic principles involved in the new technique will be of interest to photographers generally.

A laboratory device, or even an ordinary camera with the lens removed, and conventional film or glass plates are used in the new system, but the light source must be monochromatic, such as a laser or mercury arc lamp, and picture-taking at present is restricted to still objects.

A picture made by this system yields a completely blurred negative. However, when this image is projected by the same monochromatic light used in taking the picture, the result is a clear, sharp picture indistinguishable from photographs made conventionally.

The announcement in the December issue of the *Journal of the Optical Society of America* by Emmett N. Leith and Juris Upatnieks, research engineers at the Michigan Institute, explains the technique. Additional information was obtained in interviews with Mr. Leith.

To take a picture, the photographer loads the lensless camera with black-and-white film or photographic plate, and illuminates the subject, with the laser or similar monochromatic light. Since focusing is impossible in this lensless system, the distance between the subject and the camera does not matter. Focusing, in fact, is unnecessary, as the purpose is to record information about the light pattern of the subject, information that will be used later to produce an image.

At the same time, a mirror, or prism, is placed off to one side of the subject, out of the field being photographed. Most of the laser light strikes the subject and is reflected to the film in the camera. Part of the light is received by the mirror and also is reflected to the film, bypassing the subject field. This is called the reference beam and is the key to the process.

When the beam reflected from the subject and that from the mirror meet at the film plane, this is what happens according to Mr. Leith: the subject reflections reach the film in a pattern of phases. The mirror beam, consisting of undistorted monochromatic light arrives in one phase.

The term phase refers to the characteristic of light rays to travel at an irregular pace, some advancing faster than others. It has been compared also to the action of ocean waves, which move forward in a succession of crests and troughs.

At the film plane, the image beam and the mirror beam meet and interact. When the individual image ray and the reference beam are in phase, or match, they reinforce each other, producing the highest intensities (brightest picture highlights). To the degree that they are out of phase, the intensities are reduced or subtracted, producing a range of grays, or are canceled out to black.

Film ordinarily is not responsive to phase relationships, being affected only by variations in light intensities. By editing the reflected rays before they reach the film emulsion, thereby converting phase to light intensities, the reference beam enables the film to record the image.

Normal development, fixing and drying of the film produces a negative with a blurred image. It can be projected only by laser or other monochromatic light on a screen or onto a plate in a camera in order to make a transparency, or onto a sheet of photographic paper if a print is wanted. When projecting on sensitized photographic material, it is necessary to work in total darkness or by safelight illumination.

Upon projection, the image is seen as a reconstruction or reproduction of the original subject.

The blur negative consists of silver patches, in varying densities and clean areas, as in a normal negative. In ordinary printing or enlarging, the density areas hold back light in varying degrees hence recording as whites and grays in the print. The clear areas let the light through unimpeded, resulting in blacks.

The same thing happens when the laser rays come through the blur image to produce the reconstructed picture. The rays that happen to hit the darker densities are stopped and, as they do not affect the plate or printing paper, record the densities as highlights. Rays that hit patches of different densities record as a range of middle tones, and rays that come through the clear areas, because there is no density to stop them, record as blacks.

This selective process produces a pattern of emerging rays that are in the same configuration as the rays that initially were reflected from the subject to the camera.

The use of a monochromatic light such as the laser is crucial to the technique because it is constant. In other illumination, the phase relationships involved in the method would keep changing too rapidly to permit maintenance of the relationships. The change would be from instant to instant and at such a rate that it would be necessary to make exposure of perhaps a billionth of a second to achieve the desired image.

The principle of the system was introduced 15 years ago by Dennis Gabor, professor of electron physics at the Imperial College of Science and Technology in London. His results were poor and limited in applications, and other researchers since then have had no better success. In the perfection of the mirror or reference beam, the Michigan researchers feel they have improved the method.

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63E2 Hussein M. A. El-Sum, "Optical apparatus for making and reconstructing holograms," U.S. Pat. 3,083,615, Apr. 2, 1963 assigned to Lockheed Aircraft Corp.

This invention relates generally to optical systems and devices, and more particularly to means and methods for making and reconstructing holograms.

A hologram is the resultant picture obtained in a plane at a distance from an object when the scattered radiation from the object is attended by a strong coherent background radiation. Such a hologram bears no resemblance to the object; yet, it will contain all the information about the object and can be reconstructed by suitable techniques to recover the information about the object in recognizable form. Moreover, the hologram contains not only all the information about the object but also, all the information about the whole space between the hologram and the source of radiation; hence from the same hologram any other intervening objects can also be reconstructed.

The theory of holograms and experimental data in regard to their formation and reconstruction has been reported in the literature.[1–5]

A careful examination of available knowledge in the field, as generally represented by the above cited references, will reveal that complicated apparatus is involved or contemplated with regard to making and reconstructing holograms. Particularly, it is indicated that the radiation source which illuminates the object must not only be highly coherent and of monochromatic form but also, must have very small dimensions. In order to achieve this, a considerable number of filters, lenses and prisms are employed in a variety of arrangements, which are quite complex, large, critical and fragile. Also, these filters, lenses and prisms greatly increase the noise introduced into the system because of the extraneous particles, such as dirt and dust, which they unavoidably collect and the imperfections inherent in these devices.

In accordance with the present invention, greatly simplified and compact apparatus has been devised for making and reconstructing holograms. This simplified apparatus is possible as a result of the novel system arrangement employed and my discovery that the previously taught requirements as to the source of radiation are not as important as the prior art would indicate, particularly where object recognition is the main feature desired. It has thus become possible by means of the present invention to expand the possibilities of the basic theory to other desirable applications thereof other than microscopy (which is the main direction of previous work in this field), since a simple, portable, noncritical and rugged piece of apparatus for making and reconstructing holograms is now possible for field or other use.

The present invention is chiefly concerned with the novel apparatus which I have devised for making and reconstructing holograms, rather than the applications to which this apparatus can be put. However, many possible applications for this apparatus will be apparent to those skilled in the art.

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1. [49G1] 2. [51G1] 3. [52H1]
4. [56K1] 5. [56G1]

6301 John A. Osmundsen, "Scientists' camera has no lens," *The New York Times*, 55, Dec. 5, 1963.

A camera without lenses that has promise for producing sharp pictures of objects ranging from men to molecules has been developed by a team of University of Michigan engineering scientists.

The device operates on a principle radically different from that of ordinary cameras. It was conceived some 15 years ago by Dennis Gabor, professor of electron physics at the Imperial College of Science and Technology in London.

Dr. Gabor was able to produce photographs of only a very few kinds of objects of special characteristics, however, and the images were of rather poor quality.

His concept has now been expanded and developed to the point of possible commercial application by Emmett N. Leith and Juris Upatnieks of Michigan's Institute of Science and Technology.

A report on their work appears in the December number of the *Journal of the Optical Society of America*, out today. The Journal is published by the American Institute of Physics.

Mr. Leith, in a telephone interview yesterday, said that the basic idea behind the new device could be applied to the whole range of electromagnetic radiation—from radio waves through infrared visible and ultraviolet light down to the extremely short waves of X-rays.

Thus, the concept as it has now been developed may find application in a wide range of instruments, including cameras, light microscopes, photographic enlargers, electron microscopes and X-ray cameras for medical diagnosis and studies of molecules.

The process of taking a picture with the Michigan device is as baffling at first thought as are the immediate results: it is literally done with mirrors (or prisms).

Besides a mirror all that is needed is photographic film, a film holder—a 35mm camera with lens removed will do—and a point source of light of a single wavelength (monochromatic light).

The photographic negative produced with such a system is an unrecognizable smudge, bearing no visible relation whatever to the object photographed.

"Development," or reconstruction, of that image, however, results in a sharp clear picture that is remarkably faithful to the object photographed.

Perhaps the best way to understand how this works is to consider how photographic images are normally made.

Essentially, a photograph is the record of varying intensities of light reflected from an object (or transmitted through one, as with a photographic transparency). Portions of the object that reflected or transmitted light most intensely are recorded darkest on the film and vice-versa.

In that respect, the light passing from the object to the place where the image is made carries information about the object in the form of intensity of reflection. It is the pattern of variations in reflected light intensity that makes the picture.

But reflected light carries information about the object in another form as well: that of the phase of the light waves as they strike the film.

Phase is a consequence of the wave-like nature of light, which can be thought of as an endless train of ripples. Two such wavy rays of light are said to be in phase if their crests and troughs match and out of phase by varying degrees if the crests and troughs are out of step.

Crucial to the Michigan scientists' development is the fact that coherent light, in which all rays are in phase, will be reflected from an object so that the rays are out of phase in a way that matches the pattern of the object.

That is, the reflected phase pattern is an image of the object, but one that will not register as such on photographic film—or on the eye, for that matter—which is insensitive to the phases of light.

Film and eyes are sensitive to light intensity, however, and so the invisible pattern of phases would be visible if it could be converted to a corresponding pattern of intensities. This is essentially what the Michigan scientists have done.

They do this—taking a black-and-white photographic transparency as an example—by shining one beam of coherent (in phase) light through the side onto a photographic film and another "reference" beam of the same light direct onto the film without passing through the transparency.

In this way, the light that passes through the transparency arrives at the film in a pattern of phases and the reference beams arrives there all of one phase.

At each point on the film, then, the phase of the rays of light through the transparency is compared with the phase of the light ray from the reference beam.

In that way, the reference beam acts as a carrier signal, as in radio communications. The phase comparisons, crest for crest and trough for trough at each point on the negative, are automatically translated into intensities.

Where wave crests of transmitted and reference beams match they reinforce each other and the intensity is highest. Intensity is lowest where troughs coincide and in between elsewhere.

Although that pattern of intensities represents the image of the photographed object, it does not appear so because no lenses were used.

The negative itself, acts as a lens, however, when coherent light is shown through it onto a screen or on photographic paper for printing.

The negative acts as a lens by converging each ray of light that passes through it precisely as the light had been bent by the object it went through or which reflected it to produce the image in the negative.

Mr. Leith said that considerable magnification can also be achieved with this sort of system, and hence it would be used in microscopy throughout the entire spectrum. He and Mr. Upatnieks are now developing the system for use with X-rays, an area in which they believe its greatest promise may lie.

The reasons for this is that no lens system has yet been found for focusing X-rays, and as the Michigan scientists have now clearly demonstrated, their system gets along very well without lenses.

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63V3 P. J. Van Heerden, "Note on optical information storage in solids," *Appl. Optics*, *2:* 764, 1963.

In a paper on optical information storage in solids [P. J. van Heerden, [63V2]] the author calculated the information storage capacity of an alkali halide crystal in a particular case to be about 10^{13} bits per cm^3. Although this figure is correct, it is somewhat misleading by itself, because in actual cases this capacity cannot be fully taken advantage of. In general it can be shown that the efficiency of information storage goes down with the square root of the number of instalments (separate pictures) in which the information is put in. As an example, take a crystal of 1 cm^3, with 10^{15} color centers. Assume that we want to store 3000 pictures of 1 cm^2 each. There will now be available 3×10^{11} color centers per picture. When each picture is defined by 10^8 waves of independent directions, the computation analogous to the one in the paper leads to a signal-to-noise ratio of unity. The amount of information stored is now $3000 \times 10^8 = 3 \times 10^{11}$ bits. This number at the same time gives the theoretical maximum to which the optical storage capacity of the crystal could be utilized.

62*1 "Pictures using the hologram technique," Block Associates advertisement, *J. Opt. Soc. Am.*, *52:* VIII, Feb. 1962.

Pictures of a field of view as shown in [Fig. 1] were made using the hologram technique described in our December advertisement [61Y1]. [Figures 2 and 3] show images of this field of view obtained by reconstruction of the hologram. By photographic copying of the original negatives at a low enough gamma, we can show the reconstruction, photographic grain (an irreducible background) and background illumination from other orders of re-construction which is by design out of the field.

The reticle used consisted of two zone-plate patterns which were crossed as described before. The resulting pattern, photoetched from thin metal, was therefore self-supporting, and resembles a mesh of nonuniform spacing. The re-constructed image of [Fig. 2] was obtained at the first-order positive focus of one of these zone-plates. Other orders of diffraction contribute light outside the field of interest, the dark patch at the upper left.

[Figure 3] was obtained at the first order positive focus of the moiré zone-plate formed as the product of the first two zone-plates. It is seen to give higher spatial resolution, as would be expected, since the moiré zone-plate has a double number of zones.

62M1 L. Mertz, "The Fresnel sandwich," Block Associates advertisement, *J. Opt. Soc. Am.*, *52:* X, July 1962.

In a previous note[1] we showed that one can perform Fourier transformation in terms of multiplication and combination. In particular if f,F are a Fourier transform pair, and $T = \exp 2\pi i x^2$ (the Fresnel kernel), then

$$f = [(F \cdot T)^* T] \cdot T$$

Here · denotes multiplication and * convolution.

Since both multiplication and convolution are readily performed optically, we can thus construct an amusing, if not very practical, two-dimensional Fourier transformer. This is a sandwich of three coarse Fresnel zone plates. The zone plates are not used for any focusing properties, but their shadows provide the Fresnel kernel function T.

The sizes of the zone plates are such that the central point of either outer zone plate would project a shadow of the middle zone plate congruently on to the opposite zone plate. If the zone plates are equidistant, this means that the middle zone plate is half size.

The first multiplication $(F \cdot T)$ is obtained by placing a transparency of the input function F in contact with the first zone plate and diffusely illuminating. The convolution $(F \cdot T)^* T$ is obtained on the plane of the last zone plate as the projected shadow through the middle plate. The final multiplication by T is obtained as the transmission through the bottom plate and is thus the Fourier transformation of the original transparency F.

This is a two dimensional Fourier transformer employing incoherent illumination. The unfortunate aspect is that a transparency cannot properly represent the Fresnel kernel in that negative values of transmission are not available. This limitation leads to a considerable grey bias and a spurious Fresnel zone image superimposed on the final transformation, when black and white transparencies are employed.

A proper subtractive technique could in principle remove these problems. Also the wavelengths should be short enough compared to the general dimensions so that diffraction does not badly blur the projection.

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1. L. Mertz, Block Associates advertisement, *J. Opt. Soc. Amer.*, April 1962.

61M2 L. Mertz, "Fresnel coding for photographic devices," Block Associates advertisement, *J. Opt. Soc. Am.*, *51:* IX, May 1961.

The Fresnel coding techniques described previously[1,2] have certain advantageous photographic applications as indicated in the following two examples.

In the first application, suppose the entrance slit of a spectrograph is replaced with a Fresnel zone plate. Each spectrum line is then recorded as an image of this zone plate on the photographic plate. Each zone plate image on this photographic plate may then be used as a lens to reimage a monochromatic point source. That is, each zone plate image acts as an individual lens and so reconstructs the spectrum. This procedure is the same as the hologram reconstruction technique of Gabor.[3] The differences from Gabor's technique are in the method of forming the hologram. No coherent background is necessary, the central zone is predetermined as dark or bright, and the outer rings containing the detail resolution do not suffer from chromatic aberration.

In practice it is usually desirable to make a photographic reduction of the original since a small scale and positive image are desirable for the reconstruction. It is also usually desirable to bleach the image and thus have phase zone plates for the reconstruction. Note that one dimensional zone plates are adequate, whereby the system becomes the photographic equivalent of the Girard grill.[4]

The main object of the technique is that for diffuse sources the exposure time can be greatly reduced. At this moment I am unable to give a critical comparison of the relative signal-to-noise with this method as compared to a standard slit spectrograph. However, there are two indications that coding should improve the signal-to-noise; first, the exposure time is reduced and second, by distributing the information more uniformly over the plate, the plate can be utilized more efficiently with respect to quantum efficiency and information storage.[5]

The second application of the Fresnel coding technique is as a short wavelength imaging system, especially suitable for ultraviolet star mapping. The technique consists of using a coarse self supporting zone plate in place of a lens. In the hard UV there is little diffraction; each star records simply as a shadow of the zone plate. The image reconstruction is exactly as the case above.

The object of the technique is that the system requires neither refractive nor reflective materials which are unavailable in the hard UV, and that it still allows large primary apertures necessary for short exposures.

1. L. Mertz, Block Associates advertisement, *J. Opt. Soc. Amer.*, Jan. 1960.
2. J. Mertz, Block Associates advertisement, *J. Opt. Soc. Amer.*, Feb. 1960.
3. [49G1]
4. Girard, *Optica Acta, 7:* 81, 1960.
5. Fellgett, *Monthly Nat. Roy. Astron. Soc., 118:* 395, 1958.

61Y1 N. O. Young, "A reticle camera for pictures in hard UV, x-rays, or particles," Block Associates Advertisement, *J. Opt. Soc. Am. 51:* II, Dec. 1961.

Conventional optical imaging techniques fail at wavelengths shorter than 1,000 A, although pictures of distant objects can still be obtained by shadowcasting or by diffraction.[1] Efficient use of the photographic film and perfect achromatism is obtained with our hologram technique[2,3] in which a large reticle rather than a pinhole casts shadows on the film. A difficulty of this hologram technique as previously described is that bright points in the original object field show up against an illuminated background in the final image, resulting in a loss of contrast.

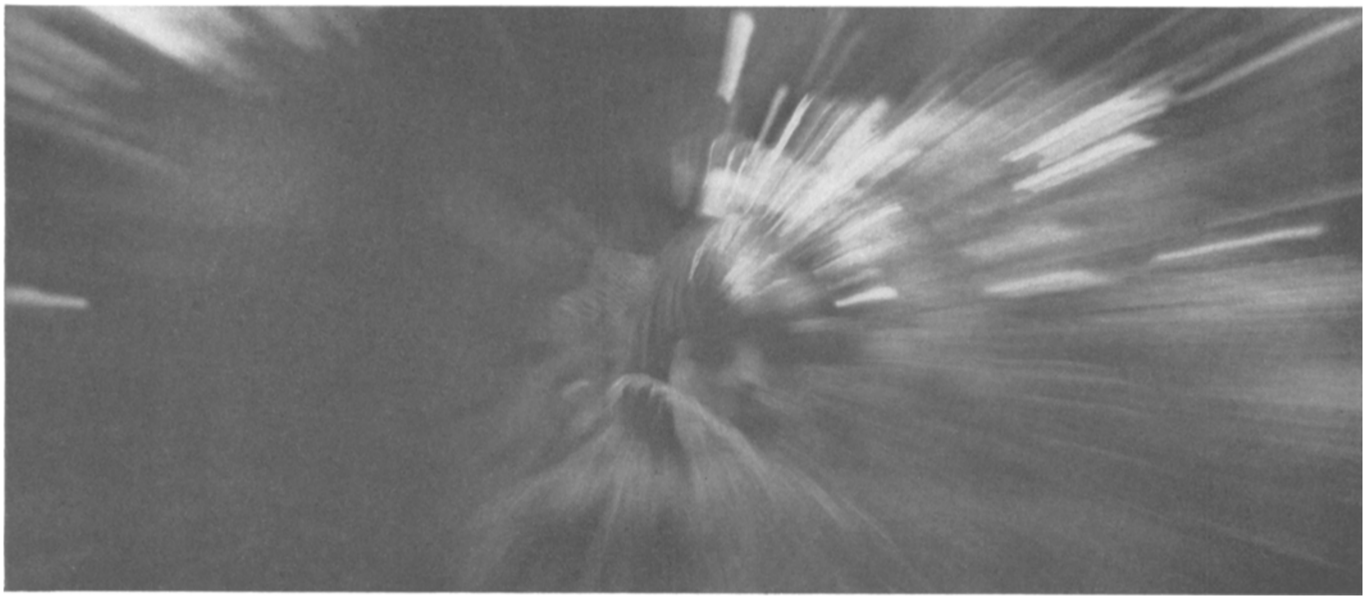
Complete suppression of this background, and some preliminary experiments with the improved technique are reported here.

In the hologram technique, the pinhole of a pinhole camera is replaced by a Fresnel zone-plate whose narrowest transparent zone has at least the width of the pinhole diameter.[4] Consequently, the zone-plate reticle is much too close to the film to show any focussing effects: it merely casts shadows which are very slightly blurred replicas of itself. Thus, the reticle can be of any size, and preferably large.

Each bright point in the object field will now appear as a zone-plate on the film. The distribution in object space has thus been Fresnel coded, and the resulting distribution is the hologram[5] of the object space distribution. The original appearance of object space (in wavelengths admitted by filtering ahead of the reticle, say x-rays) is regained by reconstruction from the hologram. This is done at visible wavelengths, each zone-plate element in the hologram acting independently and focussing a collimated beam to a point.* By reconstruction, we thus obtain a point-to-point correspondence between object space and the final image.

Advantages of the hologram technique are that aberrations do not limit the reticle camera aperture, the film distance, or the angular field. Instead, these parameters are mainly limited by the film size and vignetting. Other limits, not considered here, are set by diffraction at the reticle (not wanted), the practical limits of reticle construction, and film fogging from low space frequency illumination in the object field.

Reconstruction of holograms in the simple fashion described, results in undesirable background illumination. This is because each zone-plate in the hologram not only passes the collimated beam undiffracted, but has many foci at different axial distances f_m. The zone-plate reticle has a



pattern in which the radius r_n of the nth zone edge is given by $r_n = k\sqrt{n}$, where k is the radius of the central disc. Every element of the hologram will have this pattern, and each one will have foci due to its zones acting in groups of $m = 1, 3, 5, \ldots, f_m = \pm k^2/m\lambda$. Thus while the first order focus of the hologram ($m = 1$) for example, corresponds to the distribution in the original object field, stray light from all the other orders reduces the contrast.

Complete background suppression has been obtained by using a reticle in which the center of the zones lies outside the reticle. We note that for any zone-plate, all the foci lie on a line passing through the center of the zones. Therefore, by using a mask, all but one order of diffraction can be blocked.

The mask is arranged so that only the first order focus is transmitted, and the reconstructed image is seen in front of the hole in the mask. The illumination at the plane of the mask from the other foci is shown in grey.

Experiments were made using a reticle going from zones 40 to 203 cut out by etching from shimstock. In order to have a self-supporting structure, the reticle comprised two such zone patterns intersecting at about right angles near the center of the reticle. As a result, two independent reconstructions of a hologram in the same order could be observed This reticle was 2½ in. in diameter and mounted 2½ in. away from the film plane. Some artificial stars were made by back-lighting a perforated mask, and this was photographed with the reticle camera. The resulting negative was then re-photographed onto copy film having been reduced in size by a factor of 20. Finally, this minification was chemically bleached to give a hologram suitable for reconstruction by diffraction which had phase rather than transmission structure.

A reconstruction obtained by using Hg green from a high-pressure source. The background was too faint to photograph in the same exposure with the reconstructed object field. Interestingly, the background had a granular appearance which seemed to arise about equally from grain in the film from the reticle camera (reproduced in the minification), and from scattering in the bleached minification.

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* Airy disc.

1. A. V. Baez, *J. Opt. Soc. Amer.*, *51:* 4, 405–412, April 1961.
2. [63M1] 3. [61M2]
4. Optimum size pinholes were discussed by Rayleigh, cf. R. W. Wood, *Physical Optics*, 272, 3rd Ed., MacMillan, 1934.
5. Born & Wolf, *Principles of Optics*, 452 ff., Pergamon Press, 1959.

58R1 G. L. Rogers, "Diffraction microscope and the ionosphere—use of a satellite," *J. Atmos. Terr. Phys.*, *12:* 220–221, 1958.

In [57R1], a sober estimate of the value of diffraction microscopy in ionosphere studies was given, and it appeared, with the techniques then available, that the use was likely to be limited. The demonstration of a satellite capable of carrying a continuously emitting transmitter completely changes the prognosis, and the possibility of using diffraction microscopy in ionosphere studies now appears to be good, for the following reasons:

(a) The use of a transmitter beyond the *E*- and *F*-regions, or between them, means we can now get a transmitted diffraction pattern, closely analogous to that of the original Gabor method, without having to rely on a problematical quiet period in the ionosphere to secure sufficiently specular reflection.

(b) The speed of the satellite is high, and may be determined accurately, as can its height and the height of the layers being studied. This means that ionosphere drift is relatively unimportant, and a substantially instantaneous image may be obtained. While the method will give no information about ionospheric movement, it may give information about ionospheric structure.

The value of V_g required for the formula [in paragraph 4 of the above paper] is to a first approximation the velocity of the satellite as projected through a point in the layer studied. This can be measured before interpreting the diffraction pattern and does not have to be determined later. Thus f_2 is readily calculated (within limits) and the position on the optical bench where the reconstructed image of the ionosphere will appear determined in advance: this greatly simplifies the search for it. A single aerial now gives a one-dimensional picture. Moreover, the value of the scale factor, p, is now much greater, and the problems of working near the limits of photographic reproduction are less acute. On the other hand the radio record must reproduce changes up to 100 c/s.

(c) The direction of the satellite's motion is known in advance. Two-dimensional recording with a transverse system of aerials becomes much easier, as the base-line direction can be chosen beforehand. Moreover, at shorter wavelengths, the total span of aerials is much reduced. For $\lambda = 4$ m transmissions, for instance, 101 aerials spaced 50 m apart would suffice for the *E*-region, rather wider spacings or shorter wavelengths being required for the *F*-region. Since the "speed of scan" is also known, the production of a photographic plate which represents the ground diffraction pattern in two dimensions with the same scale transverse to the path as along it, is much simplified: the main optical problem is thus overcome. Any small errors remaining will be easily dealt with by angling the plate to the beam in reconstruction.

(d) If it should prove possible to use very small wavelengths in the millimetre region, the diffraction effects would be so small that the pattern produced could be regarded as a direct projected image, without any need for reconstruction. Against this, the contrast of the ionosphere to waves in this region is probably very low.

(e) Opportunity is taken to point out that the very high speed of the satellite provides us with a body with $v/c \simeq 2{\cdot}5 \times 10^{-5}$, and a value of $\sqrt{1 - v^2/c^2}$ differing from 1 by about 3 parts in 10^{10}. This should be within the accuracy attainable with a caesium atomic clock. There will be considerable difficulty, both in principle and in practice, in comparing the satellite clock with an earth clock, and a study of these difficulties will throw further light on the concept we give the name of "time," and underline Einstein's essential wisdom in asserting that space-time is a continuum, and any attempt to divide time out of it is an illusion. One possible approach is indicated briefly below.

(f) A couple of caesium atomic clocks, one on earth and one on a satellite, the latter controlling the phase of the satellite transmitter, could be used to provide a "coherent background" for the Gabor and Goss method. It is only necessary to hold them in phase for the period of 10–15 s during a single transit, so the relativistic correction is here unimportant. It should be noted, in passing, that the longitudinal Doppler shift will produce beats on the record, which correspond to the outer zones of a Newton's ring system passing over the ground aerial. The phase of the centre of this system should give information as to the phase of the two oscillators, local and satellite, as the latter passes overhead, provided the distance of the satellite can be measured to a fraction of a wavelength. By comparing this with the phase obtained at next transit, it might be possible to rate the satellite clock, but many observations would be necessary before a result could be obtained sensibly independent of random sources of error. For instance, there will be undetermined phase-paths in the ionosphere, unless we can use a wavelength short enough to avoid ionosphere absorption, yet long enough to enable the distance in wavelengths to be determined accurately.

57R1 G. L. Rogers, "Diffraction microscopy and the ionosphere," *J. Atmos. Terr. Phys.*, *10:* 332–337, 1957.

The application of diffraction microscopy to Mitra records is considered. It is shown that its application to existing records might result in some slight improvement, probably scarcely justifying the effort. If, however, tests should show that the combination would work with aerial spacings of 3–10 λ, the advantages of the combined method would be substantial.

An important practical limitation on any type of Mitra method is the complexity of the record normally obtained, and it may prove impossible adequately to analyze any but the simplest of them by any technique.

The question of future development is briefly touched on.

It has been suggested in a preliminary note (Rogers, [56R2]) that the technique of diffraction microscopy might be applied to the interpretation of Mitra records (Mitra, 1949) of ionospheric movement. The establishment of the method would take some time, and before launching a full-scale investigation, it is desirable to form an estimate of (a) how far diffraction microscopy can help in developing the Mitra technique and (b) how the Mitra technique itself stands in relation to other techniques (e.g. following meteor-trail drifts) which have subsequently been developed. This paper addresses itself to the first of these questions: the second must be left to others more versed in ionospheric matters than the writer.

57R2 G. L. Rogers, "An experimental verification of diffraction microscopy, using radio waves," *J. Atmos. Terr. Phys.*, *11:* 51–53, 1957.

An aircraft has been deliberately flown over the receivers of a station during Mitra recording. The contribution of the aircraft to the Mitra pattern has been isolated by diffraction microscopy, and a one-dimensional image of it has been recovered. The location of this image on the optical bench is in satisfactory agreement with the theory.

56G1 D. Gabor, "Improvements in and relating to optical apparatus for producing multiple interference patterns," U.S. Pat. 2,770,166, Nov. 13, 1956 (assigned to Nat. Research Devel. Corp., London).

This invention relates to optical apparatus of the kind with which a specimen or a portion thereof can be illuminated by an illuminating beam of coherent light and a photographic record can be obtained of a specimen interference pattern produced as a result of the illumination. The term "coherent light" refers to monochromatic light supplied from a single source of small dimensions. The said specimen illuminating beam, after diffraction at the specimen or the illuminated portion thereof, constitutes an information-carrying beam and the said interference pattern results from the interference of the information-carrying beam with a background beam which has not been affected by the specimen. If the photographic record is suitably processed and illuminated, a magnified representation of the specimen, or the illuminated portion thereof, can be reconstructed in space. Optical apparatus of this kind have been described in the Proceedings of the Royal Society, Section A, volume 197, 1949, at pages 454 to 487[1] and in the Proceedings of the Physical Society, Section B, volume 64, 1951, at pages 449 to 469.[2]

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1. [49G1] 2. [51G1]

56R2 G. L. Rogers, "A new method of analysing ionospheric movement records," *Nature, 177:* 613–614, 1956.

In 1948, Gabor proposed a system of microscopy by reconstructed wave-fronts which is, in effect, a two-stage image-forming process using Fresnel diffraction, with the option of changing wave-length half-way. Hitherto the process has been used in conversions from a short wave-length, for example, electron optical or X-ray, up to visible light. There is no reason, however, why the method should not be used to scale down a wave-length, and this allows the optical examination of any radio wave pattern which is generated by Fresnel diffraction from a sufficiently small object in an otherwise coherent main beam. The following phenomena suggest themselves as capable of investigation by this technique:

(1) Occultation of a radio-star by a sample of *F2* region consisting of relatively small patches in an otherwise clear moving ionospheric sky.

(2) Ionospheric movement records when the ionosphere is largely a smooth reflector with small imperfections moving across it.

(3) Records obtained when a sensibly smooth reflector has absorbing or phase-contrast patches moving below it; for example, sporadic *E* below F_1, or meteor trails below *E*.

(4) The need for a small object in an otherwise coherent beam may be removed, by supplying a coherent beam artificially from elsewhere, after the Gabor and Goss round the square interferometer. In the case of radio signals, this is relatively easy, as a signal can be taken from the transmitter's master oscillator, suitably attenuated, and fed into the receiver, where it combines with the downcoming signal in accordance with the well-known coherent demodulator technique. In this case, the signal passed direct from the transmitter may conveniently be two or three times the strength of the maximum reflected signal, so that the phase of the sum-term never departs too far from that of the larger signal. Alternatively, the analogy with the Gabor and Goss interferometer may be made complete by replacing the optical "quadrature prism" by an analogous radio network consisting of two coherent demodulator receivers, one working directly from the transmitter's master oscillator, the other from this signal after passing through a 90° phase-shifting network. The outputs from both receivers must be recorded, and may later be combined optically in a Gabor and Goss interferometer. This later technique removes all restriction on the degree of roughness in the ionosphere which may be investigated.