2

ARRAY DESIGN: LITERATURE SURVEY FOR A HIGH-RESOLUTION IMAGING SONAR SYSTEM - PART 1

AR-008-615

DAVID G. BLAIR

MRL-TN-658

DECEMBER 1993

APPROVED
FOR PUBLIC RELEASE

MATERIALS RESEARCH LABORATORY

DSTO

Array Design: Literature Survey for a High-Resolution Imaging Sonar System – Part 1

David G. Blair

MRL Technical Note
MRL-TN-658

Abstract

This report, together with the proposed "Part 2", surveys the literature relevant to the design of a sonar array for imaging mines with a resolution approaching 1 mm. Written as a descriptive and sometimes critical review, the report draws out the connections to mine imaging. Background areas surveyed include acoustic propagation and scattering, signal processing and display. The theory of array beamforming is traced, beginning from basics and including the near field and broadband signals. Three-dimensional beamforming, by the delay-and-add method and by backpropagation (numerical holography), are discussed. Working systems and related development work are described, including sonar systems, high-resolution underwater imaging, imaging in medicine and nondestructive evaluation, synthetic aperture, acoustic holography and tomography.

37Pg

DEPARTMENT OF DEFENCE
DSTO MATERIALS RESEARCH LABORATORY

Published by

DSTO Materials Research Laboratory
Cordite Avenue, Maribyrnong
Victoria, 3032 Australia

Telephone: (03) 246 8111
Fax: (03) 246 8999

AR No. 008-615

APPROVED FOR PUBLIC RELEASE

Contents

Array Design: Literature Survey for a High-Resolution Imaging Sonar System — Part 1

1. *Introduction*

Australian maritime defence policy recognizes the need for an enhanced minehunting capability. At the longer ranges, sonar arrays are used for the detection and classification of minelike objects. For the inspection of mines at close range (1 to 10 metres), rather than risk a human diver as at present, it is preferable to use a remotely operated vehicle (ROV). Existing ROVs can image the minelike object using a television camera and hence visible light. However in some Australian waters the turbidity is high, due to suspended particles, with the result that such images are either unobtainable or of poor quality. In these circumstances the use of acoustic waves provides a possible alternative. To study and develop this possibility the Mine Imaging Task was set up within the Maritime Operations Division of the Materials Research Laboratory. Calculations taking account of both attenuation and resolution suggest that acoustic waves in the 1 to 10 MHz range perform better than light in high-turbidity conditions and are capable of producing adequate images, possibly with a resolution as small as 1 mm. A high-resolution imaging sonar array of this kind has other potential uses besides minehunting, both within defence and in the wider commercial area.

Array design is a key part in the overall project of developing the imaging sonar system. The current literature survey was undertaken to assist DSTO staff and their coworkers involved in designing the array. The latter is a challenging task, requiring the use of theoretical and practical knowledge drawn from a wide range of disciplines. While it is often convenient to study array design separately from other aspects of the system, in the end the design chosen must take these other aspects into account. For example, absorption and fluctuations in the ocean medium lead to a degradation in the performance of the array. In addition, an array with too many elements may result in a system that is prohibitively expensive due to the costs of digitizing and storing the output signals. Again, a given array demands that an algorithm of a certain type be used if an image of the intended quality is to be obtained; and this may require a level of computing power that is unobtainable or too costly. For these reasons, areas beyond strict array design are included in the current survey.

The present report (Part 1), together with a proposed second report (Part 2), constitute the output of the array design survey. Section 2 of this report reviews literature on the "front-end" components of the total system: first, the propagation of acoustic waves in the ocean medium, and second, the electroacoustic transducers which interface with the medium. Section 3 discusses the "back end"; which comes down to signal processing plus a small segment on display. The spatial aspects of signal processing are postponed to Section 4, which looks at the fundamental properties of arrays of transducer elements, including the theory of beamforming in both the far and the near field and alternative beamforming methods. Section 5 surveys work on acoustic imaging systems and sonar, including complete systems already implemented, whether in the ocean, in medicine or elsewhere, and alternative techniques: synthetic aperture, acoustic holography, and tomography. Finally Section 6 discusses briefly some further topics that are of urgent relevance to the current imaging project.

It is intended, in Part 2, to survey the literature on other topics relevant to array design. These include: first, special array topics, particularly work on sparse arrays, including the random array and multiplicative arrays such as the Mills cross; second, other concepts in arrays and acoustics including array optimization and superresolution; third, related techniques outside acoustics; and fourth, adaptive techniques, particularly those that compensate for fluctuations in the medium. In addition, Part 2 is to deal with some developments that lie within the topic areas of Part 1 but which have been omitted from Part 1 due to time constraints.

For a broad introduction to the main topic areas, the following books are recommended. The acoustic properties of the ocean environment in which the proposed arrays are to operate are surveyed in Clay and Medwin (1977) and Urick (1983). Sonar arrays are described in Burdic (1991) and Urick (1983); for further references see Section 5.1. In medicine, acoustic imaging systems have reached a highly developed stage; such systems are reviewed in Webb (1988), particularly the chapter by Bamber and Tristram (1988); in Fry (1978), particularly the chapters by Kikuchi (1978) and by Robinson and Kossoff (1978); and in other books quoted in Section 5.2. Kino (1987) describes systems used in nondestructive evaluation (NDE).

2. *Front-End Components of the System*

In Section 2.1 we discuss the ocean medium, including the radiation of acoustic waves from sources, their propagation, reflection, scattering and absorption. Electroacoustic transducers—devices that convert between electrical and acoustic energy—are discussed in Section 2.2. The beamforming properties of arrays of transducer elements are in Section 4.

2.1 *The Medium; Acoustic Waves*

2.1.1 *General*

The acoustic properties of the ocean are surveyed in Clay and Medwin (1977), Urick (1982), Urick (1983) and Brekhovskikh and Lysanov (1991). The book by Morse and Ingard (1968) develops theoretical acoustics from its fundamental equations and solves a considerable number of "classical" problems such as the scattering of acoustic waves by a sphere. Kinsler *et al.* (1982) also discuss acoustics but with the emphasis more on applications.

There is a well-known body of knowledge, described in a number of books, on each of the following topics: use of Huygens' principle, the wave equation and simple solutions, simple theories of reflection, ray tracing in an inhomogeneous medium, the sonar equation (energy balance), scattering and absorption by bodies and bubbles, concepts such as target strength and volume backscattering coefficient, the acoustic properties of the sea floor, and reverberation. For example, Clay and Medwin (1977) discuss all of these, Urick (1983) almost all, and some of the other references in Section 2.1 discuss a number of these topics. *Reverberation*, and wave *attenuation* by absorption and scattering, are significant limiting factors for the proposed imaging sonar.

Brekhovskikh and Lysanov (1991) discuss a wide range of mathematical problems arising in ocean acoustics, as also do Kravtsov and Orlov (1990) (whose results apply to both acoustics and optics). Etter (1991) discusses in detail models of the ocean, with an emphasis on structure on a larger scale than that of the current imaging project. Ziomek (1985), while saying little in detail about the ocean, gives a mathematical model in which the ocean is described as an acoustic communication channel—more precisely, as a linear, random filter.

Ambient acoustic noise in the ocean is a limiting factor on the performance of sonar systems, though it becomes less of a limitation at the high frequencies at which high-resolution sonar would operate. This noise, its sources, its spectrum, and its spatial and temporal correlation properties are discussed for example by Urick (1983), by Clay and Medwin (1977), and by Burdic (1991).

Small-scale *fluctuations* in the temperature and velocity of the medium cause an acoustic wave to undergo *backscatter*, attenuation and *loss of coherence*, all of which may be significant in limiting the performance of the proposed imaging sonar. Such effects are discussed in detail by Tatarski (1967), Ishimaru (1978) and Brekhovskikh and Lysanov (1991) (see also Morse and Ingard 1968). Some of these discuss also the related effects due to suspended particles and gas bubbles (see also Clay and Medwin 1977).

Self-noise is acoustic noise generated by the transducer instrument or vehicle itself, due in part to its motion through the water (see e.g. Urick 1983). The Doppler effect leads to a change in frequency between the transmitted and received signals (e.g. Urick 1983); it is discussed briefly in Section 5.7.

2.1.2 *Reflection and Scattering*

For reflection and scattering from objects whose size is large compared to a wavelength and having a shape that is not simple, a number of theories have been proposed in order to reduce the exact mathematical problem to one that is at least manageable by a computer. Such theories have been proposed or redescribed by Clay and Medwin (1977), Kino (1987), Neubauer (1986), Ishimaru (1978) and Urick

(1983). Horton (1972) gives a good early review. The four works last mentioned also include experimental results. The recent book by Ogilvy (1991) gives a detailed treatment and includes a good account of Kirchhoff theory. Lhemery (1991) gives a time-domain approach leading to a formula said to be easy to compute. Some of the above authors describe their work as "for rough surfaces", but the meaning seems to be that their work applies not only to smooth but also to rough surfaces. Randomly rough surfaces are discussed by Ogilvy (1991) and also by Ishimaru (1978). Urick (1982) devotes two chapters to reflection and scattering from the sea surface and sea floor with some emphasis on empirical formulae.

Among the complicating factors is the fact that when an acoustic wave (longitudinal bulk wave) penetrates a solid, in general some of the energy is converted into shear waves ("mode conversion"). Similarly creeping or circumferential waves may be excited; these are discussed by Horton (1972) and in some detail by Neubauer (1986). Ayme-Bellegarda and Habashy (1992) comment on the complication that energy can be trapped in a high acoustic "Q" layer and later scattered back to the receiver.

The medical literature contains much on the attenuation, scattering and other effects that various body tissues have on acoustic waves, including considerable theory, which may be applicable in the mine imaging area; see the appropriate chapters of Fry (1978), Hill (1986), and other books listed in Section 5.2. In Hill (p. 237), a useful distinction is made between the discrete scatterer model and the inhomogeneous continuum model.

2.2 Transducers

A transducer may be a projector (transmitter) or a hydrophone (receiver). In either case, it may be a transducer array, which consists of a number of transducer elements; we postpone array properties to Section 4 and concentrate for now on non-array transducers and on single elements from an array. A comprehensive treatment of underwater transducers, including equivalent circuits and the theory of piezoelectric materials, is given in the book by Stansfield (1990). Transducers are also discussed in some detail by Burdic (1991), Kino (1987) and Kinsler and Frey (1962) (i.e. the earlier edition).

Some key parameters describing the performance of transducers are the *hydrophone sensitivity* and the projector sensitivity (also called the *receiving response* and the transmitting response). (The projector sensitivity may be expressed in terms of current or of voltage.) Under a wide range of conditions, the sensitivities on receive and transmit are related by the electroacoustic *reciprocity theorem*. As pointed out by Stansfield (1990), the transducer behaves as a four-terminal network and further parameters are needed to describe it. These parameters (in the linear region, at a given frequency) are an electrical impedance and a mechanical impedance. (Their roles are similar to that of the internal resistance of a battery.) Related to this mechanical impedance is the radiation impedance. The above four references (also Kinsler *et al.* 1982 and to some extent Urick 1983) discuss these quantities and obtain formulae for the case of a rigid circular piston mounted in an infinite baffle. The terms directional index, beam pattern and beamwidth, discussed in Section 4, apply also to transducers.

Gough and Knight (1989) describe "how, by using some simple concepts and straightforward experiments, reasonably complicated acoustic projectors can be designed and built by almost anyone ...". Some interesting developments regarding transducer array technology are described in Section 4.7

In array theory it is commonly assumed that the elements do not interact; however in practice they do. The effects are discussed by Stansfield (1990) and briefly by Steinberg (1976). Even if the total effect is considerable, all is not lost: each output voltage then becomes a linear combination of the input pressures, and matrix theory can be applied.

3. *Back-End Components: Signal Processing*

The design of the array is heavily influenced by signal processing considerations. For, even though the signal processing is carried out on the signal after it has been received by the transducer elements (or, on the transmit side, prior to transmission), the array designer must see to it that, from the limited information that is passed on by the transducers, there is a way by which an image of sufficient quality can be constructed. In Section 3 we concentrate on the temporal aspects of signals, leaving the spatial aspects to Section 4.

3.1 Basic Theory

There are many books dealing with the basics of signal processing, including the following topics: linear network theory, Fourier transform, quantities such as cross-correlation, discrete Fourier transform, windowed waveforms, amplitude and phase modulation, Hilbert transform, analytic signal and analog filters; sampling theory, including Nyquist theorem, reconstruction, quadrature sampling and similar efficient methods for sampling a bandpass signal; random processes, including quantitative description of noise. Good references on the above include Bateman and Yates (1988), Papoulis (1977), Proakis and Manolakis (1992), Crochiere and Rabiner (1983), Baher (1990), Oppenheim and Schafer (1975), Jackson (1989), Kunt (1986), Roberts and Mullis (1987), de Coulon (1986) and Ziemer and Tranter (1985). (Not all the references cover all topics.) Rihaczek (1985) gives an excellent discussion of the analytic signal (the use of complex signals). Van den Enden and Verhoeckx (1989) give an excellent coverage of multirate filters.

3.2 Detection of Signals in Noise

A common problem in sonar is the detection (active or passive) of a discrete target in the presence of noise. The basic theory involves the topics of detection probability, false-alarm probability, the detection threshold, receiver-operating-characteristic (ROC) curves, and the application of maximum likelihood; also the theory of optimal receivers. Urick (1983) discusses the above, and turns briefly to generalizations. Optimal receivers are discussed in somewhat more detail by Rihaczek (1985). One important situation is where the transmitted signal is known (and does not suffer distortion), the noise is additive, white and gaussian, and the aim is to maximize the signal-to-noise ratio at the output of a filter (not necessarily linear). The optimum filter turns out to be the *matched filter*, that is, a crosscorrelator, correlating the received signal plus noise with a replica of the transmitted signal. (In practice it may be desirable to first apply a simple filter to remove the noise that lies outside the frequency band occupied by the signal.) For coloured noise, one precedes the matched filter by a prewhitening filter. If the transmitted signal is *not* known, the optimal filter (under rather similar conditions) is a simple square-law detector.

A comprehensive work on detection in noise is van Trees (1971) who, in a lengthy mathematical treatment, covers detection and also the related problem of the estimation of parameters, particularly range and Doppler shift, in the presence of noise. Other good references on statistical signal processing are Orfanidis (1985), Therrien (1992) and Wilmshurst (1990).

3.3 *Spread Spectrum; Pulse Compression*

As pointed out by Rihaczek (1985), the group of techniques known as *pulse compression* or *spread spectrum*, covers a wider range than either term would suggest, and would more properly be called *large time-bandwidth product* sonar (or radar, in Rihaczek's case). The latter name alludes to the uncertainty principle, which says that the product of the time, i.e. the duration, of a signal, and its passband-width cannot be less than a certain value, of order unity. In the relevant techniques, the product is made considerably greater than that value. One subgroup of methods involves expanding the bandwidth in some way, transmitting the expanded signal, and finally recovering the original signal by remapping the received signal into the original bandwidth. [Dixon (1984) uses the term "spread spectrum" to refer to just this subgroup.] However one can equally well expand the duration of the signal, and later remap it into the original (short) duration; this is the origin of the term "pulse compression". Pulse compression can be used for a number of purposes, but the one relevant here is high-resolution *range measurement*. A very short pulse with very high power would be ideal for this purpose, were it not for the nonlinearities and related problems that then arise. By a pulse compression method one can convert a short pulse (approximating that ideal) into a *coded pulse* with the same energy but less power, lasting for a longer time. The remapping of the received signal enables a resolution to be achieved which is essentially the width of the original "short pulse".

Ranging by pulse compression is discussed in some detail by Rihaczek (1985), Ziomek (1985), Burdic (1991) and Kino (1987); Rihaczek also includes an excellent intuitive account. For ranging, the most commonly used coded pulse is the *linear chirped pulse* (or *linear FM pulse*). But many other codings are possible (Dixon 1984, Rihaczek 1985), for example maximal sequences, m-sequences and Gold code sequences. Each of these may be applied as "direct sequence modulation" or according to a more complicated rule. In direct sequence modulation, the code modulates the carrier via AM, FM or phase modulation; the code may cause alternation between two states (e.g. two frequencies) or switching among many such states. Dixon (1984) gives a full discussion of "spread spectrum" systems in the sense of his definition (see above); included is a limited discussion of ranging.

The *autocorrelation* properties of a code are important, so that one temporal part of a code does not masquerade as another part. Similarly, if several different codes are being received at the same time, their *crosscorrelation* properties are important (Dixon 1984). The *ambiguity function* (or auto-ambiguity function), a measure of the joint distribution of the signal in time and frequency, is of special importance when both range and Doppler shift are being measured simultaneously; it is discussed by each of the four references (Rihaczek to Kino) in the group above. Its value at a frequency shift of zero is important when pulse compression is used in the absence of Doppler shift; indeed the value then equals the *autocorrelation function*.

As will be discussed in Section 3.4, signal-to-noise ratio plays an essential role in a proper analysis of range accuracy and resolution since, in zero noise, one could achieve arbitrary accuracy without pulse compression. Using a coded pulse serves to improve the signal-to-noise ratio (Kino 1987). Elias and Moran (1978) designed a correlation system for nondestructive evaluation using a pseudorandom binary noise coded pulse; the system was tested using a centre frequency of 5 MHz. They concluded that "If the sample environment is sufficiently clean ... it is relatively easy to obtain signal noise improvements of 20 to 40 dB compared to the conventional systems".

In regard to the proposed imaging system, note that the pulse compression technique can fail if the medium fluctuates too rapidly in time. (However, it is not clear that a short pulse fares any better, for it must still contend with fluctuations with respect to space.)

3.4 Other Topics in Signal Processing

We first discuss accuracy and resolution. (These remarks apply to both range and bearing measurements.) A clear distinction must be made between accuracy and resolution, and also between each of these and the "resolution" given by the Rayleigh criterion. The latter often does give a good measure of the resolution in classical optics, but in acoustics the correspondence is considerably less close; Rihaczek (1985) suggests calling the Rayleigh resolution the *nominal resolution*. (There is an alternative called the Sparrow criterion, discussed in Kino 1987, which is more generally applicable than the Rayleigh criterion.) *Accuracy* refers essentially to a single target; it is the precision or error with which the range or other parameter of the target is measured. ***Resolution*** concerns whether, in the presence of one or more ***other targets***, a particular target can be distinguished as separate.

These matters are discussed by Steinberg (1976) and particularly well by Rihaczek (1985). The latter also discusses ***ambiguity***, of which three types are common, corresponding essentially to the grating-lobe problem, the sidelobe problem and the error arising from a simple beam pattern such as the gaussian. Each of these authors derives formulae for the accuracy and resolution of the range. Both of the latter depend on the signal-to-noise ratio; the resolution depends also (in the context of just two targets) on the ratio of the strengths of the two signals. Rihaczek also treats related matters such as target detection in clutter. (For the effect of noise on the accuracy and resolution of *bearing*, see Section 4.6.)

We turn briefly to the *implementation* of signal processing. Haddad and Parsons (1991) include a good discussion of the hardware implementation. Skolnik (1980) and Steinberg (1976) include a number of circuits for analog signal processing useful for arrays. Digital methods are covered in detail by many of the books referenced in Section 3.1 (as indicated by their titles).

3.5 *Image Processing and Display*

Image processing aims to achieve such tasks as improving degraded images (based on some *a priori* knowledge concerning the original image), modifying an image so that certain features are emphasized, removing various types of noise from an image, image data compression, image analysis to extract certain features (e.g. edge detection), and reconstructing an image from many projections of it (discussed in Section 5.7). Good introductions to these topics are Jain (1989) and Pratt (1991). Work drawn from recent research literature is described or reproduced in Stark (1987) and in Chellappa and Sawchuk (1985a, 1985b). A closely related area is that of ***display***, usually on a computer monitor screen.

The principles of display in medicine, and the associated processing, are discussed in Hill (1986, Chapters 7 and 8) and more fully in Webb (1988, Chapters 12-14). In particular, the A-, B- and C-scan are described (together with the TM- or M-scan, related to the A-scan). During processing, the radiofrequency signal is rectified, and ***time-gain compensation*** (TGC) is usually applied. The purpose of the latter is to make at least a rough allowance for the severe attenuation; without TGC the more distant scatterers would look extremely faint compared to those at close range. The inclusion of nonlinear processing prior to display (often by logarithmic scaling) is important because of the perceptual properties of the eye; often a knob is provided to allow manual adjustment to the scaling function so that certain features can be emphasized rather than others. Webb also discusses three-dimensional image display and computer requirements.

Recently considerable work has been done on displaying three-dimensional fields of data (volume visualization), as described in the book by Kaufman (1991). Kasturi and Jain (1991a, 1991b) discuss computer vision, the attempt to use computers to produce realistic, usually two-dimensional, visual images.

4. *Arrays: Fundamental Properties*

4.1 *Introduction to Arrays; the Far Field*

4.1.1 *General*

A transducer array converts energy from electrical (circuit) energy to the energy of some field or wave, or *vice versa*. The field may be electromagnetic, as in radar, radioastronomy or microwave arrays, or it may be elastic or *acoustic* (same as elastic but restricted to fields specified by a scalar quantity). There is a large body of theory that is common to all these types of transducer array. For this reason some of the references in this report are to books or articles written primarily for application to a nonacoustic field (particularly radar). However it is also true that the numerical values differ between the different fields, as do the methods of converting energy, and both these have considerable design implications. (Also the vector nature of some of the fields leads to some additional properties being possessed by some of the arrays.)

An *array*, which has discrete elements, may be distinguished from an *aperture*, which is continuous in space. An array may be a transmitter or a receiver—called in the context of underwater acoustics a *projector* array or a *hydrophone* array respectively—and the same array may act as both.

4.1.2 Monofrequency Case: Basic Theory

In a number of books, the theory of arrays is developed as follows. One first considers the *monofrequency* case (often called the *continuous-wave* or cw case, since the waveform extends over all time with constant amplitude), it being noted that every signal can be expressed as a sum of such signals. The complex pressure (or other field) produced by a projector array is expressed, in a "Huygens wavelet" approximation, as a linear combination (sum or integral) of the source strengths along the array (in one or more dimensions). The *far field* or *Fraunhofer region*, by definition, consists of those points such that a spherical wave emanating from the point approximates to a plane wave across the region of the array (to within some fraction of a wavelength). It is shown that, in the far field, the pressure can be expressed as a spatial Fourier transform (one-, two- or three-dimensional) of the source distribution or *aperture function* (a term applicable also to receiving arrays). The angular distribution of pressure, or its squared modulus, is variously called the (complex) *radiation pattern*, the *response function*, the *pattern function*, the *beam pattern*, the *directivity function* or the *power pattern*. Usually the name refers to the function obtained after a normalization (especially in the case of the directivity function). There is not complete consistency between authors regarding whether a given name is to be applied to the pressure or to its squared modulus. (However the term "power pattern" always refers to the latter.) The *beamwidth*, or spread of the power pattern, may be measured (defined) in a number of ways; in sonar the "3 dB beamwidth" is the most used. The terms *directional index* and *array gain* are introduced as measures of array performance.

Shading (*apodization, tapering*) is introduced, that is, the multiplication of the (possibly discretized) uniform source distribution by some envelope or "*window function*", usually tapered towards the edge of the array. A number of window functions, particularly in one dimension, are discussed along with the resulting beam patterns and beamwidths. Generally there is a tradeoff between beamwidth (a simple measure of resolution) and sidelobe level. The latter is concerned with the rate at which the power pattern decreases as the bearing moves away from the main beam. The product theorem (essentially the Fourier convolution theorem) is stated with applications—first, to the case of elements that are identical to each other but are not delta functions, and second, to 2-D apertures that are a combination of a distribution in each of the x and y directions. Planar arrays are briefly discussed, and the field of a uniform circular aperture (i.e. a circular piston) is given.

It is shown that the introduction, into the source strengths, of a linear phase shift across the array causes essentially no change in the beam pattern except for a translation in bearing (more precisely, the sine of the bearing—see Section 4.1.3) and hence "*steers*" the beam. (It should be noted here that, within an element, the phase shift applied is normally constant, not linear, so that, when the product theorem is applied, the beam pattern of a steered array of delta functions is to be combined with the pattern of an *unsteered* element.)

A similar line of reasoning can be developed for *hydrophone arrays*. (In some books, however, the reasoning is omitted and just the results are stated.) Here the most common reasoning is not in terms of Huygens wavelets; rather the output from an element is essentially the integral of the pressure over the element's surface. The receive beam pattern is then the response of the array to a plane wave, as a function of the direction of arrival of that wave. In other words, the array acts as a *spatial filter*, usually with a response function that is sharply peaked. It turns out that the fundamental results for beam patterns on receive are the same as on transmit: the Fourier relation, the effects of each window, and steering. Here steering (to a given direction of arrival) is achieved by applying a phase shift to each element's electrical output before summing to obtain the overall response of the array (before squaring).

Urick (1983) follows a program much as described above; however the treatment is rather brief. Steinberg (1976) gives a quite full treatment with an emphasis on mathematical techniques for obtaining the beam pattern, given the array; also much is said on measures of beamwidth. The discussion by Burdic (1991) is also quite full, and (unlike the preceding two treatments) includes the reasoning for a hydrophone array. Kino (1987) covers most of the topics, with some emphasis (in Section 3.2) on plane piston transducers. He comments (p. 218) that "electronically scanned arrays and other synthetic imaging techniques, such as acoustic holography, ... give far more flexibility and speed, and tend to eliminate some of the difficulties due to internal reflections that are associated with physical lenses, but with the penalty of considerable complexity"; and (p. 226) that "It is desirable to eliminate physical lens systems because of the problem of varying their focal length and because of their size". Ziomek's (1985) discussion is quite comprehensive; however the fact that he begins from a rather advanced framework may be a source of difficulty for readers. (There are some occasional but striking errors in Ziomek, often associated with an unannounced change in notation.) Kinsler *et al.* (1982) include a segment on arrays.

4.1.3 Additional Far-Field Properties

In an active system involving both a projector array and a hydrophone array (a *two-way system*), the far-field beam pattern is the product of the two patterns; the equivalent single aperture function is the convolution of the aperture functions (Steinberg 1976, p. 198; Smith *et al.* 1991). (This result holds only in a model which ignores multiple scattering.)

In some respects, rather than use spherical polar coordinates, it is more natural to describe a direction by specifying (u,v), or (u,v,w); these are *direction cosines* (or sines) (see Ziomek 1985, or a radioastronomy book such as Perley *et al.* 1989). This is because the Fourier relation (mentioned above), connecting aperture function with beam pattern, applies directly to the beam pattern as a function of the direction cosines (or alternatively as a function of the spatial frequency components). Thus if a linear or planar array is subjected to a change of scale (stretching), the beam pattern is simply scaled as a function of u and v. In the case of a linear array, for a number of simple shading functions the sidelobe nulls are equally spaced in u. A similar result holds for a square or rectangular array, in terms of u and v. Also, with respect to u and v, a product theorem for planar arrays applies (Ziomek 1985, p. 126). For linear or planar arrays, the application of a linear phase shift to "steer" the array (as discussed earlier) leads exactly to a translation of the beam pattern in terms of u and v (Ziomek 1985, p. 133). This last result applies to arrays of delta functions rather than to arrays of extended *unsteered* elements; however the overall beam pattern is then easily found from the product theorem provided the elements are identical.

Nonplanar arrays include arrays on a curved surface, which may be cylindrical or spherical, or may be *conformal*, that is, conforming to the shape of the vessel, e.g. the hull of a submarine. Nonplanar arrays include also volume arrays, in which the elements are distributed throughout a volume; in practice such arrays are useful only at long wavelengths and therefore low frequencies. Properties of general nonplanar arrays are discussed by Ziomek (1985) and briefly by Burdic (1991); properties of spherical and/or cylindrical arrays are discussed in books by Ziomek (1985) and Gething (1991) and in articles by Anderson and Munson (1963), and Queen (1970).

4.2 The Near Field; The Fresnel Approximation

4.2.1 Fresnel and Related Approximations

One may develop approximations that improve on the far-field approximation as follows, at least for planar arrays. Consider for definiteness a transmitting array; in the derivation of the pressure in the far field, the exponent (the phase) was expanded as a series of terms proportional to range times positive powers of the ratio of element displacement (from the array centre) to range; the coefficients depend on the angular coordinates of the field point. As noted for example by Ziomek (1985, p. 35), at the next stage one may distinguish two approximations. In the (full) *second-order approximation*, one retains all terms up to and including the entire term in element displacement squared. In the *Fresnel approximation*, within the second-order term one retains only those angular terms (in powers of u and v) that constitute the leading term for angles near broadside. For a planar array, the *broadside, boresight* or *polar* direction is the direction perpendicular to the array. The Fresnel approximation is sometimes called the *paraxial approximation*, but really it is the result of applying a paraxial approximation to the result of the second-order approximation.

Within the Fresnel approximation, for a linear array the addition of terms in x^2 to the phase in the exponent (where x is a transverse coordinate of an element) produces *focusing*: the angular pattern that would have been obtained in the far field is now obtained at some finite range. A formula for the *depth of field* can be obtained (e.g. Steinberg 1976, p.53; Kino, p. 191). These results are readily generalized to planar arrays. The now-classic book on optics by Goodman (1985) is often quoted in regard to the Fresnel approximation. Kino (1987, p. 234) points out that a certain separability holds within the full second-order approximation. (A similar result holds within the Fresnel approximation.) More precisely, for a linear array, if the quadratic term is held fixed while the linear term is scanned over the bearings, there exists a curve (range versus bearing) along which the "focus" moves. This fact is utilized in one scanning system.

Many further results have been developed within the Fresnel approximation. For example Ziomek (1985) defines the "near-field directivity function"; and the approximation is often assumed in acoustic holography.

4.2.2 *Near Field: The General Case*

We now consider beamforming —angular beamforming at a given range— *anywhere* in the near field (subject only to the range exceeding one aperture length), that is we step outside the two approximations just discussed. This is achieved by the time-delay-and-add method described below in Section 4.6.2. Note that sharp *angular* beamforming is achieved even if the waveform is not of a type specified in Section 4.6.2—for example even if it is a monofrequency wave.

Smith *et al.* (1991) state that (provided that time-delays appropriate to the near field are used), at any range, the broadband angular response (and *a fortiori* the monofrequency angular response) in the main lobe and near side lobes can be approximated to first order by the far-field angular response taken at the centre frequency. (Presumably when the passband-width becomes comparable with the centre frequency, the result holds only for the main lobe.) As a corollary, this response, in the case of a two-way system, is equal to the product of the transmit and receive response functions.

Kikuchi (1978) gives contour graphs of beam patterns produced in the near field by various transducers with circular symmetry. In Hill (1986, pp. 46-56), E.B. Miller develops in some detail the mathematics of acoustic radiation from planar sources with emphasis on its decomposition into plane waves. The treatment is exact even in the very near field (apart from the neglect of evanescent waves). This work overlaps that on holography in Section 4.4.

4.3 *Focusing by Geometry*

Focusing at a given range can be achieved electronically as above, or by means of curved transducers, acoustic lenses or mirrors—the methods of "geometrical acoustics" (analogous to geometrical optics). Such techniques are discussed by Kikuchi (1978) and by other medical references given in Section 5.2. Kino (1987) discusses the focused spherical transducer and the acoustic microscope, and (p. 232) shows a mathematical similarity between "all lenses, whether electronic, physical or holographic".

4.4 *Numerical Reconstruction in Acoustic Holography*

While parts of this topic are only of marginal relevance to the current project, work in this area leads to one important spin-off for the project that will be discussed in Section 4.6.2: it provides an alternative method of carrying out beamforming.

4.4.1 *Theory*

"Acoustic holography" started out as a discipline involving the production of holograms, and was quite separate from array beamforming. (For references to techniques for producing holograms, see Section 5.6.) But the term has widened in scope over the years. Within acoustic holography, techniques were developed for the *numerical reconstruction* of the image, as opposed to optical reconstruction. An important early paper on numerical reconstruction was Sondhi (1969). Thus, in its widest sense, "holography" came to mean the recording of a field at a surface in such a way as to include the phase information, followed by reconstruction of the three-dimensional field and/or an image of the target. (With this definition the use of an array, at least if followed by digitization and storage of the data, qualifies as holography.)

For some authors, "holography" covers a range intermediate between the above two extremes. For them, first, the order of signal processing operation is held to be relevant. Thus Keating (1973), in a paper on processing requirements and methods, states that "The basic difference between phased-array sonar and acoustical holography is the order in which the temporal and spatial operations are carried out". Second, the use of short pulses or pulse compression is held by these authors to be outside the domain of holography, which historically concentrated on narrow-band techniques; with this usage the range resolution obtainable by holography is limited to the depth of field (see the quotation from Kino below). On the other hand, Ylitalo *et al.* (1989) (see Section 4.6.2 below) use "holography" in the widest sense, for they describe as "holographic" a method that is broadband and gives good range resolution. In this report, the term "acoustic holography" is always used either in the intermediate or in the widest sense, never in the narrowest (hologram) sense.

In monofrequency holography, the basic numerical reconstruction problem is: Given the field on a plane (or other surface) (or a sampled, windowed version thereof), and assuming an ideal medium, what is the field throughout the half-space from which the field was propagated? An answer would tell us what the sources "look" like from the receiving surface and would give us at least some information about the three-dimensional distribution of the sources. For the full-plane problem, there is an exact solution, given by Maynard *et al.* (1985), in which the field at the receiver plane is expressed as a sum of plane waves. In words, by a 2-D Fourier transform of the data in the receiver plane, one obtains the amplitude of the incoming wave that has given values of the x and y components of the wavevector. Since we are dealing with the monofrequency case (known frequency), the z component of this wave is easily calculated. The incoming field is thus expressed as a sum of plane waves, each of which can be traced back in time; thus one can reconstruct the field throughout the half-space. Numerical reconstruction is almost always by this method or a variant of it; such methods are called *backward propagation* or *backpropagation*.

A distinction is made in the literature between *standard reconstruction* and near-field reconstruction (sometimes called standard and near-field acoustic holography). In the context of holography the "near field" refers to distances that are closer to the receiver plane than a few wavelengths. In view of this unfortunate difference from the terminology in array theory, we shall always refer to the holographic concepts as the *lambda near field* and *lambda-near-field reconstruction*. Clearly the current acoustic vision project has no need to consider reconstruction in the lambda near field, where the range would be less than about 1 mm!

Reviews of backpropagation have been given by Maynard *et al.* (1985) and by Perez-Matzumoto *et al.* (1989). They begin with *forward* propagation and note that, for a monofrequency field propagating freely, the field at one plane z=constant can be expressed as a 2-D spatial convolution of the field at any previous plane z=constant with a transfer function, also called the Green's function G, for which an exact expression is given. When the relationship between the two planes is expressed in terms of plane waves (Fourier transform), these waves are of two types: propagating and evanescent. Standard reconstruction simplifies the inverting of the *G* operator by, among other things, ignoring the evanescent waves; because they are rapidly attenuated, the method is still able to produce good results. In fact standard reconstruction simply replaces the inverse of *G* with the complex conjugate of *G*.

Lambda-near-field reconstruction is prone to instabilities in practice (Boyer *et al.* 1971, Perez-Matzumoto *et al.* 1989) and so is best avoided if not needed. Henceforth we concentrate on standard reconstruction. Then, when one makes further approximations valid when the range is much greater than one wavelength, backpropagation reduces, in the space domain, to an equation given by Sutton [1979, equation (1)] who, in the context of sonar, comments that the method gives an essentially exact reconstruction even in the very near field. Sutton's equation is further discussed in Section 4.6.2. He also gives a brief description in the spatial frequency domain. Maynard *et al.* (1985) also discuss the case where the receiving array lies on a surface other than a plane, in particular cylindrical and spherical surfaces.

4.4.2 Applications

Boyer *et al.* (1971) describe the implementation of backpropagation and show images produced in an experiment performed at 5 MHz. A transverse resolution of 0.5 mm is achieved (possibly at a quite short range).

Kino (1987, pp. 277-291) devotes a section to surveying "acoustic holography" in the intermediate sense but with emphasis on analog reconstruction methods. He makes interesting comments as follows: "Acoustic holography excited a great deal of interest ... it is now rarely used because in addition to unwieldy optics ... only a very narrow band of frequencies can be used ... and, as a result, ... the problems of speckle and interference fringes ... still occur ... . Thus the range definition will be the same as the depth of focus". Its usefulness is said to be limited to special objects such as isolated flaws and vibrating surfaces. And if computer reconstruction is being used, he says, it makes sense to switch to short-pulse synthetic aperture time-delay imaging, "which has the advantage of good range resolution".

4.5 Broadband Signals; Time-Domain Results

The theory discussed so far in Section 4 has concentrated almost exclusively on monofrequency signals. Strictly speaking, any signal limited in time will violate this condition, and, if one uses a short pulse (just a few wavelengths) or pulse compression, the *relative bandwidth* (passband-width as a fraction of the centre frequency) may become an appreciable fraction of unity (0.1 to 0.5, say). One may analyse this situation in the time or the frequency domain.

In the *frequency domain*, the beam pattern from the total signal is a superposition of the (amplitude) beam patterns from the component frequencies (Rihaczek 1985, pp. 82-85; Steinberg 1983). By considering how far one must move from the centre of the main lobe before the component beam patterns become appreciably "out of step" (say, a sidelobe peak approaching a trough), one can find where the monofrequency beam pattern ceases to be an adequate representation. Rihaczek shows that, for common arrays, the sidelobes with significant distortion are at least *N* beamwidths removed from the centre, where *N* is of the order of the inverse relative bandwidth. (This result is subject to the condition that no phase modulation is applied across the array except for the purpose of steering, see Rihaczek, p. 85.) Note that this is a far-field result. However, in the near field, we may be confident that a given sidelobe will be appreciably distorted only if *either* it is distorted in the broadband, far-field case *or* it is distorted in the monofrequency, near-field case. For the latter case, unfortunately no general result describing where significant distortion begins has been found in the literature; however the finding of Smith *et al.* (1991) given in Section 4.2 above puts a reassuring limit on the distortion of the lobes in practice.

Steinberg (1983, pp. 78-89) (who considers only the far field and the Fresnel region) discusses "frequency diversity", including both *coherent combining* (i.e. the use of a broadband signal as just discussed) and *incoherent combining* (the superposition of power patterns from different signals). For the broadband signal case, he shows that, when distortion does occur, it leads (at least on average) to a *reduction* in the peak sidelobes, often a very considerable reduction (see also Kino 1987, p. 269). This is reassuring for imaging purposes, because the designer is content provided the sidelobes are known to be *below* a certain value. Similarly broadbanding can yield the benefit of a significant reduction in grating lobes (Rihaczek 1985, DiFranco and Rubin 1963). In broad accord with these reductions are results obtained by a number of authors (e.g. Kino 1987, Sections 3.4, 3.5; Robinson *et al.* 1974), who find that, for a pulse limited in time, beyond a certain sidelobe the beam pattern drops strictly to zero (or, in some cases, as the bearing is changed at constant range, becomes strictly zero throughout certain intervals of bearing). Kikuchi (1978) discusses the literature on time-domain results for short pulses.

For broadband signals, particularly for short pulses, it is often advantageous to analyse the situation in the *time domain*. Thus, building on earlier work of Tupholme (1969) and Stepanishen (1971), Robinson *et al.* (1974) calculated the pressure field produced in the near field when a circular piston is excited by certain simple waveforms. Tancrell *et al.* (1978) presented numerical results for rectangular pistons and linear arrays. Dietz *et al.* (1978) calculated the combined effect of a transmitter and a receiver in certain configurations having circular symmetry, still for a broadband pulse but now calculated using the frequency domain. On the basis of the low sidelobes achieved, they suggest that their work could be the basis for the synthesis of sparse arrays.

4.6 Further Beamforming Results

4.6.1 Errors and Resolution

The distinction between accuracy, resolution and "nominal resolution", made in Section 3.4, applies to bearing as much as to range measurements. Steinberg (1976) derives expressions for both the accuracy and resolution of bearing estimates. As with range, these depend on the noise level and the ratio of signal strengths.

There are other sources of error besides those already mentioned. The effect of errors in the placement of array elements is discussed by Steinberg (1976, 1983). The digitization of signals leads to errors, as discussed quantitatively in many of the signal processing books. Steinberg (1976) discusses, for phased arrays, the effects of "hard limiting", an extreme form of digitization in which only one bit is retained, representing the sign of the voltage. Hard limiting can be of value when there is a need to limit the data transmission rate. In similar vein, Metherell (1969) discusses "phase-only" holograms, in which the amplitude is not recorded, and claims to show, both by theory and by experiment, that there is no significant reduction in the resulting image quality.

4.6.2 *Three-Dimensional Beamforming*

We now address the question of *3-D beamforming*, that is, processing signals so as to achieve high resolution in range and both angular coordinates simultaneously (by a method applicable in both the far and the near field). We assume an ideal medium (in particular, no dispersion), and consider a hydrophone array combined with a *point* projector. (It appears that a necessary condition for three-dimensional beamforming to be possible, is that the projecting surface is either a point, or a spherical surface that produces effectively the same pressure field as a point.) If the projected wave is a short pulse (very few wavelengths), beamforming for a given point can be achieved by the *(time-)delay-and-add* method; that is, each received signal is delayed by an amount, equal to a constant minus the round-trip time, and the resulting signals are added (see for example Knudsen 1989). Alternatively, if the wave is a suitable broadband coded pulse, each received signal is first cross-correlated with the projected pulse, before proceeding as above.

An alternative method of 3-D beamforming is via the holographic or *backpropagation* method, described in Section 4.4 above. This "pure" backpropagation method can be extended to include a point projector (and the extraction of an image of the target), yielding what we shall call the "active" backpropagation method (for which no reference has been found). Actually Section 4.4 considered only a monofrequency signal. If instead the signal is a short pulse, one re-expresses the pulse in terms of its frequency components; each frequency component of the received field can then be backpropagated by the above method. For a broadband coded pulse, one first cross-correlates each received signal with the projected signal and then proceeds as for the short pulse.

The pure backpropagation formula of Sutton (1979), mentioned in Section 4.4, when extended to broadband signals and expressed in time domain, has a physical interpretation that is intuitively appealing, as follows: the field at each point on the receiver surface is regarded as sending out Huygens wavelets backwards in time.

The question arises: Do the delay-and-add method and the backpropagation method yield identical results? In fact it can be shown that they do, provided that one uses a particular version of the delay-and-add method. This particular version, for the case of pure backpropagation, is as follows. First, a $1/R$ amplitude spreading factor is to be included. Second, include an orientation factor equal to the cosine factor in equation (1) of Sutton (1979). Third, to obtain reconstructed pressure, use as the source strength the time derivative of pressure.

The active backpropagation technique is significant for the current sonar project because it gives an alternative method of obtaining the image from the responses at the hydrophone array (a method still valid in the very near field). The backpropagation method may be faster: for a perfect medium, for each value of the depth coordinate z, the method can be implemented as a sequence of FFTs (two spatial plus one temporal FFT followed later by the inverses of these), possibly augmented by a linear or other interpolation.

A possible third method of beamforming is described in the following papers. For a short pulse, Alasaarela *et al.* (1982) and Ylitalo *et al.* (1989) discuss what they call "ultrasound holographic B-scan", or UHB, imaging. Their method as reported actually gives a reconstruction of a B-scan plane only. The authors claim advantages for their method over "conventional B-scan" imaging. For a coded pulse, the corresponding theory has been given by Yamamoto (1984). The method may turn out to be equivalent to the above backpropagation method; however the description given is somewhat different and, in some respects, unclear.

4.7 Other Work on Arrays

Wells (1977, p. 240) quotes work of Meindl *et al.* (1974), who concluded, in the context of medical ultrasonic transducers and preprocessing, that the most important research objective should be to generate images comparable to those of high-resolution radar. They also gave numerical goals, which are not all that different from the goals of the current sonar project.

Wells (1977, pp. 240-248) also summarizes the problems associated with *two-dimensional* (2-D) imaging *arrays* and progress made up to that date. He quotes the work of Maginness *et al.* (1974), who built a 32x32 2-D array in which multiplexing switches are constructed as an integral part of the array; the switches consist of field effect transistors arranged so that access to any element is obtained via two address signals. Wells (1977, p. 244) also describes a method due to Havlice *et al.* (1973) for addressing each element of an array in sequence. Erikson and Zuleeg (1977) designed a system in which the N^2 signals from an $N\times N$ receiving array can be retrieved using just $2N$ terminals arranged along two adjacent edges. Of these, N are for addressing and hence only N signals are being retrieved at any one time. A simple preamplifier is permanently attached to each element. In regard to the current project, this idea could save on digitizing equipment. Meindl (1979), following a research program into cascade charge-coupled device (C3D) electronic lenses, constructed a 32 channel, 10000 charge-coupled element lens, to be used in a 4.5 MHz ultrasonic imaging system.

Hill (1986, p. 306) also discusses the possible use of two-dimensional arrays, including the use of the "Sokolov tube" or "ultrasonic image camera". In essence the latter device is the same as the ultrasound camera described in Section 5.6 below; in the use under discussion the piezoelectric sheet at the front of the tube becomes the hydrophone array. This system looks promising for the current project, where its role would be quickly and cheaply to multiplex many signals into one for ease of subsequent transmission; it would appear that the system is capable of extremely fast "switching" times.

Rihaczek (1985, p. 82) describes a proposal due to Urkowitz *et al.* (1962) in which the concept of "pulse-compression" is applied in space (in bearing) instead of time. For a linear array, Maranda (1989) compares, for their computational efficiency, methods of digital beamforming in the frequency domain.

Some work directly on the *design* of arrays is as follows. Steinberg (1976) shows how the z-transform can be used to design linear arrays with specified properties. Taylor (1955) uses the theory of analytic functions to design line antennas (and arrays) with what are claimed to be optimal combinations of narrow beamwidth and low sidelobes. The patterns resemble those of Dolph-Tchebycheff arrays in that the levels of the first few sidelobes are approximately equal. Urick (1983) discusses design, based largely on the sonar equation (energy balance); he comments on the reverberation limit and on the variation of range with frequency.

5. Acoustic Imaging Systems; Sonar Systems

5.1 Sonar Systems, Devices and Processing

Sonar arrays are described in Burdic (1991) and Urick (1983), and in references in those books. Somers and Stubbs (1984) review *sidescan sonar*, an active system which builds up a 2-D view of the sea-bottom. To achieve this, the ship tows an active sonar whose beam pattern points out to the side but is fan-shaped, being very broad in the vertical direction. In one "ping", range-gating enables the sonar to map a one-dimensional "slice" of the sea floor, which is assumed to be flat. Mitson (1984) reviews *sector-scanning sonar*, which again is active and produces a 2-D view. In most designs this image is produced in one "ping" (pulse); this process is called "within-pulse scanning". A number of quite different sector-scanning designs are described. Both these articles include reproductions of images obtained. Synthetic aperture sonar is discussed in Section 5.5.

Sonar signal processing has been reviewed by a number of authors. The discussion by Baggeroer (1978) includes analog and digital methods, the implementation of correlation receivers and matched filters, environmental processing (which uses a model of the environment to remove much of its distorting effects), spread spectrum, and beamforming in passive sonar by DIMUS (digital multiple beam steering) systems and by an adaptive system called the DICANNE (digital interference cancelling adaptive null network equipment) system. Knight *et al.* (1981), after discussing digital processing theory at length, describe the implementation for typical sonar systems. Advanced functions are then discussed, including adaptive beamforming, synthetic aperture, coherence processing for passive localization and random arrays; many (253) references are given. The more recent treatment by Owsley (1985) tends to concentrate on passive arrays. Topics of interest include optimum beamforming via the cross-spectral density matrix, and high-resolution array processing, particularly via careful estimation of the time delay(s) between arrivals at different sensors.

The chapter by Owsley actually forms part of a larger work (Haykin 1985) on array signal processing, treating other areas which have some relevance to the project: exploration seismology, radar processing for angle-of-arrival estimation, synthesis radio telescope arrays, and tomographic imaging with diffracting and nondiffracting sources.

5.2 Medical Imaging Systems

In medicine, imaging via ultrasound has reached a highly developed stage. However it should be noted that the ranges involved are usually less than 0.25 metre.

There are many *books* that *survey* medical ultrasound imaging. In Hill (1986), the use of ultrasonics in medicine is extensively reviewed, with in-depth physical and mathematical explanations. Included are the generation and detection of acoustic fields, the propagation and scattering of waves in tissue, the principles involved in good display of image data, and the various imaging techniques (including miscellaneous items such as acoustic microscopy and holography). Of special relevance is Chapter 8 on pulse-echo imaging. Another extensive review is the work edited by Fry (1978), covering the same topics with different emphases. The more recent review by Webb (1988) is somewhat shorter. Wells (1977) covers similar ground to the above authors; included are interesting comments on the display of three-dimensional data. Other books on the use of ultrasound in medicine are: Fish (1990), Hussey (1985), McDicken (1991), Wade (1976) and the recent book by Hykes *et al.* (1992). Wilson (1991) briefly reviews recent developments in medical diagnostic ultrasound. Two specific points of note from the above work of Fry are as follows. Kikuchi (1978) discusses the effects of various shadings of a circular aperture. Robinson and Kossoff (1978) discuss focusing on transmit using coaxial annular elements, and "*dynamic focusing*" on receive, in which the range for which the array is focused is varied with time as the short pulses reflected from successive depths reach the receiving array.

We now turn to works on more *specific topics*. The significant developments in 3-D computer reconstructions for cardiac applications have been reviewed by McCann *et al.* (1988). In Smith *et al.* (1991) and the companion paper von Ramm *et al.* (1991), the authors investigate designs for 3-D medical imaging in real time and report experimental results. Smith *et al.* comment that a practical 16x16 array system should be achievable in the near future at 3.5 MHz; but that larger arrays or higher frequencies will require an advance in the application of VLSI technology. An interesting configuration included is the "double Mills cross" (a possibly misleading name, since the response of one arm is not multiplied by the response of the other arm). In this, the transmit and receive array each consist of a cross: the one cross is rotated by 45° with respect to the other. Presumably the use of two crosses in place of two linear arrays at 90° leads to a 12 dB boost to the main lobe but at the expense of introducing sidelobes in new directions. Von Ramm *et al.* report experiments applying parallel processing to the double Mills cross. Delay lines are required, but fewer than in a "conventional" system. The system involves synthetic aperture, because each transmit pulse covers only a small range of solid angles (and not all ranges). The system is said to be "real-time"; however it may fail to be "real-time" in the proposed *sonar* application because, first, the echo times are longer and second, it is proposed to use a larger number of channels (array elements).

5.3 *Underwater Imaging Systems*

We review here progress on systems designed to produce high-resolution images in water at ranges exceeding 0.5 metre. The systems, moreover, are to produce the images quickly and be suitable for attachment to a vehicle. Sutton (1979) reviews the problem, setting it in a broad context, and discussing three basic types of technique said to be the ones appropriate to the task: focused (i.e. using an acoustic lens or reflector), beam-forming and holographic (with either numerical or analog reconstruction); relevant mathematics is included.

5.3.1 *Demonstrated All-Electronic Systems*

From 1977 or earlier, authors have reported the construction of all-electronic underwater imaging systems described as "high-resolution", for example Granger *et al.* (1977), Sutton (1979), Sutton *et al.* (1980), Powers *et al.* (1980), Nitadori *et al.* (1980) and Koppelmann and Keating (1980). Of these, Nitadori *et al.* use a "multi-beam scanning" technique developed by Nitadori (1975) (see Section 5.5). Their 1980 system uses a 4x4 projector array and a 32x32 hydrophone array (together equivalent to 128×128) to produce an image of 256x256 pixels at one range in 2 seconds via a dedicated FFT processor. Respectable images are shown. Koppelmann and Keating have verified that a single "ping" can generate a 40x40x 54 voxel image. Sutton includes quite reasonable images. Sutton *et al.* make the interesting comment: "... it is necessary that the diffuse reflections not be buried in the noise of the system. The reflected highlights may be as much as 60 dB above the diffuse returns".

More recently Knudsen (1989) reports the construction of a prototype 3-D imaging system (called DAISY) with a new digital beamformer. The latter is based on delay-and-add, but much computation time is saved by using cascaded look-up tables to determine the exact delays. Using a broadband omnidirectional projected signal with frequency range 25 to 50 kHz, 3-D beamforming is achieved at ranges down to one aperture, which is 1.2 metre. The sparse planar array has only 64 elements and the directions are processed in series. It appears that a 2-D C-scan of 181×181 pixels at each of eight ranges can be produced in 65 milliseconds.

5.3.2 *Other Work on All-Electronic Systems*

Cao *et al.* (1991), and Cuschieri and Cao (1992), present the design concepts for a 3-D sonar imaging system for unmanned underwater vehicles, for ranges up to 200 metres. The array configuration consists of two linear arrays at right angles, one each for projector and hydrophone operation; the analysis is limited to the far field. The digital processing is based on "multiple cross-spectral analysis", which involves both frequency and wavenumber. They discuss two methods of generating the cross-spectra, one of which is described as "superresolution". The projected signal is broadband noise and cross-correlation of each received signal with the projected signal is performed.

Young (1977) has tested a linear receiving array which is chirp-focused (see Section 5.4). This hybrid analog-digital device can focus at ranges down to one metre; its range resolution is limited to the depth of field. Bahl and Powers (1990) attempt to perform a realistic computer simulation of the imaging process of a sector-scan sonar scanning various scenes. They hope eventually to devise and test methods of reconstructing a 3-D image from what is basically a 2-D imaging system by using other cues such as acoustic shadows and echo intensity.

5.3.3 *Acoustic Lenses and Mirrors*

One obvious way to produce real-time images is via *acoustic lenses* and *mirrors*. Acoustic lenses are discussed by, for example, Clay and Medwin (1977); some references on their use are given elsewhere in this report. The lenses are simple and cheap to implement, but have drawbacks as listed in Section 4.1.2. In particular, even with a (controlled) deformable lens, the range resolution is limited to the depth of field. (One might be able to remove this limitation by using, say, a short pulse and time-gating, but this becomes problematic in the near field.)

Some authors have obtained images via lenses or mirrors as a forerunner to developing a useful imaging system. Thus, Green *et al.* (1968) first give a considerable amount of theory and discussion of options, then describe their apparatus and present images obtained at a range of 1 to 4 metres in turbid water.

They also discuss the differences between specular and diffuse reflection and the related problem of speckle, pointing out that broadband insonification largely removes the latter. Unlike this active system, the recently developed system of Buckingham *et al.* (1992) (see also Yam 1992) is described as neither "active" nor "passive"; it relies on ambient noise ("*acoustic daylight*") to insonify the object. Their experiments so far have used a single parabolic reflector "as an acoustic lens".

5.4 NDE and Other Acoustic Imaging Systems

Kino (1987) surveys acoustic imaging systems in NDE (especially) and in medicine. Besides topics mentioned elsewhere in this report, he discusses synthetic aperture (pp. 262-271), acoustic holography (pp. 277-296), the acoustic microscope (pp. 197-206) and chirp-focused systems (p. 251). The last mentioned may be transmitters or receivers, analog or digital. In receive, each element's signal is multiplied by a delayed chirp, the delay varying linearly with position. This process achieves focusing at a fixed distance from the array, with scanning in time parallel to the array. Also problems with these systems are pointed out. Kino also devotes over 200 pages to transversal filters, which are basically tapped delay lines with each tap connected to a common input or output line. These analog devices can perform a very wide range of signal processing functions in NDE and elsewhere, most often at frequencies in the range 10 MHz to 1 GHz. The functions include the correlation filter, the inverse filter and the Fourier transform. Many of the devices make use of surface acoustic waves.

Corl *et al.* (1978) describe a synthetic aperture system for NDE imaging that is digital and real-time, in which they transmit from one element at a time, receive on the same element, and repeat for the successive array elements. Ludwig and Roberti (1989) use the same approach; they note first, that a 3-D image can thus be obtained by moving a single transducer over a plane, and second, that beamforming is achieved (as in other configurations) simply by adding the signals after applying time-delays equal to minus the respective round-trip times (plus a constant). Schmitz and Wosnitza (1980) describe experiences in holography for NDE using both optical and numerical reconstruction. They find it is possible to vastly improve the range resolution of the optical method by also making time-of-flight measurements. Collins *et al.* (1977) report a "curvilinear" holography system for imaging defects in rock at ranges up to 0.5 metre. The C-scan image is obtained in 15 seconds. Souquet *et al.* (1977) discuss chirp-focused transmitter theory, including time-apodization applied to the chirp waveform.

Jacka *et al.* (1989) describe an "acoustic radar" system developed in the Division of Radiophysics, CSIRO for imaging through air in a mine (e.g. coalmine) at ranges from 1.5 to 5 metres. The system involves two linear arrays at 90°, one each for transmitting and receiving, each having 16 elements. (Actually the whole system is then duplicated, so that the left and right halves of the view are obtained independently.) The authors use a coded pulse, and also an increased sampling interval based on the passband-width. For this apparatus, Seagar *et al.* (1989) describe a fast Fourier domain method for 3-D beamforming, within an approximation (adequate for their application) in which the focus is exact at one range only.

Ljunggren *et al.* (1980) report the application of a holographic reconstruction method to measurements made with an array in a fiord. While the measurements are made in water, they are used to probe the geological structure down to 90 metres below the water bottom. The authors claim that the backpropagation (or inverse diffraction) method gives much better results than conventional seismic pulse-echo methods.

5.5 *Synthetic Aperture*

Synthetic aperture techniques (see e.g. Kino 1987) basically involve moving an element-like transducer to many locations, recording the data (including phase) for each location, and finally reconstructing an image in the same way as if all the data had been obtained simultaneously via a physical array. Many variations on this theme are possible (see e.g. Sutton 1979, Hildebrand and Brenden 1972). A special issue of a journal (IEEE 1992 in the reference list) has been devoted to synthetic aperture processing in sonar. The book by Hovanessian (1980) is a quite readable introduction to synthetic array *radars* and imaging radars. Synthetic aperture imposes more severe constraints on the stability of the medium, since the time-scale of fluctuations must in general exceed the time taken to record a whole set of data. There may also be increased difficulty in knowing the relative locations of all the "elements". (Some applications of synthetic aperture have been noted already in Sections 5.1 to 5.4.)

Within the special issue mentioned above, Hayes and Gough (1992) review the new area of broadband synthetic aperture sonar, based on ideas discussed in Gough (1986). The latter describes an approach to synthetic aperture sonars based on continuous transmission with some form of frequency coding, permitting the survey ship to move ahead much faster. Gough makes a further suggestion to reduce the effects of fluctuations in the medium: a phase-differential method. In that method, the basic datum used to generate the image is not the phase change along one acoustic path but the difference between two such phase changes obtained at different receiver positions (or equivalently, the angle of arrival).

Nitadori (1975) proposed a synthetic aperture method (the "multi-beam scanning method") for underwater acoustic imaging in which several elements are used simultaneously on transmit. He says that thus "we can obtain as many picture elements as the product of the number of transmitters times the number of receivers". Among the advantages claimed for the method (over single-element transmission) is that the requirement for environmental stability can be greatly relaxed. The transmitted beam consists of a number of pencil beams (essentially grating lobes) and the corresponding picture elements are resolved in a single "ping". Thus "the environmental variations [between "pings"] ... only cause positional errors of the picture elements that are resolved by different pulse transmissions".

5.6 *Methods in Acoustic Holography*

The area of acoustic holography, aspects of which were discussed in Section 4.4 above, was comprehensively surveyed by Hildebrand and Brenden (1972). The first group of data-gathering methods covered—and there are many such methods—is scanned acoustic holography, in which data is collected serially; in the final analysis this group comes down to synthetic aperture, but restricted to the monofrequency case. Second, there is liquid-surface holography, in which usually, the liquid surface, disturbed by both the scattered and the reference acoustic field, is used to reflect light which is made to produce the final image; the hologram itself is at the surface. Third, other methods are discussed briefly, including: the ultrasound camera, in which the acoustic field reaches a piezoelectric plate, which is in turn scanned by an electron beam, leading to the emission of secondary electrons; the particle cell; and Bragg diffraction imaging, in which light is "Bragg-scattered" by the quasi-periodic acoustic field. Among the applications discussed by Hildebrand and Brenden is underwater viewing. Some other references on holography are given in other parts of Section 5.

5.7 *Other Acoustic Techniques*

The use of the *Doppler shift* is widespread in both sonar and medical systems. Doppler should probably be ignored in the early stages of the current array design. Measurable shifts will no doubt be present in the final system and there may be a need to allow for them in the signal processing.

Tomography, in its original sense, is a technique in which an image is reconstructed from many projections of it; it was applied in particular to incoherent imaging with X-rays; furthermore the transmitted beam, rather than the reflected or scattered beam, was observed. This reconstruction problem is discussed in Jain (1989) and in other references in Section 3.5 as well as the tomography references which follow; for that problem there is a key result called the *projection slice theorem* or projection theorem. The term tomography has since been extended to include more complex situations; in particular diffraction tomography, in which the wave properties of the propagating field must be taken into account. Usually the latter requires an extra dimension of data to be collected, for the angle between the incident and the detected scattered beam must be varied as well. These techniques are discussed in Kak (1985); and also in Webb (1988, p.100) and other medical imaging books cited in Section 5.2. The work by Kak on diffracting sources includes the Fourier diffraction projection theorem and a "filtered-backpropagation" algorithm.

6. *Discussion*

As the proposed Part 2 of this literature survey will not be available for some time, it is appropriate to summarize aspects of the remaining literature having an urgent relevance to the imaging project.

Sparse arrays, and in particular *random arrays*, are clearly important for the project. A rather thorough coverage of random arrays is given in the trilogy of books: Steinberg (1976), Steinberg (1983), and Steinberg and Subbaram (1991).

For further accounts of *recent research* on imaging via arrays, the reader is referred to the appropriate journals (and other serials) as follows.

Journals (and serials) on acoustic imaging techniques and arrays:

Acoustical Imaging [formerly called Acoustical Holography, until the end of Volume 7 (1977)]—proceedings of a series of conferences, published in NewYork: Plenum Press.
IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control
Journal of the Acoustical Society of America (relevant sections therein)
Ultrasonic Imaging
Ultrasonics

Other journals on areas relevant to imaging array design (in some cases containing also some articles directly on acoustic imaging techniques and arrays):

Digital Signal Processing (a review journal)
Geophysics
IEE Proceedings, Part F: Radar and Signal Processing
IEEE Journal of Oceanic Engineering
IEEE Transactions on Signal Processing [formerly called IEEE Transactions on Acoustics, Speech, and Signal Processing, until the end of Volume 38 (1990)]
IEEE Transactions on Antennas and Propagation
Signal Processing
Soviet Physics—Acoustics

Journals with some coverage of acoustic imaging techniques and arrays:

IEEE Transactions on Medical Imaging
Ultrasound in Medicine and Biology

Some articles from the above serials are as follows. Farcy *et al.* (1988) describe a towed acoustic system called the SAR ("Systeme Acoustique Remorque"), incorporating side-scan sonar, and give images of the sea-bed produced by it. Johnston (1988) discusses the processing of results from a sparsely-sampled, phase-insensitive, two-dimensional array. In similar vein, Mallart *et al.* (1990) discuss partially coherent transducers and present the theory of incoherent processing. The use of incoherence (or "phase-insensitivity" in the case of Johnston) is said to produce some advantages, in particular the reduction of speckle. (These two articles are mentioned by way of broader background, not because incoherence is thought to be advantageous to the current project.) Song and Park (1990) designed an ultrasonic B-mode imaging system which, by using quadrature sampling and other digital techniques, achieves improved speed and resolution. Their "pipelined-sampled-delay-focusing" method largely removes the need for data to be placed in memory.

7. *References*

Alasaarela, E., Tervola, K., Ylitalo, J. and Koivukangas, J. (1982). UHB Imaging. In: Ash, E.A. and Hill, C.R. (Eds.), *Acoustical Imaging, Vol. 12*, pp. 687-696. New York: Plenum Press.

Anderson, V.C. and Munson, J.C. (1963). Directivity of spherical receiving arrays. *Journal of the Acoustical Society of America*, 35, pp. 1162-1168.

Ayme-Bellegarda, E.J. and Habashy, T.M. (1992). On multidimensional ultrasonic scattering in an inhomogeneous elastic background. *Journal of the Acoustical Society of America*, 91, pp. 3104-3115.

Baggeroer, A.B. (1978). *Sonar signal processing*. In: Oppenheim, A.V. (Ed.), *Applications of digital signal processing*, pp. 331-437. Englewood Cliffs, N.J.: Prentice-Hall.

Baher, H. (1990). *Analog and digital signal processing*. Brisbane: John Wiley.

Bahl, R. and Powers, J.P. (1990). *Computer model of a high-resolution imaging sonar* (Technical Report No. NPS62-90-011). Monterey, Calif.: Naval Postgraduate School.

Bamber, J.C. and Tristram, M. (1988). Diagnostic ultrasound. In: Webb, S. (Ed.), *The physics of medical imaging*, pp. 319-388. Bristol, England: Adam Hilger.

Bateman, A. and Yates, W. (1988). *Digital signal processing design*. London: Pitman.

Boyer, A.L., Hirsch, P.M., Jordan, J.A., Lesem, L.B. and Van Rooy, D.L. (1971). Reconstruction of ultrasonic images by backward propagation. In: Metherell, A.F. (Ed.), *Acoustical Holography, Vol. 3*, pp. 333-348. New York: Plenum Press.

Brekhovskikh, L.M. and Lysanov, Yu.P. (1991). *Fundamentals of ocean acoustics*, 2nd ed. Berlin: Springer-Verlag.

Buckingham, M.J., Berkhout, B.V. and Glegg, S.A.L. (1992). Acoustic daylight: Imaging the ocean with ambient noise. *Journal of the Acoustical Society of America*, 91, p. 2318.

Burdic, W.S. (1991). *Underwater acoustic system analysis*, 2nd ed. Englewood Cliffs, New Jersey: Prentice-Hall.

Cao, P., Cuschieri, J.M. and Sudhakar, R. (1991). A high resolution 3-D sonar imaging system for autonomous underwater vehicles. In: *Oceans '91: Ocean technologies and opportunities in the Pacific for the 90's*, pp. 1019-1026. New York: IEEE Press.

Chellappa, R. and Sawchuk, A.A. (1985a). *Digital image processing and analysis, Vol. 1: Digital image processing*. New York: IEEE Computer Society.

Chellappa, R. and Sawchuk, A.A. (1985b). *Digital image processing and analysis, Vol. 2: Digital image analysis*. New York: IEEE Computer Society.

Clay, C.S. and Medwin, H. (1977). *Acoustical oceanography; principles and applications*. New York: John Wiley.

Collins, H.D., Spalek, J., Lechelt, W.M. and Gribble, R.P. (1977). A scanned curvilinear acoustical holography system for geological inspectionof internal structures in rock. In: Kessler, L.W. (Ed.), *Acoustical Holography, Vol. 7*, pp. 549-568. New York: Plenum Press.

Corl, P.D., Grant, P.M. and Kino, G.S. (1978). A digital synthetic focus acoustic imaging system for NDE. In: McAvoy, B.R. and de Klerk, J. (Eds.), *IEEE Ultrasonics Symposium 1978 proceedings*, pp. 263-268. New York: IEEE Press.

Crochiere, R.E. and Rabiner, L.R. (1983). *Multirate digital signal processing*. Englewood Cliffs, N.J.: Prentice-Hall.

Cuschieri, . M. and Cao, P. (1992). 3-D sonar system for UUVs. *Sea Technology*, 33, number 12, pp. 47-53.

De Coulon, F. (1986). *Signal theory and processing*. Norwood, Mass.: Artech House.

Dietz, D.R., Norton, S.J. and Linzer, M. (1978). Wideband annular array response. In: McAvoy, B.R. and de Klerk, J. (Eds.), *IEEE Ultrasonics Symposium 1978 proceedings*, pp. 206-211. New York: IEEE Press.

DiFranco, J.V. and Rubin, W.L. (1963). A high-resolution interferometer radar with low angle ambiguity. *IEEE Transactions on Antennas and Propagation*, AP-11, pp. 197-198.

Dixon, R.C. (1984). *Spread spectrum systems*, 2nd ed. New York: John Wiley.

Elias, C.M. and Moran, T.J. (1978). A pseudorandom binary noise NDE ultrasonic correlation system. In: McAvoy, B.R. and de Klerk, J. (Eds.), *IEEE Ultrasonics Symposium 1978 proceedings*, pp. 311-315. New York: IEEE Press.

Erikson, K.R. and Zuleeg, R. (1977). Integrated acoustic array. In: Kessler, L.W. (Ed.), *Acoustical Holography, Vol. 7*, pp. 423-445. New York: Plenum Press.

Etter, P.C. (1991). *Underwater acoustic modelling: principles techniques and applications*. London: Elsevier.

Farcy, A., Voisset, M., Augustin, J.M. and Arzelies, P. (1988). Acoustic imagery of the sea-bed. In: Kessler, L.W. (Ed.), *Acoustical Imaging, Vol. 16*, pp. 589-599. New York: Plenum Press.

Fish, P. (1990). *Physics and instrumentation of diagnostic medical ultrasound*. Chichester, England: John Wiley.

Fry, F.J. (Ed.) (1978). *Ultrasound: its applications in medicine and biology — Parts 1 and 2*. Amsterdam: Elsevier Scientific.

Gething, P.J.D. (1991). *Radio direction finding and superresolution*, 2nd ed. London: Peter Peregrinus.

Goodman, J.W. (1985). *Statistical optics*, 2nd ed. New York: John Wiley.

Gough, P.T. (1986). A synthetic aperture sonar system capable of operating at high speed and in turbulent media. *IEEE Journal of Oceanic Engineering*, OE-11, pp. 334-339.

Gough, P.T. and Knight, J.S. (1989). Wide bandwidth, constant beamwidth acoustic projectors: a simplified design procedure. *Ultrasonics*, 27, pp. 234-238.

Granger, L.C., Greene, P.L. and Zilinskas, G. (1977). An experimental digital beamforming sonar. In: Kessler, L.W. (Ed.), *Acoustical Holography, Vol. 7*, pp. 447-459. New York: Plenum Press.

Green, P.S., Bellin, J.L.S. and Knollman, G.C. (1968). Acoustic imaging in a turbid underwater environment. *Journal of the Acoustical Society of America*, 44, pp. 1719-1730.

Haddad,R.A. and Parsons, T.W. (1991). *Digital signal processing: Theory, applications, and hardware*. New York: Computer Science Press.

Havlice, J.F., Kino, G.S. and Quate, C.F. (1973). A new acoustic imaging device. In: *IEEE Ultrasonics Symposium 1973 proceedings*, 13-7. New York: IEEE Press.

Hayes, M.P. and Gough, P.T. (1992). Broad-band synthetic aperture sonar. *IEEE Journal of Oceanic Engineering*, 17, pp. 80-94.

Haykin, S. (Ed.) (1985). *Array signal processsing*. Englewood Cliffs, N.J.: Prentice-Hall.

Hildebrand, B.P. and Brenden, B.B. (1972). *An introduction to acoustic holography*. New York: Plenum Press.

Hill, C.R. (Ed.) (1986). *Physical principles of medical ultrasonics*. Chichester, England: Ellis Horwood.

Horton, C.W. (1972). A review of reverberation, scattering, and echo structure. *Journal of the Acoustical Society of America*, 51, pp. 1049-1061.

Hovanessian, S.A. (1980). *Introduction to synthetic array and imaging radars*. Dedham, Mass.: Artech House.

Hussey, M. (1985). *Basic physics and technology of medical diagnostic ultrasound*. London: Macmillan.

Hykes, D., Hedrick, W.R. and Starchman, D.E. (1992). *Ultrasound physics and instrumentation*. St. Louis, Missouri: Mosby Year Book.

IEEE (Institute of Electrical and Electronics Engineers) (1992). Special issue on acoustic synthetic aperture processing. *IEEE Journal of Oceanic Engineering*, 17, number 1.

Ishimaru, A. (1978). *Wave propagation and scattering in random media, Vol. 2: Multiple scattering, turbulence, rough surfaces, and remote sensing*. New York: Academic Press.

Jacka, C.E., Loew, E., Ostry, D.I., O'Sullivan, J.D. and Seagar, A.D. (1989). Ultrasonic range detection and imaging in a mine environment. In R.F. Barrett (Ed.), *Proceedings of Australian Symposium on Signal Processing and Applications 17-19 April 1989*, pp. 28-32. Adelaide: Institute of Electrical and Electronics Engineers.

Jackson, L.B. (1989). *Digital filters and signal processing*, 2nd ed. Boston, Mass.: Kluwer Academic.

Jain, A.K. (1989). *Fundamentals of digital image processing*. Englewood Cliffs, N.J.: Prentice-Hall.

Johnston, P.H. (1988). Sparsely-sampled phase-insensitive two-dimensional arrays: Spatial interpolation and signal-dependent aperture. In: Kessler, L.W. (Ed.), *Acoustical Imaging, Vol. 16*, pp. 19-28. New York: Plenum Press.

Kak, A.C. (1985). Tomographic imaging with diffracting and nondiffracting sources. In: Haykin, S. (Ed.), *Array signal processsing*, pp. 351-428. Englewood Cliffs, N.J.: Prentice-Hall.

Kasturi, R. and Jain, R. (1991a). *Computer vision: principles*. Los Alamitos, Calif.: IEEE Computer Society Press.

Kasturi, R. and Jain, R. (1991b). *Computer vision: advances and applications*. Los Alamitos, Calif.: IEEE Computer Society Press.

Kaufman, A. (1991). *Volume visualization*. Los Alamitos, Calif.: IEEE Computer Society.

Keating, P.N. (1973). Comparison of processing requiremnets in phased-array sonar and acoustical holography. *Journal of the Acoustical Society of America*, 54, pp. 786-788.

Kikuchi, Y. (1978). Transducers for ultrasonic systems. In: Fry, F.J. (Ed.), *Ultrasound: its applications in medicine and biology — Part 1*, pp. 289-342. Amsterdam: Elsevier Scientific.

Kino, G.S. (1987). *Acoustic waves: devices, imaging, and analog signal processing*. Englewood Cliffs, N.J.: Prentice-Hall.

Kinsler, L.E. and Frey, A.R. (1962). *Fundamentals of acoustics*, 2nd ed. New York: John Wiley.

Kinsler, L.E., Frey, A.R., Coppens, A.B. and Sanders, J.V. (1982). *Fundamentals of acoustics*, 3rd ed. New York: John Wiley.

Knight, W.C., Pridham, R.G. and Kay, S.M. (1981). Digital signal processing for sonar. *Proceedings of the IEEE*, 69, pp.1451-1506.

Knudsen, D.C. (1989). A new beamformer for acoustic imaging. In: *Oceans '89: an international conference addressing methods for understanding the global ocean*. New York: IEEE Press.

Koppelmann, R.F. and Keating, P.N. (1980). Thrree-dimensional acoustic imaging. In: Metherell, A.F. (Ed.), *Acoustical Imaging, Vol. 8*, pp. 267-279. New York: Plenum Press.

Kravtsov, Iu.A. and Orlov, Iu. I. (1990). *Geometrical optics in inhomogeneous media*. Berlin: Springer-Verlag.

Kunt, M. (1986). *Digital signal processing*. Norwood, Mass.: Artech House.

Lhemery, A. (1991). Impulse-response method to predict echo-responses from targets of complex geometry. Part I: Theory. *Journal of the Acoustical Society of America*, 90, pp. 2799-2807.

Ljunggren, S., Lovhaugen, O. and Mehlum, E. (1980). Seismic holography in a Norwegian fiord. In: Metherell, A.F. (Ed.), *Acoustical Imaging, Vol. 8*, pp. 299-315. New York: Plenum Press.

Ludwig, R. and Roberti, D. (1989). A nondestructive ultrasonic imaging system for detection of flaws in metal blocks. *IEEE Transactions on Instrumentation and Measurement*, 38, pp. 113-118.

Maginness, M.G., Plummer, J.D. and Meindl, J.D. (1974). An acoustic image sensor using a transmit-receive array. In: Green, P.S. (Ed.), *Acoustical Holography, Vol. 5*, pp. 619-631. New York: Plenum Press.

Mallart, R., Fink, M., Laugier, P. and Abouelkaram, S. (1990). Partially coherent transducers: The random phase transducer approach, *Ultrasonic Imaging*, 12, pp. 205-228.

Maranda, B. (1989). Efficient digital beamforming in the frequency domain. *Journal of the Acoustical Society of America*, 86, pp. 1813-1819.

Maynard, J.D., Williams, E.G. and Lee, Y. (1985). Nearfield acoustic holography (NAH): 1. Theory of generalized holography and the development of NAH. *Journal of the Acoustical Society of America*, 78, pp. 1395-1413.

McCann, H.A., Sharp, J.C., Kinter, T.M., McEwan, C.N., Barillot, C. and Greenleaf, J.F. (1988). Multidimensional ultrasonic imaging for cardiology. *Proceedings of the IEEE*, 76, pp. 1063-1073.

McDicken, W.N. (1991). *Diagnostic ultrasonics: Principles and use of instruments*, 3rd ed. Edinburgh: Churchill Livingstone.

Meindl, J.D. (1979). *Single chip lenses for ultrasonic imaging* (Technical Report No. AFOSR-TR-80-0699). Washington, D.C.: Air Force Office of Scientific Research.

Meindl, J.D., Brody, W.R., Green, P.S., Hileman, R. and Kopel, L. (1974). *Ultrasonic transducers: Signal detection and preprocessing*. Chevy Chase: A.E.M.B.

Metherell, A.F. (1969). The relative importance of phase and amplitude in acoustical holography. In: Metherell, A.F., El-Sum, H.M.A. and Larmore, L. (Eds.), *Acoustical Holography, Vol. 1*, pp. 203-221. New York: Plenum Press.

Mitson, R.B. (1984). Review of high-speed sector-scanning sonar and its application to fisheries research. *IEE Proceedings, Part F: Radar and Signal Processing*, **131**, pp. 257-269.

Morse, P.M. and Ingard, K.U. (1968). *Theoretical acoustics*. New York: McGraw-Hill.

Neubauer, W.G. (Ed.) (1986). *Acoustic reflection from surfaces and shapes*. Washington, D.C.: Naval Research Laboratory.

Nitadori, K. (1975). Synthetic aperture approach to multi-beam scanning acoustical imaging. In: Booth, N. (Ed.), *Acoustical Holography, Vol. 6*, pp.507-523. New York: Plenum Press.

Nitadori, K., Mano, K. and Kamata, H. (1980). An experimental underwater acoustic imaging system using multi-beam scanning. In: Metherell, A.F. (Ed.), *Acoustical Imaging, Vol. 8*, pp. 249-266. New York: Plenum Press.

Ogilvy, J.A. (1991). *Theory of wave scattering from randomly rough surfaces*. Bristol, England: Adam Hilger.

Oppenheim, A.V. and Schafer, R.W. (1975). *Digital signal processing*. Englewood Cliffs, N.J.: Prentice-Hall.

Orfanidis, S.J. (1988). *Optimal signal processing: An introduction*, 2nd ed. New York: McGraw-Hill.

Owsley, N.L. (1985). Sonar array processing. In: Haykin, S. (Ed.), *Array signal processsing*, pp. 115-193. Englewood Cliffs, N.J.: Prentice-Hall.

Papoulis, A. (1977). *Signal analysis*. New York: McGraw-Hill.

Perez-Matzumoto, A.E., Fahy, F.J. and Elliot, S.J. (1989). *Near-field acoustic holography* (ISVR Technical Report No. 179). Southampton, England: Institute of Sound and Vibration Research, University of Southampton.

Perley, R.A., Schwab, F.R. and Bridle, A.H. (Eds.) (1989). *Synthesis imaging in radio astronomy: a collection of lectures from the Third NRAO Synthesis Imaging Summer School*. San Francisco: Astronomical Society of the Pacific.

Powers, J.P., de Blois, J.Y.R., O'Bryon, R.T. and Patton, J,W. (1980). A computer-aided ultrasonic imaging system. In: Metherell, A.F. (Ed.), *Acoustical Imaging, Vol. 8*, pp. 235-248. New York: Plenum Press.

Pratt, W.K. (1991). *Digital image processing*, 2nd ed. New York: John Wiley.

Proakis, J.G. and Manolakis, D.G. (1992). *Digital signal processing: principles, algorithms, and applications*, 2nd ed. New York: Macmillan.

Queen, W.C. (1970). The directivity of sonar receiving arrays. *Journal of the Acoustical Society of America*, 47, pp. 711-720.

Rihaczek, A.W. (1985). *Principles of high-resolution radar*, revised version. Los Altos, Calif.: Peninsula.

Roberts, R.A. and Mullis, C.T. (1987). *Digital signal processing*. Reading, Mass.: Addison-Wesley.

Robinson, D.E. and Kossoff, G. (1978). Pulse echo visualization. In: Fry, F.J. (Ed.), *Ultrasound: its applications in medicine and biology — Part 2*, pp. 589-636. Amsterdam: Elsevier Scientific.

Robinson, D.E., Lees, S. and Bess, L. (1974). Near field transient radiation patterns for circular pistons. *IEEE Transactions on Acoustics, Speech, and Signal Processing*, ASSP-22, pp. 395-403.

Schmitz, V. and Wosnita, M. (1980). Experiences in using ultrasonic holography in the laboratory and in the field with optical and numerical reconstruction. In: Metherell, A.F. (Ed.), *Acoustical Imaging, Vol. 8*, pp. 651-683. New York: Plenum Press.

Seagar, A.D., Ostry, D.I. and Jacka, C.E. (1989). Fourier domain beamforming and its hardware implementation for an ultrasonic phased array. In: *IREECON 1989 International* (Proceedings of conference held in Melbourne, 11-15 September 1989), pp. 295-298. Melbourne: Institution of Radio and Electronics Engineers.

Skolnik, M.I. (1980). *Introduction to radar systems*, 2nd ed. New York: McGraw-Hill.

Smith, S.W., Pavy, H.G., and von Ramm, O.T. (1991). High-speed ultrasound volumetric imaging system — Part I: Transducer design and beam steering. *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, 38, pp.100-108.

Somers, M.L. and Stubbs, A.R. (1984). Sidescan sonar. *IEE Proceedings, Part F: Radar and Signal Processing*, 131, pp. 243-256.

Sondhi, M.M. (1969). Reconstruction of objects from their sound-diffraction patterns. *Journal of the Acoustical Society of America*, 46, pp.1158-1164.

Song, T.K. and Park, S.B. (1990). A new digital phased array for dynamic focusing and steering with reduced sampling rate, *Ultrasonic Imaging*, 12, pp. 1-16.

Souquet, J., Kino, G.S. and Waugh, T. (1977). Chirp focused transmitter theory. In: Kessler, L.W. (Ed.), *Acoustical Holography, Vol. 7*, pp. 475-493. New York: Plenum Press.

Stansfield, D. (1991). *Underwater electroacoustic transducers: A handbook for users and designers*. Bath, England: Bath University Press.

Stark, H. (Ed.) (1987). *Image recovery — theory and application*. New York: Academic Press.

Steinberg. B.D. (1976). *Principles of aperture and array system design — including random and adaptive arrays*. New York: John Wiley.

Steinberg, B.D. (1983). *Microwave imaging with large antenna arrays: radio camera principles and techniques*. New York: John Wiley.

Steinberg, B.D. and Subbaram, H.M. (1991). *Microwave imaging techniques*. New York: John Wiley.

Stepanishen, P.R. (1971). Transient radiation from pistons in an infinite planar baffle. *Journal of the Acoustical Society of America*, **49**, pp. 1629-1638.

Sutton, J.L. (1979). Underwater acoustic imaging. *Proceedings of the IEEE*, **67**, pp. 554-566.

Sutton, J.L., Thorn, J.V., Booth, N.O. and Saltzer, B.A. (1980). Description of a Navy holographic underwater acoustic imaging system (AIS). In: Metherell, A.F (Ed.), *Acoustical Imaging, Vol. 8*, pp. 219-234. New York: Plenum Press.

Tancrell, R.H., Callerame, J. and Wilson, D.T (1978). Near-field, transient acoustic beam-forming with arrays. In: McAvoy, B.R. and de Klerk, J. (Eds.), *IEEE Ultrasonics Symposium 1978 proceedings*, pp. 339-343. New York: IEEE Press.

Tatarski, V.I. (1967). *Wave propagation in a turbulent medium*, 2nd printing. New York: Dover.

Taylor, T.T. (1955). Design of line-source antennas for narrow beamwidth and low side lobes. *I.R.E. Transactions — Antennas and Propagation*, AP-3, pp. 16-28.

Therrien, C. (1992). *Discrete random and statistical signal processing*. Englewood Cliffs, N.J.: Prentice-Hall.

Tupholme, G.E. (1969). Generation of acoustic pulses by baffled plane pistons. *Mathematika*, **16**, pp. 209-224.

Urick, R.J. (1982). *Sound propagation in the sea*, revised ed. Los Altos, Calif.: Peninsula.

Urick, R.J. (1983). *Principles of underwater sound*, 3rd ed. New York: McGraw-Hill.

Urkowitz, H., Hauer, C.A. and Koval, J.F. (1962). Generalized resolution in radar systems. *IRE Proceedings*, 50, pp. 2093-2105.

Van den Enden, A.W.M. and Verhoeckx, N.A. M. (1989). *Discrete-time signal processing: an introduction.* Englewood Cliffs, N.J.: Prentice-Hall.

Van Trees, H.L. (Ed.) (1971). *Detection, estimation, and modulation theory, Part III: Radar-sonar signal processing and gaussian signals in noise.* New York: John Wiley.

Von Ramm, O.T., Smith, S.W. and Pavy, H.G. (1991). High-speed ultrasound volumetric imaging system — Part II: Parallel processing and image display. *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, 38, pp. 109-115.

Wade, G. (Ed.) (1976). *Acoustic imaging: cameras, microscopes, phased arrays and holographic systems.* New York: Plenum Press.

Webb, S. (Ed.) (1988). *The physics of medical imaging.* Bristol, England: Adam Hilger.

Wells, P.N.T. (1977). *Biomedical ultrasonics.* London: Academic Press.

Wilmshurst, T.H. (1990). *Signal recovery from noise in electronic instrumentation*, 2nd ed. Bristol, England: Adam Hilger.

Wilson, L.S. (1991). Recent developments in medical diagnostic ultrasound. *Acoustics Australia*, 19, pp. 5-10.

Yam, P. (1992). Sound system: using the ocean's noise to image undersea objects. *Scientific American*, 267, number 1, p. 17.

Yamamoto, T. (1984). Holographic B-scope imaging using wide-band chirped ultrasound, *IEEE Transactions on Sonics and Ultrasonics*, 31, pp. 362-366.

Ylitalo, J., Alasaarela, E. and Koivukangas, J. (1989). Ultrasound holographic *B*-scan imaging. *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, 36, pp. 376-383.

Young, J.W. (1977). Electronically scanned and focused receiving array. In: Kessler, L.W. (Ed.), *Acoustical Holography, Vol.7*, pp. 387-403. New York: Plenum Press.

Ziemer, R.E. and Tranter, W.H. (1985). *Principles of communications: systems, modulation, and noise*, 2nd ed. Boston, Mass.: Houghton Mifflin.

Ziomek, L.J. (1985). *Underwater acoustics: a linear systems theory approach.* New York: Academic Press.

REPORT NO. MRL-TN-658	AR NO AR-008-615	REPORT SECURITY CLASSIFICATION Unclassified

TITLE

Array design: Literature survey for a high-resolution imaging sonar system - Part 1

AUTHOR(S) David G. Blair	CORPORATE AUTHOR DSTO Materials Research Laboratory PO Box 50 Ascot Vale Victoria 3032

REPORT DATE December, 1993	TASK NO. ADS 92/257	SPONSOR
FILE NO. G6/4/8-4623	REFERENCES 136	PAGES 38

CLASSIFICATION/LIMITATION REVIEW DATE	CLASSIFICATION/RELEASE AUTHORITY Chief, Maritime Operations Division

SECONDARY DISTRIBUTION

Approved for public release

ANNOUNCEMENT

Announcement of this report is unlimited

KEYWORDS

Ultrasonic imaging
Acoustic imaging
Sonar arrays
Acoustic arrays
Ultrasonic arrays
High resolution sonar
Beamforming
Signal processing

ABSTRACT

This report, together with the proposed "Part 2", surveys the literature relevant to the design of a sonar array for imaging mines with a resolution approaching 1 mm. Written as a descriptive and sometimes critical review, the report draws out the connections to mine imaging. Background areas surveyed include acoustic propagation and scattering, signal processing and display. The theory of array beamforming is traced, beginning from basics and including the near field and broadband signals. Three-dimensional beamforming, by the delay-and-add method and by backpropagation (numerical holography), are discussed. Working systems and related development work are described, including sonar systems, high-resolution underwater imaging, imaging in medicine and nondestructive evaluation, synthetic aperture, acoustic holography and tomography.

Array Design: Literature Survey for a High-Resolution Imaging Sonar System - Part 1

David G. Blair

(MRL-TN-658)

DISTRIBUTION LIST

Director, MRL - title page only
Chief, Maritime Operations Division
Mr B. Wild
Dr David G. Blair
MRL Information Services

Chief Defence Scientist (for CDS, FASSP, ASSCM) 1 copy
Director (for Library), Aeronautical Research Laboratory
Head, Information Centre, Defence Intelligence Organisation
OIC Technical Reports Centre, Defence Central Library
Officer in Charge, Document Exchange Centre 8 copies
Air Force Scientific Adviser, Russell Offices
Navy Scientific Adviser
Scientific Adviser, Policy and Command
DGFD (Sea)
Senior Librarian, Main Library DSTOS
Librarian - MRL Sydney 5 copies
Librarian, H Block
Librarian, Australian Defence Force Academy
Serials Section (M List), Deakin University Library, Deakin University, Geelong 3217
NAPOC QWG Engineer NBCD c/- DENGRS-A, HQ Engineer Centre, Liverpool
Military Area, NSW 2174
ABCA, Russell Offices, Canberra ACT 2600 4 copies
Head of Staff, British Defence Research and Supply Staff (Australia)
NASA Senior Scientific Representative in Australia
INSPEC: Acquisitions Section Institution of Electrical Engineers
Head Librarian, Australian Nuclear Science and Technology Organisation
Senior Librarian, Hargrave Library, Monash University
Library - Exchange Desk, National Institute of Standards and Technology, US
Exchange Section, British Library Document Supply Centre
Acquisition Unit (DSC-EO/GO), British Library, Boston Spa, Wetherby Yorkshire LS23 7BQ, England
Library, Chemical Abstracts Reference Service
Engineering Societies Library, US
Documents Librarian, The Center for Research Libraries, US
Library, Deakin University
Army Scientific Adviser, Russell Offices - data sheet only
Director General Force Development (Land) - data sheet only
DASD, APW2-1-OA2, Anzac Park West, Canberra ACT - data sheet only
SO (Science), HQ 1 Division, Milpo, Enoggera, Qld 4057 - data sheet only
Counsellor, Defence Science, Embassy of Australia - data sheet only
Counsellor, Defence Science, Australian High Commission - data sheet only
Scientific Adviser to DSTC Malaysia, c/- Defence Adviser - data sheet only
Scientific Adviser to MRDC Thailand, c/- Defence Attache - data sheet only

Mr Ashley Deacon, Business Manager - Sensors, GEC Marconi Systems Pty Ltd
Faraday Park, Railway Road, Meadowbank, NSW 2114 2 copies
Mr M.F. Sage, Marketing Director, Rockwell Systems Australia Pty Ltd
PO Box 165, North Ryde, NSW 2113
Dr A.R. Collins, Sonartech Advanced Processing Systems, 58 Bay St, Rockdale, NSW 2216
Mr Francois Duthoit, Head of Engineering, Thompson Sintra Pacific Pty Ltd, Unit 18
112-118 Talavera Rd, North Ryde, NSW 2113 2 copies

DISTRIBUTION LIST
(Continued)

Mr A.F. Cook, General Manager, Australian Sonar Systems Pty Ltd, Innovation House West, 1st Avenue, Technology Park, SA 5095	
Mr M. Williams, General Manager Development, AWA Defence Industries Pty Ltd, PO Box 96, North Ryde, NSW 2113	
Dr Bob Harrison, Manager NDE, ANSTO, New Illawarra Road, Lucas Heights, NSW 2234	2 copies
Dr Ron Johnson, Warren Centre J07, University of Sydney, NSW 2006	
Dr Richard Ng, Ausonics, 16 Mars Road, Lane Cove, NSW 2066	
Professor Trevor Cole, Department of Electrical Engineering, University of Sydney, NSW 2006	
Dr Ling Guan, Department of Electrical Engineering, University of Sydney, NSW 2006	
Dr D. Robinson, Ultrasonics Institute, CSIRO Division of Radiophysics, 126 Greville Street, Chatswood, NSW 2067	2 copies
Dr Gavin Tulloch, Silicon Technologies, 9 Bayldon Road, Queanbeyan, NSW 2620	
Dr Sid French, Wholohan Grill and Partners Pty Ltd, PO Box 79, St Leonards, NSW 2065	
Professor Warren Yates, School of Electrical Engineering, University of Technology, Sydney, PO Box 123, Broadway, NSW 2007	
Mr D. Georg, Engineers Australia, PO Box 588, Crows Nest, NSW 2065	
Mr John Small, Industry Development, Acquisitions and Logistics Office, Dept. of Defence, PO Box K500, Haymarket, NSW 2000	
Emeritus Professor Leslie Kay, Ultrasonic Spatial Sensing, Titore Way, PO Box 124, Russell, New Zealand	
Mr Michael J. Cusdin, Electronic Systems Development, University of Canterbury, Private Bag 4800, Christchurch, New Zealand	
Professor P.T. Gough, University of Canterbury, Dept. of Electrical and Electronic Engineering, Private Bag, Christchurch, New Zealand	
Dr John Dunlop, School of Physics, University of New South Wales, Kensington, NSW 2033	
Chief Librarian, Fisher Library, University of Sydney, Sydney NSW 2006	
Dr Donald McLean, CSIRO Division of Radiophysics, Vimiera Rd (corner Pembroke Rd), Epping, NSW 2121	
Dr Ken Hews-Taylor, CSIRO Division of Applied Physics, National Measurement Laboratory, Bradfield Rd, West Lindfield, NSW 2070	
Dr Ian Whitehouse, Nautronix Ltd, PO Box 1352, Fremantle, WA 6160	
Commander Chris Donald, DASD	
Mine Warfare Systems Centre, PD	
MHI, PD	
MHC, PD	
Mr Jim Thompson, MOD Sydney	
Dr Ian Jones, MOD Sydney	
Mr John Shaw, MOD Sydney	
Mr Mike Bell, MOD Sydney	
Dr Martin Lawrence, MOD Sydney	
Dr Stuart Anstee, MOD Sydney	
Dr Brian Ferguson, MOD Sydney	
Dr Ranjit Thuraisingham, MOD Sydney	
Dr Doug Cato, MOD Sydney	
Mr Max Andreaus, MOD Sydney	
Dr Kurt Benke, MOD Melbourne	
Dr Roger Neill, MOD Melbourne	
Dr Ross Barrett, MOD Salisbury	3 copies
Dr Alan Burgess, MOD Salisbury	