SCIENTIFIC AMERICAN

ACOUSTICAL HOLOGRAPHY

ONE DOLLAR

50

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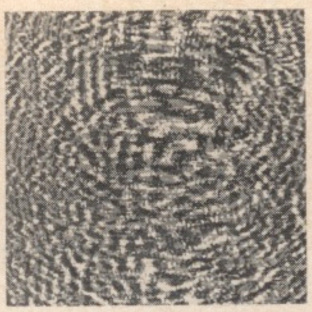

THE COVER

The picture on the cover is a hologram produced by "illuminating" an object not with coherent light waves, as is done in making an optical hologram, but with coherent sound waves (see "Acoustical Holography," page 36). The object was illuminated with three pure tones of sound whose ratios correspond to those of the primary colors red, green and blue. The acoustical hologram from each tone was translated into a black-and-white television image and photographed. To produce the composite image on the cover, each of the holograms was printed in a color corresponding to the wavelength of the "illuminant." If the three-color hologram were illuminated with coherent white light (that is, a beam containing a balanced mixture of red, green and blue light, each from a coherent source), the original object would be reconstructed in three dimensions and in colors corresponding to the reflectivity of the object at different acoustical wavelengths.

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Cover photograph by Alexander F. Metherell

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ARTICLES

DEPARTMENTS

ACOUSTICAL HOLOGRAPHY

By "illuminating" an object with pure tones of sound instead of with a beam of coherent light one can create acoustical holograms that become three-dimensional pictures when viewed by laser light

by Alexander F. Metherell

Optical holography, the technique for making three-dimensional pictures with the aid of laser beams, has given rise to a new form of holography in which sound waves instead of light waves are used to create the initial hologram. A laser beam is then employed to reconstruct, or translate, the acoustical hologram into a recognizable pictorial image. In other words, acoustical holography makes it possible to create an optical wave-field analogue of an acoustical wave field. Since sound waves can penetrate opaque objects ranging from living tissues to metal structures, the new imaging technique has promising applications in many areas of medicine and technology.

Optical holography, sometimes called the wave-front reconstruction process, became practical with the development of the laser, which provides an intense light source whose waves are coherent, or in step. An optical hologram is formed by directing a laser beam at an object and recording on a photographic plate the interference patterns produced when the light waves reflected from the object interact with a portion of the undisturbed laser radiation, which serves as a reference beam. Although the hologram produced in this fashion appears to be a meaningless jumble, it actually contains in coded form all the information the eye would intercept if it were located at the position of the photographic plate. The code can be broken by illuminating the hologram with another laser beam, which reconstructs the original scene.

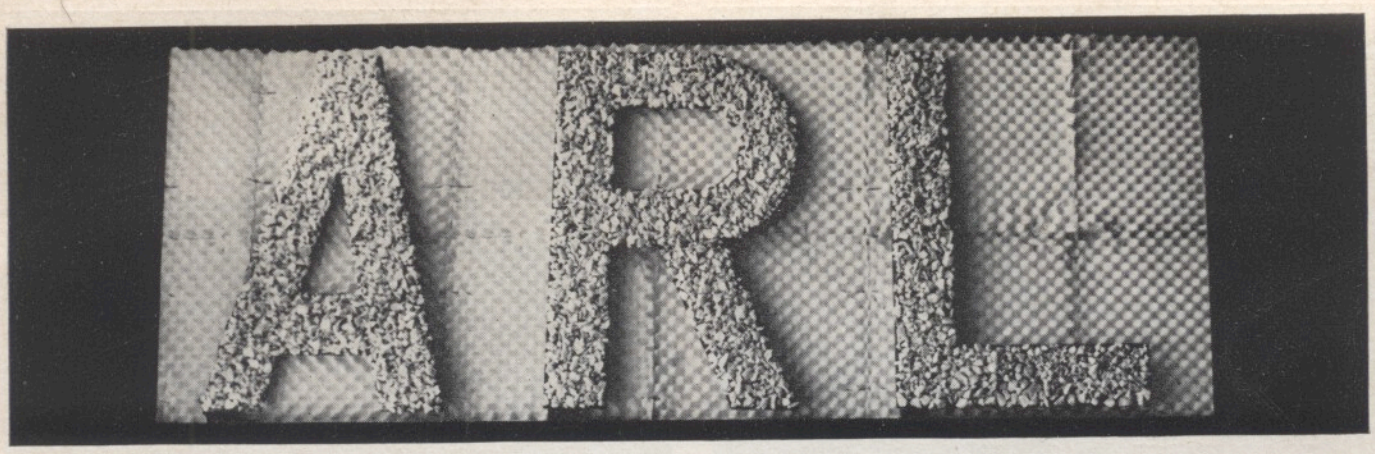
In order to produce an acoustical hologram the scene to be recorded is "illuminated" with a pure tone of sound instead of a laser beam. The objects in the scene disturb the sound waves and produce interference patterns analogous to those produced by light waves. As we shall see, it is not always necessary to use a reference beam in acoustical holography, and the hologram pattern can be recorded in various ways. Once recorded, the acoustical hologram can be reconstructed with a laser beam exactly as if it were an optical hologram.

What are the advantages of using sound instead of light? The interaction of sound with solids and liquids is different from the interaction of electromagnetic radiation. Sound can travel a considerable distance through dense, homogeneous matter and lose little energy, and yet it will lose a significant amount of energy when it passes through an interface. This loss is due to reflection at the interface. In contrast, electromagnetic radiation such as X rays will lose a significant amount of energy passing through matter and yet lose a negligible amount at an interface. Therefore sound can be singularly effective in medical diagnosis, in nondestructive testing and in seeing underwater and underground because it is mostly the discontinuities of internal organs, tumors, flaws, submerged objects or subterranean strata, rather than the bulk matter, that is of interest to the observer.

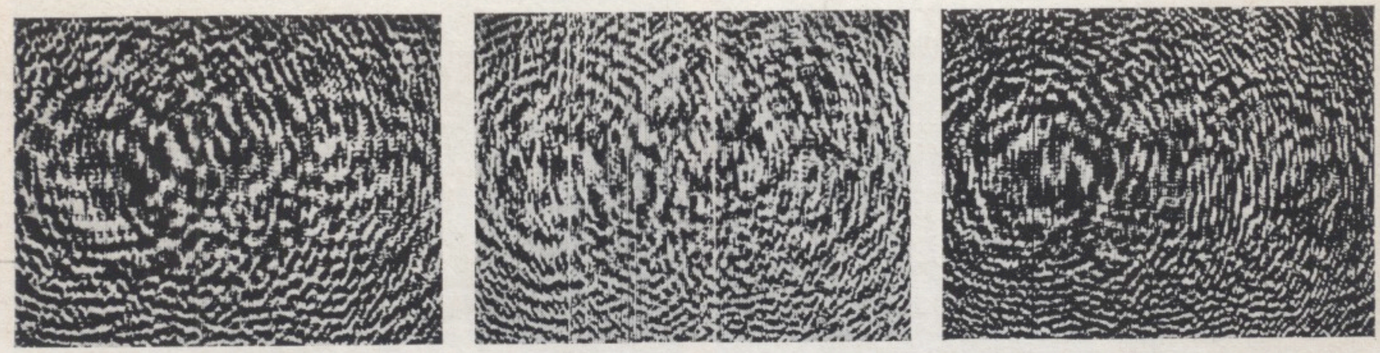
Acoustical imaging is of course not new; there are sonar devices that produce pictures similar to those on a radar screen. This type of imaging is currently employed in prospecting for oil and minerals. Similar scanning methods are also being used by physicians for the detection of brain tumors and for examining the unborn child. In these applications the sound usually has a frequency of between one million and 10 million cycles per second. Another conventional acoustical imaging technique employs what may be best described as an acoustical camera. In this method sound waves bounced off an object are focused with an acoustical lens onto an image converter that translates the pattern of sound intensity into a pattern of visible light.

The limiting feature of both of these conventional sound-imaging methods is that the images show only two dimensions. They are two-dimensional because the methods detect only the intensity (the square of the amplitude) of the sound waves in the sound images. What these methods are unable to record is phase information, that is, the arrival time of the crest of the wave from the object with respect to the arrival time of the crest of a reference wave of the same frequency. The most powerful feature of holography is that phase information as well as intensity information is retained in the hologram and can subsequently be "played back" in the optical image, with the result that the optical image is three-dimensional. Thus in acoustical holography there is a total transfer of information from the acoustical wave field to the visible optical wave field.

The simplest way to understand how a hologram works is to think of it as a coded diffraction grating. Consider first of all a simple point object that is illuminated by a plane wave produced by a coherent source at infinity [*see illustration on page 40*]. The point object scatters part of the wave, which then radiates spherically away from the point object. Both the spherical (object) wave and the plane (reference) wave fall on a plane that is perpendicular to the direction of propagation of the reference wave. At some points on the plane the object wave is in phase with the reference wave, so that the two waves constructively interfere with each other and are therefore added together to increase the wave amplitude. At other points on the plane the object wave is out of phase

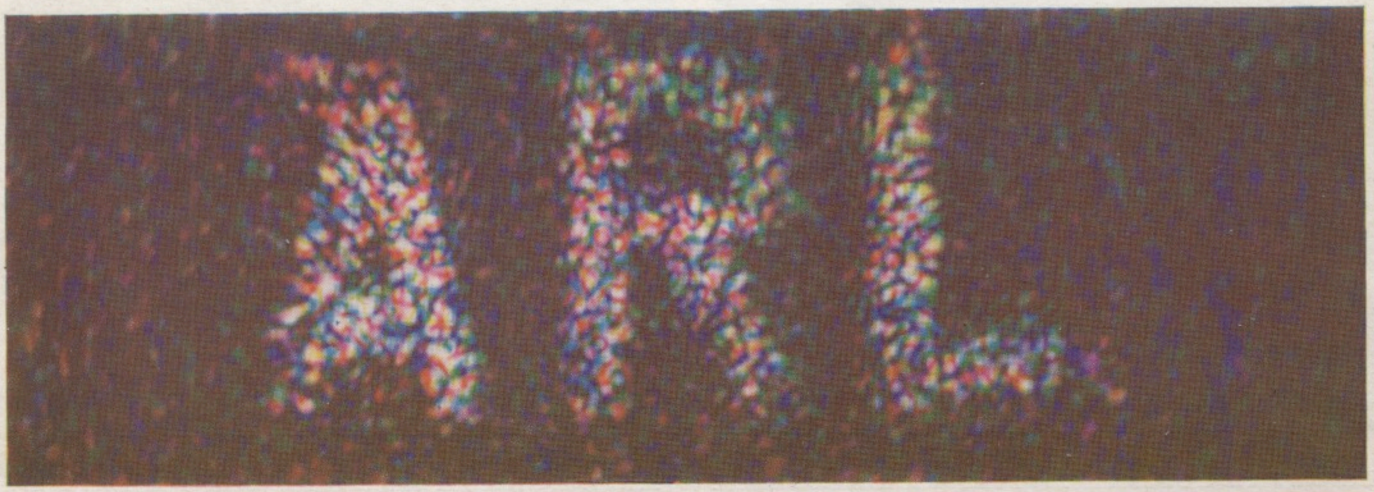


SUBJECT OF ACOUSTICAL HOLOGRAM, reconstructed in three colors at the bottom of the page, was a group of three letters formed from pebbles of various sizes. The holograms (*below*) were made by sound waves of 15,000, 18,000 and 21,000 cycles per second.

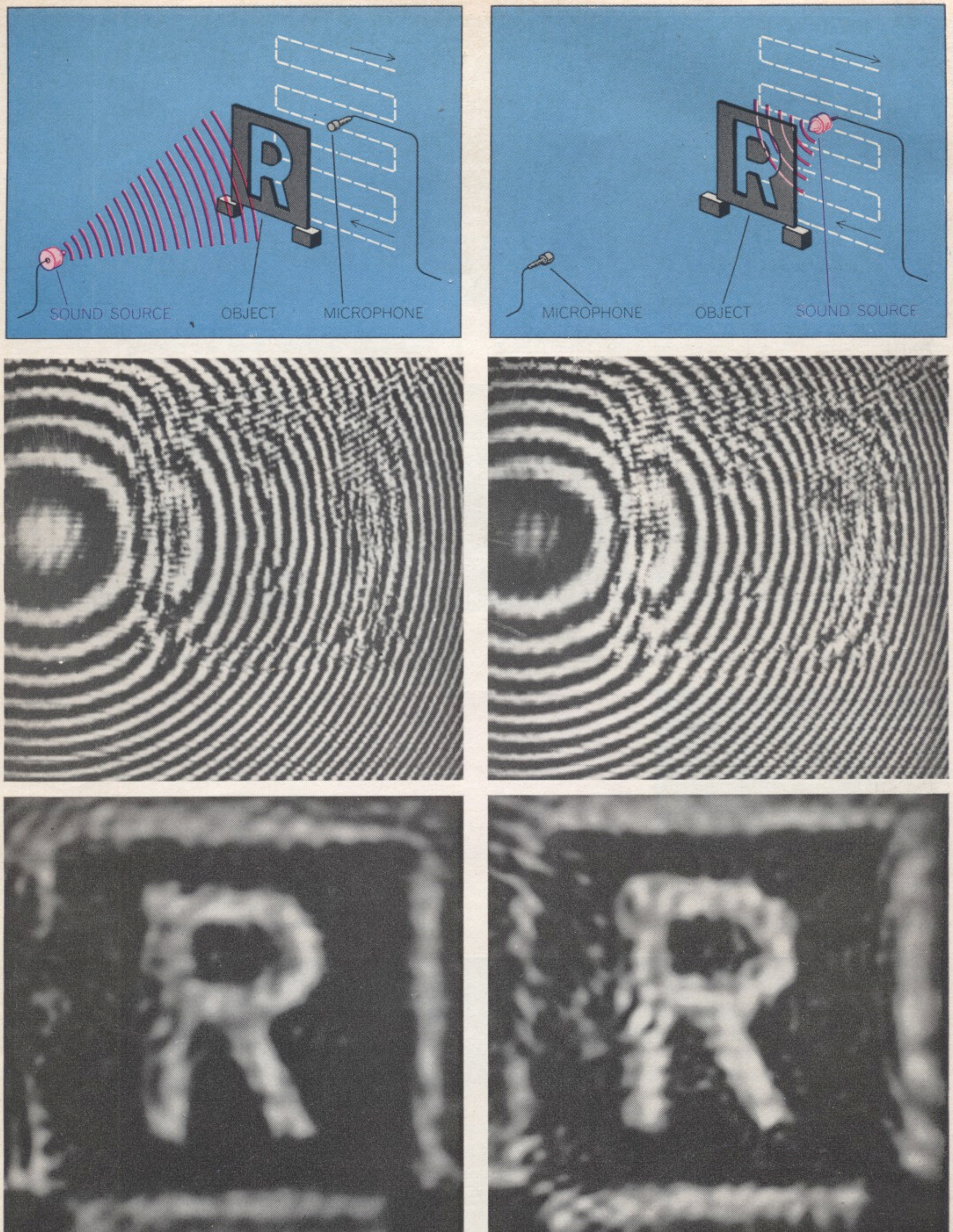


ACOUSTICAL HOLOGRAMS, one for each wavelength, are the electronic analogues of the reflected interfering sound waves as they appear on a cathode ray tube. A three-color montage of these three images is on the cover of this issue of SCIENTIFIC AMERICAN.

RECONSTRUCTED IMAGES FROM HOLOGRAMS are made by shining a coherent beam of laser light through black-and-white transparencies of the holograms. Here the reconstructed image of the hologram made with sound of 15,000 cycles is printed in blue ink, the one made with sound of 18,000 cycles is printed in red and the image made with sound of 21,000 cycles is printed in yellow.



FINAL THREE-COLOR RECONSTRUCTION of the pebble pattern is made by superposing the blue, red and yellow reconstructed images. The hard surfaces of the pebbles reflected the three wavelengths of sound about equally. The letters stand for Advanced Research Laboratories of the McDonnell Douglas Corporation, where these images were made by the author, Sidney Spinak and E. J. Pisa.



EQUIVALENT HOLOGRAMS and reconstructions are obtained whether the microphone is moved in a raster pattern while the source is stationary (*left column*) or whether the sound source is moved while the microphone is held stationary (*right column*). The object scanned in both cases is a cutout of the letter *R* in a panel four feet on a side. The acoustical holograms are the two images in the middle of the page; the laser-beam reconstructions are at the bottom. The experiment was done by the author and Spinak.

with the reference wave, so that the two waves destructively interfere, thereby canceling each other and decreasing the wave amplitude. If we record the amplitude (intensity) in the plane as variations of density on a photographic plate, the resulting pattern will be a continuous set of concentric circles centered on the point on the plane that is obtained by projecting a line from the light source through the point object onto the plane. This pattern closely resembles a Fresnel zone plate, an optical device in which a round bull's-eye is surrounded by concentric rings of regularly decreasing thickness. In the point-object hologram, however, the density of the rings varies outward from the center in a sine-wave pattern, and simultaneously the frequency of the sine wave increases.

A well-known property of a zone plate is that the diffraction effects of the rings will cause the plate to act as a lens. When illuminated with a wave, the zone plate will focus the wave. However, it acts simultaneously as if it were both a positive and a negative lens. If the holographic zone-plate pattern is illuminated by the plane (reference) wave alone, the negative-lens effect of the zone plate will cause a diverging spherical wave to emerge from the plate, thereby producing a "virtual" image of the point in the same position the point object originally occupied. At the same time the positive-lens effect will create a converging wave that will produce a real image of the point.

Hence the wave that emerges from a hologram has three components. First there is the attenuated part of the illuminating wave that passes right through the hologram. This is called the zero-order wave. Second there is the diverging spherical wave that appears to come from the virtual image of the point. This is a first-order diffracted wave that is the true reconstruction of the original spherical wave that radiated from the point object when the hologram recording was made; it is called the true reconstructed wave. Third there is the converging spherical wave that forms the real image of the point. This too is a first-order diffracted wave, but because it is opposite in curvature to the diverging wave it is called the conjugate wave.

The two images the hologram produces are normally such that one is a virtual image located where the original object used to be and the other is a real image formed on the other side of the hologram. Under certain circumstances, however (by illuminating the hologram with a spherical wave instead of a plane parallel beam), both images can be virtual or both can be real. Therefore it is confusing to name them the virtual and the real images. To avoid this confusion one is called the true image (resulting from the true reconstructed wave) and the other is called the conjugate image (resulting from the conjugate wave).

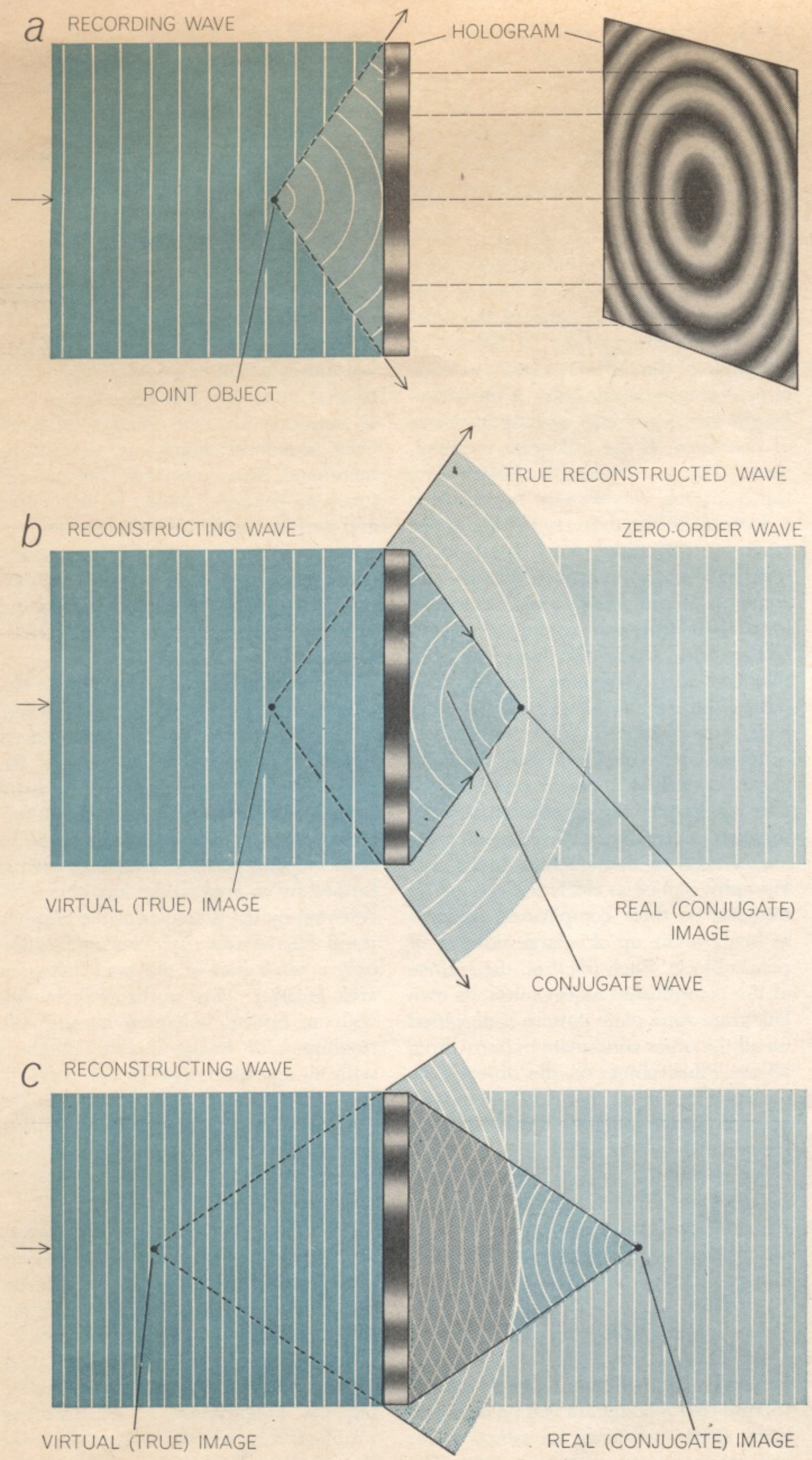
Let us now consider what happens when the hologram is illuminated with a beam whose wavelength is shorter than the wavelength used to record the hologram zone-plate pattern. In diffraction the angle of the diffracted wave increases or decreases as the ratio of the wavelength to fringe (ring) spacing increases or decreases. If the hologram is illuminated with a wavelength shorter than the recording wavelength, the result is a decrease in the diffracted angle of the emerging diffracted wave fronts. The true and conjugate waves diverge and converge more slowly and therefore form their true and conjugate images farther away from the hologram, but they are still formed on the axis that passes through the center of the hologram zone-plate pattern.

So far I have discussed only the hologram created by a simple point object. The holography of complicated objects, such as the figurines and chessmen commonly used to demonstrate optical holography, can be as easily understood by thinking of their complicated surfaces as being made up of a large number of point objects. Each point on the surface of the complicated object forms its own hologram zone-plate pattern superposed on all the other zone-plate patterns from all the other points on the object. The resulting hologram then has the appearance of an unintelligible mass of broken fringes and grainy blobs, but in reality each zone-plate component acts independently of all the others in the reconstruction process to reproduce its individual point on the surface of the object image.

Inasmuch as a hologram can be recorded at one wavelength and reconstructed with a different wavelength, it follows that a hologram can be recorded using single-frequency acoustical waves and reconstructed with laser light. The main effect of this is that the resulting visual image is distorted because of the difference in wavelength between the sound used to record the hologram and the light used to reconstruct it. The illustration on page 41 shows how a simple arrangement of three points is stretched out in one direction (along the axis of the recording beam) when the reconstructing wavelength is shorter than the recording wavelength. The stretching out, or longitudinal magnification, is equal to the ratio of the recording wavelength to the reconstructing wavelength. When the recording wavelength is sound at a million cycles per second in water and the reconstructing wavelength is the red light from a helium-neon laser, the image will be stretched out some 500 times. This results in an apparent (but not actual) loss of the three-dimensional effect that is so dramatic when an observer views the reconstruction of a conventional optical hologram. The longitudinal distortion has led some people to consider that the images obtained from acoustical holograms are two-dimensional. This is not true. One can still focus on different planes in the image and perform optical data-processing operations (such as spatial filtering) to improve the images. A number of methods have been suggested for eliminating the distortion but none is completely satisfactory.

The three-dimensional perception obtained in viewing the true virtual image in a conventional optical hologram is largely due to the parallax effect obtained when the viewer moves his head from side to side and looks through different parts of the optical hologram. In each viewing position the image seen is formed by an area on the hologram represented by the diameter of the viewer's pupil. Hence from each viewing position only a small part of the total hologram area is used. This works well enough with an optical hologram because the resolution, or image quality, obtained with an aperture equal to the pupil diameter is perfectly acceptable since the optical hologram was recorded at optical wavelengths. Image resolution is directly related to the ratio of aperture to recording wavelength.

Since the wavelengths used to record acoustical holograms are so large compared with the aperture of the eye, the image resolution provided by an acoustical hologram would be completely unacceptable if one simply viewed it with the unaided eye. Accordingly (disregarding the longitudinal image distortion problem) it may never be feasible to use the parallax effect in viewing the reconstructed image from an acoustical hologram. To obtain acceptable image quality in the reconstruction the viewing aperture must approach the size of the entire hologram. As a result the observation of the reconstructed images from an acoustical hologram will most probably always be done by using the entire hologram and observing the real image as it is focused on a screen. The ob-



OPTICAL HOLOGRAM OF POINT is a series of concentric rings (*a*) representing the intensity pattern that results when the waves scattered from the point are summed with the crests or troughs of the plane recording wave, which acts as a reference wave. The hologram is reconstructed (*b*) by illuminating it with the reference wave alone. The diffraction effect of the hologram fringes causes two first-order diffracted wave fronts to emerge in addition to the attenuated zero-order wave. One is the true reconstruction of the original object wave, which forms a virtual (true) image of the point at its original position. The other wave front is the conjugate reconstructed wave, which forms a real (conjugate) image of the point. If the hologram is illuminated with a wave that has only half the length of the original wave (*c*), the reconstructed images are shifted to twice their normal distance.

servational benefit of the third dimension in the image comes from being able to move the screen throughout the depth of the image.

The methods available for recording acoustical holograms are numerous because of the many different methods that are available for recording sound. In optical holography a photographic plate is normally used to record the hologram. To record an acoustical hologram it is necessary to have an acoustical equivalent of the photographic plate. A natural first approach is to see if sound can be recorded directly on photographic film. It can be. A piece of photographic film that has been exposed to light can be placed in a weak fixing solution. If, while the film is in the fixing bath, it is exposed to high-intensity sound, the regions of high sound intensity speed up the fixing process. Subsequent development of the differentially fixed photographic film yields an image corresponding to the sound levels at its surface. This method has been used to record acoustical hologram interference-fringe patterns. The method has serious limitations, however, because the recording sound must be very intense indeed (about one watt per square centimeter), and even then exposures typically run to 30 minutes.

Another method involves placing a starch plate in an iodine solution. Exposure to sound causes the iodine to stain the starch, thereby recording the sound pattern. Here again high intensity levels and long exposure times are required.

If a high-frequency sound source, for example a piezoelectric transducer vibrating at a frequency of five million cycles per second, is placed in a tank of water and aimed toward the surface, the water will bulge up where the sound hits the surface. If two such high-frequency sources are submerged and pointed toward the surface, the acoustical beams will interfere and the resulting interference pattern will reveal itself as a stationary ripple pattern. If an object is now placed in one of the beams, the ripple pattern on the surface will be the hologram of the object.

Such an image can be reconstructed by two methods. The first is a "real time" method that merely involves illuminating the surface with a laser. The ripple pattern acts much as an optical phase hologram; the true image of the object appears below the surface and the conjugate image appears as a real image above the surface. The longitudinal distortion, which is due to the difference between the acoustical and the optical wavelengths, causes the reconstructed images to appear much farther from the surface than the actual object is. The second method is to photograph the ripple pattern, thereby obtaining a hologram that can be reconstructed in the usual manner.

When the first method is used, the longitudinal distortion introduced by the disparity in length between sound waves and light waves will ordinarily shift the reconstructed image so far from the surface that it must be viewed with a telescope. The need for a telescope can be avoided, however, by placing an acoustical lens between the object and the surface in such a way that the three-dimensional image formed by the lens is projected onto the surface. The reference wave remains as before but the hologram is now a focused hologram, so that on reconstruction the reconstructed image appears in the surface [*see illustration on next page*]. In early experiments acoustical lenses created serious aberrations in the holographic image, but recent work with liquid-filled acoustical lenses has led to quite satisfactory results.

Two major problems arise from the use of a water surface. First, the surface is very sensitive to unwanted vibrations and to larger-scale motions that break up the ripple pattern. Second, the object beam and reference beam must be reasonably well balanced in intensity at the surface. Otherwise streams form on the surface, and they also break up the hologram ripple pattern. This limits the usable area of the water surface, which in turn limits the aperture and hence the quality of the final reconstructed image. The technique has been improved by covering the water surface with a thin membrane and placing an oil film a few millimeters thick on top of the membrane so that the ripple pattern forms on the oil surface instead of on the water. When the oil-film method is combined with the newer types of acoustical lens, and when the sound is pulsed in short bursts, the practicability of the ripple technique is greatly enhanced.

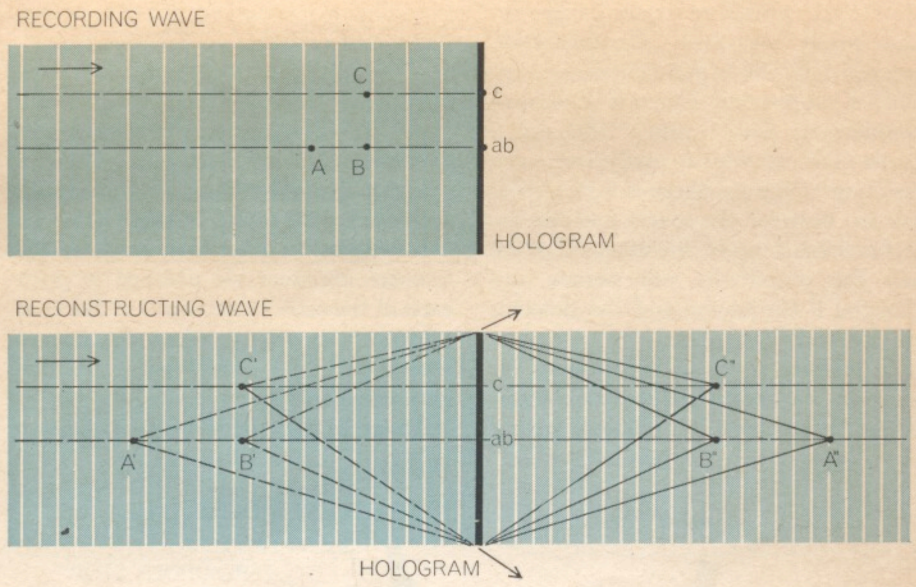
Recently this method has been used to record some of the best reconstructed images obtained so far. A group under the direction of Byron B. Brenden at the Pacific Northwest Laboratory of the Battelle Memorial Institute has produced a motion-picture film that shows the real-time acoustical holographic image of a goldfish made with sound at a frequency of nine million cycles per second. The skeleton of the fish and its denser internal organs are clearly visible [*see top illustration on page 43*]. The motion of the internal organs, the opening and closing of the fish's mouth and the raising and lowering of its dorsal fin are all vividly represented. Such a real-time system, which allows the observer to follow the motion of the object and thus assists in its interpretation, has great merit. Image interpretation can prove to be difficult if the observer is viewing a stationary image. These and other results demonstrate beyond doubt that acoustical holography can be of significant value in medical diagnosis.

There are other methods for recording the holograms produced on or immediately below a liquid surface. These include mechanical scanning of a detector below the liquid surface and the electronic scanning of a piezoelectric transducer. These methods, however, offer no significant advantages over the method I have described. I shall therefore pass on to an experimental technique for scanning acoustical images formed in air that has been used by our group at the Douglas Advanced Research Laboratories of the McDonnell Douglas Corporation. There are no obvious practical applications for the air-scanning method because the wavelengths employed are some 20 to 100 times longer than those readily generated in water, with the result that resolution is much inferior. (The wavelengths in air lie between 29 and 14 millimeters, corresponding to sound frequencies between 12,000 and 25,000 cycles per second.) Nevertheless, the air-scanning method has proved to be a flexible laboratory tool for investigating different aspects of acoustical holography.

In a typical experiment the object to be scanned is a letter of the alphabet cut out of a sheet of Masonite a few feet square. The sound source is placed on one side of the sheet and the scanning microphone is moved through a raster pattern on the other side. The output of the microphone modulates the intensity of a spot on a cathode ray tube, and a time exposure of the face of the tube provides the hologram.

One might wonder what would happen if the microphone were held stationary and if the sound source were moved through the raster pattern. One can appreciate that when the sound source is stationary the interference pattern of sound waves on the far side of the object is "frozen" in space. The role of the microphone is to sample a particular plane of this frozen pattern. If, however, the microphone is fixed and the source is moved, the interference pattern in the plane in which the microphone is now located must change from moment to moment.

Will the hologram recorded under these constantly changing conditions resemble the one created when the microphone travels through the frozen pattern? Surprisingly (although there is really no reason for surprise), the two pat-



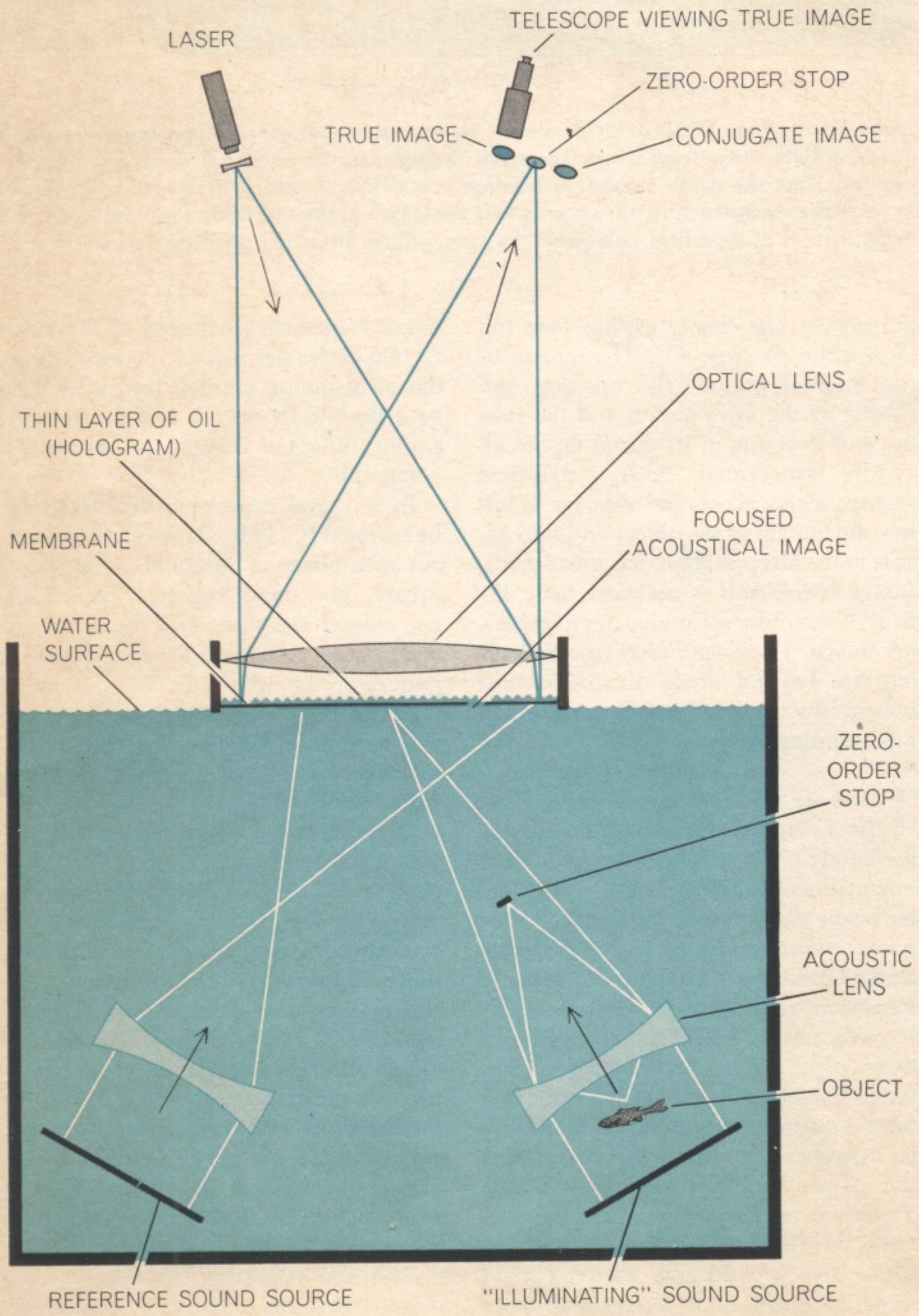
LONGITUDINAL DISTORTION occurs in acoustical holography because the reconstructing light waves from a laser are much shorter than the acoustical waves used for recording. Here the depth separation between two points, *A* and *B*, is magnified twofold because the reconstructing wave is only half the length of the recording wave. In actual reconstructions of acoustical holograms the longitudinal distortion often exceeds 500 times.

terns are identical, as are the images reconstructed from them [*see illustration on page 38*]. This experiment shows that when a single-point source is used to illuminate an object acoustically and a single-point detector is used to scan the resulting hologram, there is a reciprocal relation between the source and the detector. That is to say, the detected phase and the amplitude will remain unchanged if the source and the detector are physically transposed.

In another series of experiments we scanned the wave pattern not transmitted by an object but reflected from it to produce the hologram. Here the object was the three letters *A*, *R* and *L* (standing for Advanced Research Laboratories). Each letter consisted of a mosaic of pebbles of various sizes and was about four feet tall. We wanted to see how the holograms would differ if we illuminated the letters with sound of three different wavelengths. In order to make these differences apparent we planned to print each of the reconstructions in a different color and so obtain, when the images were superposed, a single reconstruction in three colors.

To make the sound-to-color analogy complete we chose wavelengths of sound that bear the same relation to one another as the wavelengths of the primary colors blue, green and red. The approximate dominant wavelengths for these three colors are 420, 525 and 630 nanometers, and they are in the ratio 4:5:6. Accordingly we selected sound wavelengths of about 16, 20 and 24 millimeters, corresponding to frequencies of 21,000, 18,000 and 15,000 cycles per second.

As we had expected when we planned the experiment, a target consisting of hard pebbles acts as a "white" reflector of sound, with the result that the holograms at each wavelength are very similar and the letters in the final three-color reconstruction contain roughly equal amounts of each color [*see illustration on page 37*]. In three-color printing the primary colors red, green and blue are reproduced by mixtures of their complementary colors: cyan ("blue"), magenta ("red") and yellow. To create the pattern on the cover of this issue of *Scientific American* the three acoustical holograms were superposed and printed in colors corresponding to the wavelengths of the sound that produced them. If the pattern on the cover were reproduced in the form of a color transparency and were illuminated with a coherent beam of white light (in the form of a balanced mixture of coherent red, green and blue light), the letters *ARL* in the resulting reconstruction would appear white.



LIQUID-SURFACE ACOUSTICAL HOLOGRAPHY provides interference patterns that can be reconstructed instantaneously. The focused acoustical image of the object forms diffraction fringes with a reference beam at the surface of an oil film, after being transmitted through the water and a membrane. The acoustical image of the object coded in the oil "hologram" is decoded continuously by a laser beam and viewed through a telescope.

In early experiments with acoustical holography the methods used were straightforward acoustical analogues of optical methods. It gradually became apparent, however, that entirely new techniques could be introduced that have no equivalent in optical holography. For example, when electronic detection is used, the output from the detector (microphone) is an electrical signal of the same frequency and phase as the acoustical signal. Therefore, instead of mixing the acoustical object wave with an acoustical reference wave and sensing the sum of the two, the reference wave can be simulated electronically by detecting the acoustical object wave alone and adding the electrical output from the detector to an electrical reference signal. This signal is taken directly from the electronic signal generator used to power the illuminating sound source. The electronic summation then corresponds to the interference between the object wave and the reference wave. Electronic simulation of the reference wave is now almost invariably used.

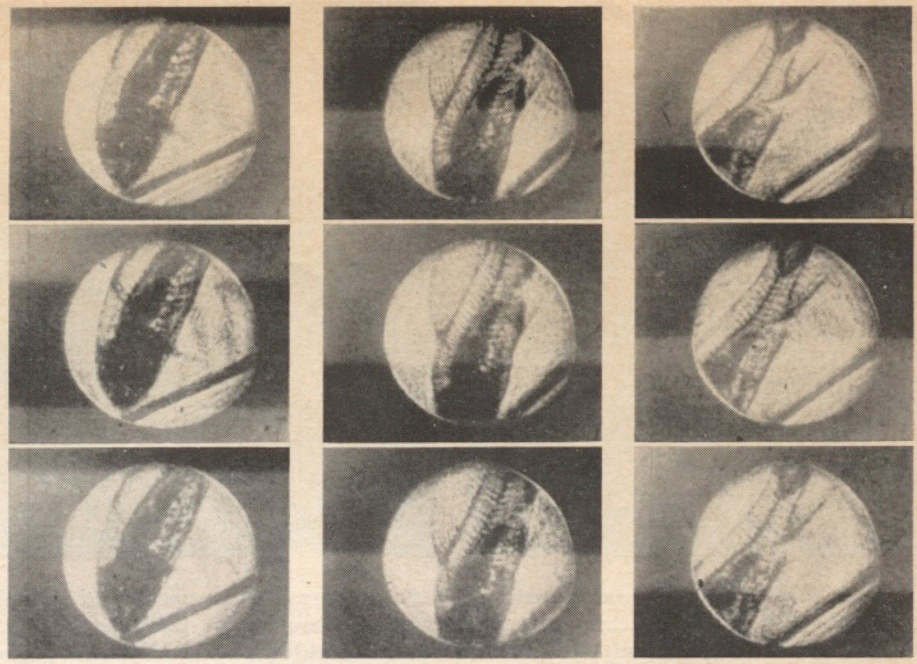
Another major advantage of this kind

of detection is that one can perform operations on the detected object signal before it is added to the electronic reference signal. We have performed such operations in investigating the relative importance of the two components in the object wave that are normally recorded in a hologram: phase and amplitude. This has led to the recording of phase-only acoustical holograms. The phase-only hologram is made by taking the electrical object wave, whose amplitude and phase vary as the detector scans, and setting the amplitude at a constant value (no matter how much the acoustical amplitude varies) but retaining the phase of the object wave. The resulting phase-only hologram is recorded by summing this constant-amplitude object signal with a constant-amplitude reference signal. The phase-only hologram differs in appearance from the conventional hologram only in that the contrast of the interference fringes is constant over the hologram plane instead of varying in contrast. (The variations in the conventional acoustical hologram correspond to variations in amplitude of the object wave.) The reconstructed images from phase-only holograms are generally sharper at the edges than reconstructions from conventional acoustical holograms [*see upper illustration on next page*]. Moreover, the relative acoustical brightness scale in the object is retained in some cases.

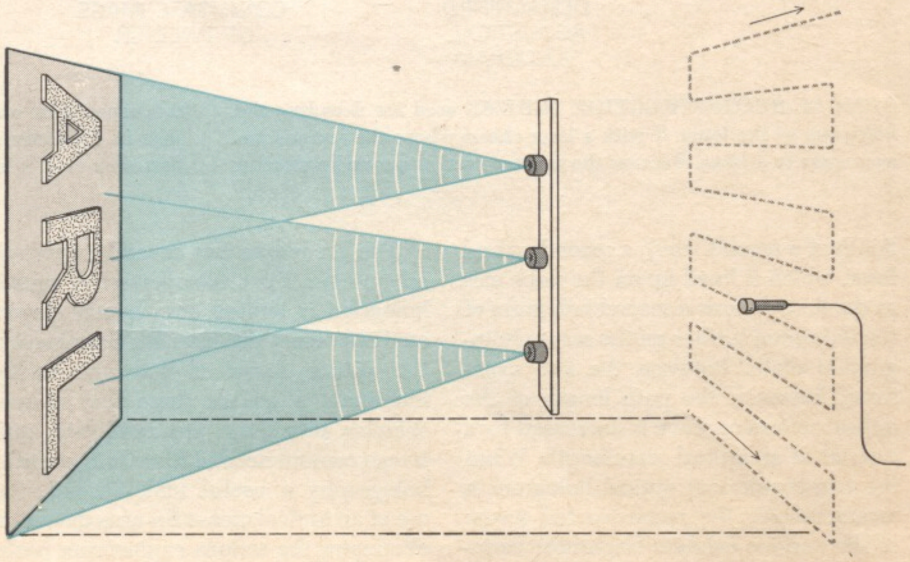
Another trick that is possible with sound waves but not with light waves has led to the development of a new technique called temporal reference holography. As the term indicates, the object wave is recorded with respect to the time at which the recording is made rather than with respect to a reference wave. This is done by recording the pressure potential of the acoustical object wave at some selected instant within the acoustical cycle. The main advantage that temporal reference holography has over conventional acoustical holography is a much higher recording speed, which provides more satisfactory images of moving objects.

The Douglas Advanced Research Laboratories are now working on a technique suitable for medical diagnosis in which temporal reference acoustical holograms generated by sound waves with a frequency of one million cycles per second can be recorded in half a millionth of a second. The technique applies a new form of optical interferometric holography called subfringe interferometry, a term indicating that the displacements recorded are less than one optical wavelength. This is in contrast to conventional interferometry, where the displacements are many optical wavelengths.

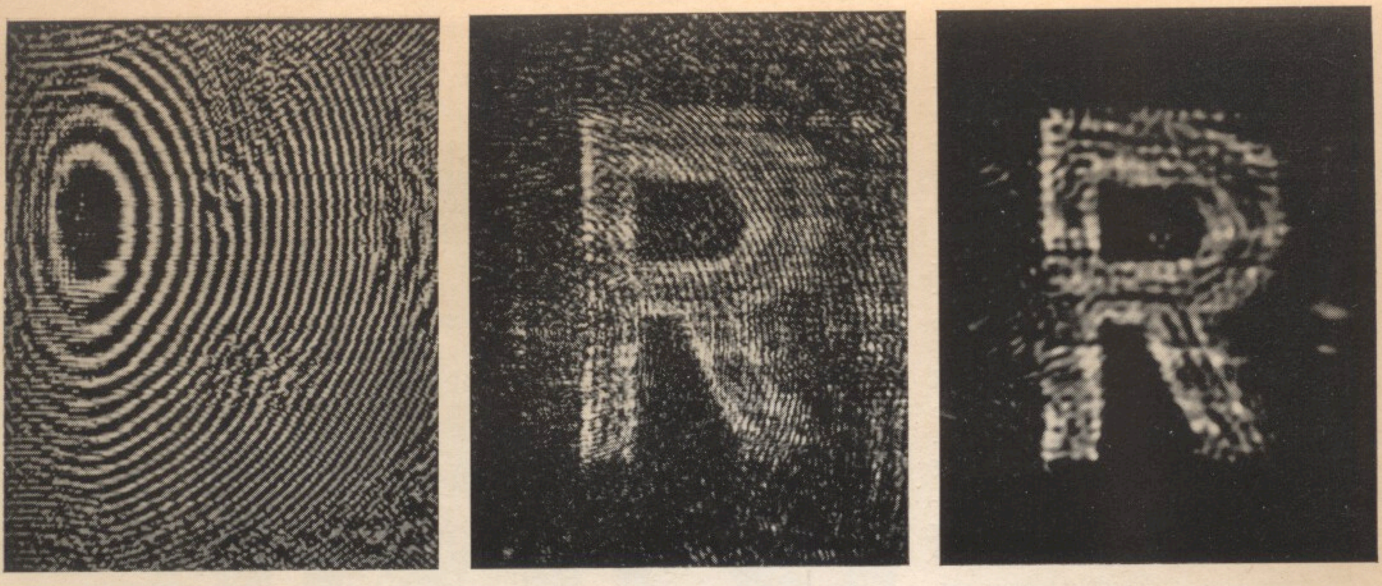
Briefly, the method works as follows. The acoustical object wave is allowed to fall on a surface, causing it to vibrate with an amplitude much less than an optical wavelength. This surface is slightly deformed by the acoustical wave striking it. The deformation is recorded by shining a pulsed laser on the surface and making an optical hologram of it on a photographic plate. After half an acoustical cycle has passed (that is, half a mil-



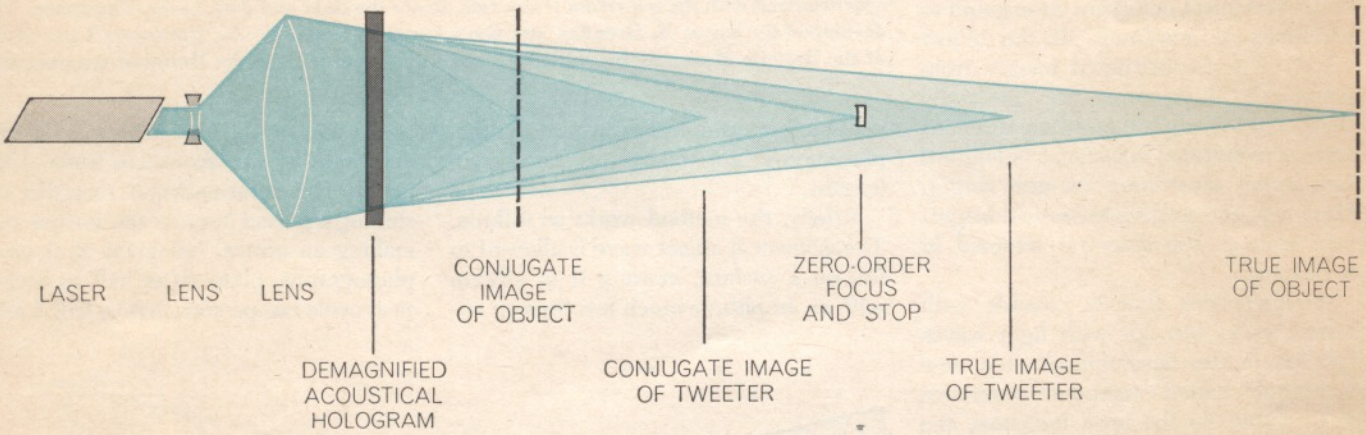
ACOUSTICAL VIEW OF GOLDFISH was provided by the liquid-surface method of holography illustrated on the opposite page. The 16-millimeter movie camera that recorded these reconstructions of the holograms as they were displayed on a television screen was not quite synchronized with the television frame rate, hence the light and dark bands. The system was developed by Byron B. Brenden and Gary Langlois at the Pacific Northwest Laboratory of the Battelle Memorial Institute. The work was sponsored by the Holotron Corporation.



HOLOGRAPHIC PATTERN IN AIR was scanned to make the holograms reproduced on page 37. The letters *ARL*, formed of pebbles, were "illuminated" by three "tweeters," all operating in phase at the same frequency. The pattern of the reflected sound waves was scanned by a microphone and processed in a circuit that provided the electronic equivalent of a reference beam. The summed output wave was then displayed on a cathode ray tube and photographed. Holograms were recorded at 15,000, 18,000 and 21,000 cycles. The method of reconstructing the holograms is depicted in the lower illustration on the next page.



CUTOUT OF LETTER *R* was "illuminated" with a tweeter operating at 18,000 cycles per second, using the arrangement shown on page 38. In this case, however, the intensity of the holographic pattern was held constant electronically and only the phase information was recorded, producing a phase-only hologram (*left*). The reconstruction in the middle shows what happens when the out-of-focus image of the tweeter and the out-of-focus conjugate image are both allowed to reach the plane where the true image of the *R* is in focus (*see diagram below*). At the right the two out-of-focus images have been blocked off, leaving only the true image of the letter.



OPTICAL RECONSTRUCTION SCHEME used for decoding the hologram of the letter *R* with a laser shows where the various images come to a focus. Because the tweeter used as a sound source in this experiment was "visible" to the microphone through the openings in the letter *R*, it is recorded in the hologram and one can therefore view it in sharp focus in the reconstruction if one wishes.

lionth of a second later), a second pulsed laser, which is lined up on the same axis as the first, records a second hologram of the deformed surface on the same photographic plate. Between the two exposures, however, the path length of the optical reference wave is decreased by a quarter of an optical wavelength. When the two-component optical hologram is reconstructed, the reconstructed image of the surface exhibits brightness variations that are proportional to the acoustically induced displacement, or deformation, that occurred between the two pulsed-laser exposures. The reconstructed image of the surface obtained in this way is a temporal reference acoustical hologram of the acoustical-wave field impinging on the surface.

The technique has several important advantages. First, the aperture of such a hologram is limited only by the power available from the laser for illuminating the surface. A pulsed laser can readily illuminate a surface three feet square, thereby providing the resolution and image content needed to make acoustical holography a useful tool. Second, the use of an optical means for area detection eliminates the serious engineering problems that would be involved in trying to build large-aperture arrays of electronic detectors. Third, the extremely high recording speed means the system is little affected by object motion.

The liquid-surface technique and the technique for optical recording of temporal reference acoustical holograms, both of which are currently under development, show great promise as being truly practical systems for operation at high ultrasonic frequencies. Such frequencies, which lie in the megacycle range, will be required in medical diagnosis and in the nondestructive testing of materials. The acquisition of high-quality images of the human body showing the soft-tissue structures of organs and vessels will make new clinical information available to the physician. Such a system will be a valuable complement to present pulse-echo methods and X-ray techniques. Acoustical holography for imaging objects below the surface of the sea and below the surface of the earth is under development but appears to be somewhat farther off.

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