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Holography, 1948–1971

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I have the advantage in this lecture, over many of my predecessors, that I need not write down a single equation or show an abstract graph. One can, of course, introduce almost any amount of mathematics into holography, but the essentials can be explained and understood from physical arguments.

Holography is based on the wave nature of light, and this was demonstrated convincingly for the first time in 1801 by Thomas Young, in a wonderfully simple experiment. He let a ray of sunlight into a dark room, and placed a dark screen in front of it, pierced with two small pinholes, and beyond this, at some distance, a white screen. He then saw two darkish lines, one on each side of a bright line, which gave him sufficient encouragement to repeat the experiment, this time with a spirit flame as light source, with a little salt in it, to produce the bright yellow sodium light. This time he saw a number of dark lines, regularly spaced, the first clear proof that light added to light can produce darkness (Fig. 1). This phenomenon is called interference. Thomas Young had expected it because he believed in the wave theory of light. His great contribution to Christian Huygens's original idea was the intuition that monochromatic light represents regular, sinusoidal oscillations, in a medium which at that time was called "the ether." If this is so, it must be possible to produce more light by adding wave crest to wave crest, and darkness by adding wave crest to wave through.

Light that is capable of interferences is called "coherent," and it is evident that, in order to yield many interference fringes, the light must be *very* monochromatic. Coherence is conveniently measured by the path difference between two rays of the same source, by which they can differ while still giving observable interference contrast. This is called the coherence length, an important quantity in the theory and practice of holography. Lord Rayleigh and Albert Michelson were the first to understand that it is a reciprocal measure of the spectroscopic line width. Michelson used it for ingenious methods of spectral analysis and for the measurement of the diameter of stars.

Let us now jump a century and a half, to 1947. At that time I was very interested in electron microscopy. This wonderful instrument had at that time produced a hundredfold improvement in the resolving power of the best light microscopes, and yet it was disappointing, because it had stopped short of resolving atomic lattices. The de Broglie wavelength of fast electrons, about 1/20 angstrom, was short enough but the optics was imperfect. The best electron objective that one can make can be compared in optical perfection to a raindrop rather than to a microscope objective, and through the theoretical work of O. Scherzer it was known that the electron objective could never be perfected. The theoretical limit at that time was estimated at 4 angstroms, just about twice what was needed to resolve atomic lattices, while the practical limit stood at about 12 angstroms. These limits were given by the necessity of restricting the aperture of the electron lenses to a few thousandths of a radian, at which angle the spherical aberration error is about equal to the diffraction error. If one doubles this aperture so that the diffraction error is halved, the spherical aberration error is increased eight times, and the image is hopelessly blurred.

After I had pondered this problem for a long time, a solution suddenly dawned on me, one fine day at Easter 1947, more or less as shown in Fig. 2. Why not take a bad electron picture, but one which contains the *whole* of the information, and correct it by optical means? It had been clear to me for some time that this could be done, if at all, only with coherent electron beams, with electron waves that have a definite phase. But an ordinary photograph loses the phase completely, it records only the intensities. No wonder we lose the phase, if there is nothing to compare it with! Let us see what happens if we add a standard to it, a "coherent background." My argument is illustrated in Fig. 2, for the simple case when there is only one object point. The interference of the object wave and of the coherent background or "reference wave" will then produce interference fringes. There will be maxima wherever the phases of the two waves are identical. Let us make a hard positive record, so that it transmits only at the maxima, and illuminate it with the reference source alone. Now the phases are of course right for the reference source A, but, as at the slits the phases are identical, they must be right also for B; therefore, the wave of B must also appear, *reconstructed*.

A little mathematics soon showed that the principle was right, also for more than one object point, for any

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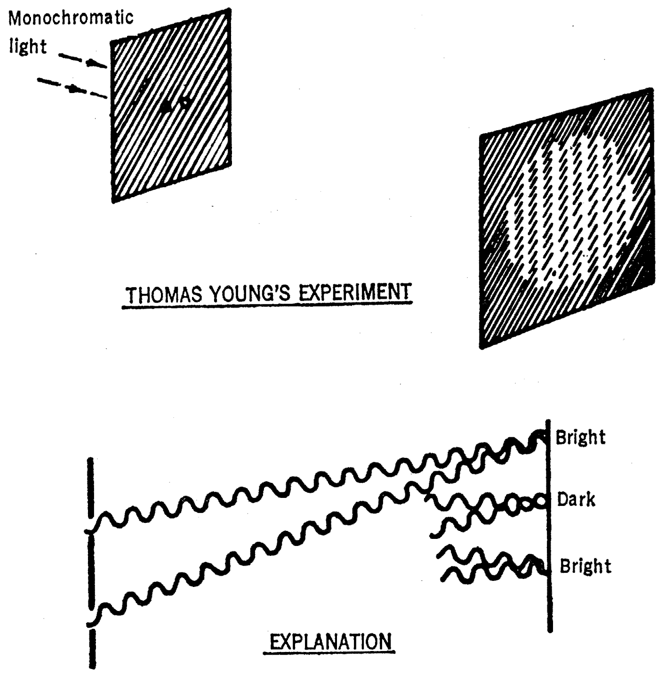


Fig. 1. Thomas Young's interference experiments, 1801.

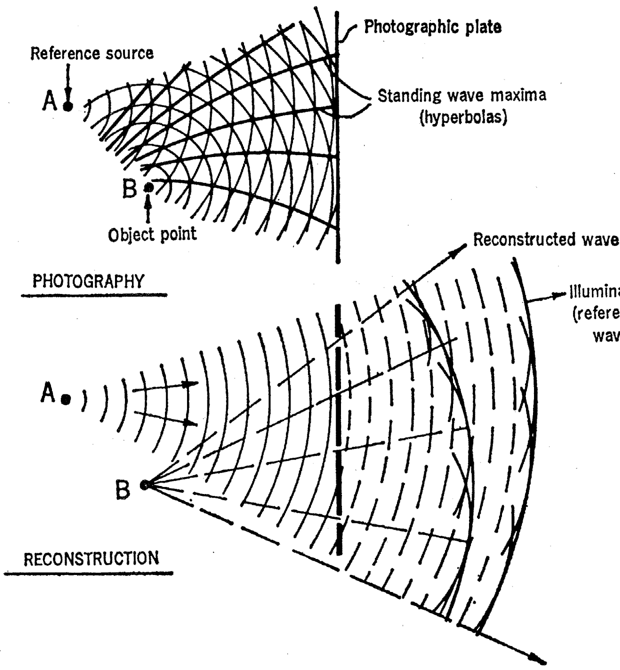


Fig. 2. The basic idea of holography, 1947.

complicated object. Later on it turned out that in holography nature is on the inventor's side; there is no need to take a hard positive record; one can take almost any negative. This encouraged me to complete my scheme of electron microscopy by reconstructed wave fronts, as I then called it and to propose the two-stage process shown in Fig. 3. The electron microscope was to produce the interference figure between the object beam and the coherent background, that is to say, the nondiffracted part of the illuminating beam. This interference pattern I called a "hologram," from the Greek word *holos*—the whole, because it contained the whole of the information. The hologram was then reconstructed with light, in an optical system which corrected the aberrations of the electron optics (*1–3*).

In doing this, I stood on the shoulders of two great physicists, W. L. Bragg and Fritz Zernike. Bragg had shown me, a few years earlier, his "x-ray microscope," an optical Fourier-transformer device. One puts into it a small photograph of the reciprocal lattice and obtains a projection of the electron densities, but only in certain exceptional cases, when the phases are all real and have the same sign. I did not know at that time, and neither did Bragg, that Mieczislav Wolfke had proposed this method in 1920, but without realizing it experimentally (*4*). So the idea of a two-stage method was inspired by Bragg. The coherent background, on the other hand, was used with great success by Fritz Zernike in his beautiful investigations on lens aberrations, showing up their phase and not just their intensity. It was only the reconstruction principle which had escaped them.

In 1947 I was working in the research laboratory of the British Thomson-Houston Company in Rugby, England. It was a lucky thing that the idea of holography came to me via electron microscopy, because, if I had thought of optical holography only, the director of research, L. J. Davies, could have objected that the British Thomson-Houston Company was an electrical engineering firm and not in the optical field. But, as our sister company, Metropolitan Vickers, made electron microscopes, I obtained the permission to carry out some optical experiments. Figure 4 shows one of our first holographic reconstructions. The experiments were not easy. The best compromise between coherence and intensity was offered by the high-pressure mercury lamp, which had a coherence length of only 0.1 millimeter, enough for about 200 fringes. But in order to achieve spatial coherence, we (my assistant Ivor Williams and I) had to illuminate, with one mercury line, a pinhole 3 microns in diameter. This left us with enough light to make holograms about 1 centimeter in diameter

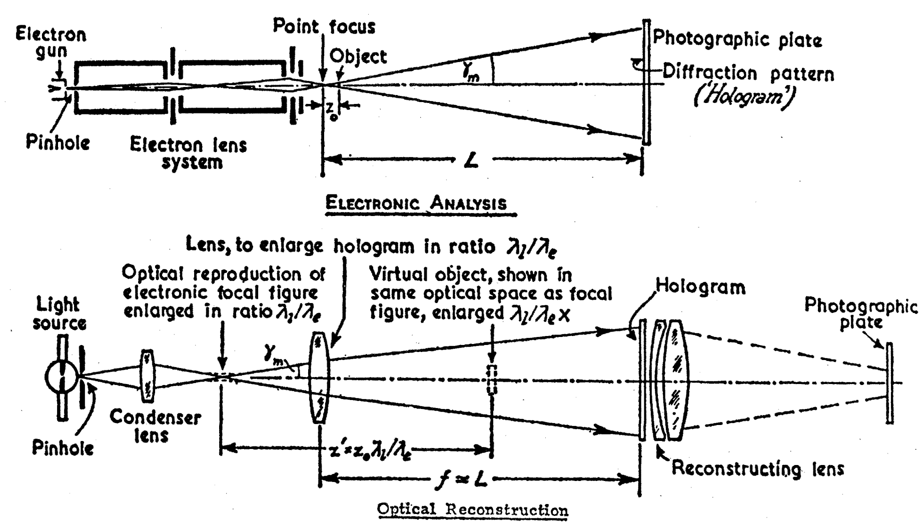
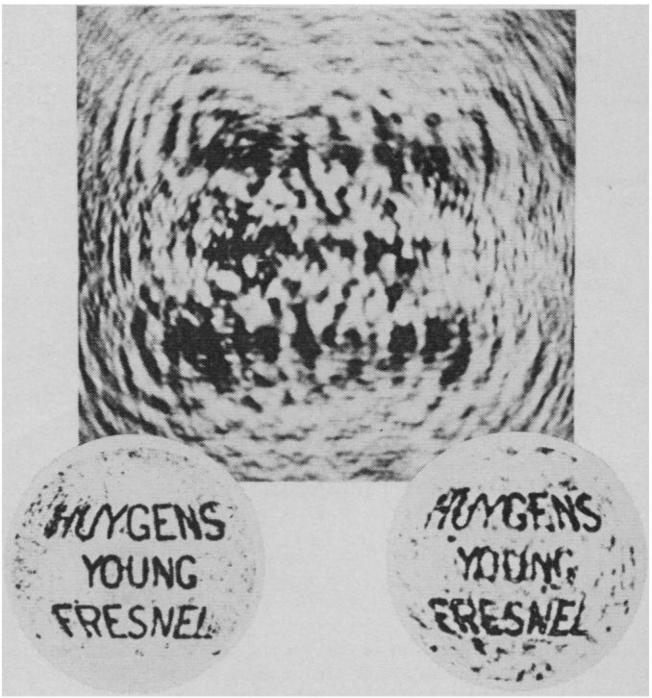


Fig. 3. The principle of electron microscopy by reconstructed wave fronts (*2*).



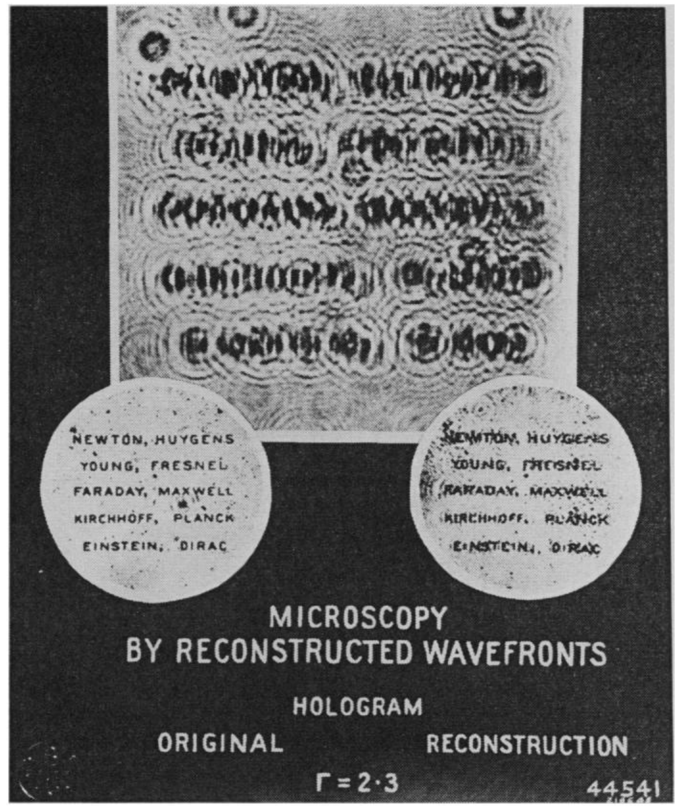


Fig. 4 (left). First holographic reconstruction, 1948. Fig. 5 (right). Another example of early holography, 1948 (2).

of objects, which were microphotographs about 1 millimeter in diameter, with exposures of a few minutes, on the most sensitive emulsions then available. The small coherence length forced us to arrange everything in one axis. This is now called "in line" holography, and it was the only arrangement possible at that time. Figure 5 shows a somewhat improved experiment, the best of our series. It was far from perfect. Apart from the *schlieren*, which cause random disturbances, there was a systematic defect in the pictures, as may be seen by the distortion of the letters. The explanation is given in Fig. 6. The disturbance arises from the fact that, instead of one image, there are *two*. Each point of the object emits a spherical secondary wave, which interferes with the background and produces a system of circular Fresnel zones. Such a system is known after the optician who first produced it, a Soret lens. This is, at the same time, a positive and a negative lens. One of its foci is in the original position of the object point; the other is in a position conjugate to it, with respect to the illuminating wave front. If one uses "in-line holography," both images are in line and can be separated only by focusing. But the separation is never quite perfect, because in regular, coherent illumination every point leaves a "wake" behind it, which reaches to long distances.

I will explain later with what ease modern laser holographers have gotten rid of this disturbance, by making use of the superior coherence of laser light which was not at my disposal in 1948.

However, I was confident that I could eliminate the second image in the application which alone interested me at that time: seeing atoms with the electron microscope. This method, illustrated in

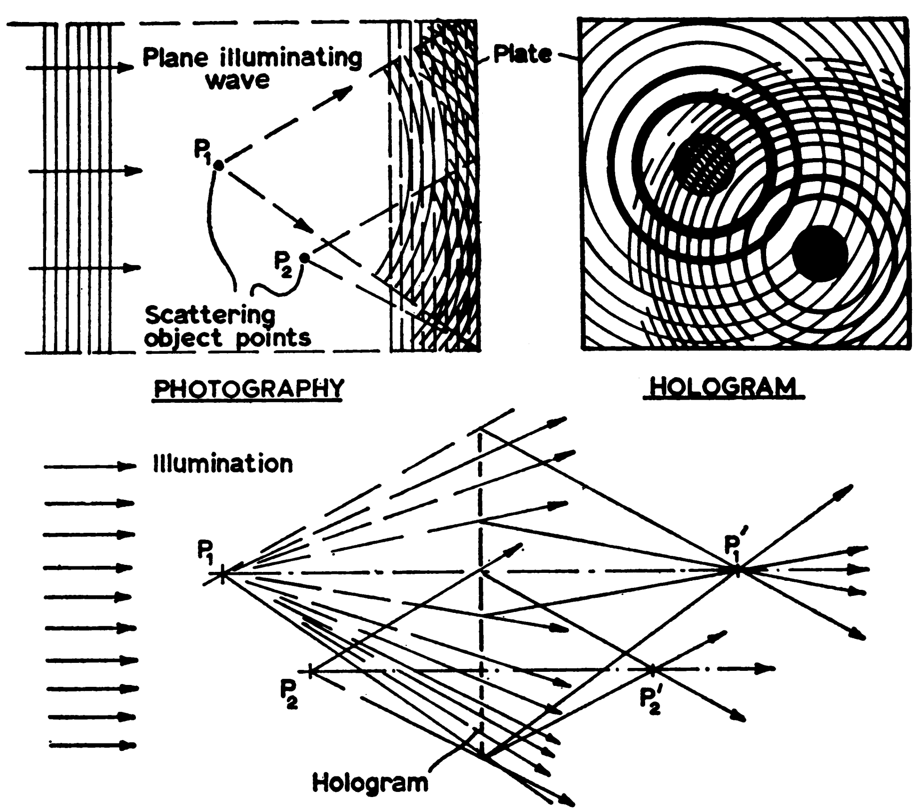
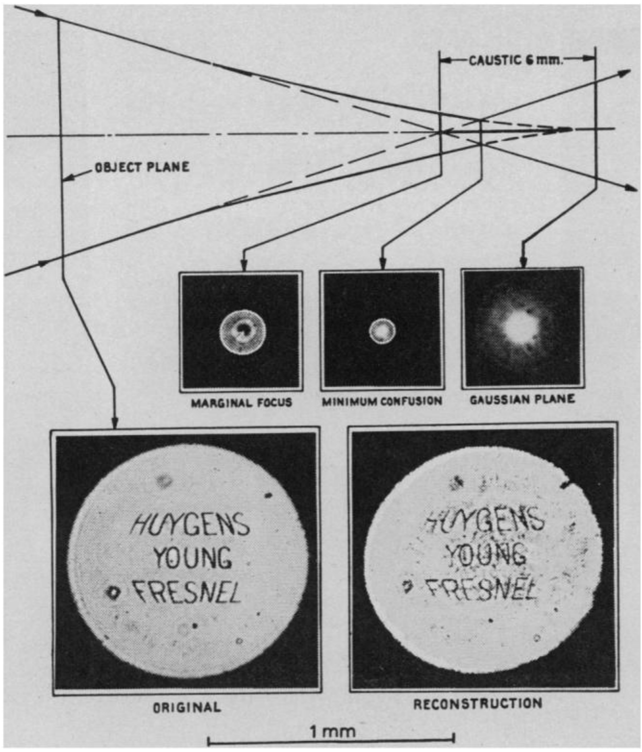


Fig. 6. The second image. Explanation in terms of Soret lenses as holograms of single object points.



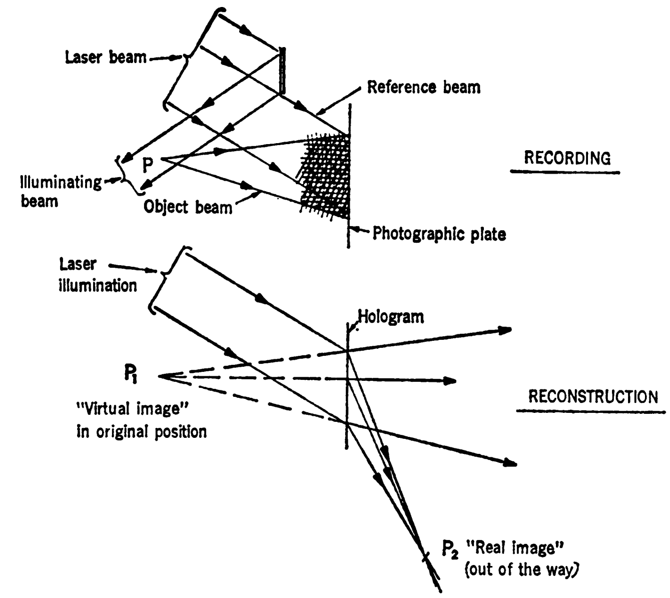


Fig. 7 (left). Elimination of the second image by compensation of the spherical aberration in the reconstruction (*3*). Fig. 8 (right). Holography with skew reference beam (*12*).

Fig. 7, utilized the very defect of electron lenses, the spherical aberration, in order to defeat the second image. If an electron hologram is taken with a lens with spherical aberration, one can afterwards correct *one* of the two images by suitable optics, and the other has then twice the aberration, which washes it out almost completely. Figure 7 shows that a perfectly sharp reconstruction, in which as good as nothing remains of the disturbance caused by the second image, can be obtained with a lens so bad that its definition is at least ten times worse than the resolution that one wants to obtain. Such a very bad lens was obtained by using a microscope objective the wrong way round, and using it again in the reconstruction.

So it was with some confidence that 2 years later, in 1950, we started a program of holographic electron microscopy in the research laboratory of the Associated Electrical Industries, in Aldermaston, under the direction of Dr. T. E. Allibone, with my friends and collaborators M. E. Haine, J. Dyson, and T. Mulvey (*5*). By that time I had joined Imperial College, and took part in the work as a consultant. In the course of 3 years we succeeded in considerably improving the electron microscope, but in the end we had to give up, because we had started too early. It turned out that the electron microscope was still far from the limit imposed by optical aberrations. It suffered from vibrations, stray magnetic fields, creep of the stage, and contamination of the object, all made worse by the long exposures required in the weak coherent electron beam. *Now*, 20 years later, would be the right time to start on such a program, because in the meantime the patient work of electron microscopists has overcome all these defects. The electron microscope resolution is now right up to the limit set by the spherical aberration, about 3.5 angstroms, and only an improvement by a factor of 2 is needed to resolve

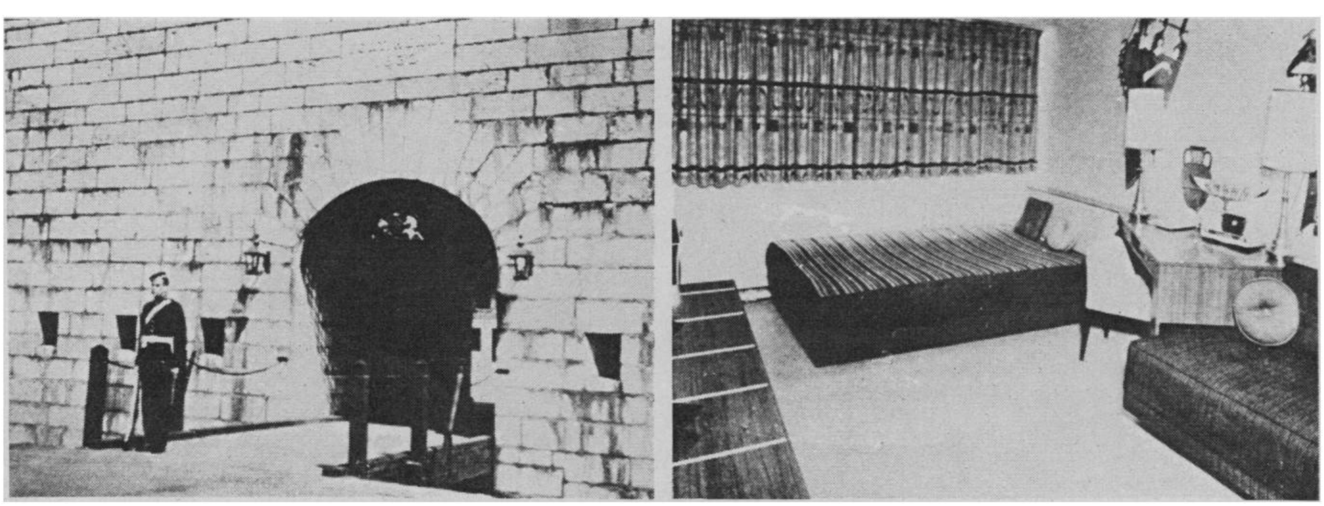


Fig. 9. First example of multiple-image storage in one hologram (*14*).

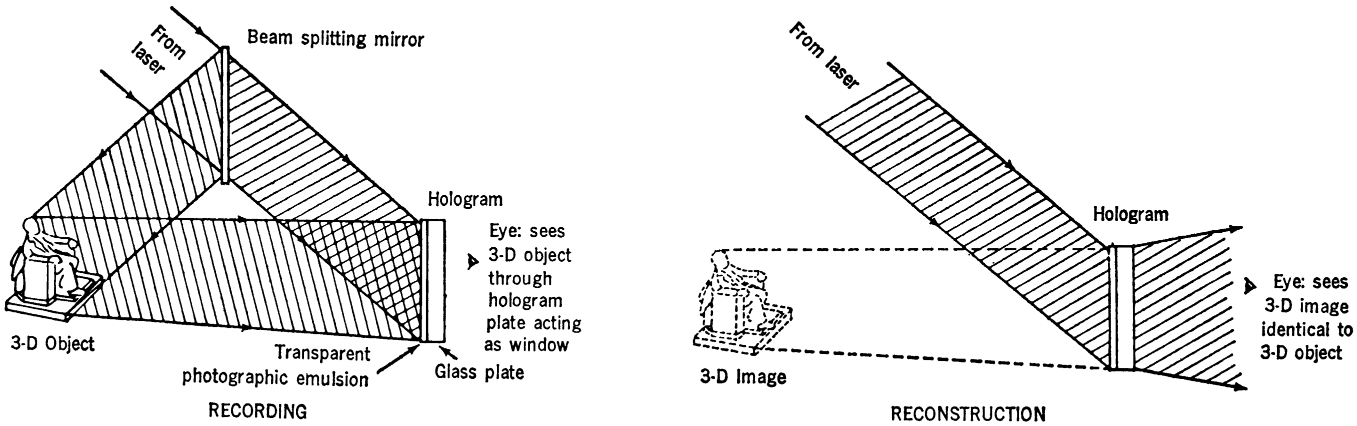


Fig. 10. Three-dimensional holography of a diffusing object with laser light.

atomic lattices. Moreover, there is no need now for such very long exposures as we had to contemplate in 1951, because, by the development of the field emission cathode, the coherent current has increased by a factor of 3 to 4 orders of magnitude. So perhaps I may yet live to see the realization of my old ideas.

My first papers on wave-front reconstruction evoked some immediate responses. G. L. Rogers (*6*) in Britain made important contributions to the technique, by producing, among other things, the first phase holograms and also by elucidating the theory. In California Alberto Baez (*7*) and Hussein El-Sum and P. Kirkpatrick (*8*) made interesting forays into x-ray holography. For my part, with my collaborator W. P. Goss, I constructed a holographic interference microscope, in which the second image was annulled in a rather complicated way by the superimposition of two holograms, "in quadrature" with one another. The response of the optical industry to this was so disappointing that we did not publish a paper on it until 11 years later, in 1966 (*9*). Around 1955 holography went into a long hibernation.

The revival came suddenly and explosively in 1963, with the publication of the first successful laser holograms (*10*) by Emmett N. Leith and Juris Upatnieks of the University of Michigan, Ann Arbor. Their success was due not only to the laser, but to the long theoretical preparation of Leith, which started in 1955. This was unknown to me and to the world, because Leith, with his collaborators Cutrona, Palermo, Porcello, and Vivian, applied his ideas first to the problem of the "side-looking radar" which at that time was classified (*11*). This was in fact two-dimensional holography with electromagnetic waves, a counterpart of electron holography. The electromagnetic waves used in radar are about 100,000 times longer than light waves, while electron waves are about 100,000 times shorter. Their results were brilliant, but, to my regret, I cannot discuss them for lack of time.

When the laser became available in 1962, Leith and Upatnieks could at once produce results far superior to mine, by a new, simple, and very effective method of eliminating the second image (*12–14*). This is the method of the "skew reference wave," illustrated in Fig. 8. It was made possible by the great coherence length of the helium-neon laser, which even in 1962 exceeded that of the mercury lamp by a factor of about 3000. This made it possible to separate the reference beam from the illuminating beam; instead of going through the object, the reference beam could now go around it. The result was that the two reconstructed images were now separated not only in depth, but also angularly, by twice the incidence angle of the reference beam. Moreover, the intensity of the coherent laser light exceeded that of mercury many millionfold. This made it possible to use very fine-grain, low-speed photographic emulsions and to produce large holograms, with reasonable exposure times.

Figure 9 shows two of the earliest reconstructions made by Leith and Upatnieks in 1963, which were already greatly superior to anything that I could produce in 1948. The special interest

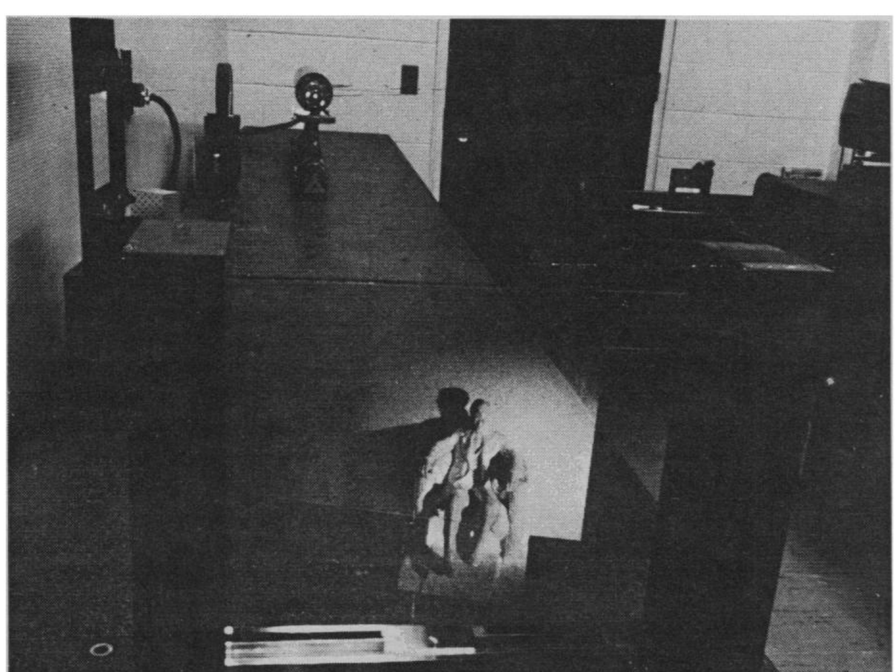


Fig. 11. Three-dimensional reconstruction of a small statue of Abraham Lincoln. [Courtesy of Prof. G. W. Stroke, State University of New York, Stony Brook (*15*)]

of these two images is that they are reconstructions from *one* hologram, taken with different positions of the reference beam. This was the first proof of the superior storage capacity of holograms. Leith and Upatnieks could soon store 12 different pictures in one emulsion. Nowadays one can store 100 or even 300 pages of printed matter in an area which by ordinary photography would be sufficient for one.

From then on progress became very rapid. The most spectacular result of the first year was the holography of three-dimensional objects, which could be seen with two eyes. Holography was, of course, three-dimensional from the start, but in my early, small holograms one could see this only by focusing through the field with a microscope or short-focus eyepiece. But it was not enough to make the hologram large, it was also necessary that every point of the photographic plate should "see" every point of the object. In the early holograms, taken with regular illumination, the information was contained in a small area, in the diffraction pattern. In the case of rough, diffusing objects no special precautions are necessary. The small dimples and projections of the surface diffuse the light over a large cone. Figure 10 shows an example of the setup in the case of a rough object, such as a statuette of Abraham Lincoln. The reconstruction is shown in Fig. 11. With a bleached hologram ("phase hologram") one has the impression of looking through a clear window at the statuette itself (*15*).

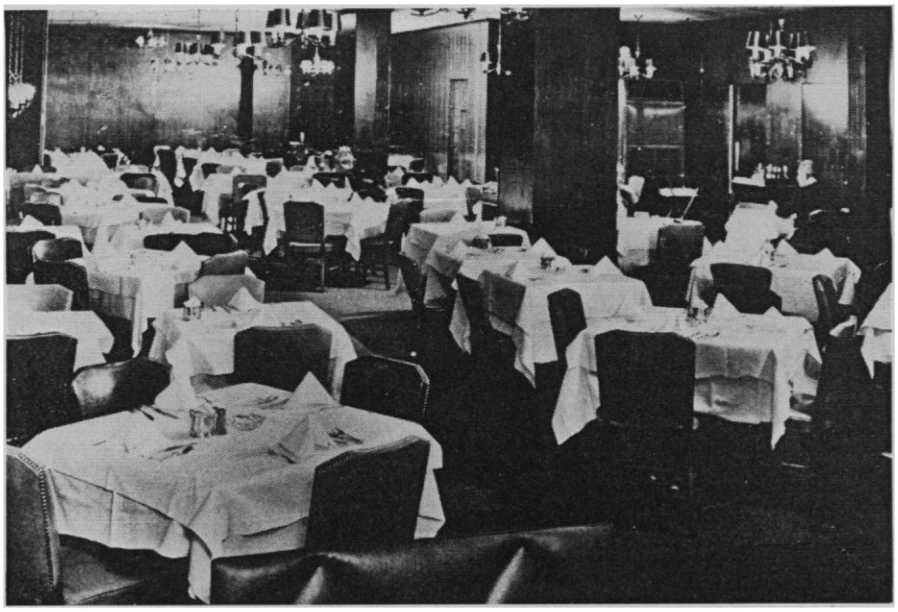


Fig. 12. Reconstruction of a plane transparency, showing a restaurant, from a hologram taken with diffused illumination (*14*).

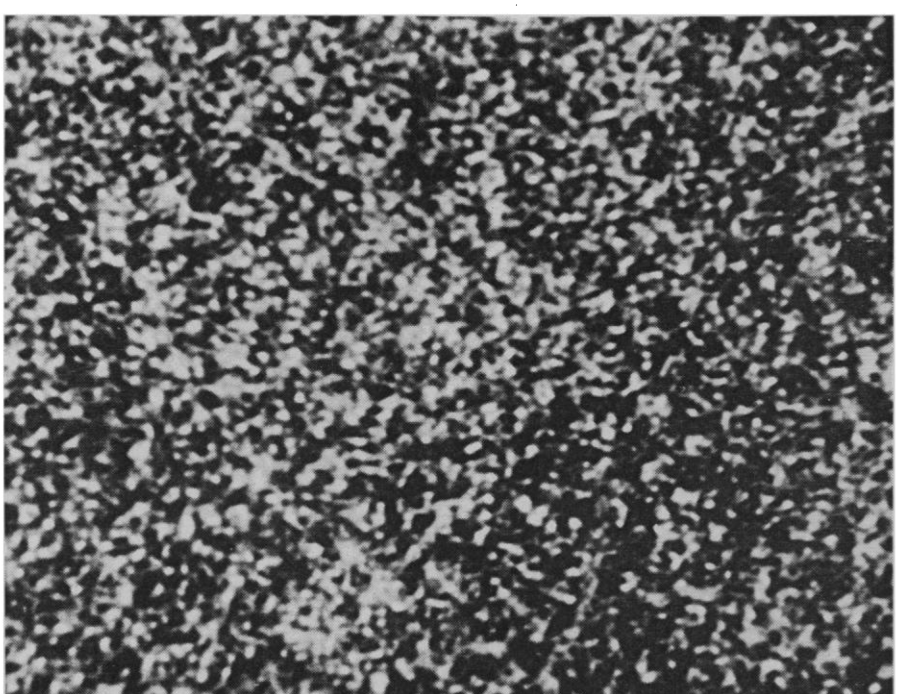


Fig. 13. Strongly magnified image of hologram taken with diffused illumination. The information is conveyed in a noiselike code (*14*).

If the object is nondiffusing, for instance, if it is a transparency, the information is spread over the whole hologram area by illuminating the object through a diffuser, such as a frosted glass plate. The appearance of such a "diffused" hologram is extraordinary; it looks like noise. One can call it "ideal Shannon coding," because Claude E. Shannon has shown in his communication theory that the most efficient coding is such that all regularities seem to have disappeared in the signal; it must be "noiselike." But where is the information in this chaos? It can be shown that the information is not as irregular as it appears. It is not as if grains of sand had been scattered over the plate at random. It is rather a complicated figure, the diffraction pattern of the object, which is repeated at random intervals, but always in the same size and orientation.

A very interesting and important property of such a diffused hologram is that any small part of it, large enough to contain the diffraction pattern, contains information on the whole object, and this can be reconstructed from the fragment, only with more noise. A diffused hologram is therefore a *distributed memory*, and this has evoked much speculation with respect to whether human memory is not perhaps, as it were, holographic, because it is well known that a good part of the brain can be destroyed without wiping out every trace of a memory. There is no time here to discuss this very exciting question. I want only to say that, in my opinion, the similarity with the human memory is functional only, but certainly not structural.

I have shown that in the development of holography the holograms have become always more unlike the object, but the reconstruction has become always more perfect. Figure 12 shows an excellent reconstruction by Leith and Upatnieks of a photograph, from a diffused hologram like the one in Fig. 13.

The pioneer work carried out at the University of Michigan, Ann Arbor, led also to the stabilization of holographic techniques. Today hundreds if not thousands of laboratories possess the equipment of which an example is shown in Fig. 14: the very stable granite slab or steel table and the various optical devices for dealing with coherent light, which are now manufactured by the optical industry. The great stability is absolutely essential in all work carried out with steady-state lasers, because a movement of the order of a quarter wavelength during the exposure can completely spoil a hologram.

However, from 1965 onward there has developed an important branch of holography where high stability is not required, because the holograms are taken in a small fraction of a microsecond, with a pulsed laser.

Imagine that you had given a physicist the problem: "Determine the size of the droplets which issue from a jet nozzle, with a velocity of 2 Mach. The sizes are probably from a few microns upwards." Certainly he would have thrown up his hands in despair! But all it takes now is to record a simple in-line hologram of the jet, with the plate at a safe distance, with a ruby laser pulse of 20 to 30 nanoseconds. One then looks at the "real" image (or one reverses the illuminating beam and makes a real image of the virtual one), one dives with a microscope into the three-dimensional image of the jet and focuses the particles, one after the other. Because of the large distance, the disturbance by the second image is entirely negligible. Figure 15 shows a fine example.

As the research workers of the TRW Instruments laboratories have shown, it is possible to record in one hologram the infusoria in several feet of dirty water, or the insects in a meter of air space. Figure 16 shows two reconstructions of insects from one hologram, focusing on one after the other. The authors, C. Knox and R. E. Brooks,

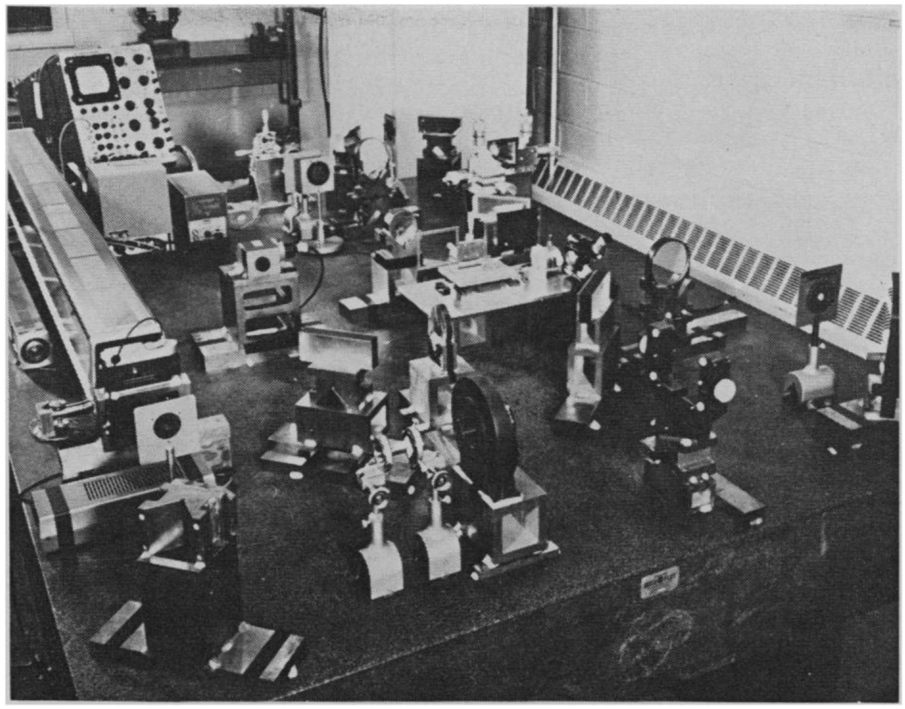


Fig. 14. Modern holographic equipment.

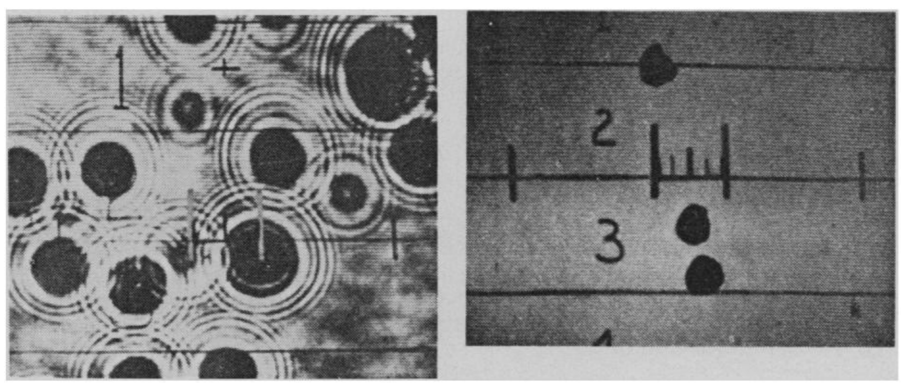


Fig. 15. Holography of jets. (Left) Hologram of aerosol particles in spray; (right) aerosol particles focused. [Courtesy of Laser Holography, Inc., Santa Barbara, California]

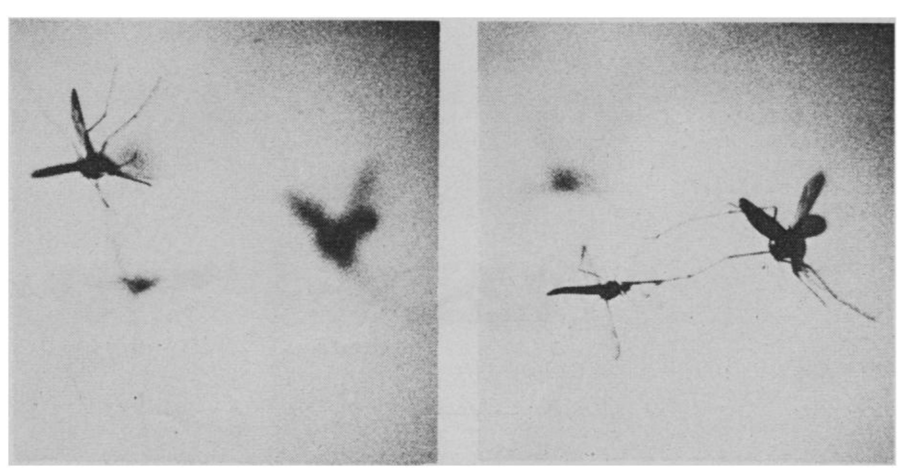


Fig. 16. Observation of mosquitoes in flight. Both pictures are extracted from one hologram. [Courtesy of C. Knox and R. E. Brooks, TRW Instruments, Redondo Beach, California]

also made a cinematographic record of a holographic film, in which the flight of one mosquito is followed through a considerable depth, by refocusing in every frame (*16*).

Another achievement of the TRW group, Ralph Wuerker and his colleagues, leads us into another branch of holography, to holographic interferometry. Figure 17 shows a reconstruction of a bullet, with its train of shock waves, as it meets another shock wave. But it is not just an image, it is an interferometric image. The fringes show the loci at which the retardation of light is by integer wavelengths, relative to the quiet air, before the event. This comparison standard is obtained by an earlier exposure. This is therefore a double-exposure hologram, such as will be discussed in more detail later (*17*).

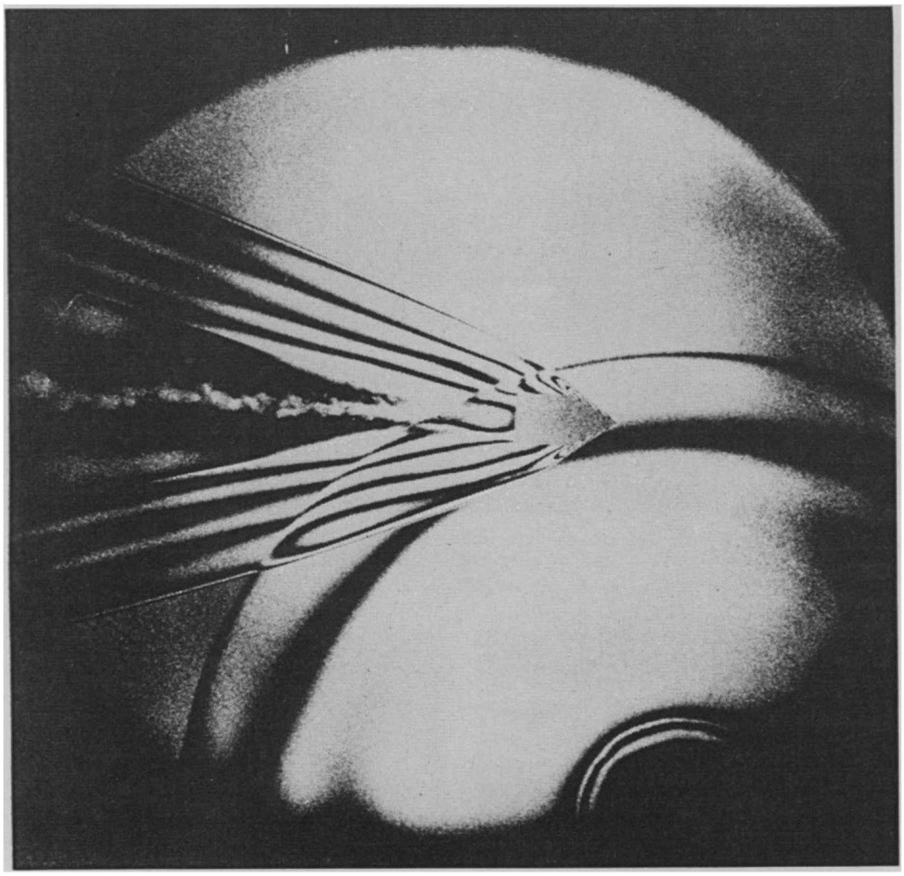


Fig. 17. Dynamic holographic interferometry. This reconstruction of a holographic interferogram shows the interaction of two air shock fronts and their associated flows. [Courtesy of Dr. R. F. Wuerker and his associates, TRW Physical Electronics Laboratory, Redondo Beach, California]

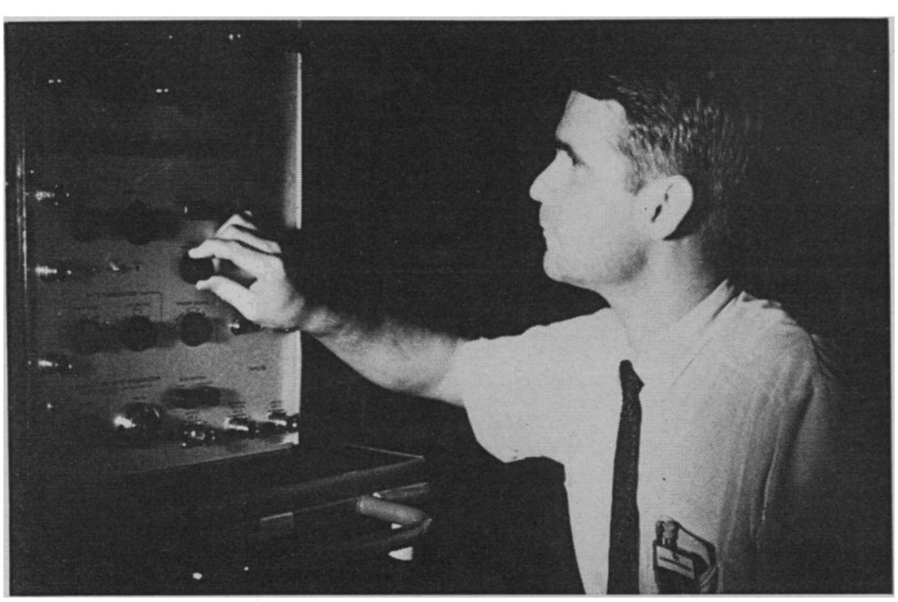


Fig. 18. Holographic portrait. [L. Siebert, Conductron Corporation (now merged into McDonnell-Douglas Electronics Company, St. Charles, Missouri)].

Figure 18 shows another high achievement of pulse holography: a holographic, three-dimensional portrait, obtained by L. Siebert. It is the result of outstanding work in the development of lasers. The ruby laser, as first realized by T. H. Maiman, was capable of short pulses, but its coherence length was of the order of a few centimeters only. This is no obstacle in the case of in-line holography, where the reference wave proceeds almost in step with the diffracted wavelets, but, in order to take a photograph of a scene of, say, 1 meter in depth with reflecting objects, one must have a coherence length of at least 1 meter. Nowadays single-mode pulses of 30-nanosecond duration with 10 joules in the beam and coherence lengths of 5 to 8 meters are available, and have been used recently for taking my holographic portrait.

In 1965 R. L. Powell and K. A. Stetson at the University of Michigan, Ann Arbor, made an interesting discovery. Holographic images taken of moving objects are washed out. But if double exposure is used, first with the object at rest, then in vibration, or simply, by prolonged exposure, fringes will appear, indicating the lines where the displacement amounted to multiples of a half wavelength. Figure 19 shows vibrational modes of a loudspeaker membrane, recorded in 1965 by Powell and Stetson (*18–20*); Fig. 20 shows the vibrational modes for a guitar, taken by K. A. Stetson in the laboratory of Professor Erik Ingelstam (*21*).

Curiously, both the interferograms of the TRW group and the vibrational records of Powell and Stetson preceded what is really a simpler application of the interferometrical principle, and what historically ought to have come first—if the course of science would always follow the shortest line. This is the observation of small deformations of solid bodies by double-exposure holograms. A simple explanation is as follows: We take a hologram of a body in state *A*. This means that we freeze in wave *A* by means of a reference beam. Now let us deform the body so that it assumes state *B*, and take a second hologram in the same emulsion with the same reference beam. We develop the hologram and illuminate it with the reference beam. Now the two waves A and B, which have been frozen in at different times, and which have never "seen" one another, will be revived simultaneously, and they interfere with one another. The result is that Newton fringes will appear on the object, each fringe corresponding to a deformation of a half wavelength. Figure 21 shows a fine example of such a holographic interferogram, made in 1965 by K. A. Haines and B. P. Hildebrand. The principle was discovered simultaneously and independently also by J. M. Burch in England, and by G. W. Stroke and A. Labeyrie at the University of Michigan, Ann Arbor.

Nondestructive testing by holographic interferometry is now by far the most important industrial application of holography. This application gave rise to the first industrial firm based on holography, GCO (formerly G. C. Optronics), in Ann Arbor, Michigan; the following examples are reproduced by courtesy of GCO. Figure 22 shows the testing of a motor car tire. The front of the tire is holographed directly, and the sides are seen in two mirrors, right and left. A little time is needed for the tire to settle down before a first hologram is taken. Then a little hot air is blown against it, and a second exposure is made, on the same plate. If the tire is perfect, only a few, widely spaced fringes will appear, indicating almost uniform expansion. But where the cementing of the rubber sheets was imperfect, a little blister appears, as seen near the center and near the top left corner, only a few thousandths of a millimeter high, but indicating a defect that could become serious. Alternatively, the first hologram is developed, replaced exactly in the original position, and the expansion of the tire is observed "live."

Other examples of nondestructive testing are shown in Fig. 23; all are defects which are impossible or almost impossible to detect by other means, but which reveal themselves unmistakably to the eye. A particularly impressive piece of equipment manufactured by GCO is shown in Fig. 24. It is a holographic analyzer for honeycomb sandwich structures (such as those shown in the middle of Fig. 23) which are used in airplane wings. The smallest welding defect between the aluminum sheets and the honeycomb is safely detected at one glance.

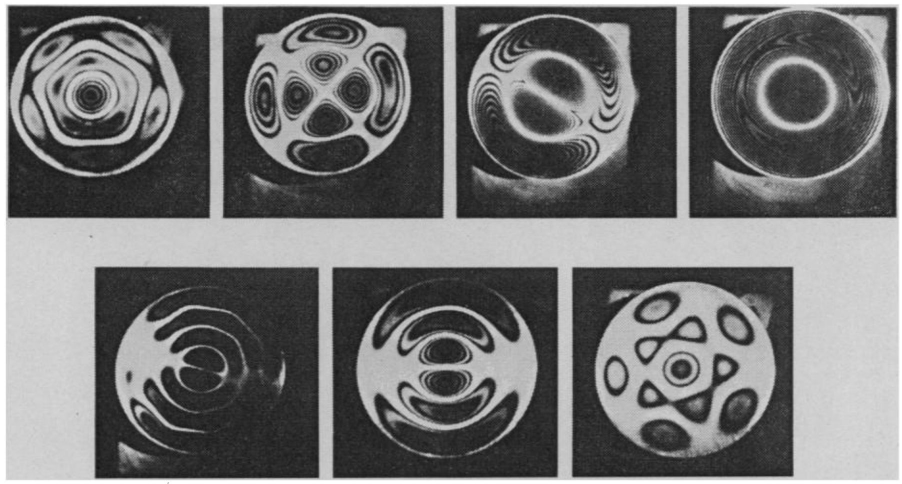


Fig. 19. Vibrational modes of a loudspeaker membrane, obtained by holographic interferometry (*19*).

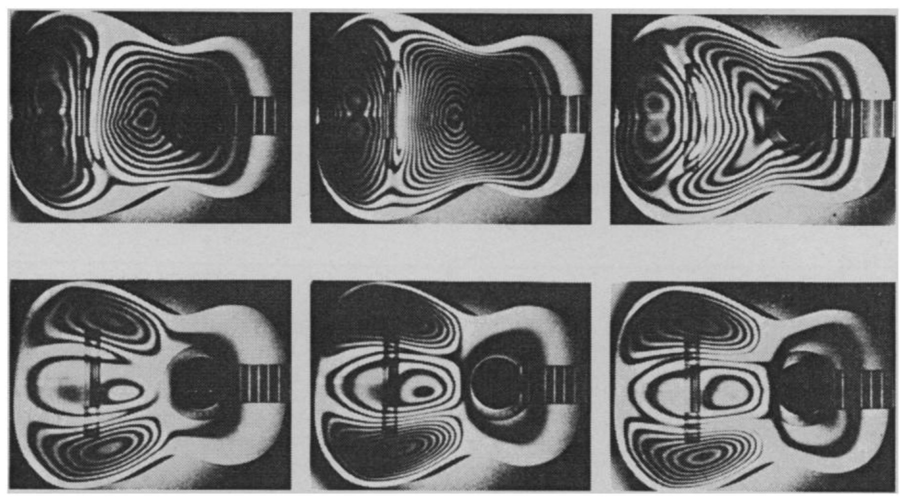


Fig. 20. Vibrational modes of a guitar, recorded by holographic interferometry. [Courtesy of Dr. K. A. Stetson and Prof. E. Ingelstam, University of Michigan, Ann Arbor]

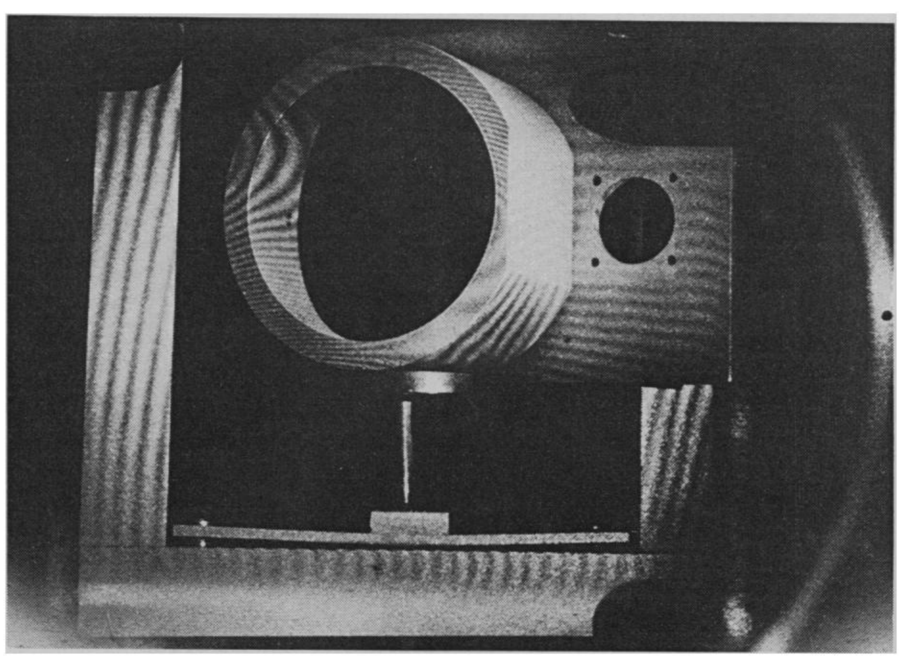


Fig. 21. An early example of holographic interferometry by double exposure [K. A. Haines and B. P. Hildebrand, 1965 (*19*)].

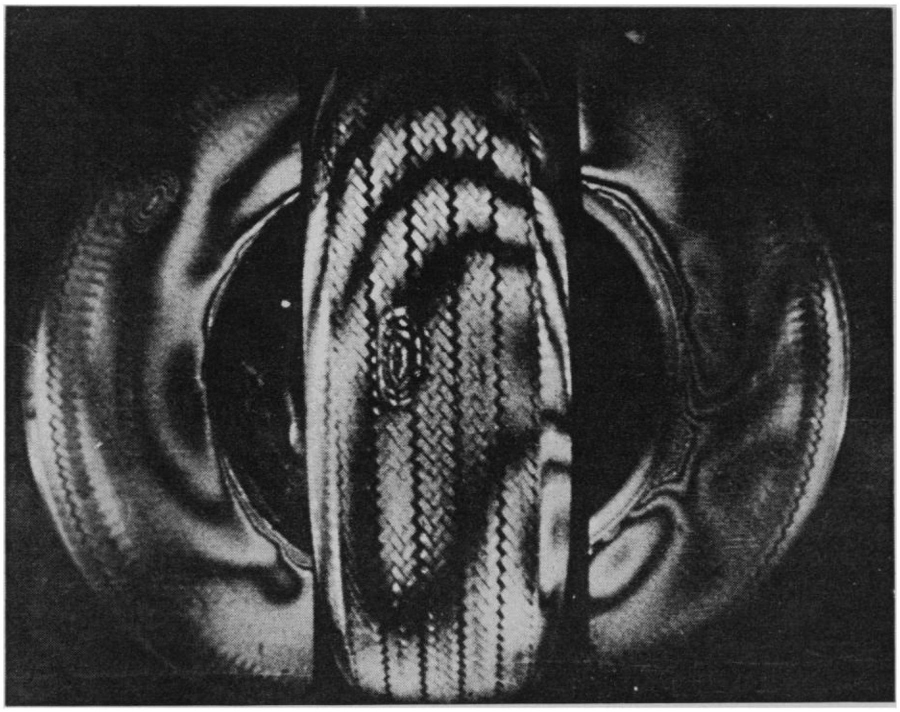


Fig. 22. Nondestructive testing by holography. Double-exposure hologram, revealing two flaws in a tire. [Courtesy of Dr. Ralph Grant and GCO, Ann Arbor, Michigan]

While holographic interferometry is perfectly suited for the detection of very small deformations, with its fringe unit of 1/4000 millimeter, it is a little too fine for checking of the accuracy of workpieces. Here another holographic technique called "contouring" is appropriate. It was first introduced by Haines and Hildebrand, in 1965, and has been recently much improved by J. Varner, also at the University of Michigan, Ann Arbor. Two holograms are taken of the same object, but with two wavelengths which differ by, for example, 1 percent. This produces *beats* between the two-fringe system, with fringe spacings corresponding to about 1/40 millimeter, which is just what the workshop requires (Fig. 25).

From industrial applications I now turn to another important development in holography. In 1962, just before the "holography explosion," the Soviet physicist Yu. N. Denisyuk published an important paper (*22*) in which he combined holography with the ingeni-

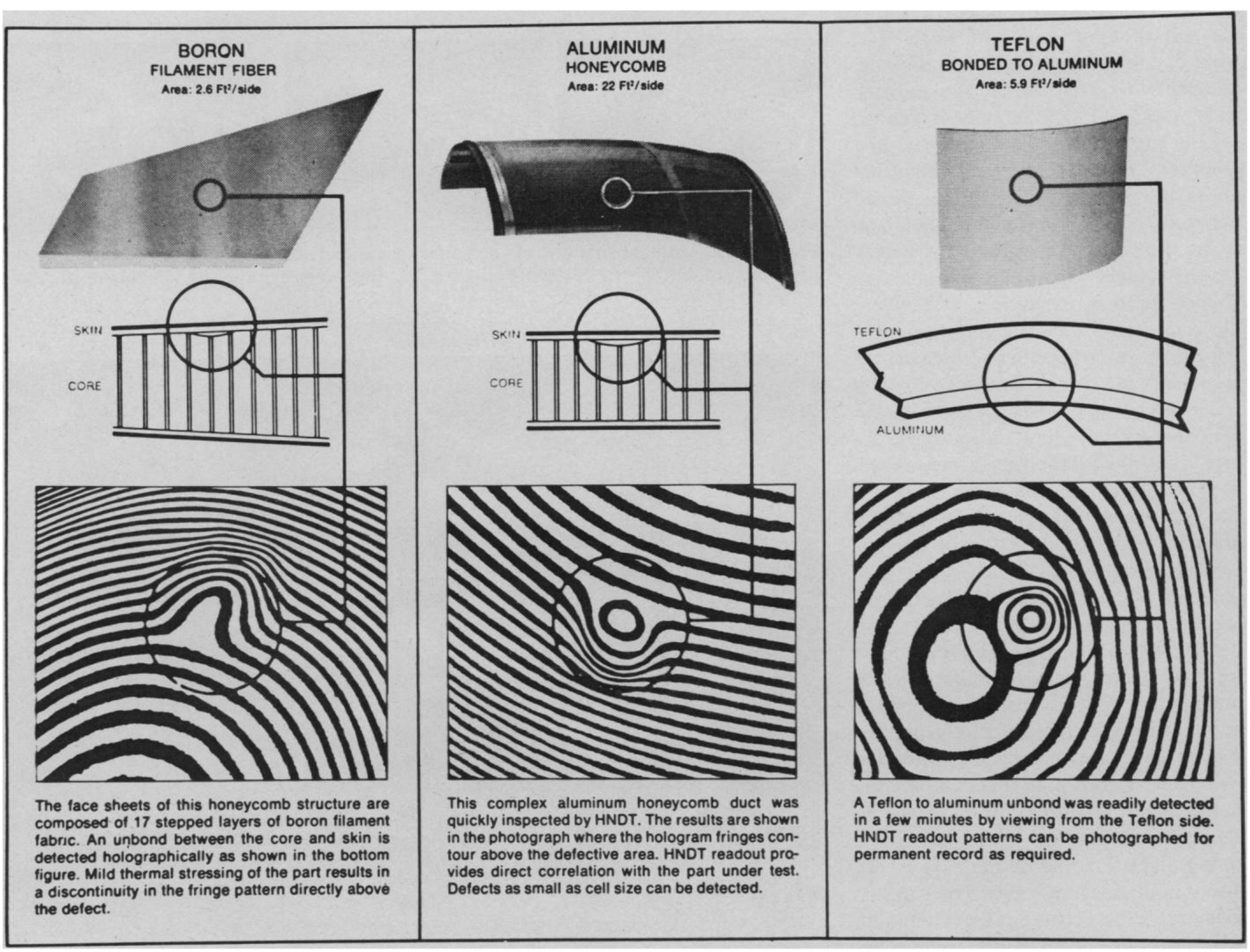


Fig. 23. Examples of holographic nondestructive testing. [Courtesy of GCO, Ann Arbor, Michigan]

ous method of photography in natural colors, for which Gabriel Lippmann received the Nobel Prize in 1908. Figure 26, A and B, illustrates Lippmann's method and Denisyuk's idea. Lippmann produced a very fine-grain emulsion with colloidal silver bromide and backed the emulsion with mercury, serving as a mirror. Light falling on the emulsion was reflected at the mirror and produced a set of standing waves. Colloidal silver grains were precipitated in the maxima of the electric vector, in layers spaced by very nearly a half wavelength. After development, the complex of layers, illuminated with white light, reflected only a narrow wave band around the original color, because only for this color did the wavelets scattered at the Lippmann layers add up in phase.

Denisyuk's suggestion is shown in Fig. 26B. The object wave and the reference wave fall in from opposite sides of the emulsion. Again standing waves are produced, and Lippmann layers, but these are no longer parallel to the emulsion surface; they bisect the angle between the two wave fronts. If now, and this is Denisyuk's principle, the developed emulsion is illuminated by the reference wave, the object will appear in the original position and (unless the emulsion has shrunk) in the original color.

Though Denisyuk showed considerable experimental skill, lacking a laser in 1962, he could produce only an "existence proof." A two-color reflecting hologram which could be illuminated with white light was first produced in 1965 by G. W. Stroke and A. Labeyrie (*20*) and is shown in Fig. 27.

Since that time, single-color reflecting holograms have been developed to high perfection by new photographic processes, by K. S. Pennington and J. S. Harper (*24*) and others, with reflectances approaching 100 percent; but two- and even three-color holograms are still far from being satisfactory. It is one of my chief preoccupations at the present to improve this situation, but it would take too long to explain and it would be also rather early to enlarge on this.

An application of holography that is certain to gain high importance in the next few years is information storage. I have mentioned before that holography allows the storage of 100 to 300 times more printed pages in a given emulsion than ordinary microphotography. Even without utilizing the depth dimension, the factor is better than 50. The reason is that a diffused hologram represents almost ideal coding, with full utilization of the area and of the gradation of the emulsion, while printed matter uses only about 5 to 10 percent of the area, and the gradation not at all. A further factor arises from the utilization of the third dimension, the depth of the emulsion. This possibility was first pointed out in an ingenious paper by P. J. van Heerden (*25*), in 1963. Theoretically it appears possible

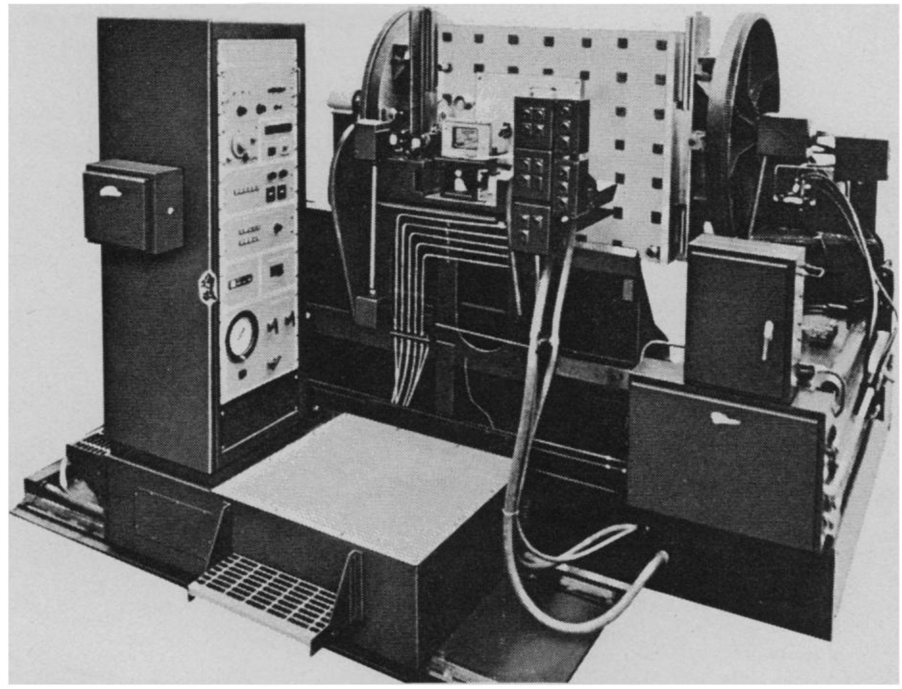
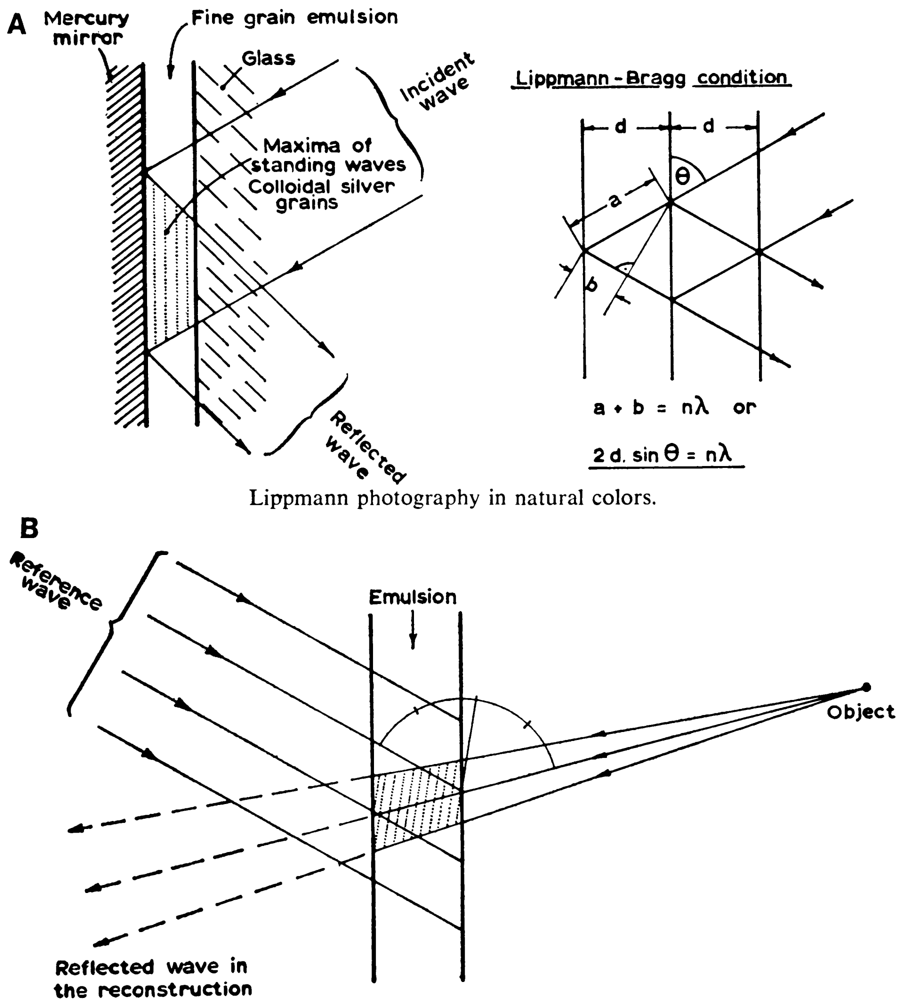


Fig. 24. Holographic analyzer Mark II for sandwich structures, GCO, Ann Arbor, Michigan.

Fig. 25. Holographic contour map of a medal made by a method initiated by B. P. Hildebrand and K. A. Haines (*30*). Improved by J. Varner, University of Michigan, Ann Arbor, 1969.



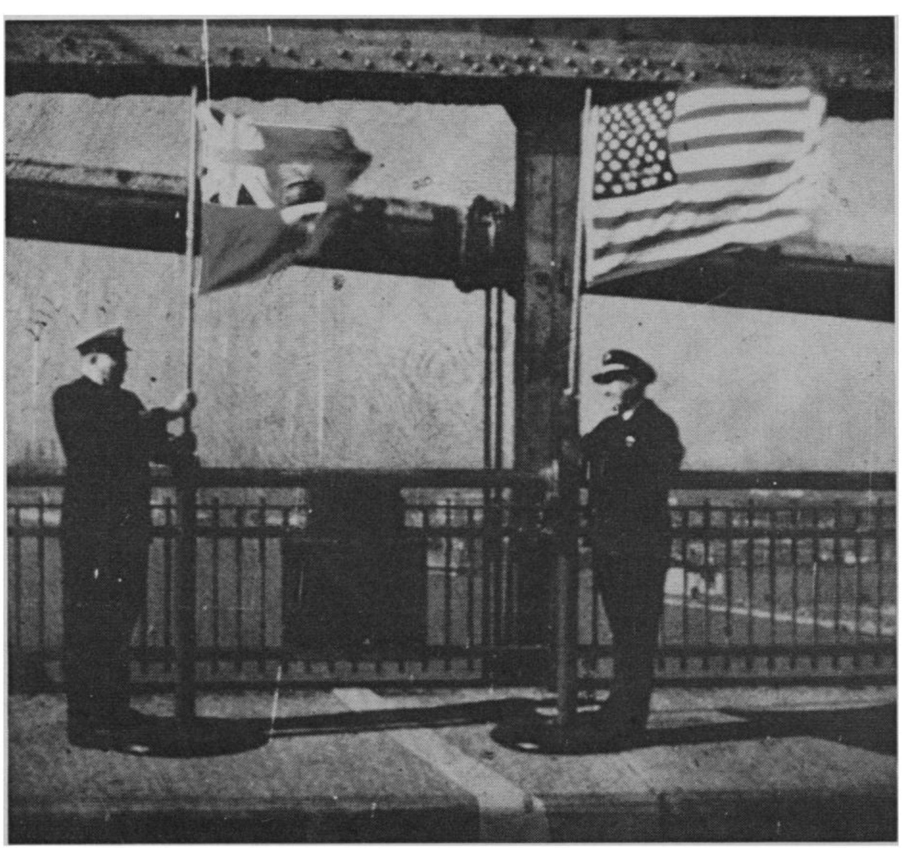


Fig. 26 (top). Lippmann-Denisyuk reflection holography in natural colors. Fig. 27 (bottom). First two-color reflecting hologram, reconstructed in white light (*20*).

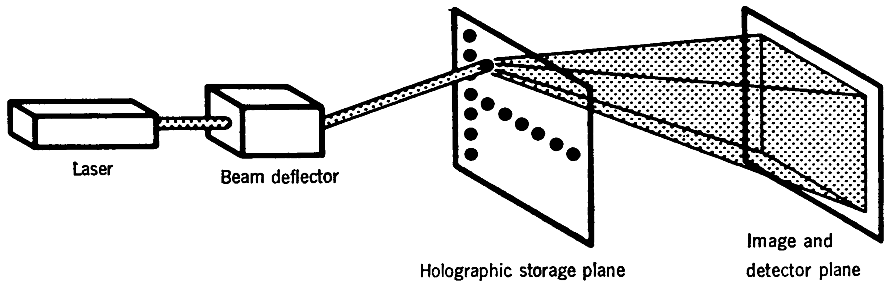
to store one bit of information in a cube about one wavelength on an edge. This is far from being practical, but the figure of 300, previously mentioned, is entirely realistic.

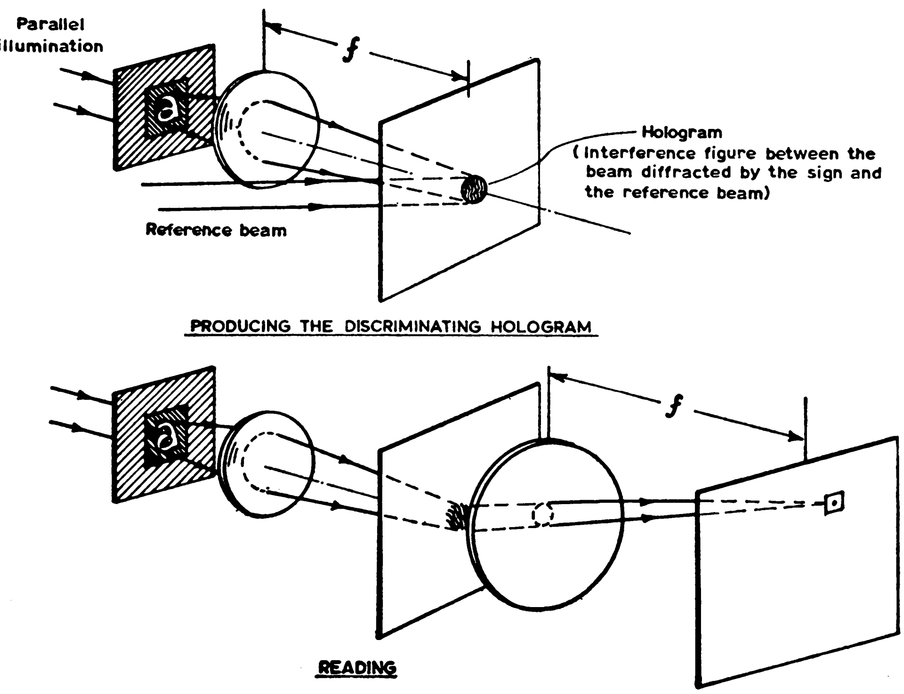
However, even without this enormous factor, holographic storage offers important advantages. A binary store, in the form of a checkerboard pattern on microfilm, can be spoiled by a single grain of dust, by a hair, or by a scratch, while a diffused hologram is almost insensitive to such defects. The holographic store, illustrated in Fig. 28, is, according to its author, L. K. Anderson (*26*), only a modest beginning, yet it is capable of accessing, for instance, any one of 64×64 printed pages in about a microsecond. Each hologram, with a diameter of 1.2 millimeters can contain about 10^4 bits. Reading out this information sequentially in a microsecond would, of course, require an impossible wave band, but powerful parallel reading means can be provided. One can confidently expect enormous extensions of these "modest beginnings," once the project of data banks is tackled seriously.

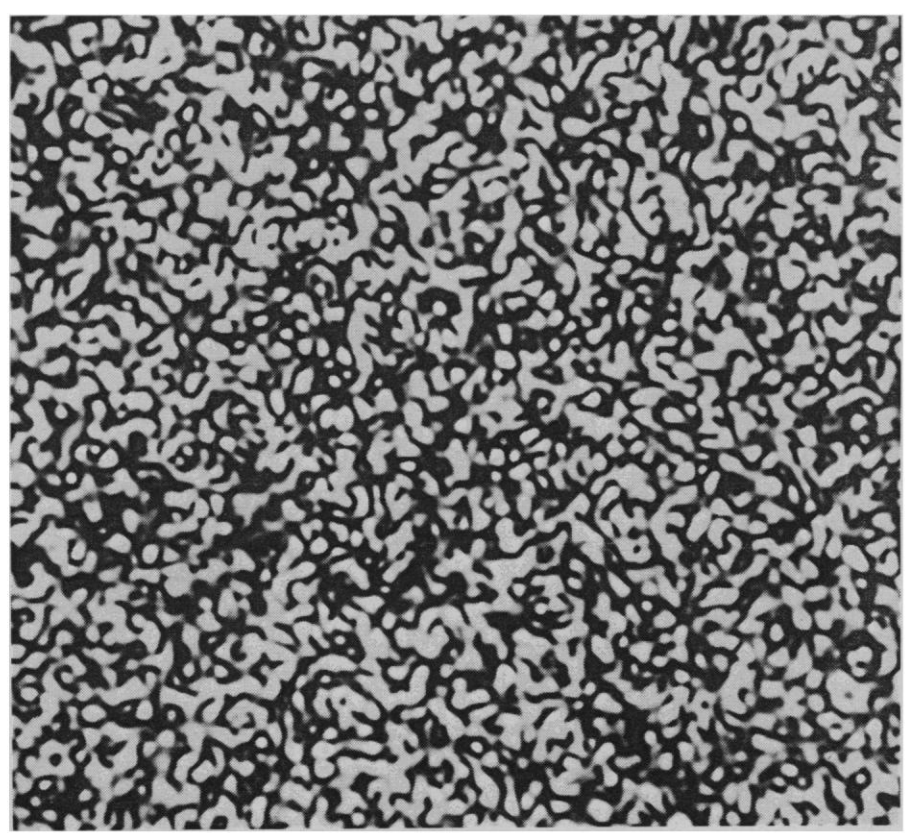
Another application of holography, which is probably only in an early stage, is pattern and character recognition. I can only briefly refer to the basic work which A. Vander Lugt (*27*) has done in the field of pattern recognition. It will be sufficient to explain the basic principle of character recognition with the aid of Fig. 29.

Let us generalize a little on the basic principle of holography. In all previous examples a complicated object beam was brought to interference with a simple or spherical reference beam, and the object beam was reconstructed by illuminating the hologram with the reference beam. But a little mathematics shows that this can be extended to any reference beam *which correlates sharply with itself*. The autocorrelation function is an invariant of a beam; it can be computed in any cross section. One can see at once that a spherical wave correlates sharply with itself, because it issues from a "point." But there are other beams which correlate sharply with themselves, for instance, those which issue from a fingerprint, or from a Chinese ideogram, or, in an extreme case, those which issue from a piece of

Fig. 28 (top). Holographic flying spot store (L. K. Anderson and R. J. Collier, Bell Telephone Laboratories, Murray Hill, New Jersey, 1968). Fig. 29 (middle). The principle of character recognition by holography. Fig. 30 (bottom). Laser speckle showing the appearance of a white sheet of paper, uniformly illuminated by laser light.





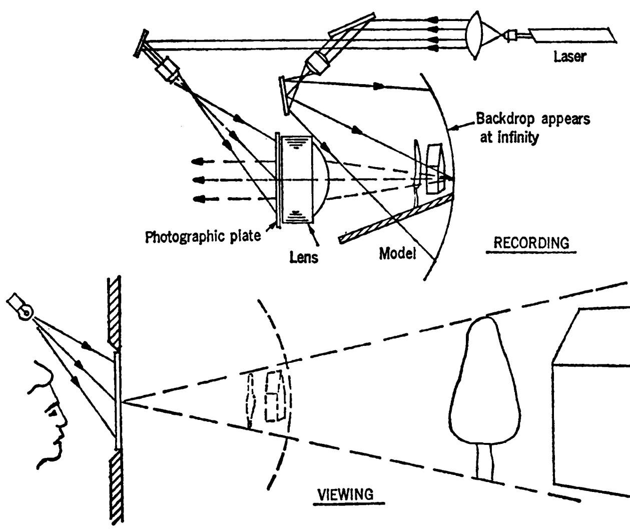


frosted glass. Hence it is quite possible, for instance, to translate, by means of a hologram, a Chinese ideogram into its corresponding English sentence and vice versa. Prof. Butters and M. Wall of Loughborough University have recently created holograms which from a portrait produce the signature of the owner, and vice versa. In other words, a hologram can be a fairly universal translator. It can, for instance, translate a sign which we can read to another or which a machine can "read."

Figure 29 shows a fairly modest realization of this principle. A hologram is made of a letter "a" by means of a plane reference beam. When this hologram is illuminated with the letter "a," the reference beam is reconstructed, and can activate, for instance, a small photocell in a certain position. This, I believe, gives an idea of the basic principle. There are, of course, many ways of printing letters, but it would take me too long to explain how to deal with this and other difficulties.

With character recognition devices we have already taken half a step into the future, because these are likely to become important only in the next generation of computers or robots, to which we must transfer a little more human intelligence. I now want to mention briefly some other problems that are half or more than half in the future.

One, which is already very actual, is the overcoming of laser speckle. Everybody who sees laser light for the first time is surprised by the rough appearance of objects which we consider as smooth. A white sheet of paper appears as if it were crawling with ants. The crawling is put into it by the restless eye, but the roughness is real. It is called "laser speckle," and Fig. 30 shows a characteristic example of it. This is the appearance of a white sheet of paper in laser light, when viewed with a low-power optical system. It is not really noise; it is information that we do not want, information on the microscopic unevenness of the paper in which we are not interested. What can we do about it?



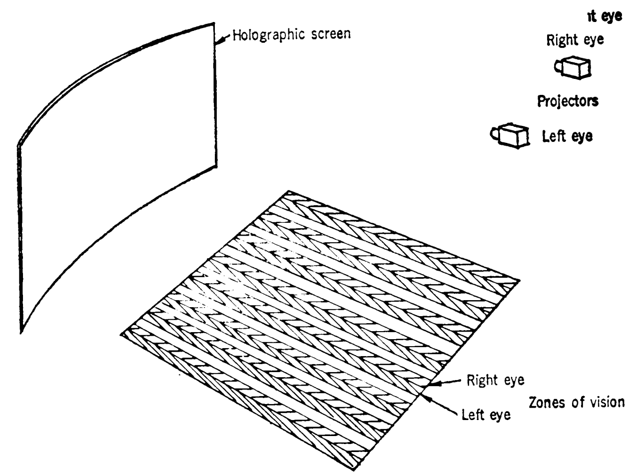


Fig. 31 (left). Panoramic holography. Fig. 32 (right). Three-dimensional cinematography with holographic screen.

In the case of rough objects the answer is, regrettably, that all we can do is to average over larger areas, thus smoothing the deviations. This means that we must throw a great part of the information away, the wanted with the unwanted. This is regrettable but we can do nothing else, and in many cases we have enough information to throw away, as can be seen by the fully satisfactory appearance of some of the reconstructions from diffused holograms which I have shown. However, there are important areas in which we can do much more, and where an improvement is badly needed. This is the area of microholograms, for storing and for display. They are made as diffused holograms, in order to ensure freedom from dust and scratches, but by making them diffused, we introduce speckle, and to avoid this such holograms are made nowadays much larger than would be ideally necessary. I have shown recently (*28*), that the advantages of diffused holograms can be almost completely retained, while the speckle can be completely eliminated by using, instead of a frosted glass, a special illuminating system. This, I hope, will produce a further improvement in the information density of holographic stores.

Now let us take a more radical step into the future. I want to mention briefly two of my favorite holographic brainchildren. The first of these is panoramic holography, or one could also call it holographic art.

All the three-dimensional holograms made so far extend to a depth of a few meters only. Would it not be possible to extend them to infinity? Could one not put a hologram on the wall, which is like a window through which one looks at a landscape, real or imaginary? I think it can be done, only it will be not a photograph but a work of art. Figure 31 illustrates the process. The artist makes a model, distorted in such a way that it appears in perspective, and extending to any distance when viewed through a large lens, as large as the hologram. The artist can use a smaller lens, just large enough to cover both his eyes when making the model. A reflecting hologram is made of the model, and it is illuminated with a strong, small light source. The viewer will see what the plate has "seen" through the lens, that is to say, a scene extending to any distance, in natural colors. This scheme is under development, but considerable work will be needed to make it satisfactory, because we must first greatly improve the reflectance of three-color holograms.

An even more ambitious scheme, probably even farther in the future, is three-dimensional cinematography, without viewing aids such as Polaroids. The problem is sketched out in Fig. 32. The audience (in one plane or two) is covered by zones of vision, having the width of the normal eye spacing, one for the right eye, one for the left, with a blank space between two pairs. The

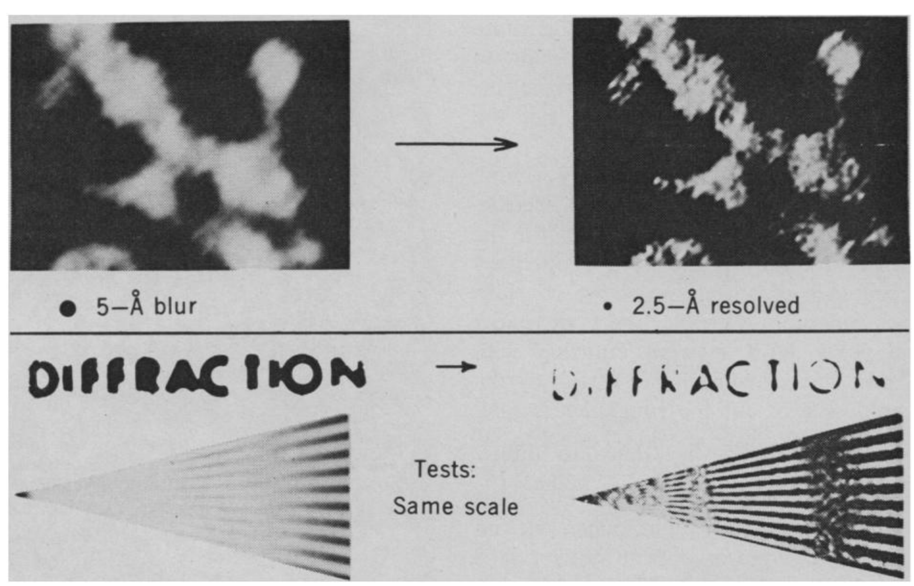


Fig. 33. (Left) Scanning transmission electron micrograph of virus made by Prof. A. Crewe, University of Chicago; (right) micrograph sharpened by holography; holographically deblurred by Prof. G. W. Stroke, 1971. The bottom photographs prove that the effect could not be obtained by hard printing, because some spatial frequencies which appear in the original with reversed phase had to be phase-corrected.

two eyes must see two different pictures, a stereoscopic pair. The viewer can move his head somewhat to the right or left. Even when he moves one eye into the blank zone, the picture will appear dimmer but not flat, because one eye gives the impression of "stereoscopy by default."

I had spent some years of work on this problem, just before holography, before I realized that it is strictly insolvable with the orthodox means of optics, lenticules, mirrors, and prisms. One can make satisfactorily small screens for small theaters, but with large screens and large theaters one falls into a dilemma. If the lenticules or the like are large, they will be seen from the front seats; if they are small, they will not have enough definition for the back seats.

Some years ago I realized, to my surprise, that holography can solve this problem too. Use a projector as the reference source, and, for instance, the system of left viewing zones as the object. The screen, covered with a Lippmann emulsion, will then make itself automatically into a very complicated optical system such that, when a picture is projected from the projector, it will be seen only from the left viewing zones. One then repeats the process with the right projector, and the right viewing zones. Volume (Lippmann-Denisyuk) holograms display the phenomenon of directional selectivity. If one displaces the illuminator from the original position by a certain angle, there will be no reflection. We put the two projectors at this angle (or a little more) from one another, and the effect is that the right picture will not be seen by the left eye and vice versa.

There remains, of course, one difficulty, and this is that one cannot practice holography on the scale of a theater, and with a plate as large as a screen. But this problem too can be solved, by making up the screen from small pieces, not with the theater but with a *model* of the theater, seen through a lens, quite similar to the one used in panoramic holography.

I hope that I have conveyed the feasibility of the scheme, but I feel sure that I have conveyed also its difficulties. I am not certain whether they will be overcome in this century, or in the next.

Ambitious schemes, for which I have a congenital inclination, take a long time for their realization. As I said at the beginning, I shall be lucky if I shall be able to see in my lifetime the realization of holographic electron microscopy, on which I started 24 years ago. But I have hope, because I have been greatly encouraged by a remarkable achievement of G. W. Stroke (*29*), which is illustrated in Fig. 33. Professor Stroke has recently succeeded in deblurring micrographs taken by Professor Albert Crewe, of the University of Chicago, with his scanning transmission electron microscope, by a holographic filtering process, improving the resolution from 5 angstroms to an estimated 2.5 angstroms. This is not exactly holographic electron microscopy, because the original was not taken with coherent electrons, but the techniques used by both Crewe and by Stroke are so powerful that I trust them to succeed also in the next, much greater and more important step.

Summing up, I am one of the few lucky physicists who could see an idea of theirs grow into a sizable chapter of physics. I am deeply aware that this has been achieved by an army of young, talented, and enthusiastic researchers, of whom I could mention only a few by name. I want to express my heartfelt thanks to them, for having helped me by their work to this greatest of scientific honors.

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It is impossible to do justice to the hundreds of authors who have significantly contributed to the development of holography. The number of articles exceeds 2000, and there are more than a dozen books in several languages. An extensive bibliography may be found, for instance, in: T. Kallard, Ed., *Holography* (Optosonic Press, New York, 1969 and 1970). Other books include: E. S. Barrekette, W. E. Kock, T. Ose, J. Tsujiuchi, G. W. Stroke, Eds., *Applications of Holography* (Plenum, New York, 1971); H. J. Caulfield and Sun Lu, *The Applications of Holography* (Wiley-Interscience, New York, 1970); R. J. Collier, C. B. Burckhardt, L. H. Lin, *Optical Holography* (Academic Press, New York, 1971); J. B. DeVelis and G. O. Reynolds, *Theory and Applications of Holography* (Addison-Wesley, Reading, Mass., 1967); M. Françon, *Holographie* (Masson, Paris, 1969); H. Kiemle and D. Röss, *Einführung in die Technik der Holographie* (Akademische Verlagsgesellschaft, Frankfurt am Main, 1969); *Introduction to Holographic Techniques* (Plenum, New York, in press); W. E. Kock, *Lasers and Holography: An Introduction to Coherent Optics* (Doubleday, Garden City, N.Y., 1969); Yu. I. Ostrovsky, *Holography* (in Russian) (Nauka, Leningrad, 1970); E. R. Robertson and J. M. Harvey, Eds., *The Engineering Uses of Holography* (Cambridge Univ. Press, London, 1970); G. W. Stroke, *An Introduction to Coherent Optics and Holography* (Academic Press, New York, ed. 1, 1966; ed. 2, 1969); J. Ch. Viénot, P. Smigielski, H. Royer, *Holographie Optique: Developments, Applications* (Dunod, Paris, 1971).

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