Buried Object Scanning Sonar for AUVs

S. G. Schock
J. Wulf
Department of Ocean Engineering
Florida Atlantic University
Boca Raton, FL 33431 U.S.A.
schock@oe.fau.edu

Abstract- **A 252 channel FM sonar is developed to generate images of objects buried in sediments using reflection tomography. An omnidirectional source, transmitting FM pulses over the band of 2 to 12 kHz, illuminates buried targets. The backscattered signals are measured with 252 hydrophones and processed with a digital matched filter. Coherent nearfield focusing generates a 3D map of acoustic intensity for each transmission event. As the sonar approaches and passes buried targets, the processor generates 3D matrices of acoustic intensity, overlapping in space and referenced to a coordinate system fixed to the seabed. The co-located pixels are added incoherently to generate a multi-aspect image of the target. The change in vehicle position between transmissions is measured with a DVL(doppler velocity log) and IMU (inertial measurement unit). The resulting reflection tomographic images provide target shape information useful for target classification. The sonar can be mounted on small AUVs by replacing the 252 channel, 1.5 m diameter array with one meter long line arrays mounted as wings. The receiver aperture is generated synthetically using the near field focusing processor which performs time delay focusing based on the positions of the hydrophones in the line array and vehicle motion data. A comparison between synthetic swath and tomographic images of a rigid spherical target in water shows the improvement provided by reflection tomography.**

I. INTRODUCTION

In reference [1], Schock et al. describes a 32 channel FM sonar that generated real time images of pipes and ordnance buried in sand. The beam of a 6 element line array of projectors is electronically steered back and forth in the along track direction. A 32 element planar array of hydrophones digitizes the backscattering from the portion of the seabed illuminated by the transmission beam. A time delay focusing processor sums the hydrophone outputs to form a 2D matrix of image pixels representing a vertical slice of the seabed. A sequence of vertical slices forms a 3D matrix of voxels which can be viewed from different angles by the operator to allow 3D visualization of buried targets.

Images of buried targets shown in [1] lack some shape information making visual classification based on target shape difficult. The images were generated by maintaining the transmitter and receiver beams at a constant grazing angle as the sonar passed over the targets. Each transmission produced an across track slice of the seabed at the preset steering angle. A sequence of transmissions generated a sequence of vertical image slices. The 2D matrices of pixel amplitudes were stored in a 3D matrix. A projection of the 3D matrix on vertical and horizontal planes provided plan and side views of the targets in the seabed using the maximum intensity projection (MIP) algorithm.

The sonar was programmed so that during each run two real time MIP images were generated for 2 grazing angles. The MIP images of the buried targets showed that each grazing angle provided unique shape information about the target and that the specular echoes from the targets generated the greatest contribution to the information in the images. We concluded that a wide range of grazing angles should be used during image construction to capture the shape of the buried target.

A new FM buried object scanning sonar has been designed and constructed with an omnidirectional source to overcome the limitation of the previous sonar design. The objective is to generate composite images and target strength measurements for target classification in real time. Specular echoes from target surfaces are processed to generate image pixels which are mapped to an absolute coordinate system. As the sonar approaches and passes a target, a composite image is constructed.

Real time processing is required to provide the AUV host platform with target data for adjusting the AUV mission or for relaying survey data to the support ship or other AUVs. Because the bandwidth of acoustic modems over long ranges is on the order of 100 baud, it is desirable to reduce the sonar data to small packets containing information such as image snippets, location, burial depth, target strength, target dimensions, etc. Such information can be relayed to a support ship or to another AUV allowing adaptive tasking of AUV operations.

II. SONAR DESCRIPTION

A drawing of the BOSS vehicle is showing in Figure 1. The vehicle contains a receiving array with 252 hydrophone elements mounted with equal spacing on a 1.5 meter diameter circular disk and a spherical acoustic source mounted in the same horizontal plane as the receiver. The acoustic transceiver can scan for buried targets at all azimuths and grazing angles greater than 10 degrees. The source generates an FM pulse over the band of 2 to 12 kHz. Target backscattering, measured by the 252 hydrophones in the circular receiver, is processed by a CPU executing nearfield focusing, image construction and detection algorithms. The circular receiving array provides azimuth independent scattering rejection and incorporates a V wing shape to provide spatial rejection of the coherent part of the sea surface reflection.

Fig. 2 shows the 14 segments of the 252 element circular disk receiver. Each array segment has embedded ADCs operating at a sampling rate of 48 kHz which limits the upper operating frequency of the sonar to 24 kHz. The digital hydrophone data are multiplexed so that each array segment provides a serial stream of data to the sonar processor which is packaged in a canister located under the fairing at the front of the vehicle.

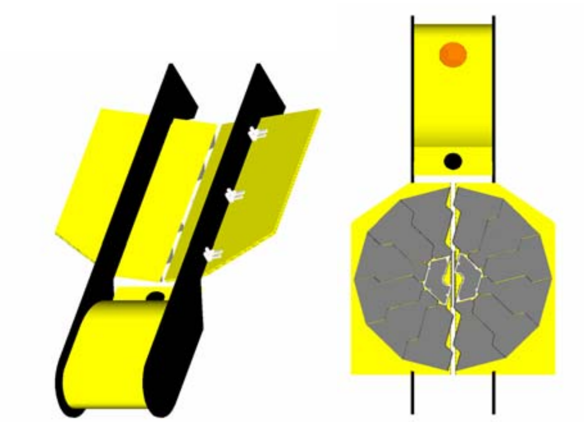

Fig. 1. Views of sonar vehicle showing 1.5 meter diameter disk of 252 hydrophones, spherical projector and doppler velocity log.

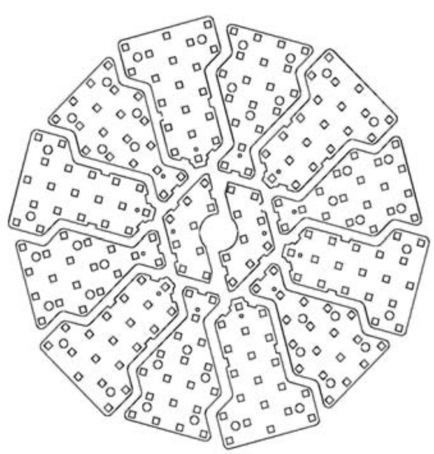

Fig 2. Receiving array consisting of 252 hydrophones. Each segment provides a signal serial stream of digitized and multiplexed hydrophone data.

The sonar can be deployed in AUV and towed modes. In the towed mode, the 3D image data is relayed from a towed vehicle to the topside display via 100 base-T ethernet. The operator monitors plan views and vertical profiles of the seabed showing the target images within the sediment volume. In the AUV mode, all processing is performed within the sonar module which reduces the data sets to a size which can be handled by the AUV acoustic communication link to the AUV support ship. BOSS provides its AUV host with target image snippets and location information that can relayed to the AUV support ship as the AUV is conducting its search and classification mission.

The sonar processor configuration for the AUV mode is shown in Fig. 3. The 14 high speed serial lines containing multiplexed hydrophone data pass through the wall of the pressure vessel housing the sonar processor. An IDE interface board provides the interface between the PC and the digital data stream, and provides DAC channels for FM signal generation, timing signals to ensure simultaneous sampling of all 252 channels and low rate ADCs for low bandwidth sensors. Nearfield focusing, image generation, and target detection are performed by a Pentium processor. Target image snippets and target strength information is sent to the AUV host via ethernet. The underwater canister also contains a linear power amplifier for driving the spherical projector through a matching transformer. The expected power consumption of the sonar is between 60 and 100 Watts at 48 VDC, not including the power required for the DVL and 3- axis motion sensor.

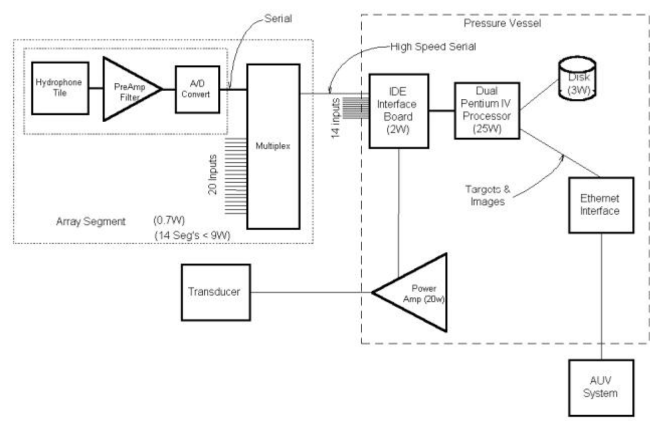

Fig. 3. Block diagram of data flow in hydrophone array segments and the sonar processor

Schock and Wulf[2] conducted simulations of the nearfield beamformer to determine the effective resolution of point targets as a function of the target position in the sonar field of view and the optimum elevation angle of the receiver disk. The simulations showed that the spatial resolution of the buried object scanning sonar operating with a pulse band of 2 to 12 kHz will vary from 3.2 cm to 1.3 meters for targets within an across track range of 20 meters. However, because targets pass through the sonar field of view at various aspect angles, parts of the target can be measured at the temporal resolution which is much higher than the spatial resolution. The results show that target dimensions can be measured with an accuracy approaching 3 cm at ranges out to 20 meters provided that, as the target passes through the sonar field of view, target dimension measurements are made at locations where the spatial measurement direction is within 45 degrees of the direction of maximum temporal resolution.

Simulations of the rejection of surface scattering as a function of array elevation angle show that a scatterer above the sonar array can be rejected by as much as 40 dB for receiver array elevation angles between 37 and 41 degrees.

III. SIGNAL PROCESSING

The BOSS transmits a linear FM pulse with following form:

$$x(t) = a(t)\cos\phi(t) \tag{1}$$

where $a(t)$ is the amplitude weighting and the instantaneous phase is given by

$$\phi(t) = 2\pi f_c t + \pi b t^2 \tag{2}$$

The instantaneous frequency is

$$f_i = \frac{1}{2\pi}\frac{d\phi(t)}{dt} = f_c + b\,\mathrm{t} \tag{3}$$

where b is the sweep rate with units of Hz/sec. For BOSS, the amplitude modulation is a rectangular envelope so the expression for the pilot signal that drives the acoustic transmitter is given by

$$x(t) = \begin{matrix} A\cos\phi(t) & -T/2 \le t \le T/2 \\ 0 & |t| > T/2 \end{matrix} \tag{4}$$

In practice, the ends of the FM sweep are slightly tapered to prevent the generation of harmonics.

The sonar processor performs real time correlation to compress the reflected FM signals in time to zero phase wavelets. The frequency spectrum of an acoustic return, measured at the hydrophone n, is given by

$$Y_n(f) = X(f)H_X(f)H_n(f)H_R(f) + N(f) \tag{5}$$

where $X(f)$ is the Fourier transform of the pilot signal,

$$X(f) = \int_{-\infty}^{\infty} x(t)e^{j2\pi ft}dt \tag{6}$$

and $H_X(f)$, $H_R(f)$, and $H_n(f)$ are the transmitting voltage response of the projector, the receiving response of the array and the frequency response of the seabed including targets, respectively. The noise spectrum consists of ambient noise, electronic noise, self noise, etc. The output of the correlation filter is the analytic signal, given by

$$s_n(t) = \int_0^{\infty} y_n(\tau)f(t+\tau)d\tau \tag{7}$$

where the $f(t)$ is the correlation replica and $y_n(t)$ is the output of hydrophone n.

The correlation filter is called a matched filter when $y_n(t)$ contains a known signal in white noise and $f(t)$ is the known noise-free signal. A matched filter provides the optimal signal to in-band noise improvement for a known signal in noise. The signal to noise improvement for a matched filter processing a known signal in white noise is given by

$$SNR_{out} - SNR_{in} = 10\log_{10} TW \tag{8}$$

where T is the pulse length and W is the pulse bandwidth. Note that an increase in pulse length or pulse bandwidth, improves the signal to in-band noise ratio at the output of a matched filter.

The matched filter, which maximizes the peak energy to rms noise ratio at the output of the filter, maybe a good filter for generating reflection profiles of the seabed, but it does not provide data with a flat frequency spectrum because the receiver and projector do not have flat responses. For BOSS it is desirable to have a flat output spectrum so the target strength of a target can be measured as a function of frequency. The correlation filter is designed so an echo from an ideal target appears have a white spectrum. The replica, given by,

$$f(t) = \int_{-\infty}^{\infty} \frac{X(f)}{H_X(f)H_R(f)} e^{-j2\pi ft} df \tag{9}$$

compensates for the frequency response of the projectors and receivers. In practice the frequency responses are measured, with the sonar vehicle inverted, using echoes from a smooth air-water interface and the corresponding amplitude and phase corrections are applied only over the operating band of the sonar. The amplitude and phase corrections compensate for resonances in the projectors thereby improving the bandwidth and time resolution of the reflection data. Since the replica is not identical to the received waveform, the matched filter does not provide the optimum processing gain because it will amplify parts of the spectrum with lower SNR. However, due to the proximity of the sonar to the seabed, SNR is high before processing so the sub-optimal matched filter is not expected to cause noisy images under most operating conditions.

As shown in Figure 4, after matched filtering, the next step in the processing sequence is nearfield focusing. The nearfield focuser processes the acoustic data from the 252 hydrophone channels to generate a 3D pixel matrix for which each pixel represents the scattering from a point under the seabed.

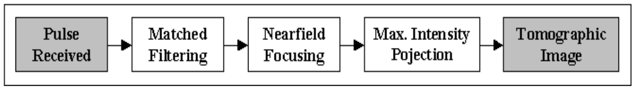

Fig. 4. Signal processing flow diagram for BOSS

The value of each pixel in the 3D matrix, calculated by applying a correction for 2 way spherical spreading and coherently summing the matched filtered data, is given by

$$A(x,y,z) = \left|\sum_{n=1}^{252} s_n(t_n) R_X R_n\right| \qquad (10)$$

where t_n is the source-focal point- hydrophone propagation time, R_X is the distance between the transmitter and focal point (x,y,z) and R_n is the distance between the focal point and hydrophone n.

In order to visualize the targets within the 3D matrix, the data is projected onto a viewing plane using Maximum Intensity Projection mapping. For example, using a right hand coordinate system where x is positive forward, y is positive starboard and z is positive down, the vertical slice of target in the along track direction, is given by

$$A(x,z) = \max[A(x,y,z)] \text{ for all y} \qquad (11)$$

Successive transmissions generate overlapping 2D matrices of $A(x,z)$. The horizontal extent of each 2 matrix is determined by the field of view of the sonar. For example, the horizontal extent of the x,y plane may be set to twice the sonar altitude. The vertical extent of the image matrix is determined by minimum and maximum sonar altitudes above the target during the survey.

The tomographic image is the incoherent sum of the co-located pixel values from the overlapping MIPs. Reflection tomography generates a vertical view of the target using

$$B(x,z) = \sqrt{\frac{1}{M}\sum_{m=1}^{M} A_m^2(x,z)} \qquad (12)$$

where M is the number of overlapping MIP slices (or transmissions) that contain pixels co-located at focal point(x,y,z).

IV. SIMULATIONS OF TOMOGRAPHIC IMAGING USING A RIGID SPHERICAL TARGET

The tomographic projection of several MIP slices is expected to provide the shape of the target since each MIP slice is generated by a transmission from a unique target aspect angle. The improvement provided by tomographic imaging over the technique of generating the image by MIP of a sequence of across track vertical slices as described in [1], is investigated by generating a synthetic sonar data for the case of a rigid sphere immersed in water and by constructing images from the synthetic data.

The frequency response of a rigid sphere in a fluid has closed form expression that is valid for all frequencies, target radii and target ranges. Consider the geometry in Figure 5.

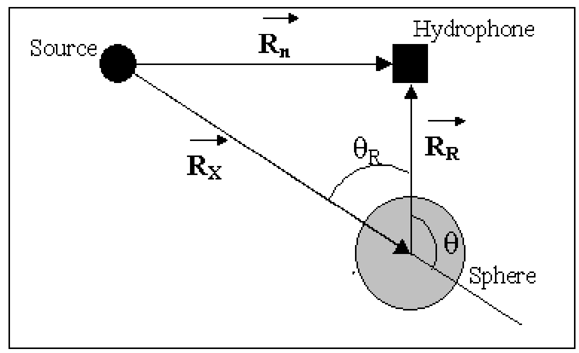

Fig. 5. Geometry for calculating frequency response of rigid sphere

The frequency response of the rigid sphere with radius a is given by [3],

$$H(f) = P_0 \sum_{n=0}^{\infty} c_n h_n(kR_R) P_n(\cos\theta) \qquad (13)$$

where

$$c_n = k(-1)^n (2n+1) h_n(kR_X) \sin\eta_n e^{-j\eta_n} \qquad (14)$$

$$\tan\eta_n = \frac{j_n'(x)}{-\eta_n'(x)} \qquad (15)$$

$$x = ka \qquad (16)$$

and k is the wavenumber of sound in seawater, $j_n(x)$, $\eta_n(x)$ and $h_n(x)$ are spherical Bessel functions,

$P_n(\cos\theta)$ are Lengendre polynomials, and P_0 is the pressure amplitude of the source.

The analytic signal for each hydrophone channel is synthesized using equation (7) after calculating the frequency spectrum of each hydrophone channel using equation (5) where the frequency response of the medium $H_n(f)$ is given by equation(13). The synthetic data set consists of 252 channels of analytic signal data generated for each vehicle position associated with each transmission event.

A synthetic data set is generated using the following parameters:

Diameter of sphere 40 cm, 100cm
Length of sonar track = 8 meters
Sonar speed = 2 meters per second
Transmission rate = 10 pulses per second
Operating band = 2- 12 kHz
Sonar altitude above target = 2 meters
Across track offset of target = 0 meters
Along track position of target = 4 meters

The synthetic data is processed with equations (10-12) to generate the tomographic image. The tomographic images of the spheres are compared to a simple MIP images.

The simple MIP image is constructed from a sequence of vertical 2D slices of the seabed. The data received after each transmission is processed by the nearfield focuser to produce a single 2D image showing the vertical profile of seabed in the across track direction. A sequence of transmissions produces a sequence of 2D slices which form a 3D image pixel matrix. The MIP algorithm provides a view of the 3D matrix. Since the simple MIP approach is based on the sonar beam being focused in one direction, say directly under the sonar, the sonar will not measure many specular reflections from the target as the sonar approaches and passes the target. As shown in the following figures, the tomographic images contain much more information about target shape than simple MIP images which are based on steering the receiver beam in only one direction.

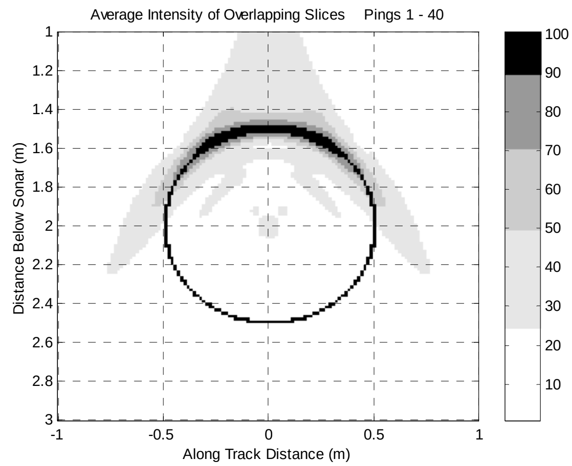

Fig. 6. Tomographic image of 1 meter diameter rigid sphere showing circumference of sphere.

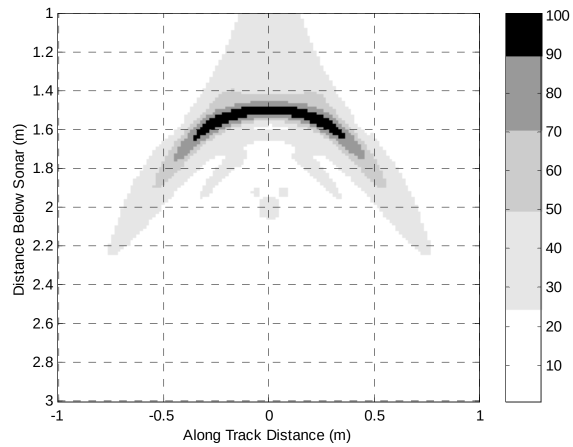

Fig. 7. Tomographic image of 1 meter diameter rigid sphere

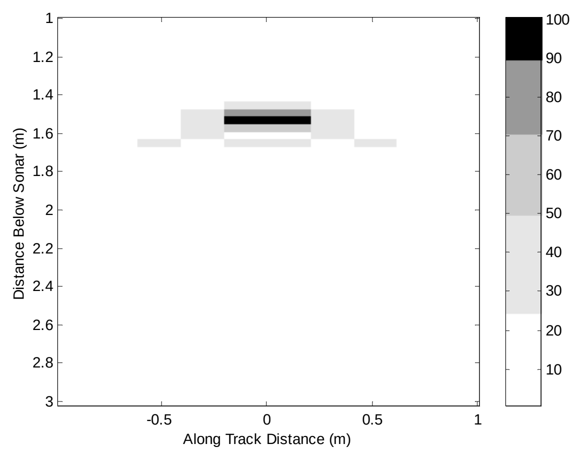

Fig. 8. Simple MIP image of 1 meter diameter rigid sphere

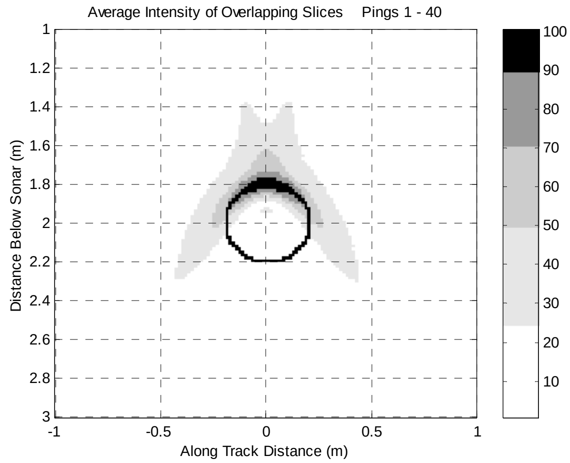

Fig. 9. Tomographic image of 0.4 meter diameter rigid sphere showing circumference of sphere.

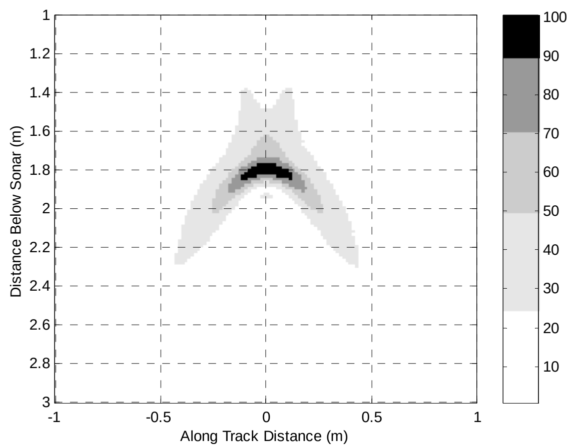

Fig. 10. Tomographic image of 0.4 meter diameter rigid sphere.

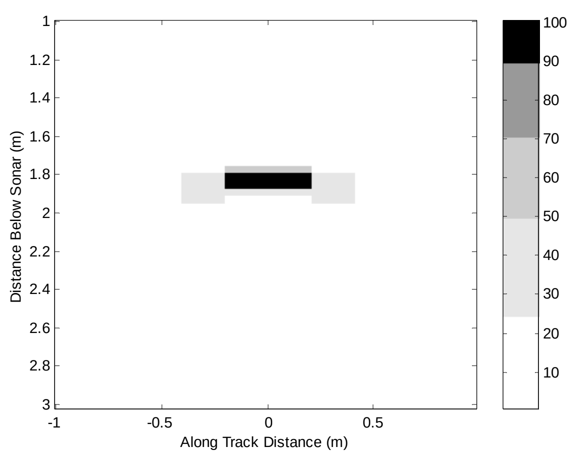

Fig. 11. Simple MIP image of 0.4 meter diameter rigid sphere.

IV. CONCLUSIONS

Buried object scanning sonar (BOSS) is designed to generate 3D images of objects at multiple aspects. Target images are constructed using a sequence of acoustic echoes generated as the sonar approaches and passes a buried target by mapping target echoes to an absolute coordinate system.

Simulations of BOSS processing show that tomographic images contain more information on target shape than simple MIP images. Simple MIP images of 20 cm and 50 cm diameter rigid spheres provide little information on target shape or size preventing recognition. Tomographic images of the spheres clearly show the upper circumference of the sphere providing shape for recognition and allowing estimation of the diameter of the sphere from the image.

Reflection tomographic imaging of buried objects is expected to a useful tool for target recognition and classification.

Acknowledgments

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