AN ABSTRACT OF THE THESIS OF



An experimental underwater acoustic imaging system has been designed and built. Operating at 650 KHz, real time acoustic images are obtainable. Using both geometrical optics and Fourier optics, the theory of image formation and resolution is presented. Other factors affecting image quality and system acuity are also discussed.

System components include a 650 KHz lead-zirconate-titanate (PZT) illuminating transducer, and f/1.4 Plexiglas acoustic converging lens, an 81 element mosaic PZT receiving transducer which is resonant at about 650 KHz, 81 amplifiers, a scanning and synchronizing system, and a display oscilloscope.

Acoustic energy reflected by the target object is collected by the lens and focused onto the image receiving transducer, which is located in the image plane. The image, appearing as a spatial acoustic pressure distribution in the image plane, is sampled by the 81 element receiver. The 81 image element voltages are amplified and sequentially transmitted to the Z-axis input of an oscilloscope. Each channel amplifier is switched, in sequence, by solid state logic switches located in the scanning circuit. The scanning circuit drives the oscilloscope in a nine line TV type raster scan. If an image element is insonified, a bright spot corresponding to the image element is lighted on the oscilloscope display.

The receiving system has a measured sensitivity threshold of 3×10^{-10} watts/cm² and a measured system resolution of approximately 2.1°. Real time images of simple styrofoam targets are displayed.

An Underwater Acoustic Imaging System

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AN UNDERWATER ACOUSTIC IMAGING SYSTEM

I. INTRODUCTION

In recent years there has been a resurgence of interest in underwater acoustical imaging systems. In clear water direct visual observation or underwater television will be generally superior to acoustical imaging. Several cases present themselves where real time acoustical imaging is superior to optical imaging. A turbid water environment, often encountered by undersea workers, presents great difficulty to optical viewing. Investigations of marine edible species may be enhanced by the use of acoustic imaging systems. The advantage of an acoustic system is the lack of environmental disruption present when high intensity undersea lights are directed on undersea marine species. Deep submergence vehicle endurance could be increased if an acoustic imaging system were to replace the high electrical power visual system. These are but a few of the uses presently envisioned.

There are, at present, various forms of side-looking and scanning sonar systems on the market. These systems display information either as shadows cast by bottom objects or as a plan position indication display similar to radar. Such systems are not suitable for close coupled work because of a large time lag, low data rate, and poor display (14, p. A-34). Several general approaches to acoustical imaging are presently used. One such technique involves the creation of an acoustic hologram in which the image can be reconstructed from the hologram with a coherent light source. The other technique is directly analogous to optical imaging. With this method acoustical images can be formed of insonified objects by collecting the reflected signal in a focusing system. The collected signal, consisting of spatial pressure variations, is focused onto an image plane, sampled by a complex piezoelectric sensor, and displayed by an oscilloscope.

Elementary acoustic image conversion was conducted in 1937 by R. Pohlman in Germany. Pohlman suggested that the orientation of small non-spherical particles, suspended in a liquid and insonified by a high frequency source, could be made visible by indirect lighting. His "Pohlman cell" followed directly. In 1937, the Russian, S. Sokolov, filed for a U. S. patent on the Sokolov tube (14, p. A-21).

Basically the Sokolov tube is a cathode ray type tube similar to a T. V. camera tube with a piezoelectric transducer used in place of the photosensitive plate (2, 11). An incident acoustic signal induces an electric charge on the plate which then modulates an electron scanning beam. There are a number of basic problems with the tube. A high frequency piezoelectric plate is extremely thin, and in order to obtain a reasonable image size, the plate must be very large

compared to its thickness. The result is a tube which cannot adequately withstand sea pressure. Equally important, it lacks both sufficient sensitivity and a signal storage capability (7, p. 2).

A small piezoelectric transducer can be mechanically scanned over the image plane, converting the two-dimensional acoustic pressure field into an electrical signal. The information rate for this method is very low due to the slow scanning method.

By electronically sampling a fixed array of piezoelectric elements, an acoustic imaging system can have a high information rate. This type of image converter would also have a very high sensitivity, making it superior to the other image converters. The basic system, as shown in figure 13, p. 48, operates at an acoustic frequency of 650 KHz using an electronically sampled 81 element (9 x 9) piezoelectric array for the image converter.

The purpose of this project was to build an operating acoustic imaging system of suitable complexity to explore the various problems inherent in acoustic imaging. For the purpose of this thesis system image acuity is considered to be less important than its capability for displaying a moving target.

II. THEORETICAL CONCEPTS

Image Formation

The foundation of geometric optics is ray theory and Snell's law. Snell's law states that

$$\frac{c_1}{\sin \theta_1} = \frac{c_2}{\sin \theta_2}$$

where c is the acoustic velocity in either media 1 or 2 and θ is the angle between the ray and a perpendicular drawn to the media interface. Another concept from geometric optics relates object distance p from a lens or mirror and image distance q from the same optical device, to f, the focal length of the device. The quantities are related as follows (9, p. 448-462)

$$\frac{1}{p} + \frac{1}{q} = \frac{1}{f} \tag{1}$$

From ray theory and Snell's law another useful formula can be derived. The formula, known as the lensmaker's equation, describes the relationship between lens curvature, focal length and index of refraction. It holds only for thin lenses, i.e., lens thickness much smaller than the curvature. The equation is (9, p. 471).

$$\frac{1}{f} = (1-\mu) \left[\frac{1}{R_1} + \frac{1}{R_2} \right]$$
(2)

where μ is the index of refraction and R_{i} the radius of curvature for either face. From the preceding three equations a simple optical system can be designed and operated with some degree of success.

In designing an acoustical imaging system an experimenter may initially use the laws of geometric optics. There is a pitfall associated with the use of geometrical optics without consideration of the fundamental differences between the geometrical optic phenomena and high frequency acoustic phenomena.

The ratio of the lens thickness to the wavelength is an important difference. Assuming an average optical wavelength, λ , of 0.6 μ meters and a lens thickness of several millimeters, the ratio is of the order of 10,000. Another way to put it is that the lens is 10,000 wavelengths thick. Sound has a wavelength of about four millimeters in Plexiglas at 650 KHz, and the average thickness of a plastic acoustic lens is 75 millimeters. For the acoustic lens the ratio is about 18. The ratio difference for the two types of lenses is three orders of magnitude (13).

Also, the ratios of wavelength to aperture diameter and wavelength to object detail size are considerably larger in acoustical imaging than they are in conventional optical imaging. Spatial and temporal signal coherence is much greater in acoustical wavefronts than in a corresponding optical wavefront (1). In fact, operation of

an electro-acoustic transducer assures almost single frequency coherent waves (13).

The fundamental differences between geometric optics and acoustical imaging require the use of a theory based on diffraction and the Kirchhoff scalar diffraction formula. Because an acoustical wave is a longitudinal or compressional wave the scalar diffraction formula can be used. A somewhat simplified version of this formula follows (10, p. 170)

$$\overline{P}(x, y, z) = \frac{1}{4\pi} \int_{A} \overline{P}(\xi, \zeta) \frac{e^{-jkr}}{r} \left[(jk + \frac{1}{r}) \hat{i}_{z} \cdot \hat{r}_{1} + jk \hat{i}_{z} \cdot \hat{s} \right] d\xi d\zeta$$
(3)

where

 $\overline{P}(x, y, z)$ complex pressure distribution in the image plane $\overline{P}(\xi, \zeta, O)$ pressure distribution over a plane aperture $\mathbf{\hat{r}}_{1}$ unit vector in the direction from the aperture point (ξ, ζ, O) to the field point p

A area of the plane aperture

r distance from aperture point to field point p

k wave number

 $\hat{\mathbf{r}}_{\mathbf{z}}$ the unit vector normal to the aperture

s direction of a ray at a given point on the aperture.



Figure 1. Spatial variables in the diffraction equation

The diffraction field is divided into three general areas: the near zone region; the Fresnel region; and the Fraunhofer or far zone region. These regions result from the mathematical approximations used when applying the scalar diffraction equation. Many authors neglect to mention the near zone region and address themselves to the Fresnel and Fraunhofer zones exclusively. In fact the Fresnel region is often called the near field region. Region boundaries are not sharply defined, though there are basic structural differences between the three regions (10, p. 173).

When a near perfect (little or no aberrations) refracting surface is placed within the aperture, the diffraction field at the focus and beyond is primarily the Fraunhofer or far zone region. The fact that the near field is much closer to the aperture than one would normally imagine can be visualized if the focusing nature of the lens is considered. Diffraction of a point source by an aperture results in a broadening of the aperture image. Addition of a lens in the aperture causes reduction in the size of the point source's image. The result is a Fraunhofer zone in the neighborhood of the focus rather than a Fresnel region.

Fourier theory, similar to that applied to electrical signal analysis, can be used to describe the characteristics of an acoustic imaging system with somewhat more simplicity than the diffraction formula. The Fourier transform relates the time domain to the frequency domain. In Fourier optics, the signal varies spatially rather than temporally. The signal is a spatial distribution of acoustic pressure in a plane perpendicular to the transmission path. The Fourier transform then relates the spatial parameter to the spatial frequency. Spatial frequency is defined as $2\pi/L$ where L is the spatial wave length. See figure 2.

An acoustic/optical system has characteristics analogous to an electrical system. It has a system frequency response and a unit impulse response. The Fourier transform of the unit impulse response is the spectral density function, or the system spatial frequency response. In Fourier optics the unit impulse response

is called Green's function, or the spatial impulse response, or the spread function.



Figure 2. Spatial wavelength

A unit impulse is thought of as a very narrow pulse having a large height and a unit area. A spatial unit impulse is simply a point source of acoustical or optical energy. The defining equation is

$$\int_{-\infty}^{\infty} \delta(\mathbf{x}, \mathbf{y}) \, d\mathbf{x} \, d\mathbf{y} = 1 \tag{4}$$

where $\delta(x, y)$ is a unit impulse or a Dirac delta function. When an aperture is illuminated by a point source the imaging system's output is the unit impulse response. Specifically, the output is a two-dimensional acoustic pressure distribution at the focus or image plane of the lens.

It is often convenient to treat the image forming system as a linear spatial filter. An image forming system consisting of a transmission medium, focusing lens and aperture is analogous to an electronic low-pass filter. According to Green, Bellin, and Knollman (1) the coherent wave impulse response of an image forming system containing a square lens aperture of side " ℓ " is

$$h(x, y) = \ell^{2} \left[\frac{\sin(\frac{\pi \ell x}{\lambda q})}{\frac{\pi \ell x}{\lambda q}} \right] \left[\frac{\sin(\frac{\pi \ell y}{\lambda q})}{\frac{\pi \ell y}{\lambda q}} \right]$$
(5)

The Fourier transform of h(x) (one dimension for simplicity) is

$$H(\omega_{\mathbf{x}}) = \lambda q G_{2\pi \ell / \lambda q}(\omega_{\mathbf{x}})$$
(6)

where $H(\omega_x)$, is the system's transfer function, and $G_{2\pi \ell/\lambda q}$ is a gate function with the high frequency cutoff at $\omega_x = \pi \ell/\lambda q$. The gate function describes the aperture and lens system as a perfect low-pass filter of spatial frequencies.

The impulse response described by equation 5 was derived for the perfect imaging system. Scattering and absorption of the acoustic wave pattern by the transmission medium has not been considered. Aberrations, such as spherical aberration, coma, chromatic aberration, curvature of field and astigmatism are not present in the lens, i.e., a perfect lens. A coherent wave source is assumed. The result is the theoretical resolution limit for an acoustic imaging system.

Assuming a perfect point source of energy, the perfect image forming system using a square aperture would focus this energy into the image plane with a spatial intensity distribution of $(\sin m/m)^2$. A sketch of $(\sin m/m)^2$ is shown in figure 3.



Figure 3. Image of a point source

Figure 3 could be observed by the image plane detectors if the imaging system was a perfect system. Since the actual imaging system and transmission medium are not "perfect" the above concepts serve only to indicate the operational performance of the system.

For a point source input, it would be ideal to obtain a point source output. Since this is impossible in an acoustic system it is necessary to look at the system parameters which can be varied to give greatest acuity to the image. In equation 5 (sin m/m) has its first zero crossing at m = $\pi = \frac{\pi \ell x}{\lambda q}$. Solving for x gives

$$\mathbf{x} = \frac{\lambda \mathbf{q}}{\ell} \tag{7}$$

Equation 7 shows the parameters which theoretically control the sharpness or acuity of the image. Increasing the dimensions of the aperture decreases the distance x at which the acoustic intensity curve first reaches zero. In other words, it makes a narrower diffraction pattern or image pulse in the image plane. Reducing the wavelength, λ , by increasing frequency will also form a sharper image. Reduction of q, the image distance, will sharpen the image, though image distance is dependent on the object distance and lens focal length described by equation 1.

In the spatial frequency domain the theoretical high frequency cutoff is at

$$\omega = \frac{\pi \lambda}{\lambda q} \tag{8}$$

Increasing the aperture size, or decreasing wavelength and image distance all contribute to increasing the imaging system's frequency response and image acuity. Considering a point source as an input, the larger the frequency range of the transfer function, $H(\omega)$, the higher will be the spatial frequency passed by the imaging system. Since a point source contains all spatial frequencies, the more frequencies passed by the system, the sharper the image.

The imaging system discussed above includes a square aperture lens. It is more significant to describe the coherent impulse response of a system using a circular aperture. According to Heuter and Bolt (3, p. 63) the image of a point source resulting from a circular aperture is

$$h(\theta) \sim \frac{2 J_1(\mathbf{x}_{\theta})}{\mathbf{x}_{\theta}}$$
(9)

The coherent impulse response, $h(\theta)$, is said to be a function of θ only because of aperture symmetry. $J_1(x_{\theta})$, is a Bessel function of the first kind, zero order, and x_{θ} is defined as

 $\mathbf{x}_{\theta} = [2\pi a/\lambda] \sin \theta$



Figure 4. Spatial parameters of a circular aperture

Figure 4 shows the spatial parameters of the circular aperture. The resulting impulse response is similar to the square aperture and is shown in figure 5.



Figure 5. Impulse response of a circular aperture and a point source object

The first zero intensity point occurs at $x_{\theta_1} = 3.83$. Then x_{θ_1} is

$$x_{\theta_1} = \frac{2 \pi a}{\lambda} \sin \theta_1 = 3.83$$

Assuming small angles of θ , $\sin\theta = \theta$. With q as the image distance $\theta_{\mathbf{l}} = x_{\mathbf{l}}^{\prime}/q$. Substituting $x_{\mathbf{l}}^{\prime}/q$ for $\sin\theta_{\mathbf{l}}$ in the above equation results in

$$\begin{bmatrix} \frac{2\pi}{\lambda} \\ \frac{\pi}{\lambda} \end{bmatrix} \begin{bmatrix} \frac{x_1}{q} \\ \frac{1}{q} \end{bmatrix} = 3.83$$

$$\theta_1 = \frac{x_1}{q} = \frac{3.83}{6.28} \frac{\lambda}{a} = \frac{.61\lambda}{a} = \frac{1.22\lambda}{D_L}$$
(10)

Equation 10 describes the half-width of the image of a point

source object.

When attempting to resolve two coherent point sources the Sparrow criteria must be used. The Sparrow criteria states that two point sources can be just resolved if the second derivative of the image intensity vanishes at a position midway between the two image points (16). The angular separation of the two coherent point sources must be equal to or greater than

$$\theta \ge \frac{1.46\lambda}{D_{L}} \tag{10a}$$

Figure 6. Resolution of two point sources

From the Sparrow resolution limit, the two most important factors controlling the resolution of a system made up of perfect components are wavelength (frequency) and lens diameter. Larger diameter lenses and higher frequencies result in better system resolution.

When considering camera lenses, the image acuity is generally reduced by aberrations, not diffraction, and the lens aperture can be reduced to increase sharpness. Though diffraction effects are increased, the magnitude of these effects are small. However, images formed acoustically are affected predominantly by diffraction (14, A-19). This is due to the longer length of the waves.

The surface character of the object can influence the nature of the acoustic reflection process. With an acoustic wavelength on the order of several millimeters, some objects or portions of the objects become small specularly reflecting planes (1). In order to obtain a satisfactory image from energy specularly reflected, the collimated sound beam emerging from the object must be totally collected by the lens. If this does not occur only the edges of the object will be imaged (1). In actual practice, the lens will subtend a rather small angle at the object, and the probability that the reflecting surface is exactly aligned with the illuminator such that the lens receives the collimated beam is small.

If, owing to object surface roughness, the phases of the various scattered waves are uncorrelated, diffuse reflections occur. Objects with a rough surface have been found to be easily imaged (1). Additionally, it has been found that rough surfaced objects with uniform reflective properties produce acoustic images which have a mottled or granular appearance. The size of the granular spots are inversely proportional to the size of the lens aperture. Mottling can be reduced through the use of broad band frequency insonification instead of a single acoustic frequency.

Curved objects, especially those which have a smooth surface, are quite difficult to image. For example, a smooth sphere presents only a very small reflecting area that can reflect the incoming waves through the lens. It is impossible for the imaging system described above to be able to differentiate the sphere from a small point reflector (1).

The problem of curved and planar specular reflectors can solve itself in an undersea environment. Marine fouling, corrosion in the form of pitting, and possibly marine deposition, will, after prolonged exposure, make most underwater objects diffuse reflectors.

As mentioned in the introduction, acoustical imaging can be superior to optical imaging in a turbid environment. Small solid particles suspended in the water column will severely attenuate and scatter a light beam, while a sound beam will be transmitted with negligible loss (14, p. A-13). This can be explained with the use of figure 7 (14, p. A-13). The abscissa, particle size, is the particle size relative to the wavelength and is plotted against the effective scattering cross section of the suspended particles. For light transmission, the shortest wavelengths of light yield the largest relative particle sizes and largest scattering cross sections while the longer acoustic wave yields small particle sizes and a negligible scattering cross section. At this point it should be mentioned that Figure 7 was derived from electromagnetic theory. Although it is widely used in acoustic work, there is no direct experimental evidence showing that it can be applied to acoustics.



Image Conversion

In evaluating the best method of image conversion, several criterion must be used. The system should have a high sensitivity, a high information rate, and be unaffected by sea pressure. There are three methods of image conversion to be considered: a Sokolov tube; a fixed matrix of piezoelectric elements which are electronically scanned; and a small piezoelectric device which is mechanically scanned across the image plane. Of the three methods the electronically sampled matrix offers greatest flexibility of operation. The mechanically scanned probe has the disadvantage of a low information rate resulting from a mechanical scan. The low strength and low sensitivity of the electron beam scanning image converter (Sokolov tube) makes it inferior to the sampled matrix (1).

According to Jacobs (4) the minimum image size resolvable is equal to λ /2, where λ is the wavelength in the transducer. The maximum resolution occurs when the piezoelectric receiving plate is operated slightly below its resonant frequency. For an air-backed receiver the plate thickness is $\lambda / 2$ (4). Therefore, the minimum image size is equal to the plate thickness. Increasing the plate diameter will improve resolution for a given object distance and wavelength by allowing additional image lines for a given lens resolution (14, p. A-35). Obviously, resolution depends on λ (thickness of transducer plate) and plate diameter, besides the resolution criteria mentioned earlier. The design of an electron beam scanning plate must account structurally for sea pressure on the incident side and a vacuum on the back side. Thus, large thin piezoelectric plates needed for optimum resolution are not feasible in the electron beam scanning image converter. In construction of the piezoelectric matrix plate, diameter to thickness ratio is not as critical because of the type of plate supporting structure.

In 1937 Sokolov stated that when an extended piezoelectric plate was insonified, the resultant piezoelectric voltage would be confined to the point on the surface which was insonified (4). Later work showed that the size of the area excited acoustically and the piezoelectric voltage distribution were directly related to the fundamental resonant frequency, and somewhat related to the angle of incidence of the acoustic wave (4). As stated earlier the thickness of this plate is $\lambda/2$, with λ the wavelength in the plate at the fundamental resonant frequency. Then the smallest image size available is $\lambda/2$. Allowing our minimum image detector element size to be $\lambda/2$, we can compare this element to a detector element limited by the Rayleigh resolution limit. If we assume an image distance, q, of 20 inches and a D_L of 10.5 inches (actual system lens diameter) we can calculate a detector size, x, in terms of λ using equation 10a.

$$x = \frac{1.46 \lambda q}{D_{L}} \approx 2.8 \lambda$$

Obviously, the lens and not plate thickness restrict system resolution.

There are several useable methods for transforming the piezoelectric mosaic element voltages to a visual presentation. Green, Bellin and Knollman (1) use a 100 element colinear array which is mechanically scanned across the image plane. Each element is terminated by a photodiode. A pencil light beam sequentially strikes each photodiode causing conduction. The signal, after amplification, is displayed on a "kinescope" (1). In the system designed by Robinson (6, p. 22), the receiver element voltages are amplified by 455KHz IF amplifiers. The signal is then rectified and stored on capacitors. The capacitors are scanned in sequence by solidstate switches driven by an integrated-circuit logic network. The logic network generates sweep and step voltages for an oscilloscope intensity modulated display.

The image conversion method used in the system discussed is similar to that of Robinson (6, p. 29-42). The voltage of each mosaic element is coupled to the base of a 2N5134 transistor amplifier. A control signal from the switching matrix is applied to the base of another 2N5134 transistor located in the emitter circuit of the first transistor. The control signal thus turns on the transistor amplifier and causes the element signal to be transmitted, in its proper sequence, to the Z-axis input of the oscilloscope. With this method 81 transistor amplifiers can be sequenced in order, giving a raster presentation on the oscilloscope.

The amplifiers are connected in parallel through 81 diodes. With the exception of the conducting amplifier, the remaining 80 diodes are back-biased, thus preventing their respective amplifiers from conducting and affecting the operation of the conducting amplifier. Back-biasing of the 80 non-conducting amplifiers is accomplished with a voltage divider circuit connected to the diodes (see figure 8). This circuit back-biases each diode until its amplifier conducts, lowering collector voltage and forward biasing the diode.



Figure 8. Block diagram of the amplifier system

An emitter-follower circuit is placed between the first and second stages to provide electrical isolation and impedance matching. The signal is amplified by a factor of ten in the second stage, whose output is connected to a 650 KHz tuned circuit. The tuned circuit filters out low frequency switching transients. A class C amplifier, following the tuned circuit filter, further amplifies and rectifies the transmitted signal so that it consists of negative going peaks of about -5 to -10 volts. Using Z-axis modulation signals between -2 and -10 volts peak will allow the system operator to obtain intensity control with the intensity control knob on the oscilloscope.

The key to remote operation of the imaging system and the proper sequencing of 81 elements lies in the implemention of an integrated-circuit logic network which sequentially controls each amplifier channel, and controls the oscilloscope's horizontal sweep and vertical deflection circuits for proper image display.

The logic network or scanning circuit, as it is called, is used to provide a logic "one" voltage pulse for turning on each channel amplifier in sequence. Thus each mosaic element can be turned on sequentially, from channel 1 to channel 81, and then automatically reset. Scanning operation is accomplished using four different types of logic circuits. Transistor-transistor-logic (TTL) was chosen because of its flexibility and capability of significant fanout. The heart of the system is the two decade counters (SN7490N) and their respective BCD -to-decimal decoder/drivers (SN7442). As shown in figure 9 both counters and decoders provide logic control to a nine by nine matrix of NOR gates (21 quadruple 2-input SN7402 gates).

One decade counter, continuously clocked, is used to drive the scanning circuit through each element in a row. The second (vertical)





Figure 9. Block diagram of the scanning circuit and synchronizing system

counter receives its clock pulse from every tenth count of the horizontal counter and shifts the scanning vertically downwards one row. Each counter is wired so as to reset itself to zero after the tenth count, allowing the cycle to start again after all δ l channels are scanned. The binary output count of each counter is converted to a decimal number by the BCD-to-decimal decoders. As illustrated in figure 9, the 81 NOR gates are driven by the decoders and not the counters. Because the decoders function on "O" logic, i.e., the output signal for any count is "O," a NOR gate using two logic zeroes gives a logic "1" output for use in switching on a channel amplifier.

The tenth count of the horizontal decoder drives an SN7404N inverter for the generation of a logic "1" clock input to the vertical counter. Once the horizontal counter sequences nine elements in a row, the next or tenth count causes a row shift and sets the matrix state to the first element in the succeeding row. The tenth count also controls a triggered sawtooth generator. Horizontal sweep voltage for the oscilloscope is provided by this sawtooth. The repetition frequency for the circuit shown in Appendix 2 can be controlled between approximately 1.6 KHz and 2.0 KHz with a maximum voltage swing of about +8 volts. The triggered sawtooth generator, basically a relaxation oscillator with negative feedback for linearity, assures that all mosaic elements are displayed sequentially in one complete

sweep by synchronizing the horizontal sweep of the oscilloscope with the scanning circuit. Figure 9a shows the timing sequence of the synchronizing system.

Vertical deflection of the oscilloscope is accomplished with a synchronized stairstep generator circuit. As shown in Appendix 3, the stairstep generator is made up of eight gated-FET switches. The gate of each FET switch receives a logic signal from the vertical decoder, starting with count number "2" and ending with count number "9." Count "10" of the vertical decoder allows time for system reset. The stairstep voltage is connected to the A channel vertical amplifier of the oscilloscope, and working in conjunction with the horizontal sweep, provides a nine line raster scan.

A better presentation is afforded when a small alternating voltage of approximately 1 volt peak-to-peak and 1 MHz is applied to the input of channel B. With the operational mode of the oscilloscope set to "add algebraic," the small alternating voltage is impressed upon the stairstep, resulting in the 81 picture elements appearing as bright squares. This is illustrated in Figure 10.

It has been stated that the 81 channels are sequentially monitored. If the signal on the channel being monitored is of sufficient amplitude the corresponding position on the CRT will be illuminated.

Clock frequency input to the horizontal counter is 16 KHz. With each element being stepped at 16KHz, the horizontal sweep frequency is 1.6 KHz. The vertical deflection goes through ten



Figure 9a. Timing sequence for the synchronizing system

				-	E			
+++++	1111	1111	1111			1111	+++++	
								1



counts giving a picture rate of 160 frames-per-second. An actual picture element will contain about 41 cycles of information.

Potential System Restrictions

With an operational underwater acoustic imaging system, the range capability is severely limited by acoustic wave attenuation at high frequencies (6, p. 14). Acoustic attenuation, though consisting of spreading, scattering, and absorption losses, is primarily a result of the viscous absorption loss phenomenon. This loss is proportional to the square of frequency (5, p. 236).

The absorption loss in sea water is dependent on two parameters, acoustic frequency and salinity of the water. As frequency increases the loss coefficient (db loss/distance) is increased. In fact, the loss coefficient depends upon frequency squared. Kinsler and Frey (5, p. 236-237) show the empirical relationship as

Loss coefficient =
$$\frac{Af^2}{B+f^2} + Cf^2$$
 (11)

where f is frequency in KHz and A, B, and C are constants which increase with temperature. The presence of dissolved salts, specifically magnesium sulfate, will increase the attenuation (absorption) loss coefficient above that of salt free water at frequencies below about 0.5 MHz.
Range of an acoustic imaging system is directly related to attenuation loss by the sonar equation. Generally, the maximum range of the system varies inversely with the frequency, so that a high frequency system has a limited range and a lower frequency system has a longer range.

System resolution, being dependent on the Sparrow resolution limit, is good at high frequency. The relationship between maximum range and resolution can be best illustrated by the graph which follows (14, p. A-35).



Figure 11. Range versus resolution for an imaging system

Thus, in the design of an operational imaging system, one of the most important tradeoffs is between range and resolution.

If sound waves pass from water to a solid lens at other than a

perpendicular aspect, a shear wave will be generated in the lens (14). The longitudinal acoustic velocity differs from the shear wave velocity resulting in a lens with two refractive indices and two focal lengths. The two images formed are not seen simultaneously because they are focused in two different planes. Problems arise when the shear mode, although weaker than the longitudinal mode, interferes with the waves of the desired image (8, p. 168).

Earlier experimenters (7, p. 12, 12) were concerned with the suppression of unwanted echo energy being collected by the system. Several methods were used to assure an echo free system. One method was a tone-burst transmission and a range-gated receiving system. The receiving system is turned on and off before the first echo can be received. It remains off for a length of time equal to the tank reverberation time. When the echoes die off the system is "enabled" and can receive a signal.

Continuous wave transmission can be used if the tank walls are mildly anechoic, i.e., if the walls attenuate incident acoustic energy. The redwood tank used in this project is anechoic to the extent of a 20 db loss on each reflection.

There is a "scattered radiation rejection" characteristic associated with the piezoelectric receiving transducer (4). At angles of incidence greater than three to five degrees from the normal, the arriving wave is either totally reflected or produces nothing more transthan a general increase in the background illumination of the target (4). Therefore, only the echoes which are intercepted by the lens and focused onto the receiving mosaic can be a problem. Because of the "echo rejection" described, and the electronic sophistication required in a range-gated tone-burst-transmission scheme, continuous wave transmission seems to be the most advantageous to use.

III. SYSTEM DESIGN CONSIDERATIONS

Initial Predictions

Following a method prescribed by Haslet (2) an initial prediction can be made about the acoustic power requirements of a prospective imaging system. Consider a target irradiated with an acoustic beam of average power, W_i , in watts. An image of the target can be produced by a lens of magnification, M = q/p, where q and p are the optical parameters previously defined. A cross-sectional area, $A_{\tau} = \alpha/M^2$, of the target is focused onto an area α of the receiver (size of one mosaic element). The following figure shows the various spatial parameters.



Figure 12. Spatial parameters of the imaging system

With the range R from the target to the illuminator equal to the object distance p, the target incident intensity can be calculated from (3, p. 63)

$$I_{\tau} = D \frac{W_i}{4\pi R^2} \quad (watts/cm^2)$$
 (12)

where W_i is the acoustic output of the illuminator and D, the directivity factor.

Assuming that the target is a perfect diffuser, i.e., reflects all of the energy perfectly into a sphere, the intensity at the lens resulting from energy reflected by the target can be calculated. The intensity I_{LENS} is

$$I_{\text{LENS}} = \frac{(\text{Power reflected by A}_{T})}{(\text{Surface area of sphere of radius } p = R)}$$
(13)
$$= \frac{I_{T}A_{T}}{4\pi R^{2}} = \frac{I_{T}\alpha}{4\pi R^{2}M^{2}}$$
(14)

The power intercepted by the lens and focused onto an area α is

$$W_{L} = I_{LENS} \quad A_{L}$$
(15)

$$=\frac{\frac{I}{\tau} \alpha A_{L}}{4\pi R^{2} M^{2}}$$
(16)

If a two inch diameter, 650 KHz transducer is used as an illuminator the directivity factor is calculated from (5, p. 175)

$$D = \left[\frac{\pi f d}{c}\right]^2$$
(17)

with f the frequency in Hz, d the plate diameter in meters, and c the acoustic velocity in water (meters/sec). With c = 1500 meters/ second, D computes as 4,000.

The target intensity, with an illuminator radiating five watts of acoustic power, is 0.107 watts/cm^2 .

Most of the power collected by the lens is focussed onto element α . An estimate of the power on element α can be obtained by assuming the following values:

M = 0.4
$$\alpha = 0.4 \text{ cm}^2$$

D_L = 25.4 cm I_T = 0.1 watts/cm²

With a $D_L = 25.4$ cm (ten inches), the area of the lens is about 500 cm². Putting the above values into equation 16 yields

$$W_{L} = \frac{\prod_{\tau} A_{L} \alpha}{4\pi R^{2} M^{2}} = \frac{(0.1)(500)(0.4)}{(4)(\pi)(122)^{2}(.4)^{2}}$$
$$= 6.68 \times 10^{-4} \text{ watts}$$

Intensity at α can be calculated by

$$I_{\alpha} = \frac{W_{L}}{\alpha} = \frac{6.68 \times 10^{-4}}{0.4}$$
(13)
$$= 1.67 \times 10^{-3} \text{ watts/cm}^{2}$$

Robinson (6, p. 28) found the sensitivity threshold of his imaging system to be 10^{-10} watts/cm², which compares closely with a 7×10^{-11} watts/cm² threshold sensitivity for the Lockheed imaging system (1). Since both systems are similar conceptually to the system described it is reasonable to assume a sensitivity threshold on the order of 10^{-10} watts/cm². Therefore a predicted intensity at the receiver of 1.67×10^{-3} watts/cm² is many orders of magnitude greater than the system threshold sensitivity.

Clearly, many important concepts have been ignored in the above prediction. Acoustic attenuation has been neglected. This is reasonable in that the total path from illuminator to receiver is less than ten feet, resulting in an intensity loss of 0.6 db at 650 KHz. Problems of diffraction, scattering loss, and spreading have not been considered. Still, the predicted intensity value is certainly good to within an order of magnitude.

Component Design

Frequency is the first major parameter to be considered. As stated previously frequency in an imaging system involves a tradeoff between range and resolution. Since this system is designed to operate within the confines of an eight foot diameter tank, the range parameter is much less significant than resolution. With resolution the criteria, a high frequency system (> 1 MHz) should be used.

Both the illuminator and receiver utilize a flat-plate,

thickness-expanding, piezoelectric transducer. For frequencies above 1 MHz the half wavelength thickness is less than about 0.0625 inches, and becomes less with increasing frequency. With a thin plate the size to thickness ratio obviously influences the bending strength of the plate. There is, in general, a relationship between the diameter and the thickness of a transducer plate, the thinner plates being of smaller diameter. A one-eighth inch thick plate could be purchased in sizes up to about $2 \ 1/2$ inches. In constructing a mosaic from 1/8 inch piezoelectric plate, 81 elements are formed by cutting the backside of the plate to a depth of 90 percent of the plate thickness (15). Enough thickness is left (about 0.012 inches) between the elements such that the plate can be handled. Considering the PZT plate as a half-wavelength air backed resonator, the resonant frequency can be easily determined. A one-eighth inch thick plate has a first resonance of approximately 650 KHz.

In the design of a 650 KHz illuminator the beam width must be considered. It should be wide enough to illuminate, uniformly, a one to two inch styrofoam target from a distance of about four feet, and narrow enough not to fill the tank with unwanted energy. The beam width, BW, of the major lobe can be calculated from

$$\sin\left(\frac{BW}{2}\right) = \frac{1.22 \lambda}{d} \tag{19}$$

which is the Fraunhofer diffraction formula, equation 10. λ is the

wavelength in water and d, the diameter of the transducer plate (5, p. 169). At 650 KHz, the wavelength in water is

$$\lambda_{\text{water}} = \frac{(1500 \frac{\text{meters}}{\text{sec}}) (39.3 \frac{\text{inches}}{\text{meter}})}{650,000 \text{ Hz}} = 0.091 \text{ inches}$$

With a two inch diameter plate, the beam width is calculated to be over six degrees, while the angle the target subtends at the illuminator is 2.4 degrees.

At a distance of $d^2/2\lambda$ from an acoustic transducer the far field or Fraunhofer region is dominant (5, p. 176). For the two inch diameter plate the far field region is considered at a distance greater than

Distance from transducer =
$$\frac{(2)^2}{(2)(0.091)}$$
 = 22 inches

To complete the illuminator a three inch diameter, four inch long stainless steel cylinder was machined. After making electrical connections to the transducer plate, a pressure release material known as Corprene is glued to the back and edges of the plate. Pressure release materials have a very low characteristic impedance when compared to water, causing the transducer to behave as a halfwavelength air-backed resonator. Mounting of the Corprene backed transducer in the housing is accomplished using a permanent potting compound, ScotchCast 8. Onto the front face of the transducer is glued a neoprene rubber window. Neoprene is an ideal window as its characteristic impedance is close to that of water, allowing almost all of the energy radiated from the transducer face to be coupled to the water. Additionally, neoprene withstands chemical attack by petroleum and other hydrocarbon products.

From a theoretical standpoint the best solid lens material is polystyrene as its characteristic acoustic impedance is close to that of water. A small impedance mismatch between water and polystyrene assures a low reflective loss at the media interface. Because of the high cost of polystyrene, Plexiglas was selected as the lens material. Acoustic impedance of Plexiglas is about ten percent higher than that of polystyrene. The refractive ability of a lens depends upon the ratio of the acoustic velocity in the lens to the acoustic velocity of the surrounding medium (reciprocal of index of refraction). In the case of Plexiglas and polystyrene the acoustic velocity is about 1.8 times greater than that of the water. Though the index of refraction is not large, it is large enough to function as a suitable lens material.

The focal length of the lens can be calculated from equation 1. In order to compute f, the focal length, several constraints must be first specified. The sum of the object and image distances is constrained to five feet. This allows enough room for the system to be properly operated in the eight foot diameter redwood tank. Assuming an object distance of three feet the image distance is

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then two feet. The focal length as computed from equation 1 is 14.4 inches. Tarnoczy (13) has corrected the lens formula, equation 3, for large aperture angles. Large apertures cause the focus to move towards the lens and the focal area to widen. The corrected lens equation is

$$f = \frac{R}{(1-\mu)} - \frac{d}{2} \left[\frac{\mu}{1-\mu} \right]$$
(20)

where R is the lens curvature, μ the index of refraction (acoustic velocity water/acoustic velocity of Plexiglas), d the maximum lens thickness, and f the focal length of the lens (13). With the index of refraction equal to

$$\mu = \frac{1500 \text{ meters/sec}}{2750 \text{ meters/sec}} = 0.546$$

and d = 3.0 inches, the radius of curvature of the plano-concave lens computes as 6.99 inches. Theoretically, acoustic rays incident to a solid lens should meet the lens perpendicularly to avoid generating shear waves. This would require a very large radius of curvature, which would be impossible to machine with the equipment on hand. Therefore, a plano-concave lens was used.

Lens diameter and mosaic element size are closely tied through the Sparrow resolution limit, equation 10a. From geometric optics a relationship between the image size and object size can be described (9, p. 473) as

$$\frac{\text{image length}}{\text{object length}} = \frac{q}{p}$$
(21)

Assuming that the imaging system is operated at distances smaller than three feet, say 2.5 feet, the image distance would be about 2.5 feet. Under these conditions a two inch object would appear as a two inch image in accordance with equation 21. A 2.25 inch square receiving transducer (commercially available) would be necessary for imaging up to a two inch object at a minimum distance of 2.5 feet.

Image element size can depend on a number of variables, i.e., resolution, number of elements required, lens diameter, frequency, to name a few. A prototype system which could resolve two points in the object plane 1/4 inch apart is a reasonable choice. Onequarter inch in the object plane is about 3/16 of an inch in the image plane. According to Warner (15) the element size should be equal to the peak-to-null resolution width of the lens, the chord of θ in figure 6. Each channel requires a set of amplifiers. Without a totally integrated-circuit electronic package the package size and wiring complexity becomes excessive. It was felt that system feasibility could be shown by a small system. Therefore, an 81 element (9x9) array was chosen as a compromise between image resolution and system complexity.

The width of an element is now specified by the number of

elements as 0.25 inches. Though slightly larger than the resolution criteria of 3/16 inches, it is acceptable. It is important to have the element width quite different from the plate thickness to prevent the simultaneous occurrence of thickness resonance and lateral resonance (15). A lateral resonance condition in the transducer plate could cause significant coupling and unwanted crosstalk between mosaic elements.

Equation 10a can be used to compute the lens diameter. Allowing x to be 0.25 inches and letting λ be 0.091 inch, the lens diameter, D_L, is

$$D_{L} = \frac{1.46 \lambda q}{x} = \frac{(1.46) (.091) (24)}{(.25)} = 12.7 \text{ inches}$$

The diameter of the lens used was 10.5 inches due to lathe geometry. Larger lens diameters could not be manufactured.

Once the mosaic element size was known, the transducer plate could be diced into 81 elements by a diamond saw. The mosaic was glued to a flat aluminum plate for mounting to the saw. After the cuts were made, 81 conductors were soldered onto the serrated side of the plate. Then the Corprene backing material was glued in place and the mosaic removed from the aluminum plate. A five inch diameter, four inch long aluminum cylinder is used as the transducer housing. The plate, conductors, and Corprene backing are permanently potted into place within the housing cavity with ScotchCast 8. Grounding of the mosaic is accomplished with a piece of circular brass shim stock in contact with the front face of the mosaic. A neoprene window was glued to the front face and sealed in place by a thin aluminum mounting ring. Television color camera cable with 82 conductors penetrates the back plate. Watertight integrity of the cable penetration is maintained with marine sealant, while the back plate to housing seal is made with an O-ring.

Open circuit sensitivity of a mosaic element can be estimated with an equation from Hueter and Bolt (3, p. 132). Assumptions include a transducer without internal losses, no energy reflection from the transducer face, and an operating frequency at or near resonant frequency. Mosaic sensitivity, defined as the open circuit output voltage divided by the effective incident acoustic pressure, is

$$\frac{V_{oc}}{p} = \frac{t}{e} (volts/\mu bar)$$
(22)

where t is the mosaic plate thickness in meters and e the piezoelectric stress constant for a thickness expanding PZT transducer. With a piezoelectric stress constant of 40.4 newtons/volt.meter, the element sensitivity is

$$\frac{v_{oc}}{p} = \frac{(1/8 \text{ inches})}{(39.3 \frac{\text{inches}}{\text{meter}})(40.4 \frac{\text{nt}}{\text{v} \cdot \text{meter}})(10 \frac{\mu \text{bar}}{\text{nt/m}^2})}$$
$$= 7.9 \times 10^{-6} \frac{\text{volts}}{\mu \text{bar}}$$

The actual sensitivity is less due to transducer mechanical losses, cable capacitance, and terminating resistance.

IV. EXPERIMENTAL RESULTS

Illuminator

Several tests were conducted on the illuminator checking theory against actual operating characteristics. Its directivity pattern and major lobe beam width were checked using a 1 MHz Straza SB62T laboratory transducer. Actual major lobe beam width at the halfpower points was measured at 3-1/2 degrees. Targets subtending angles of about two degrees will be properly illuminated.

Illuminator resonance was measured with a Dranetz Model 320 impedance meter and Model 301 phase meter. With the transducer water loaded, a mechanical resonance point (minimum mechanical impedance) was found at 645 KHz. Associated with this point is an impedance minimum of 16 ohms.

Crosstalk Problems

Because each element of the mosaic is physically connected to its adjacent elements, there can be a mutual excitation of one element by its neighbor. Using nine elements of the middle row of the mosaic, a measure of mutual excitation, or "crosstalk," was made. By electrically exciting the first element at its resonant frequency, the electrical responses of the remaining eight elements were measured. Two types of signals used were a continuous sine wave and one cycle of a sine wave. The one cycle pulse produced the greatest mutual excitation of the adjacent element, but the measured response was 32 db lower than the one volt peak-to-peak input signal.

Another source of crosstalk is the 82 conductor Belden 8283 TV color camera cable. Color camera cable is made up of eight coaxial cables, two shielded bundles each containing seven conductors, and 12 unshielded bundles each containing five conductors. Almost no crosstalk was measured on the coaxial conductors while the crosstalk within the shielded bundles is between -18 and -20 db. Crosstalk within the unshielded bundles varied from -13.2 db to -18 db. There is no appreciable crosstalk between conductors in adjacent bundles, whether the bundles are unshielded or shielded.

Receiver Sensitivity

Sensitivity of an image receiver can be deduced from a measurement of the minimum detectable voltage of a typical mosaic element, as seen at the output of the second amplifier stage. Determination of the effective acoustical-electrical conversion factor, earlier called the element sensitivity, is a necessary step. A known electrical signal of frequency 650 KHz was inserted in place of a mosaic element voltage. The electrical signal was then attenuated until a signal-to-noise ratio of unity was observed at the output of the

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second amplifier stage. Depending on which channel was tested, the minimum detectable signal varied between 0.1 millivolts and 0.5 millivolts, as read from a Type 422 Tektronix oscilloscope.

As mentioned previously the calculated conversion factor is somewhat high. A value of 5×10^{-6} volts/µbar is more reasonable, while being in agreement with other experimenters (1, 6, p. 28).

The peak-to-peak acoustic pressure which will induce an average voltage of 0.3 millivolts, peak-to-peak is

$$P = \frac{(.3 \text{ millivolts})}{5 \mu \text{ volts}/\mu \text{ bar}} = 60 \mu \text{ bars peak-to-peak}$$

The effective acoustic pressure, p, is

$$p = \sqrt{\frac{\text{Peak pressure}}{2}} = \frac{(60/2)}{1.414} = 21.4 \ \mu \text{bars}$$
(23)

The minimum detectable intensity, also called the receiver sensitivity (or sensitivity threshold), can be determined from the effective pressure by (5, p. 121)

I =
$$(10^{-7}) \frac{p^2}{\rho_0 c}$$
 (watts/cm²) (24)

In equation (24), ρ_0 is the density of fresh water in grams/cm³, c the acoustic velocity in cm/sec, and p is the effective acoustic pressure at the receiver's incident face in µbars. With ρ_0^{c} equal to the product of 1.5×10^5 cm/sec and 1 gram/cm³, the receiver sensitivity, I, is calculated from equations 23 and 24 to be 3.0×10^{-10} watts/cm², or -95 db referenced to 1 watt/cm².

Experimenters at the Naval Post Graduate School in Monterey reported a sensitivity of 1×10^{-10} watts/cm² (-100 db)(6, p. 28, 7, p. 5) as compared to the sensitivity of the Lockheed system at 7×10^{-11} watts/cm²(1). Imaging systems incorporating the Sokolov tube have sensitivities in the range of 10^{-6} watts/cm² to 10^{-7} watts/ cm² (2, 7, p. 5). From a standpoint of sensitivity the system tested is comparable to others of similar construction, and three orders of magnitude better than systems incorporating the Sokolov tube.

System Operation

Figure 13 is a block diagram of the system components and associated electronic equipment. Briefly, a Data Royal FR220 function generator provides the 650 KHz sine wave for the illuminator. The signal is amplified in a Krohn-Hite 10 watt power amplifier, the output of which is connected to the illuminator via a Krohn-Hite impedance-matching transformer.

Another Data Royal FR 220 function generator provides a +4.0 volt, 15 KHz, clock pulse to the horizontal decade counter in the scanning circuit. Three transistorized power supplies provide the necessary DC power. Five volts is provided to the scanning circuit



Matching transformer

Function Generator

Figure 13. Block diagram of the complete imaging system

and all amplifiers except the class C amplifier, which receives a+20 volts. Twenty volts is also supplied to the ramp generator. The final power supply provides a -12 volts to the stairstep generator. With the electronic package driving the horizontal sweep and vertical deflection circuits of a Tektronix 564B storage oscilloscope a TV type raster of nine lines is presented. In the "add algebraic" mode, a small alternating voltage signal from a Hewlett-Packard 3310A function generator of 1MHz results in the display shown in figure 10.

During the testing phase the object distance was set at four feet. A preliminary estimate of 20.6 inches for the image distance was computed using equation 1 and the computed focal length of 14.4 inches. The best images were attained at an actual image distance of 19 inches, which is very close to the computed image distance.

It became apparent that flat face styrofoam targets more closely resembled specular reflectors than diffuse reflectors. In order to image a particular target much alignment was necessary. The target must be positioned in such a way with respect to the illuminator, that the reflected acoustic energy could be collected by the lens. Any slight angular change from the optimum position greatly degraded image quality, and, if enough angular change was added, the image was lost completely.

When targets were moved in the image plane, the system responded properly by displaying a moving target. An image, similar

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to that displayed under static conditions, was difficult to attain because of the target alignment problem. The goal of this project was to illustrate the ability of the system to display a moving object rather than to obtain a high quality image.

Typical displays of three styrofoam targets, a cross, a square, and a disk, are shown in Figure 14. Though all images resemble the actual targets, they are not perfect replicas. There are a number of factors which contributed to image degradation.

One of the most significant parameters affecting image quality is resolution. For example, had the system operated at a higher frequency with a larger lens, smaller image elements could have been used, resulting in better resolution. The image of the disk would have been rounder had there been more elements to form the image, each element then looking at a smaller area.

Random image points appear in several of the pictures. This could stem from several causes. Crosstalk, though only significant between conductors within a bundle, could influence the image. Possible reflections from the tank wall, or scattering from lens and target supports could add additional noise at the receiver.

The cross makes up three image elements in one direction and four elements in the other direction. Actual size of the displayed image in the image plane is 3/4 inch by one inch. According to equation 21 the image size of a two inch object, 48 inches from the



Figure 14. Oscilloscope pictures of displayed images

lens is 0.833 inches. From a size standpoint the image does correspond to the object.

From equation 10a the theoretical resolution is calculated to be 0.72° . The experimental resolution was determined by continually separating two small 3/8 inch square styrofoam targets until a separation of one image element was noted on the oscilloscope display. When the two small targets reached a separation of 3/4 inch, two shapes separated by one image element were noted on the CRT screen of the oscilloscope. The experimental resolution θ is calculated to be

$$\theta = \frac{3/4 \text{ inch}}{20 \text{ inches}} \times \frac{57.3^{\circ}}{\text{radian}} = 2.1^{\circ}$$

One of the small targets was moved vertically in the image plane in order to see how much image plane movement was required for the displayed image to move vertically one image element. Threequarters inch gave a one image element movement of the displayed image. It was found that the 1/8 inch rods used for the suspension of the targets would reflect enough energy to interfere with the desired image.

During the last testing phase the signal-to-noise ratio at the mosaic was investigated. An average signal of 600 mvolts peak-topeak was compared to a noise signal estimated well below 10μ volts peak-to-peak. The signal-to-noise ratio is greater than 96 db.

V. CONCLUSIONS

The imaging system functioned as it was designed to do. It did demonstrate the feasibility of acoustic imaging, while giving an immense insight into the many problems which must be solved before an operational imaging system can be taken to sea. Not only was feasibility demonstrated, but actual real time images were produced which resembled the actual targets.

Problems to be solved include lens resolution, cable crosstalk, larger view field, lens aberrations, and proper imaging of near specular reflectors. Lens, or system resolution, can be increased with higher acoustic frequencies and larger lens diameters. But higher frequencies cause a shorter acquisition range, and the transducing equipment is more difficult to construct. With spherical lenses, larger aperture diameters mean that a thick lens is needed for short focal lengths. In designing a thick lens a different set of formulas are applicable. Aberrations associated with large diameter thick acoustic lenses may be as significant as the diffraction problem.

Other types of lenses must be investigated. Liquid lenses offer some interesting properties: a variable-focal length (depending on lens design); lens shading for reducing the side lobe levels in the lens diffraction pattern (shading implies the gradual attenuation of energy from lens center to outer rim) (7, p. 9-10); and a large field of view (6, p. 43). Zone lenses, similar to optical Fresnelzone plates, could also be investigated.

The electronic scanning and amplification package could be improved from several standpoints. One, the amplifiers and scanning matrix should be packaged as microcircuits and either deposited on the mosaic or placed within the mosaic housing. Another possibility is to encapsulate the circuits and place them in the water adjacent to the mosaic. Cable crosstalk would be completely eliminated as the only signal would be for Z-axis modulation. One DC voltage should be compatible for all electronic circuits. The principal noise contribution to the system came from the amplifier system. Increased system sensitivity could be gained with improvements in amplifier design.

Increasing the number of image or mosaic elements, for a given system resolution, automatically increases the field of view (size of object plane) in a direct proportion.

Problems of angular alignment needed for imaging a specular or near specular surfaced object could possibly be solved with the placement of many illuminators in an angular distribution such that no surface orientation exists for which reflected energy is not intercepted by the lens.

As suggested by earlier experimenters, a digital computer

simulation may be helpful in revealing potential problem areas. Many have already been found, experimentally, by the author.

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APPENDICES

APPENDIX 1

Circuit diagram of the

amplification system

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APPENDIX 2

Circuit diagram of the

sawtooth generator

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APPENDIX 3

Circuit diagram of the

stairstep generator



All FET's are 2N4360, all gate resistors are 1M Ω