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A STUDY ON RANGE GATED TEMPORAL REFERENCE ACOUSTICAL HOLOGRAPHY

FINAL TECHNICAL REPORT
UNDER CONTRACT NAS 12-2166

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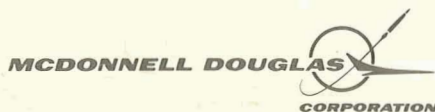
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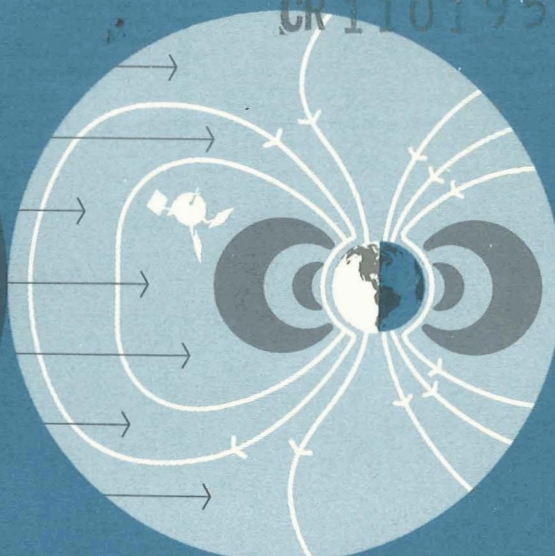
A STUDY ON RANGE GATED TEMPORAL REFERENCE ACOUSTICAL HOLOGRAPHY

REPORT MDC Q0035
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FINAL TECHNICAL REPORT

BY

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JULY 1, 1970

CREDIT

This final technical report represents the results accomplished
during the past year in a program on Range Gated Temporal
Reference Acoustical Holography. Work was carried out at
McDonnell Douglas for the National Aeronautics and Space
Administration, Electronics Research Center, Cambridge,
Massachusetts, under Contract NAS 12-2166.

ABSTRACT

This study first examines the general medical imaging requirements
for noninvasive visualization of soft tissue structures in man.
Selected imaging techniques, including both conventional pulse-echo
imaging and various acoustical holographic imaging techniques, are
then discussed, and acoustical holography is shown to exhibit distinct
advantages. A double pulsed ruby laser method of optically recording
a temporal reference acoustical hologram appears to be the most
promising holographic imaging technique currently available. The
primary conclusion of this study is that acoustical holography,
utilizing existing techniques, is generally feasible for the noninvasive
visualization of soft tissue structures in man.

CONTENTS

Section 1

INTRODUCTION

An ideal method for noninvasive visualization of soft tissue structures in man would be one capable of the following operating characteristics. First, it should be able to visualize soft tissue structures. Second, it should do so without the use of harmful radiation. Third, to be noninvasive, it should not require the introduction of foreign materials into the body, such as injections of radiopaque dyes or barium meals. Fourth, it would be desirable to record the information as a three dimensional image. Finally, it would be even more desirable to make these recordings repetitively in the form of a three dimensional movie. At present there is no system available with all of these capabilities.

To visualize soft tissue structures buried in optically opaque media it is necessary to interrogate the media with some form of radiation which will interact suitably with the soft tissue structure. The structures are characterized by the exterior surface as well as the material comprising the mass of the tissue. X-rays interact with the chemical elements comprising the tissue. The interaction is one of absorbtion, the absorbtion being greater the higher the atomic number of the element encountered. Thus, because of the calcium in the bone, X-rays show bone structure very well, but the soft tissues consisting of the lighter elements are not seen excepting when very high energy X-rays are used. In addition, since X-rays are not readily reflected by a surface, they are not affected by, and therefore do not "see," tissue interfaces.

Sound is a mechanical radiation consisting of the propagation of an elastic wave. The propagation of sound is therefore very much affected by the mechanical properties of the material through which it passes. Sound is absorbed in a homogeneous material by the dissipation of energy through viscoelastic effects, and is partially reflected when it encounters an interface where there is a mismatch in the mechanical impedance across the interface. In other words, sound can "see" interfaces.

From these simple considerations of the basic properties of X-rays and sound it follows that if we are to be able to accomplish the noninvasive visualization of soft tissue structure in man, then the choice of radiation must be sound radiation. Sound also satisfies the second requirement of being a harmless form of radiation, providing the sound intensity is maintained below a threshold safety level. X-rays, on the other hand, exhibit ionization effects at all intensity levels. Because sound interacts with the soft tissue structures, the introduction of foreign materials into the body are not necessary and thus the third requirement is satisfied. The fourth requirement, a three dimensional recording may be accomplished through the use of holography.

Section 2

ACOUSTICAL PULSE-ECHO IMAGING

Acoustical imaging for the visualization of soft tissue structures in
man is not new. Acoustical pulse-echo imaging has been used in
medical diagnosis for some time now. Pulse-echo methods will be
briefly reviewed here because there are similarities between the
fundamental properties of pulse echo imaging and acoustical holography
imaging. Clinical pulse-echo results are useful in that insight can
be gained into the image quality that can be expected from acoustical
holography imaging.

There are six different forms of pulse echo imaging used in medicine
in addition to the doppler ultrasound methods which will not be dis-
cussed here. These forms include A-mode, B-mode, T-M mode,
C-mode, mechanical compound scan and mechanical hand scan.

A-mode presentation provides information describing depth and
effective size of a reflecting surface. When the depth is measured
along the X-axis, the signal information is displayed on the CRT
along the Y-axis. The amplitude and shape of the received signal
is related to the size of the object producing the reflection. One
common use for this mode is to locate the midline of the brain and
to determine the possibility of midline shift as occurs when a
growing brain tumor has pushed the midline to one side.

B-mode presentation provides depth and position information. The
echo signals are displayed as an intensity modulation of the CRT spot

as the spot sweeps across the CRT face. The depth information is displayed along the X-axis and the transducer position is shown along the Y-axis. B-mode scan (B-scan) is obtained by lateral scanning movement of the transducer.

TM-mode presentation is sometimes called Time Motion Scan. The equipment is set to operate in the B mode except that the transducer is held stationary. A time-base generator slowly sweeps the trace in the Y direction so that effects due to motion of pulsating surfaces or objects show up clearly. This is used to demonstrate cardiac motion, bicuspit valve motion, etc.

C-mode presentation effectively gives a cross-sectional image through the subject under study. The CRT display shows the area of the body that is covered by the transducer. Reflections from the internal surfaces appear in their correct positions relative to the area covered.

Mechanical compound scan is a programmed scanning technique which provides cross sectional information pertaining to depth and position. Intensity modulation is used to show a line segment of sweep or a dot of energy reflected from an interface. The transducer is moved to achieve the scan. The movement is arranged so as to, as nearly as possible, result in the acoustical pulse impinging normally on the interface in the body. In the compound scan, echos from any discrete point within the object superimpose on the CRT thereby resulting in a certain amount of signal averaging.

Mechanical hand scan is a non-programmed scanning technique which provides cross sectional information pertaining to depth and

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position. This is accomplished in a manner similar to the mechanical compound scan described above, with the exception that the transducer is maneuvered by hand to achieve normalcy to the surface of the subject. The transducer position and the path of the sound beam are electrically synchronized with the CRT trace. This technique is one of the more common methods used in ultrasonic diagnosis.

IMAGE RESOLUTION

The spatial resolution in pulse echo imaging is determined by a number of factors. The longitudinal resolution (i.e., in the direction along the path of the sound beam) is determined by the sharpness of the pulse and the phase coherence across the sound beam. With a good transducer operating in an ideal medium the longitudinal resolution can be a fraction of an acoustical wavelength. Maximum phase coherence occurs at the point of transition between the Fresnel (near) zone and the Fraunhofer (far) zone at a distance of $a^2/(4\Lambda)$ from the transducer, where a is the transducer diameter and Λ is the acoustical wavelength.

Transverse resolution is determined by the beam width, since a point object anywhere in the beam cross section will return an echo. In the Fresnel zone the beam is essentially a collimated beam of width equal to the transducer diameter, a. At the transition point the beam diverges into the Fraunhofer zone at a half angle ϕ, where

$$\sin\phi = 1.22\Lambda/a \qquad (2.1)$$

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Both the longitudinal and transverse resolutions are degraded in medical pulse echo imaging partly due to aberrations introduced by the biological tissue but particularly by bodily movement of the patient during scanning. An essentially instantaneous recording method is necessary in order to eliminate the smearing effect due to body movement.

CLINICAL RESULTS OF PULSE-ECHO IMAGING

A considerable amount of material has been published (Refs 1 through 3) which demonstrates the clinical value of pulse echo imaging. The pulse echo images of soft tissue structures in man include among others, visualization of malignant and non-malignant tumors in the brain (Refs 4, 10, 11, and 17), in the breast (Refs 4, 17, and 18), visualization of the eye (Refs 2 and 5 through 9), [including foreign bodies (Refs 7 through 9)], cirrholic and abscessed livers (Refs 12 and 15), kidney (Refs 12, 15, and 20), spleen (Refs 12, 13, and 15), pancreas (Ref 12), aorta (Ref 12), Vena cava (Ref 12), teeth (Ref 14), uterus (Refs 15, 16, and 19), fetus (Refs 15, 16, 18, and 19), fetal death (Ref 15), bladder (Refs 15 and 20), ovarian cysts (Refs 15 and 17), and the placenta (Ref 17).

The evidence in the literature overwhelmingly supports the fact that acoustical imaging is capable of imaging soft tissue structures in man and yielding valuable clinical information. Although the quality of the images produced by pulse echo is often relatively poor, the physician still extracts useful clinical information from the images. There can be no doubt therefore, that any improvement in either

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image resolution or image quality will greatly enhance its clinical usefulness.
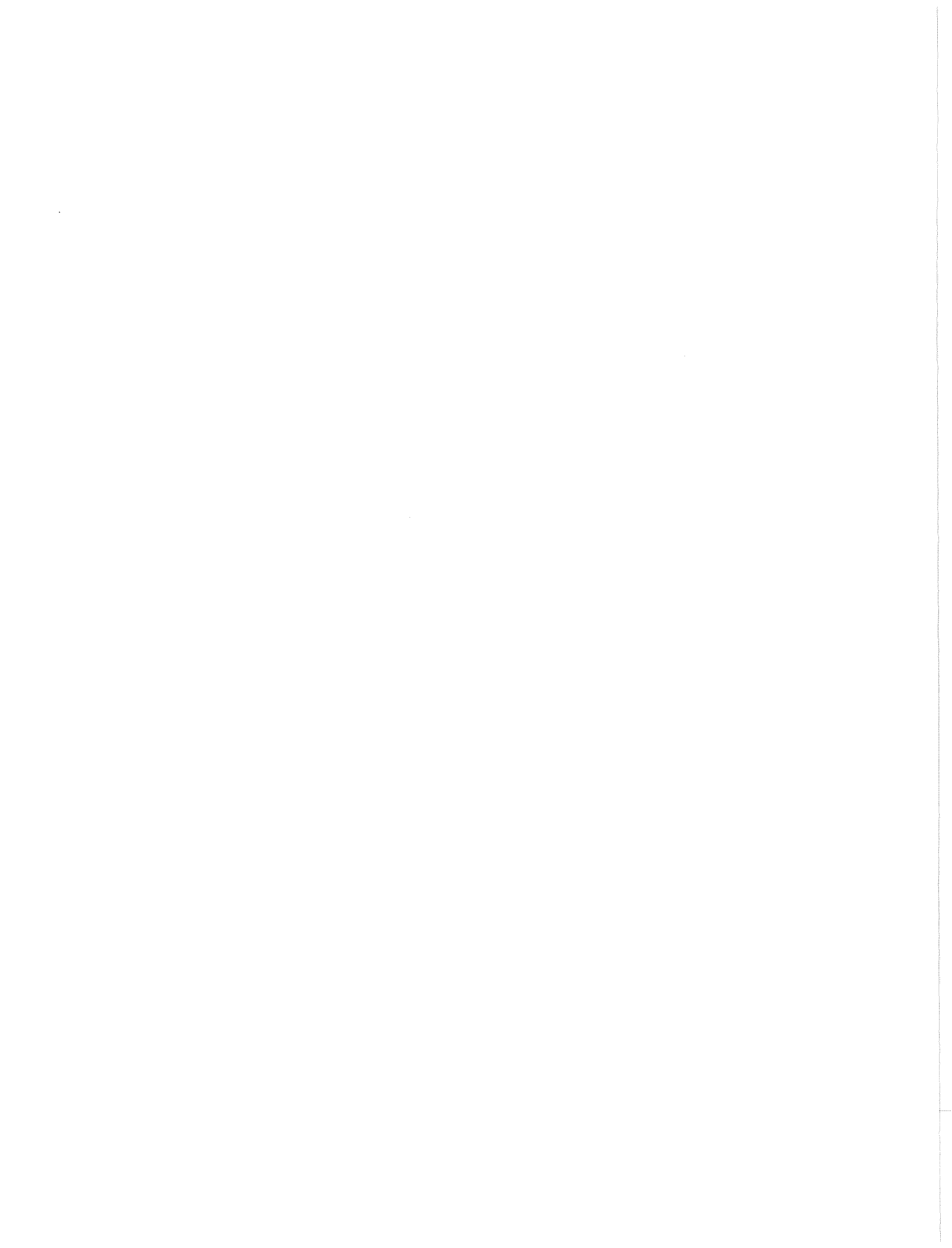
Section 3

ACOUSTICAL HOLOGRAPHY

Acoustical holography (Refs 21 and 22) is a means for producing an optical field analog of an acoustical field. The principal difference between acoustical holography and the conventional forms of acoustic imaging is that there is a total transfer of amplitude and phase information from the sound field impinging on the detection area to the optical field generated in the reconstruction process. The result is that the image information in the optical field is three dimensional.

PRINCIPALS OF HOLOGRAPHY (Ref 21)

Figure 3.1 shows the general arrangement for recording an acoustical hologram. Pure tone coherent sound U_r coming directly from a
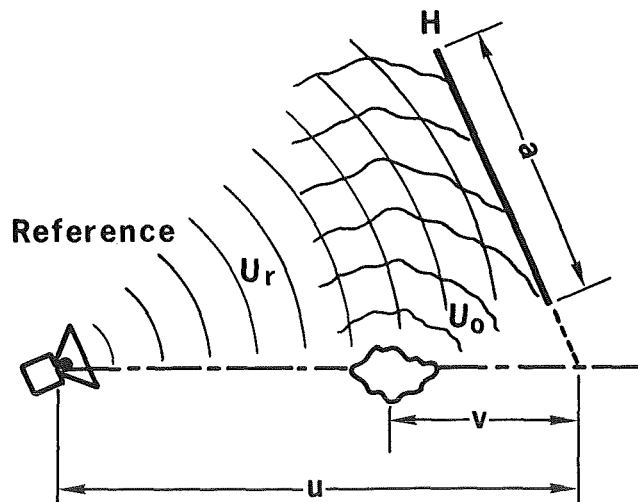
Figure 3.1 Recording geometry

reference sound source falls onto the plane H. The object is
ensonified either by the reference sound source or another sound
source driven by the same signal generator as the reference. The
sound wave U_o from the object falls onto the plane H. The
monochromatic mutually coherent waves U_o and U_r interfere with
each other and form a wave $U = U_o + U_r$. The acoustical hologram
is the recording of the intensity I of the wave U in the plane H.

$$I = UU^* = U_r U_r^* + U_o U_o^* + U_r^* U_o + U_r U_o^* \qquad (3.1)$$

where the asterisk denotes the complex conjugate.

To allow the hologram to be reconstructed with light in the second
stage of the process the intensity I is linearly recorded on
photographic film. The developed film is then the acoustical
hologram. If the film $\Gamma = 2$, and the film (acoustical hologram) is
illuminated with an optical wave U_r which is the optical analog of
the acoustical reference wave U_r, the transmitted amplitude will
be proportional to

$$U' = U_r t = I_r U_r + I_o U_r + I_r U_o + U_r^2 U_o^* \qquad (3.2)$$

where $I_r = U_r U_r^*$ and $I_o = U_o U_o^*$.

Providing the reference wave intensity is nearly uniform across the
hologram plane, I_r will act as a constant multiplicative factor. The
third term in Eq 3.2 is the optical analog of the original acoustical
object wave multiplied by the constant illuminating wave intensity.
The fourth term produces the conjugate of the object wave if the

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hologram is illuminated with U_r^* instead of U_r. The first term is the illuminating wave passing through the hologram. The second term is the wave U_r modified by I_o which in general is not a constant across the hologram and hence this becomes an interference term (which may be neglected if $|U_r| \gg |U_o|$.) Figure 3.2 illustrates a typical reconstruction arrangement. By looking down the U_o beam through the hologram a virtual true image of the original object may be seen since the U_o beam is now an optical analog of the original acoustic beam. Likewise the conjugate object wave forms a real conjugate image of the object.
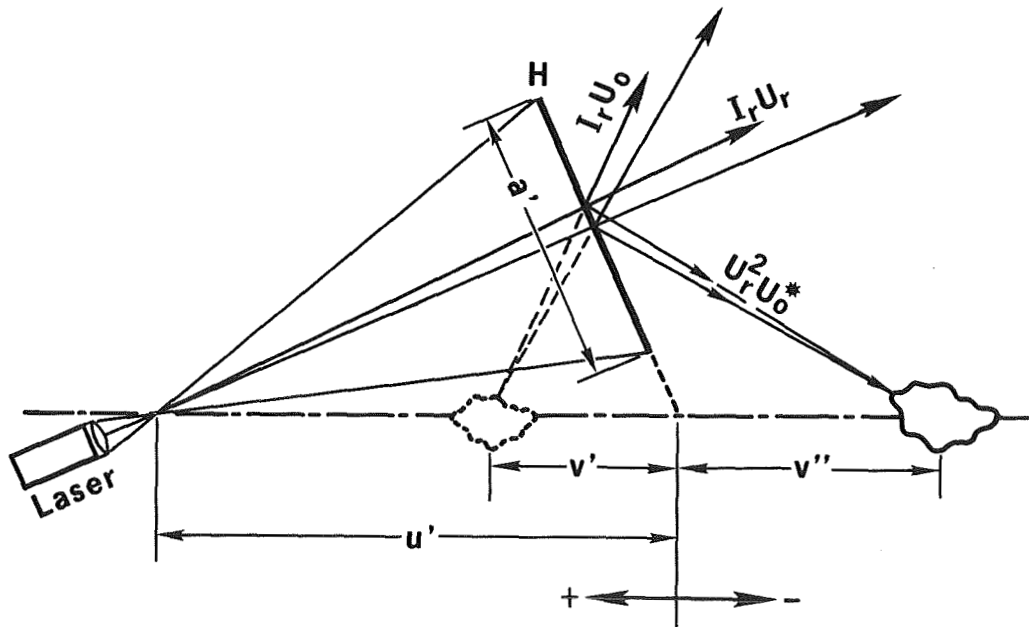

Figure 3.2 Reconstruction geometry.

IMAGE POSITION AND MAGNIFICATION (Ref 23)

Using the notation in Figures 3.1 and 3.2, the hologram may be considered to be a compound zone plate with a built-in object. To a first approximation, the equivalent focal length f is given by

$$1/f = 1/v - 1/u \qquad (3.3)$$

If $m = a'/a$ and $\mu = \lambda/\Lambda$, the ratio of the optical to acoustical wavelengths, the equivalent focal length f' of the reconstructing hologram is

$$f' = (m^2/\mu)f \qquad (3.4)$$

$$1/v' = 1/u' + 1/f' \quad \text{and} \quad 1/v'' = 1/u' - 1/f' \qquad (3.5)$$

In general the transverse and longitudinal magnification M_t and M_1 will not be the same (Ref 23). These are given by

$$M_1 = M_t^2/\mu \qquad (3.6)$$

$$M_t = [mu/(u - v)]/[1 \pm v'/(u' - v')] \qquad (3.7)$$

where the + and − signs in Eq 3.7 apply to the true and conjugate images, respectively.

An undistorted image requires that $M_t = M_1$ which is only satisfied if $m = \mu$ and $u' = \mu u$, i.e., everything is scaled in the ratio of the wavelengths.

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EXPERIMENTAL TECHNIQUES

There are many different methods available for recording the
acoustical holograms (Refs 21 and 22). Among these are the liquid
surface method, the ultrasound camera method, and the mechanically
scanned microphone method. The first of these methods involves
direct square law detection of the sound, while the last two methods
involve linear electronic detection with subsequent recording.

In the liquid surface method of acoustical holography, two high
frequency sound sources are submerged in a water tank and pointed
toward the water surface. The acoustic beams interfere, and the
resulting interference pattern, which manifests itself as a stationary
ripple pattern on the water surface, will be the hologram of an object
placed in one of the beams. This hologram can be reconstructed by
two methods. The first is a "real time" method that involves
illuminating the surface with a laser. The second method is to
photograph the ripple pattern, thereby obtaining a hologram that
can be reconstructed in the usual manner. Recently the liquid
surface method of acoustical holography has been used (by a group
at the Pacific Northwest Laboratory of the Battelle Memorial
Institute) to record some of the best reconstructed images obtained
to date.

The ultrasound camera method of recording acoustical holograms
involves the use of the Sokolov ultrasound camera, which is similar
to a television camera and display monitor except that the faceplate
of the camera tube is a half acoustic wavelength thick piezoelectric
crystal (usually quartz). When sound scattered by an object impinges

on the front of the crystal faceplate, the crystal vibrates in resonance with an amplitude and phase proportional to the impinging acoustical amplitude and phase. An electron spot raster scans the back of the crystal and the secondary electron emission is modulated by the mechanically induced piezoelectric voltage on the back of the faceplate. The secondary electron emission is picked up and amplified via an electron multiplier, and subsequently this signal is added to an electronically simulated off axis acoustic reference wave. The resulting signal is used to modulate the brightness of the spot on the television monitor, thus yielding the acoustical hologram.

The mechanical scanning method of recording acoustical holograms is basically a technique by which the hologram plane is appropriately sampled. The detected energy is converted to light and recorded in a synchronous manner on a photographic film. In most cases, an appropriate linear transducer scans a plane in the medium where a hologram is to be made. In one arrangement the signal from the transducer is amplified and then used to modulate a small light bulb which is focused on a photographic plate. In another arrangement the detected signal modulates the brightness of the scanning spot of a CRT, the face of which is photographed. So long as a linear detector is used to sample the sound field, the acoustic reference wave can be synthesized electronically.

Linear detection has the important advantage that it permits data processing to be performed on the detected signal prior to the recording. Two such operations are used commonly. First, linear electronic detection of the sound wave allows the reference beam (Figure 3.1) to be added electronically after detection of the

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acoustical object wave, thereby eliminating the need for an actual
acoustical reference source (Ref 24). Electronic synthesis of the
reference wave is now almost invariably used in electronic recording
techniques. Second, it is possible to modify the object wave signal
prior to adding it to the electronic reference. This is done in
recording a "phase only" acoustical hologram (Ref 21) where the
object signal is modified so that its amplitude is constant over the
hologram plane no matter what the detected acoustical amplitude is.
The modified object wave then contains only the phase information
in the acoustical object wave and the "phase only" hologram which
results when this is summed with the reference wave has fringes
similar to a conventional hologram but whose contrast (visibility) is
uniform instead of varying across the hologram plane. Since the
modified object wave amplitude is constant across the hologram,
the second term in Eq 3. 2 is no longer an interference term.

Figure 3. 3 shows the results (Ref 21) of a "phase only" acoustical
hologram recorded using a synthesized electronic reference and
subsequent spatial filtering to improve the image. A cutout of a
letter R , measuring 6 ft by 4 ft with 1 ft lettering widths, was
placed 6 ft in front of an 8 ft by 10 ft acoustical hologram plane
which was scanned with a microplane. A high frequency sound source
emitting 18 kHz sound (Λ = 0. 75 in.) was placed 19 ft in front of the
hologram plane (13 ft behind the R) to ensonify the object. The
"phase only" hologram is shown in Figure 3. 3 upper left. Figure 3. 3
upper right is the reconstructed true image of the R with the
out-of-focus conjugate image superimposed. Since an electronic
reference was used, the sound source which ensonified the R was
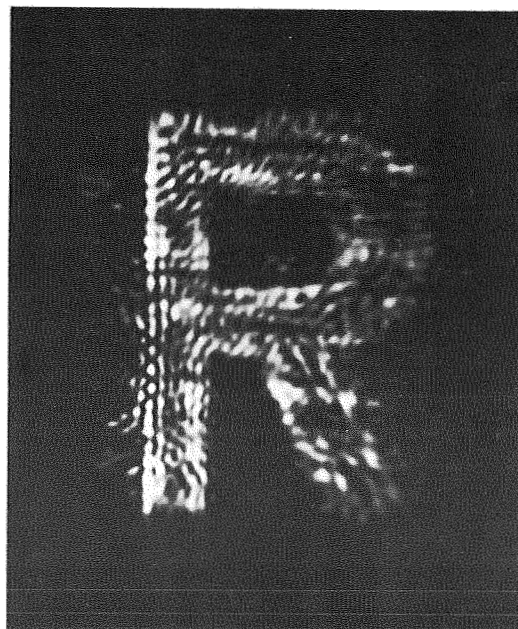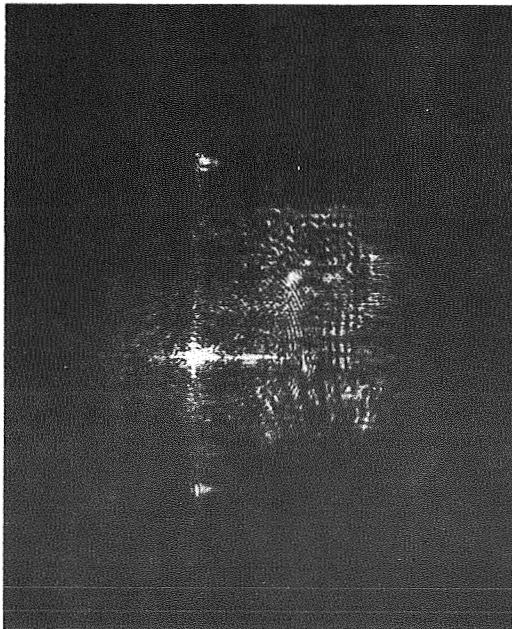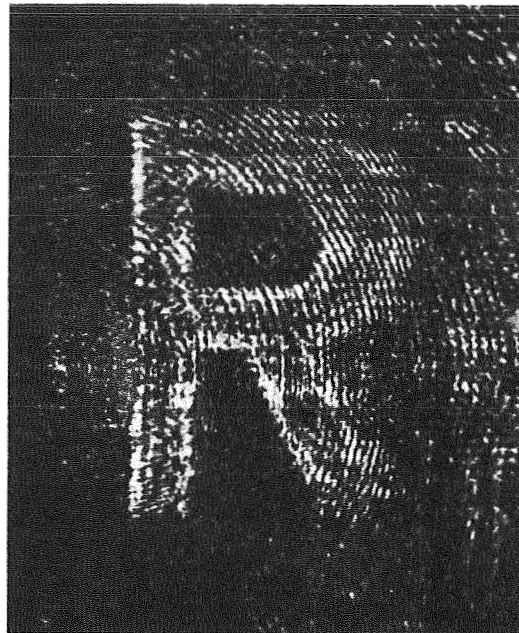itself a second object and its true image reconstructed in a different

Figure 3.3 "Phase-only" acoustical hologram.

position (Figure 3.3, lower left), which demonstrates the three dimensional nature of the image. By blocking the out-of-focus conjugate image surrounding the reconstruction of the sound source (bright dot Figure 3.3 lower left) and only allowing the sound source image to pass, the conjugate image is removed from the true R image as seen in Figure 3.3 lower right (compare with upper right). This is an example of the spatial filtering that can be done to improve the images in holography.

A color acoustical hologram was made (Ref 22) with sound at 15, 18 and 21 kHz by superimposing the respective images as red, yellow and blue components respectively to form the final color image. Such color holograms give frequency response information about the object which may prove useful in examining complex objects in medical diagnosis.

IMAGE RESOLUTION

The theoretical resolution limit of an acoustical hologram can be determined from the Rayleigh criterion, which gives the minimum resolvable separation between two point sources as

$$\sin\phi = 1.22\Lambda/a \qquad (3.8)$$

where ϕ is the angular separation of the point sources, Λ is the acoustic wavelength, and a is the diameter of the hologram. The image resolution obtainable from a hologram can also be expressed in terms of the smallest interference fringe spacing which can be

obtained in the hologram, the limit of resolution being one-half the minimum fringe spacing.

In pulse echo imaging, where the resolution is also determined by Eq 3.8 (see Eq 2.1), the diameter of the transducer is necessarily small, so that the resulting theoretical resolution limit is large, resulting in relatively poor resolution. However, in acoustical holography, where relatively large hologram apertures are readily obtainable, the limit of resolution can be made to approach the acoustic wavelength. In addition to providing improved resolution, a large aperture is desirable in order to more fully develop a "three-dimensional" image with parallax effects.

As was mentioned previously (Section 2), resolution is degraded in medical pulse echo imaging by aberrations introduced by biological tissue and, particularly, by the fact that all living tissue is dynamic in nature due to cardiac activity, respiration, etc. Likewise in acoustical holographic imaging, aberrations introduced by the human tissues will degrade the resolution of the image; however, as in pulse echo imaging, range gating techniques can be employed to minimize this effect. But, unlike pulse echo imaging, acoustical holographic techniques (e.g., the temporal reference methods discussed in Section 4) are available which allow essentially instantaneous recording, thus eliminating the image smearing effects of bodily movement.

It is apparent then that acoustical holography offers a potentially vast improvement in resolution over pulse echo techniques for biomedical imaging.

Section 4

TEMPORAL REFERENCE ACOUSTICAL HOLOGRAPHY

Temporal reference holography is a new form of holography in which linear nontime-averaged detection and recording of an object wave are accomplished instantaneously within the carrier frequency cycle. This method entails a direct recording of the wavefront, as opposed to the indirect method used in conventional time-averaged holography, where the recording is similar to, but not the same as, a conventional hologram.

Temporal reference holography is a two-stage process: In the first stage a wavefield is recorded instantaneously. Because of the nature of the process, the mathematical expression for the recorded information differs from that of a conventional hologram, and hence no reference wave is used and none is synthesized. The wavefield amplitude and phase are recorded with respect to time, not with respect to another wave -- hence the name "temporal reference." In the second stage, the original wavefield and its conjugate are reconstructed by illuminating the temporal reference hologram with a reconstructing wave. The reconstructing wave shape and its position relative to the hologram are directly related to the time when the recording was made at each point on the hologram.

Temporal reference acoustical holography offers distinct advantages for medical imaging, as will become apparent from the following discussion.

THEORY OF TEMPORAL REFERENCE HOLOGRAPHY

Recording the Temporal Reference Hologram

When an object is illuminated with a coherent monochromatic wave of frequency ω radians per second, the wave which is scattered by the object will have an amplitude and phase that are functions of position given by

$$U_1(x, y, z) = A_1(x, y, z) \exp\left\{ i[\omega t + \psi_1(x, y, z)] \right\} \qquad (4.1)$$

where A_1 and ψ_1 are, respectively, the amplitude and phase of the wave.

Assume that we can linearly detect the instantaneous value of U_1 in a detection plane $H(x_h, y_h, z_h)$ and that the instant of time $t = t_h$ when the record is made is either the same for every point on the plane (in which case t_h is a constant, independent of the position x_h, y_h, z_h on the plane), or the instant of time $t = t_h$ is different for every point on the plane (in which case t_h is a function of the positions x_h, y_h, z_h on the plane). The expression for the function which is to be recorded is thus, from Eq 4.1,

$$\mathrm{Re}[U_1]_{t=t_h} = A_1 \cos(\omega t_h + \psi_1) \qquad (4.2)$$

When a constant value B is added to Eq 4.2 (to ensure positive values) and the result is recorded on a photographic plate (whose coordinates correspond to the recording plane coordinates), the function recorded on the photographic plate is $[B + A_1 \cos(\omega t_h + \psi_1)]$, which becomes the temporal reference hologram.

Reconstructing the Temporal Reference Hologram

To reconstruct the temporal reference hologram, we illuminate the plate with a reconstructing wave U_o, given by

$$U_o = A_o \exp[i(\omega t + \psi_o)] \tag{4.3}$$

where we define A_o as constant (independent of x_h, y_h, z_h) and where ψ_o is related to the function $t_h(x_h, y_h, z_h)$ by the expression

$$\omega t_h = -\psi_o \tag{4.4}$$

The wave transmitted by the developed photographic plate is proportional to

$$U_s = U_o[B + A_1 \cos(\psi_1 - \psi_o)] \tag{4.5}$$

Putting Eq 4.5 into exponential form,

$$U_s = U_o\left\{B + \frac{1}{2} A_1 \exp[i(\psi_1 - \psi_o)] + \frac{1}{2} A_1 \exp[-i(\psi_1 - \psi_o)]\right\}$$

$$= BU_o + \frac{1}{2} A_o A_1 \exp[i(\omega t + \psi_1)] + \frac{1}{2} A_o A_1 \exp[i(\omega t - \psi_1)] \exp 2i\psi_o$$

$$= BU_o + \frac{1}{2} A_o U_1 + \frac{1}{2} A_o A_1 \exp[i(\omega t - \psi_1)] \exp 2i\psi_o \tag{4.6}$$

Equation 4.6 is the fundamental relationship identifying components of the wave emerging from the temporal reference hologram upon reconstruction. It differs from the equivalent equation produced by a conventional time-averaged square-law recorded hologram in one

significant respect: the fourth term, which appears as an additional interference term in the conventional holography equations,* and which requires that the conventional reference-wave amplitude be much larger than the object-wave amplitude, is absent from Eq 4.6.

The first term in Eq 4.6 is the undiffracted reconstructing wave passing directly through the hologram (i.e., the zero-order wave). The second term is the true reconstruction of the original object wave, with the constant amplitude $A_o/2$ acting as a multiplicative factor. The third term is the distorted reconstructed conjugate of the object wave.

The Reconstructing Wavefront U_O

For reconstruction, the reconstructing wave U_o can, in general, have any shape (i.e., any function for ψ_o). However, in practice it will usually be either plane or spherical, as determined by the phase ψ_o. If the kind of reconstructing wave to be used is known, the time of recording each point in the plane is determined from Eq 4.4.

If the reconstructing wave is a plane wave whose wavefront makes an angle θ with the hologram plane, the phase ψ_o of the illuminating wave will be constant in one direction along the plane (in the y direction, say) and will vary in the orthogonal (x) direction. If the velocity of the original object wave is a, the phase

$$-\psi_o = (\omega x \sin\theta)/a = \omega t_h \qquad (4.7)$$

_____

*See, e.g., the second term of Eq 3.2 of this report.

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If the detector is a line detector so oriented in the y direction that it can record the object wave along the line instantaneously within the wave cycle, and the line detector is swept with a constant velocity v in the x direction, the velocity v at which the recording line must move is given by

$$v = x/t_h = a/\sin\theta \qquad (4.8)$$

If $v = a$, $\theta = 90°$. If $v = \infty$ (i.e., if the entire recording is made at one instant), $\theta = 0°$.

Reconstructing With a Different Radiation and Wavelength

If the original object wavefield was an acoustical wavefield of wavelength Λ, the recorded temporal reference acoustical hologram can be illuminated with a reconstructing wave U_o' of a different wavelength from that of the original acoustical object wave; moreover, U_o' need not be an acoustical wave. The reconstructing wave U_o' may be a coherent monochromatic optical wave given by

$$U_o' = A_o' \exp[i(\omega't + \psi_o)] \qquad (4.9)$$

in which case Eq 4.6 becomes

$$U_s' = BU_o' + \frac{1}{2} A_o' U_1' + \frac{1}{2} A_o' A_1 \exp[i(\omega't - \psi_1)] \exp 2i\psi_o \qquad (4.10)$$

where

$$U_1' = A_1 \exp[i(\omega't + \psi_1)] \qquad (4.11)$$

Since ψ_1 and A_1 are the same as in Eq 4.1, it can be seen that the reconstructed wavefront U'_1 is an optical wavefield analog of the original acoustical wavefield U_1 with the ability to form an optical image of the original insonified object. However, because the wavelength λ of U'_o is in general different from the wavelength Λ of the acoustical wavefield U_1, the reconstructed image will be subjected to the same magnifications and distortions that occur when a conventional hologram is reconstructed with a different wavelength (Section 3 of this report and References 23 and 25).

TEMPORAL REFERENCE ACOUSTICAL HOLOGRAM RECORDED WITH A SOKOLOV ULTRASOUND CAMERA

The Sokolov ultrasound camera (Refs 26 through 31) is similar to a television camera and display monitor except that the faceplate of the camera tube is a half-acoustic-wavelength-thick piezoelectric crystal. When sound impinges on the front of the crystal faceplate the crystal vibrates in resonance with an amplitude and phase proportional to the impinging acoustical amplitude and phase. Because of the vibration characteristics of the crystal, there is relatively little transverse mechanical coupling on the faceplate. An electron spot raster scans the back of the crystal, and the secondary electron emission is modulated by the mechanically induced piezoelectric voltage on the back of the faceplate. The secondary electron emission is picked up and amplified via an electron multiplier, and the signal is used to modulate the brightness of the spot on the television monitor. Assuming linearity in the electronics and television phosphor, the system can be used to detect

and record the sound wave linearly. Hitherto the system had been used only to record the acoustical wave time-averaged over many wave cycles (Refs 26 and 27).

One of the limitations of the Sokolov tube is that it is sensitive only to sound impinging within $\pm 10°$ from the perpendicular, because of the impedance mismatch between water and the piezoelectric crystal (quartz). It has been pointed out previously (Ref 32) that in conventional time-averaged holography this is one case where the simulation of an off-axis reference is valuable. In the temporal reference holography situation we are not simulating a reference wave, but we need to have the actual acoustical object wave impinging close to the perpendicular.

To obtain separation between the zero order, the true image, and the conjugate image in the temporal reference case, it is necessary to have the reconstructing wavefront U_o off-axis. As described in the preceding section, this is done by scanning a vertical recording line with velocity v horizontally across the vertically placed hologram plane (the camera faceplate in this case). Unfortunately, the Sokolov tube is not a line detector; it is a scanning point detector.

In our experiments, to achieve the effect of a scanning line, the electron spot was scanned horizontally and returned to scan again with a slight vertical displacement between the scans. Care was taken to ensure that each scan started off "in step" with the preceding one (i. e., an integer number of wave cycles later). To accomplish this, the standard ultrasound circuit (Figure 4.1) was modified so that the horizontal sweep was triggered at the same point during the
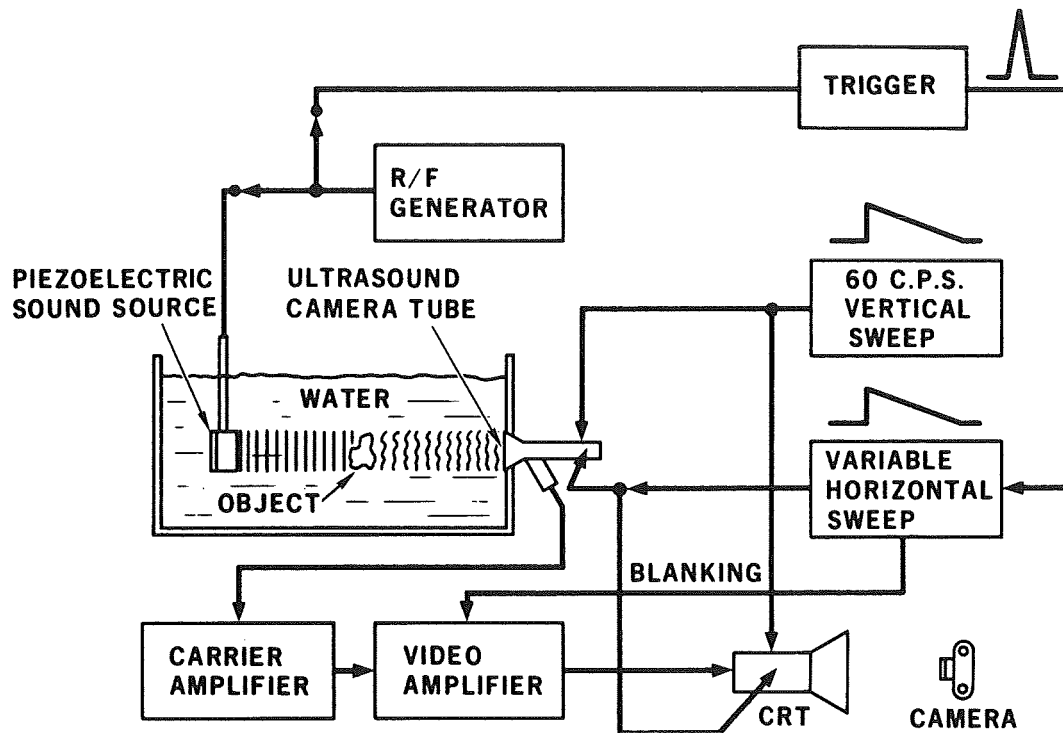
Figure 4.1   Ultrasonic camera system used to record the
non-time-averaged temporal reference
holograms.

acoustic cycle. This trigger is not essential, since without it the
horizontal sweep duration can be adjusted to be exactly an integer
number of acoustic cycles. However, it was found that in practice
the horizontal sweep is difficult to adjust with sufficient accuracy;
as a result the hologram fringes displayed on the CRT appeared to
"walk" across the screen in the horizontal direction when the
camera was free-running.

The frequency of the sound was 4.8 MHz. The horizontal sweep was
adjusted so that the electron spot in the ultrasound camera tube
scanned the piezoelectric detector with a velocity of 9450 ft/sec.

Figure 4.2 shows the recording obtained without any object between the sound source and the camera tube. The sound source radiated an approximately plane wave impinging perpendicularly onto the ultrasound camera detector. The spot was canned from left to right in Figure 4.2. Had the sound source radiated a perfectly plane wave, the fringes would have been perfectly straight, parallel, equispaced vertical fringes. The variation in fringe contrast corresponds to the variation in the sound-wave amplitude across the hologram.

Taking the sound velocity $a = 4720$ ft/sec, we have from Eq 4.8 the angle $\theta = 30°$, which is the angle that a reconstructing wave (of the same wavelength as the sound wave) must make with the hologram perpendicular, to reconstruct the acoustical wavefront. However, because the reconstructing wavelength is shorter than the recording wavelength, this angle is reduced correspondingly.

Figure 4.3 (top) shows the temporal reference hologram that was recorded in the same way as that shown in Figure 4.2, except that an object -- a cutout of the letter "X" measuring 0.75 by 0.75 in. with 0.125-in. limb widths -- was placed between the camera faceplate and the sound source. The "X" and sound source were, respectively, 6 in. and 23 in. from the camera faceplate. The diameter of the area scanned on the faceplate was 1.74 in. Thus, for perfect reconstruction the minimum resolvable distance (Ref 25) calculated by the Rayleigh criterion is 0.05 in., which means that the letter limb width is less than three resolution elements wide.

The hologram was reconstructed by placing it in the converging beam of a He-Ne laser. The true image of the "X" (Figure 4.3,
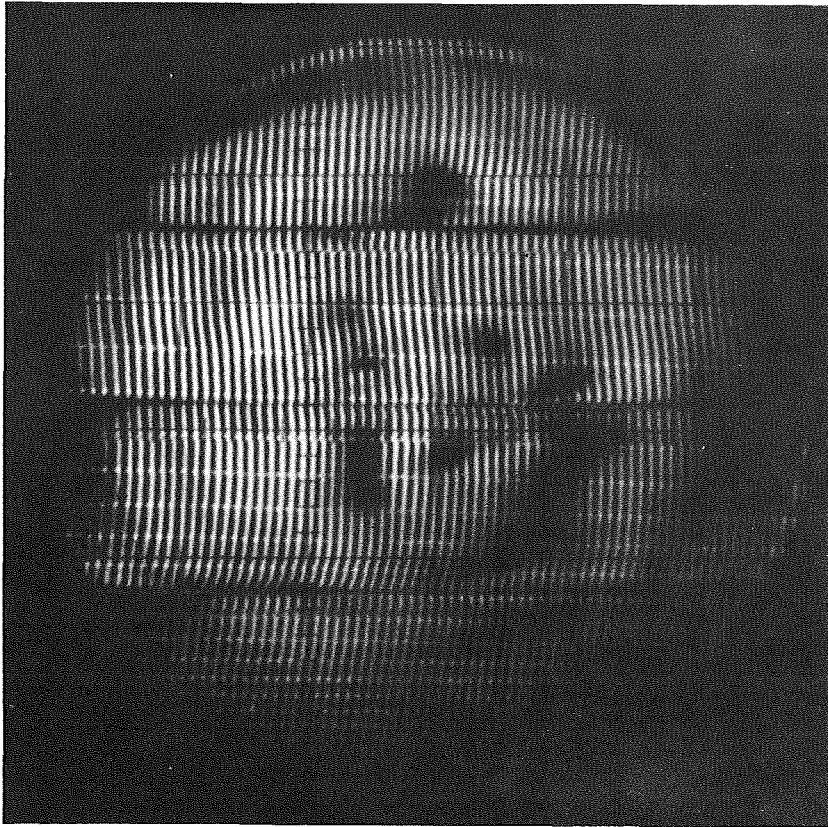
Figure 4.2 Nontime-averaged temporal reference hologram of the 4.8-MHz sound wave emitted by the piezoelectric sound source in Figure 4.1 (without object). The hologram fringes are the vertical running fringes. That they are not perfectly straight indicates that the sound wave is not perfectly plane. The variation in fringe contrast indicates a variation in the amplitude of the wave across the hologram. The scanning detection spot moves across the piezoelectric camera faceplate from left to right at a speed of 9450 ft/sec.
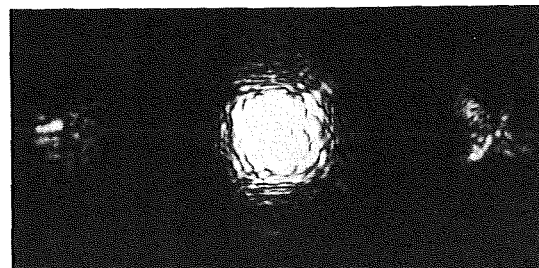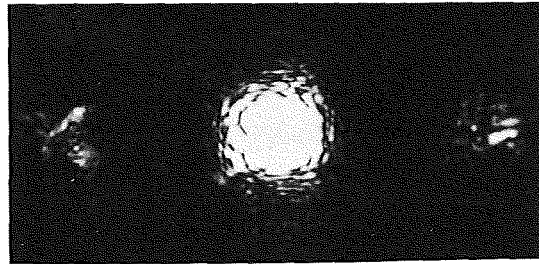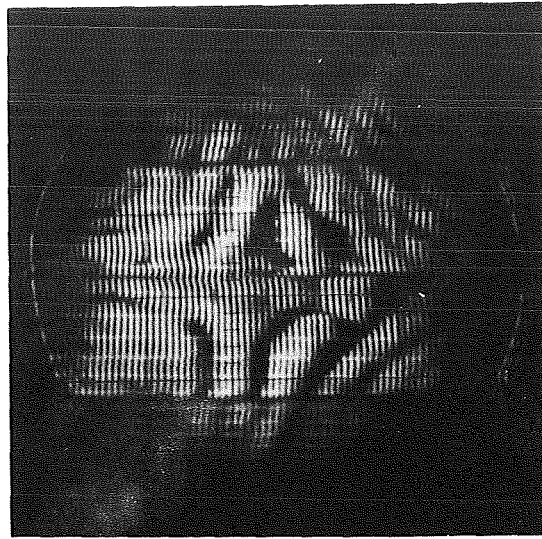
Figure 4.3 Top: Nontime-averaged temporal reference hologram
made under the same conditions as those in Fig-
ure 4.2 except that a cutout of the letter "X" was
placed between the sound source and the camera tube.
Middle: Reconstructed true image of the "X" is in
focus at the left of the zero-order beam seen in the
center of the picture. The out-of-focus conjugate
image of the "X" is to the right of the zero-order
beam. Bottom: Conjugate image on the right is in
focus; the true image on the left is out of focus.

middle) is in focus to the left of the zero-order beam, but the conjugate image is out of focus to the right. Figure 4.3 (bottom) shows the conjugate image in focus at the right and the true image out of focus at the left.

These results are inferior to those which have been obtained previously (Refs 25 and 27) with conventional time-averaged methods on the Sokolov ultrasound camera system. The resolution in the image does not equal the ideal resolution calculated with the Rayleigh criterion. The poor image quality is due to (a) the small size of the object compared with the number of resolution elements that could exist in a perfect reconstruction, (b) uneven illumination from the sound source behind the object, (c) the fact that the material from which the "X" was cut was not a perfect sound absorber and hence transmitted some sound, (d) multiple reflections between the camera faceplate and the object, and (e) nonlinearity in the final recording due to nonlinearity in the phosphor response on the CRT displaying the hologram and the photographic process to produce the Polaroid print, and hence the transparency used for reconstruction.

Because the inherent limitations of the ultrasound camera discussed above (limited aperture, small field of view, etc.) prevent images of good quality from being produced, temporal reference acoustical holograms of medical subjects would best be recorded on detection devices other than the ultrasound camera. The following section discusses a detection and recording scheme which is directly applicable to medical imaging.

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PROPOSED METHOD FOR OPTICAL RECORDING OF TEMPORAL
REFERENCE ACOUSTICAL HOLOGRAMS

General Description of Double-Exposure Subfringe Interferometric
Holography

A method for optically recording temporal reference acoustical
holograms is described below. The basic purpose of this technique
is instantaneously to record acoustically induced vibrations of a
surface whose displacements, as a function of position, are propor-
tional to the amplitude of an impinging acoustical field.

Sound is propagated through a medium via periodic displacement
(strain) of the constituent molecules. An instantaneous record of
the acoustical strain in a plane in the medium is a temporal reference
hologram of the wavefront impinging on that plane. In practice, the
plane will usually be some boundary of the propagating medium in
which an acoustically irradiated object is immersed.

The proposed technique is based on a modified form of double-
exposure interferometric holography. In conventional interferometric
holography the magnitude of the object displacements is typically
several optical wavelengths. Displacement magnitudes are determined
by applying fringe-counting techniques to the reconstructed image.
Therefore, the resulting intensity of the interference pattern is not
a linear function of displacement. In the technique of double-exposed
subfringe interferometric holography* the expected instantaneous

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*It has come to our attention that subfringe interferometric holography
has been discussed by L. O. Heflinger and R. E. Brooks, in "Research
Program on Holographic Instrumentation - Final Report," NASA
CR-73266 (TRW Systems Report 07821-6004-RO-00) 15 June 1968.

displacement amplitudes will, in general, be less than an optical wavelength. The introduction of a $\lambda/4$ optical shift between the two exposures helps to linearize the intensity with respect to displacement.

The edge view of an acoustically vibrating surface is shown in Figure 4.4. A holographic laser system instantaneously records the position of the surface. A second exposure is then made half an acoustic cycle later to double the sensitivity of the recording and cancel the effect of static deflection. Between the first and second exposures a $\lambda/4$ optical phase change is introduced into the object (or reference) beam. This phase change shifts the datum of the interference curve (Figure 4.5) from the crest at point A to the $-\lambda/4$ position halfway between the crest and the trough. A zero displacement leads to partial destructive interference at the $-\lambda/4$ position, and the intensity of the surface is a medium grey level. Small positive displacements lead to a brightening, while small negative displacements lead to a darkening. At no time should the total displacement exceed $\lambda/4$; otherwise, a crest or trough would be reached. For small total displacements not exceeding, say, $\lambda/8$, and under ideal circumstances the intensity of the interference can be considered a linear function of displacement. Theoretically, displacements down to zero amplitude could be recorded, since the slope of the interference curve (dI/dx) is constant and a maximum at the $\lambda/4$ position (whereas it is zero at the crest A). However, in practice, noise in the reconstructed image of the surface will be the limiting factor.

If very small displacements are recorded, the intensity variation of the reconstructed surface may be barely perceptible on top of the
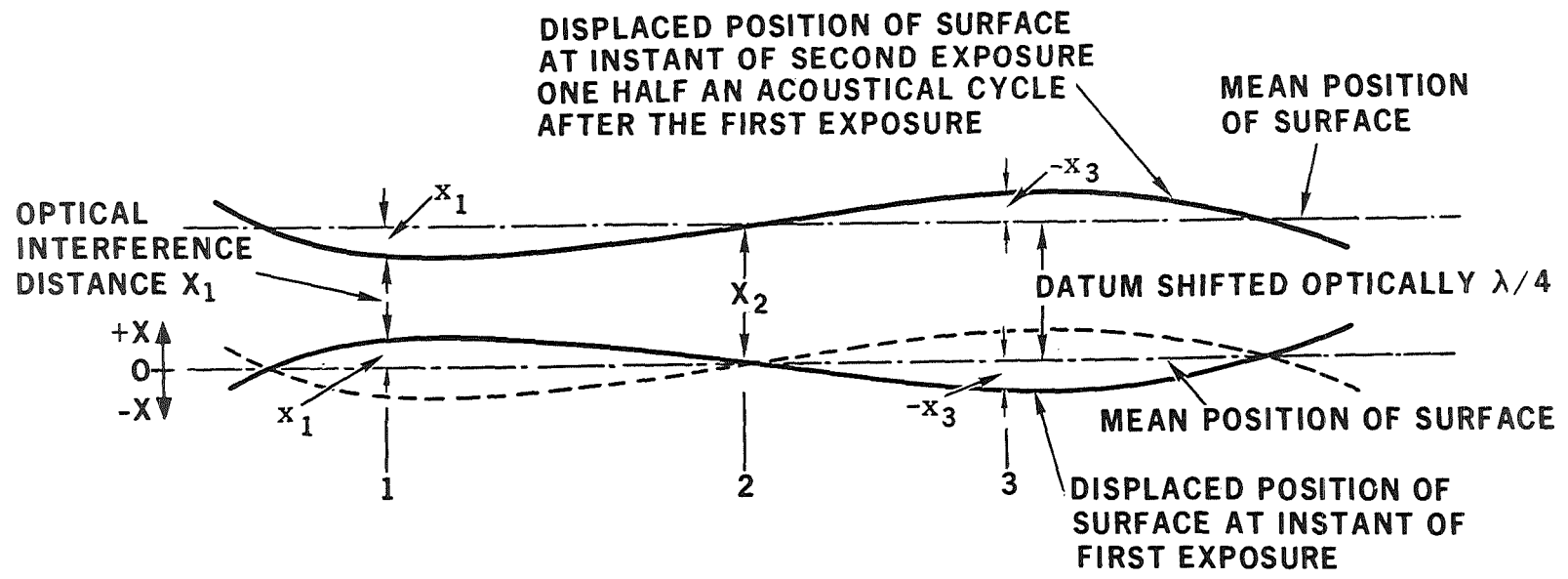
Figure 4.4 Relative positions of the two reconstructed images of the acoustically excited surface.
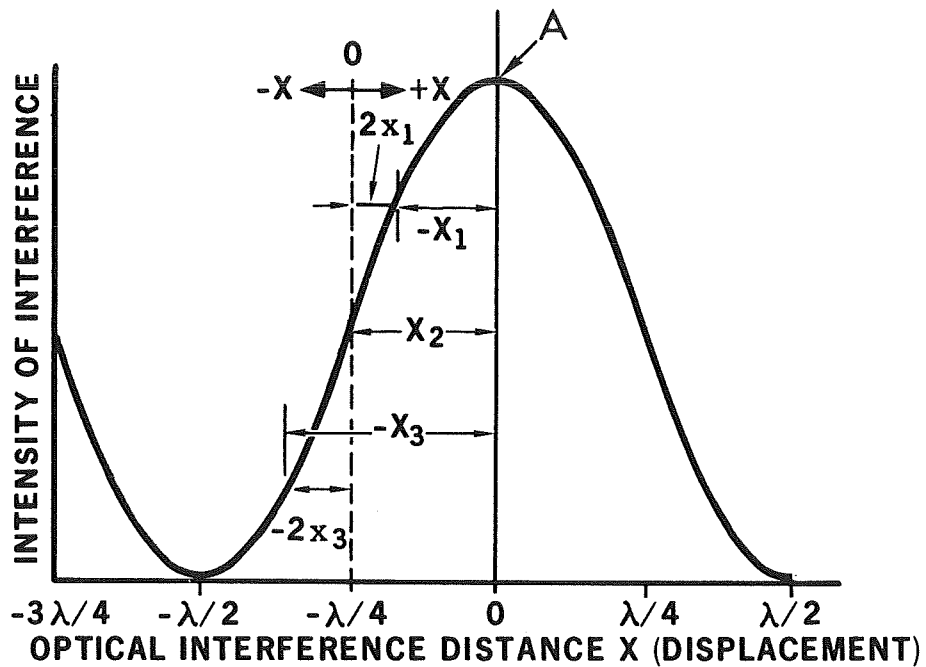
Figure 4. 5 Brightness of a point on the surface as a function of
displacement of the surface.

uniform grey level. This represents a weak spatial frequency
variation on top of a strong dc term. The dc level can be reduced
or removed by conventional coherent spatial filtering techniques,
thus effectively "amplifying" the weak spatial fringes. To maintain
a linear relationship between intensity and displacement, intensity
variations must be constrained to a range corresponding to $\lambda/8$
excursions about the $\lambda/4$ datum point. It can be shown that this
condition dictates that instantaneous surface displacements should
not exceed a magnitude of $\lambda/32$ about the mean value. The lower
bound remains to be determined experimentally.

We are presently in the process of recording temporal reference
acoustical holograms in the 1-5 MHz range using this method and

the system discussed below. Thus the two exposures at half an acoustic cycle apart will occur at intervals between 500 and 100 nsec. The extremely short period between the two exposures has the advantage of maximizing the effect of the displacement due to the megahertz acoustic radiation, while minimizing low-frequency acoustic noise superimposed on the surface. In a sense, the double-exposure recording method acts like a bandpass filter.

We propose the following method of utilizing these concepts to make temporal reference acoustical holograms. The method uses a double-pulsed ruby laser system to illuminate the entire acoustically vibrating surface at two instants, half an acoustic cycle apart. In this case t_h is the same for the entire temporal reference hologram area, and hence, from Eq 4.4, the wave used to reconstruct the temporal reference acoustical hologram must be a plane wave impinging perpendicularly to the hologram plane. This method is described in somewhat greater detail in the following paragraphs.

Double-Pulsed Laser System

One of many possible pulsed-laser arrangements based on the foregoing principles is illustrated in Figure 4.6. Utilization of a system exhibiting the essential features shown in presently underway at our laboratory.

The subject to be interrogated is insonified by an acoustical source, operating typically at 1-5 MHz. The diffracted acoustical field is
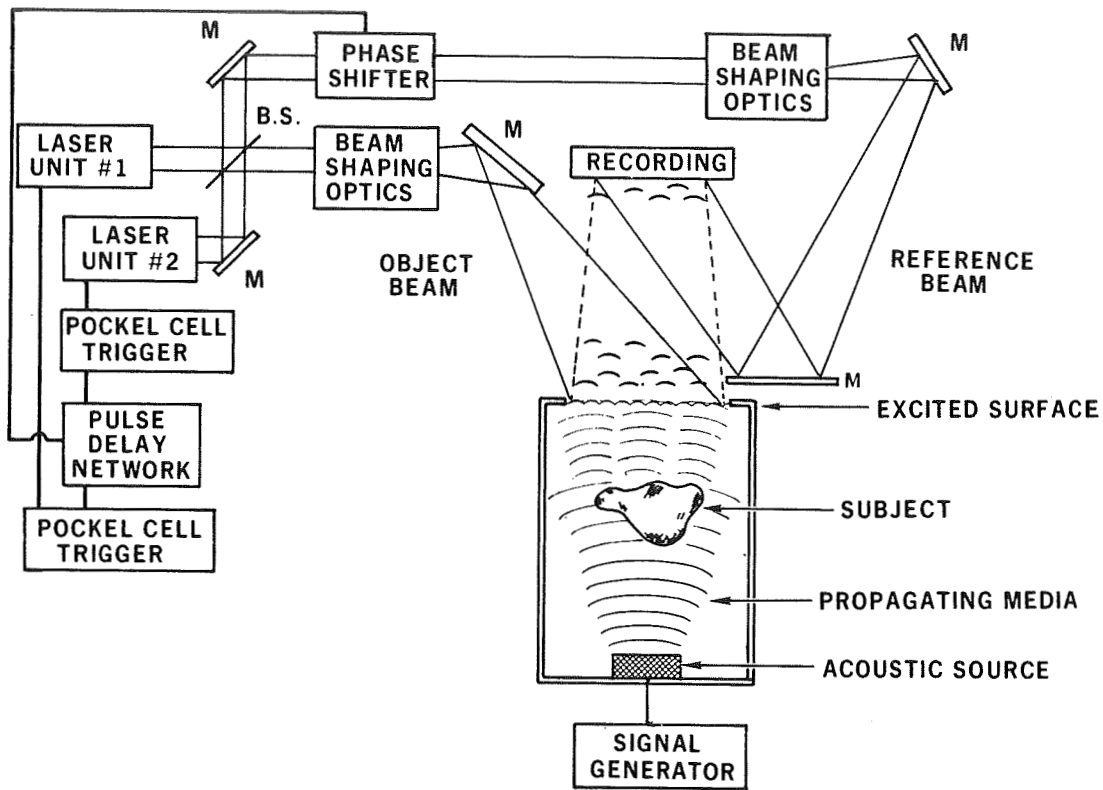
Figure 4.6 Layout of the double-pulsed-laser subfringe
interferometric holography system for
recording temporal reference acoustical
holograms.

incident on a surface which yields an instantaneous displacement at
the carrier frequency, proportional to the impinging wavefront. Two
Pockels cell Q-switched ruby lasers are employed to generate a pair
of 0.5-J pulses of 20 nsec duration at 694.3 nm. The pulses are
time-separated by a variable delay, continuously adjustable between
100 nsec and 10 μsec.

Each pulse is split by the beamsplitter into an object and reference
beam and subsequently used to record photographically a pair of
overlaid pulsed holograms of the acoustically excited surface. The

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time delay enables the recordings to be separated by the period necessary for the acoustical field to experience a 180° acoustical phase shift. In addition, a 90° optical phase shift is introduced into one of the optical channels between recordings. Under appropriate spatial and spectral stability conditions, which are generally satisfied in practice, the resultant recording is a double-exposed interferometric hologram. The resultant recording can therefore be used to reconstruct an image of the acoustically excited surface, the instantaneous displacements of which are displayed as variations in the image intensity of the excited surface. The record of the reconstructed image of the excited surface is therefore a temporal reference acoustical hologram of the incident acoustical wavefield. This temporal reference acoustical hologram may be used to reconstruct an optical wavefield analog of the original acoustical field.

Some initial results from early experiments achieved with the double pulsed ruby system are shown in Figure 4.7. A PZT ceramic transducer, driven at 385 KHz was recorded with the double pulse system. Single exposure holograms showed no indication of surface motion. However, the twelfth radial mode of the transducer is clearly visible (Figure 4.7) when the double pulse, subfringe interferometric technique is employed. Actually, this "instantaneous" record of the acoustic displacement in the transducer plane is a temporal reference acoustical hologram of the "wavefront" impinging on that plane.
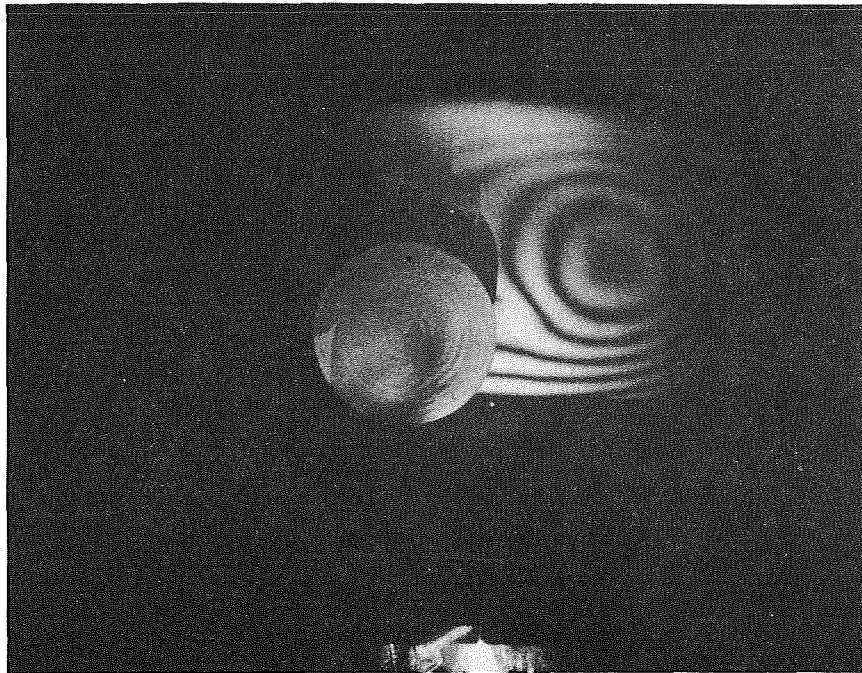
Figure 4.7   Reconstruction of subfringe interferometric hologram
obtained from double pulse ruby system.

DISCUSSION

In conventional holography the hologram is the recording of the
intensity (time-averaged over many wave cycles) of the sum of an
object wave U_l and a coherent reference wave U_r.   The mathe-
matical expression for the recorded pattern is

$$I = U_r U_r^* + U_l U_l^* + U_r^* U_l + U_r U_l^* \qquad (4.12)$$

In contrast, the temporal reference hologram is the instantaneous (nontime-averaged) recording of the object wavefield alone, with no reference wave. The mathematical expression for the recording is

$$A_1 \cos(\omega t_h + \psi_1) \qquad (4.13)$$

Since Eq 4.13 is not equal to Eq 4.12, the temporal reference hologram process does not simulate any reference wave.

The result (i.e., the reconstruction of the original object wavefield) of both processes is similar, except that temporal reference holography process does not produce the additional interference term that is present in the conventional situation.

The advantages of temporal reference holography include the following: first, the interference term just mentioned is absent from the reconstruction; second, the recording is instantaneous; third, the technique is able to tolerate greater motion of the object; fourth, time gating for viewing images within a given range can be accomplished to a greater extent than in the time-averaged situation.

The area (and hence the final resolution) of the temporal reference acoustical hologram that can be recorded can be as large an area as the laser holography system can illuminate. Optical holograms of object areas in excess of 1 m square can be recorded on standard 4 in. × 5 in. holographic plates.

The use of two optical pulses separated by half an acoustic cycle increases the system's sensitivity to sound at that frequency and effectively acts as a filter to acoustic noise signals at other frequencies.
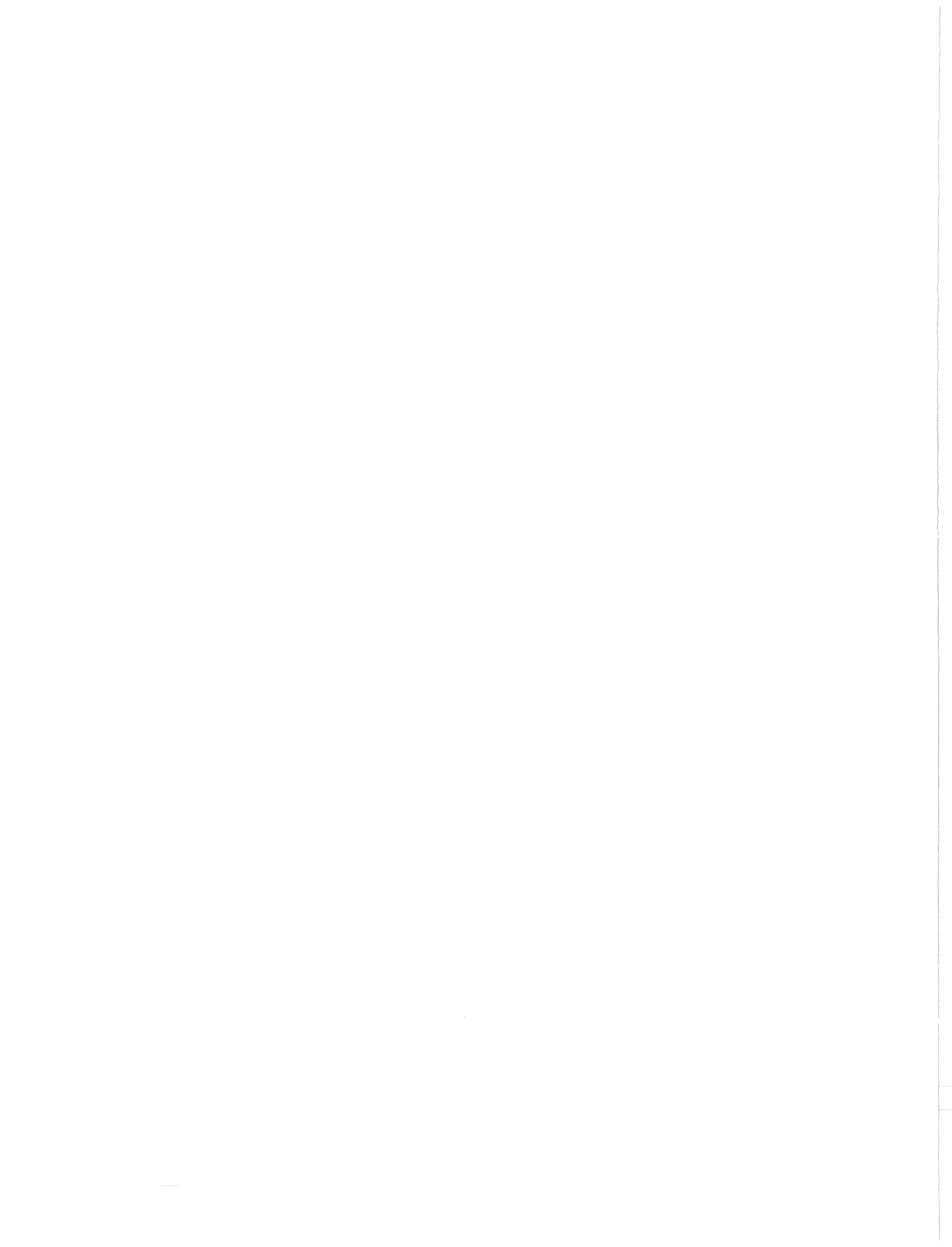
Section 5

CONCLUSIONS

After this initial study of the general medical imaging requirements
and selected imaging techniques, we can draw only a few general
conclusions regarding the feasibility of using acoustical holography
for the noninvasive visualization of soft tissue structures in man.
Although our group has not as yet achieved experimental verification
of the feasibility of using acoustical holography for imaging within
the body, the results (Refs 33 and 34) of other groups would indicate
that the prospects look good.

Aside from experimental results, this study has shown that acoustical
holography satisfies more of the general medical imaging require-
ments than any other existing technique. Acoustical holography is
certainly noninvasive and does not require the use of radiation levels
harmful to the body. Acoustical holography yields three dimensional
image information. Acoustical holography will image tissue inter-
faces within the body, just as do pulse echo techniques. However,
by utilizing the double pulsed ruby laser method of optically recording
a temporal reference acoustical hologram, the resulting image can
be expected to exhibit significantly higher resolution than is available
with either pulse echo or other holographic techniques. This is due
to the fact that the double pulse technique is essentially instantaneous
(thus eliminating all effects of body motion) and can utilize a large
aperture plus range gating techniques.

In spite of these important advantages, all acoustical holographic techniques have one drawback: reconstructions of acoustical holograms exhibit inherent longitudinal distortions due to the large disparity between the acoustical recording wavelength and the optical reconstructing wavelength. This fact may force the image to be viewed in planar sections, rather than as a true "three-dimensional" image.

In summary, it appears that acoustical holography, utilizing existing techniques, is in general feasible for the non-invasive visualization of soft tissue structures in man.

Section 6

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