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DIGITAL HOLOGRAPHIC SONAR IMAGING

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1. INTRODUCTION

Many image processing algorithms are currently being developed to aid the analysis and interpretation of sonar pixel images. However, the often neglected initial image construction process is the foundation upon which these algorithms are based. In order to make full use of the later sonar processing stages it is necessary to optimise the imaging process. Digital Holographic Sonar Imaging [1] (DHSI) achieves this in the first instance by digitally processing the raw acoustic data from the sensor; conceptually this is moving the signal processing as close as possible to the aperture. The acquisition of direct bandpass digitised data from a sonar array is unlike existing beamforming sonars where the analogue sensor data undergoes (complex) demodulation followed by digitisation [2]. In such sonars the received data at the array is lost from scan to scan. The ability of DHSI to retain the sensor signal integrity by direct digitisation is a key feature in the concept. Also with conventional sonars, in order to simplify the image construction process, certain basic assumptions are made. These include simplifying the array geometry to have equi-spaced, linearly arranged sensors while also assuming that the echo wavefront from every spatial point is linear (Fraunhofer or far-field assumption). In DHSI the image construction algorithm assumes neither, the processing is entirely based on a priori knowledge of the sensor positions and spatial points of interest. This enables spatially distributed imaging in the near/far-field using any receiver array configurations. The DHSI system consists of two distinct blocks, a data acquisition module and a digital processor for image construction, Figure 1.

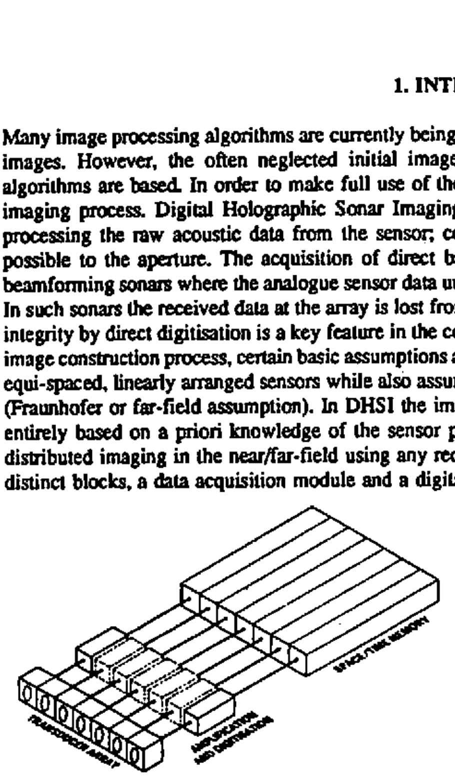

Figure 1. Digital Holographic Sonar Imaging System

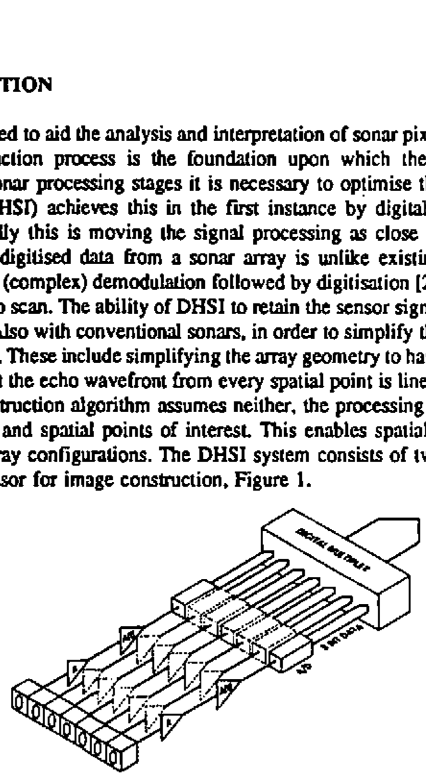

Figure 2. Parallel Architecture

2. DATA ACQUISITION

With the availability of high speed A/D conversion modules, fast data storage and DSP technology it is a natural trend to develop a sonar that is all digital. There have been a number of applications in which the data from a set of acoustic sensors have been immediately digitised and processed, [3][4]. In the related radar field, there has been an interest in replacing previous complex analogue demodulation at IF by direct digitisation [5].

In DHSI the output from each receiver array element is individually amplified and digitised, Figure 2. The digitisation rate obeys the Nyquist bandpass sampling criterion. No analogue processing, other than the usual front end amplification, is performed. The digitised echo data from a single transmit pulse contains the information for one complete image. This data can be stored in a space/time RAM memory.

3. IMAGE CONSTRUCTION

Conventional electronic beamsteering sonars are a variation on phased array technology whereby the mainlobe is deflected in azimuth. A pixel image, for example a 256 x 256 is achieved by scan-converting polar (range and beam number) data generated by the beamsteerer. The lateral resolution of the acoustic beam is controlled by the transmit wavelength and the aperture dimensions / apodization; the longitudinal resolution is governed by the auto-correlation function width of the transmit pulse. DHSI does not attempt to steer a single beam or create multiple beams. A spatial window, consisting of discrete spatial points, is defined in two dimensions. Each spatial point is uniquely defined using a priori knowledge of their geometric positions relative to each transducer array sensor. This information is pre-computed and stored in a look-up table (LUT). Optimum classical diffraction limited lateral resolution is obtained at every spatial point of interest in the pre-defined spatial window. Figure 3 illustrates the technique of creating a N x M matrix of spatial points (on a linear array plane), thus creating a spatial "window".

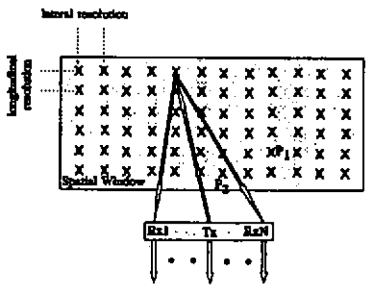

Figure 3. Spatial window concept

There is a one-to-one correspondence between each spatial point in the window and each pixel in the final image. This spatial window / LUT concept works on reception only. On transmission we need to insonify the scene with a wide pulse. A T-shaped arrangement of transmitter and receiver array is envisaged; thus on transmission there is no focusing, but on reception every spatial point in the window is focused. Figure 4 shows how the LUT is used to access the appropriate data samples in the space/time memory which correspond to spatial point P1 in the window. These blocks of data are used in the imaging algorithm.

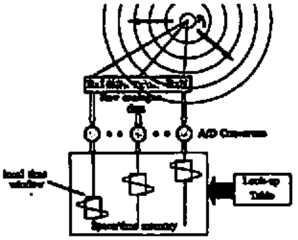

Figure 4. Look-up table processing for spatial point P1

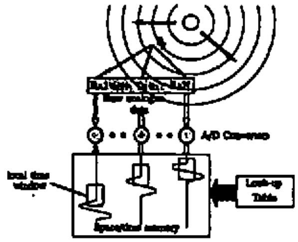

Figure 5. Look-up table processing for spatial point P2

Imaging using phase and amplitude information is also known as holographic imaging [6]. Reconstruction of an object involves backwardly propagating the complex wavefront. Essentially this is an inverse process to the wavefront propagation from the object. It is efficiently achieved in the far-field by using a 2D FFT [7]. Time domain beamforming techniques backwardly propagate using lowpass data digitised much higher than Nyquist [8]. Fine time quantization steps result in improved wavefront reconstruction and better beampatterns. Alternatives have been proposed that do not use basebanded data [9]. DHSI uses a modified time and frequency domain imaging method.

When imaging spatial point P1 , Figure 4, (or P2, Figure 5), geometric information in the LUT is used to coarsely select a weighted data block in the time domain for each sensor. Spectral estimation of the in-phase and quadrature carrier component is achieved by FIR filtering each data block. One spectral line is adequate if a Gaussian pulse envelope is used. As time shift in the time domain is equivalent to phase shift in the frequency domain, the LUT also provides the information that enables an additional fine phase shift on each channel to be achieved. A vector summation of all in-phase and all quadrature amplitudes for each array element is computed. The final pixel intensity is simply the magnitude squared component of this vector sum.

For the above discussion we have assumed a narrow band case where the transmitted pulse is a 20 cycle Gaussian weighted burst. The frequency domain calculations can thus be restricted to one spectral line. For a broadband chirped sonar we need to examine a more complex spectrum, though by careful choice of algorithm the signal processing can be minimised. DHSI is a computational intensive system, even for the narrowband case, but it is a parallel operation. An identical algorithm is used for each pixel point in the image so current DSP or LSI technology make such an approach technically viable.

Image construction is presently achieved using a software package written in C called IRIS (acronym for Image Realisation In Simulation). This allows validatation of the imaging concept and enables design calculations to be made. Synthetic data is generated based on user defined object scenarios constructed from a point target model. Array and post processing electronics can be set to configure the hardware design for the sonar linear array and its digitisation module. The image construction processing allows the choice of rectangular or polar image formats, spatial window positions and processing algorithm parameters.

4. SIMULATION RESULTS

Software simulation for two scene scenarios are presented, all image and algorithm parameters are displayed on Table 1. The first shows a plot which is a polar cut through two of the point objects in the central cluster. Both are at 60.1m, 2° either side of broadside. Scene details are given in Figure 6. Figure 7 shows polar plots using a Discrete Fourier Transform (DFT) and Quadrature Matched Filter (QMF) spectral estimation based algorithms, both use no aperture shading. These will be referred to as the DFT and QMF based algorithms. The DFT based algorithm uses bandpass sensor data sampled at 16 times the carrier frquency (1.6MHz), thus obeying the lowpass Nyquist criterion. There is a -71dB noise level, which is due to the 8 bit amplitude quantization at the ADC. The QMF based algorithm shows that by using an in-phase and quadrature matched filter (QMF), and reducing the sampling rate to 58.125 kHz, an acceptable polar plot is still obtained. A mismatch occurs between the two plots outwith +/-50° of broadside due to the use of the course bandpass sampling rate. The additional fine phase shift applied to the spectral estimates has also reduced the otherwise significant phase quantization lobes to a maximum of -40dB.
The second image shows the potentially large angle of view that can be imaged. The whole scene consists of three clusters of six points located at broadside and at both extremes of a 127 degree sector. The targets are in pairs at successive angular spacings of 2,4 and 8 degrees. Figure 7 detailed the image scene. Figure 8A shows a 255 x 255 polar plot obtained with the QMF based algorithm. In this instance the bottom-left cluster are substantially in the near field. All point reflectors are modelled as being coherent. The Rayleigh resolution criterion states that a separation of 1.5° is required based on the array dimensions and transmit wavelength (for points at broadside); for the clusters centered at +/-53.0° this is 3.15°. Thus there has been a degredation in resolution with a sampling rate reduction. Increasing the sampling frequency would improve the resolution capability, but is offset by the extra computation. Figure 8B shows a zoomed image using the same raw data set. This was obtained by generating a new LUT and re-processing. In real-time situations low sampling and course spatial windows would be used prior to detailed scene analysis using a higher resolution algorithm.

5. DISCUSSION OF THE IMPLICATION OF DHSI

The Digital Holographic Sonar Imaging concept has a variety of unique and powerful advantages over existing techniques in the general purpose survey and exploration fields. Listed below are the most obvious of these:

1. It is based on look-up table processing, the image format/spacial window can be easily modified. No scan conversion is required.
2. It is a within-pulse technique allowing wide sector imaging.
3. The look-up table can be amended for conformal arrays and array element distributions.
4. Image stabilisation can be achieved through correction of the look-up table values.
5. The technique is directly applicable to 3D imaging.

As well as the above advantages the system (Figure 1) consists of a data acquisition unit coupled to the back of an acoustic array, followed by a general purpose signal processing unit. One common signal processing unit can be digitally multiplexed to a number of sonar array/acquisition units, perhaps operating at different acoustic frequencies. Digital Holographic Imaging can be used with potential advantage to all the standard subsea acoustic imaging modes: sectorscan, sidescan, bottom profiling and swath bathymetry, Figure 9. Each application requires specific adaption and design of the array geometry. An increasingly important area is the provision of a versatile sonar processing module for advanced ROV applications, allowing processing to be adapted to the specific requirements at each stage of a long and varied mission.

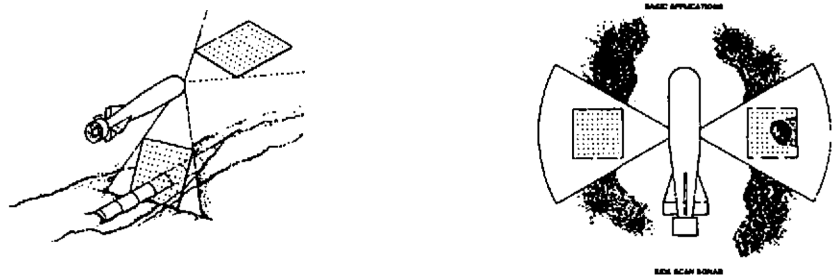

Figure 9. Bathymetric, forward and sidescan applications

The suitability of the holographic technique follows from an inherent property, namely that all information from sonar sensors is stored, within the engineering limits of the equipment, but the image is only reconstructed for the region of current interest.

6. SUMMARY

In Digital Holographic Sonar Imaging, processing of acoustic data can start at the aperture by acquiring a complete acoustic recording from the sensors. Analogue signal processing is minimised and raw data digitised as soon as is technically feasible. Image construction based on look-up table processing can be used to construct an optimised whole sector image within-pulse. Software simulation has validated the technique and illustrated some of the features of the concept. DHSI is ideally suited to the current available signal processing chips or LSI devices.

The current status of the DHSI programme allows work to continue on a detailed design for a commercial product. The technology for the front end amplification and data acquisition module has been verified. Key elements in this module such as the digital switched gain, multiplexer and A/D have been tested. Digital data has been stored into 1M byte of RAM at a digitisation rate of 10MHz. This has been achieved with off the shelf components so the figures quoted are by no means a technical limit. IRIS enables fundamental research on acoustic imaging leading to an assessment of the technique.

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7. REFERENCES

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FIGURE	IMAGE SIZE	Spatial window				Spatial sep'n		F_s (kHz)	Spec Est'n	Element Spacing
		Size		Centre						
		Δr	Δθ	r	θ	Δr	Δθ			
7	1441 x 1	/	180	60.1	0	/	0.125	1600.0	DFT	1/2
7	1441 x 1	/	180	60.1	0	/	0.125	58.182	QMF	1/2
8A	255 x 255	76.2	127	49.6	0	0.3	0.5	58.182	QMF	1/2
8B	255 x 255	4.7625	15.875	60.1	0	0.0188	0.0625	58.182	QMF	1/2

Table 1. Simulation parameters
(r, Θ in m & deg from broadside)

Note: General simulation parameters:- f_c = 100kHz, 20 cycle Gaussian pulse, 8 bit ADC, SNR 92 dB., 64 equi-spaced sensor array.

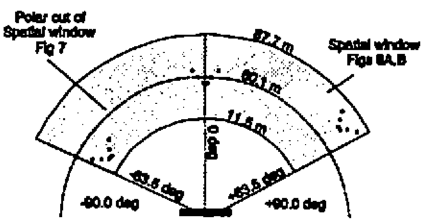

Figure 6. Scene & spatial window details

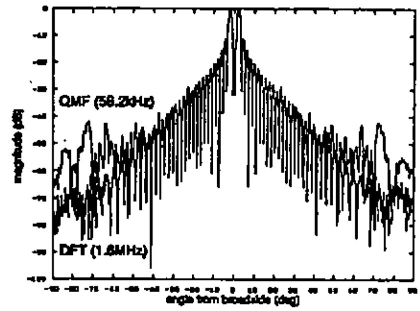

Figure 7. Polar cut of spatial window using QMF and DFT algorithms

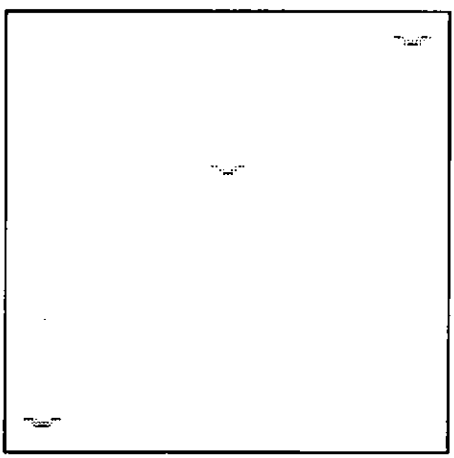

Figure 8A. QMF algorithm, wide spatial window

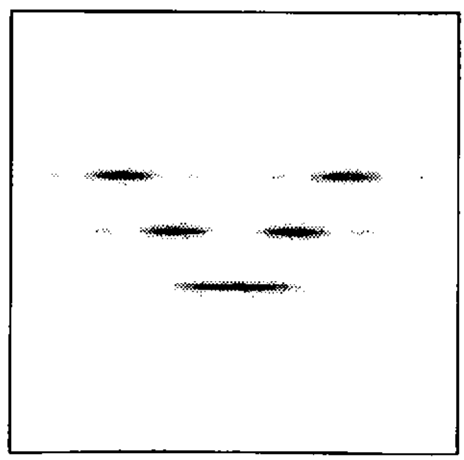

Figure 8B. QMF algorithm, zoomed spatial window