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<b>14. ABSTRACT</b> The Volume Search Sonar (VSS) uses a partial cylindrical array populated over a 286° sector to (1) transmit a stepped FM pulse over a 243° vertical fan beam centered on nadir and (2) receive with 27 fore-aft beam pairs steered symmetrically about a plane perpendicular to the axis of the cylinder. The bisectors of these beam pairs are spaced at 7.16° intervals around the cylinder. Up to 52 phasors are formed by conjugate products of adjacent beams across-track (26 phasors forward and 26 phasors aft). These phasors are further combined in groups of two phasors along-track, and two or three phasors across-track to obtain additional soundings between them. For swath bathymetry purposes, 123 of the 153 possible phasor combinations are retained to form three across-track bathymetry profiles per ping cycle in a swath angle of roughly ±73° about nadir. Each ping, a 3D patch of this swath is sampled and continuous bathymetry coverage is possible at survey speed of 25-30 knots. Seafloor acoustic backscatter imagery coregistered with the bathymetry is also obtained through this process, giving the VSS efficient reconnaissance seafloor mapping capabilities.					
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## Technical Report

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### **Bearing estimation uncertainties for the Volume Search Sonar**

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#### **Abstract**

The Volume Search Sonar uses a cylindrical receiver array consisting of 40 staves of 9 elements each mounted parallel with the axis of the cylinder, itself aligned with the fore-aft axis of the towbody on which it is installed. 27 fore-aft beam pairs are formed with 27 sub-arrays of 16 contiguous staves. Previous work (Brogan and de Moustier, 2005; 2006) has shown that time and angles of arrival of seafloor echoes received at the VSS array can be used to obtain swath bathymetry and seafloor acoustic backscatter imagery. This report is a preliminary analysis of the uncertainties in estimation of the angles of arrival of bottom echoes received by pairs of VSS beams. In monopulse processing applied to fore-aft beams with common phase centers, a signal-to-noise ratio (SNR) in excess of 15 dB is necessary for the standard deviation of the angle estimate to remain below  $0.5^\circ$  in long-range mode ( $\pm 4^\circ$  about broadside), whereas an SNR in excess of 20 dB is required to obtain the same angular uncertainty in short-range mode ( $\pm 8^\circ$  about broadside). For the conjugate product processing applied to pairs of adjacent across-track beams with distinct phase centers, an SNR in excess of 24 dB is required to maintain the standard deviation of angle estimates below  $1^\circ$ , highlighting the need to improve such estimates by filtering the real and imaginary parts of the conjugate product output.

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## I - Introduction

Given the time and angles (azimuth  $\phi$ , and polar  $\theta$ ) of arrival for an echo received from the bottom by an echo-sounder (Fig. 1), the depth and horizontal distance coordinates of the sounding are obtained by:

$$R = C t/2 \text{ (m), with sound speed } C \text{ (m/s) and two-way travel time } t \text{ (s),}$$

$$z(R, \theta) = R \cos\theta, \quad x(R, \theta, \phi) = R \sin\theta \cos\phi, \quad y(R, \theta, \phi) = R \sin\theta \sin\phi$$

The above assumes a straight path between the echo-sounder and the bottom at the end points of the actual refracted ray path, and the sound speed is the equivalent harmonic mean sound speed along that straight path.

The estimates of range and angles are uncorrelated and independent, but the estimates of polar and azimuth angles ( $\theta$ , and  $\phi$ ) are sometimes correlated, therefore, the uncertainties in depth and horizontal distance are related to the uncertainties in range and angles by:

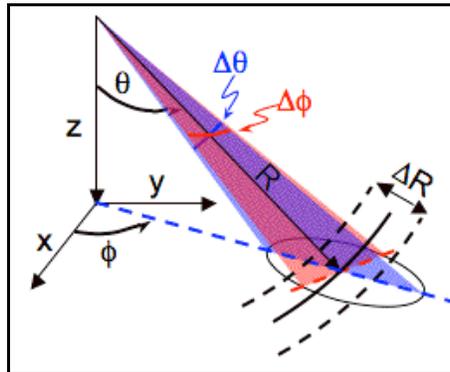
$$\sigma_z^2 = \sigma_R^2 (\partial z/\partial R)^2 + \sigma_\theta^2 (\partial z/\partial \theta)^2 = \sigma_R^2 \cos^2\theta + \sigma_\theta^2 R^2 \sin^2\theta$$

$$\begin{aligned} \sigma_x^2 &= \sigma_R^2 (\partial x/\partial R)^2 + \sigma_\theta^2 (\partial x/\partial \theta)^2 + \sigma_\phi^2 (\partial x/\partial \phi)^2 + 2\sigma_{\theta\phi} (\partial x/\partial \theta)(\partial x/\partial \phi) \\ &= \sigma_R^2 \sin^2\theta \cos^2\phi + \sigma_\theta^2 R^2 \cos^2\theta \cos^2\phi + \sigma_\phi^2 R^2 \sin^2\theta \sin^2\phi - 2\sigma_{\theta\phi} R^2 \cos\theta \cos\phi \sin\theta \sin\phi \end{aligned}$$

$$\begin{aligned} \sigma_y^2 &= \sigma_R^2 (\partial y/\partial R)^2 + \sigma_\theta^2 (\partial y/\partial \theta)^2 + \sigma_\phi^2 (\partial y/\partial \phi)^2 + 2\sigma_{\theta\phi} (\partial y/\partial \theta)(\partial y/\partial \phi) \\ &= \sigma_R^2 \sin^2\theta \sin^2\phi + \sigma_\theta^2 R^2 \cos^2\theta \sin^2\phi + \sigma_\phi^2 R^2 \sin^2\theta \cos^2\phi + 2\sigma_{\theta\phi} R^2 \cos\theta \sin\phi \sin\theta \cos\phi \end{aligned}$$

where

$\sigma_z^2$ ,  $\sigma_x^2$ , and  $\sigma_y^2$  are the variances of the (x,y,z) coordinates of the sounding,  $\sigma_R^2$ ,  $\sigma_\theta^2$ , and  $\sigma_\phi^2$  are the variances of the range and angle estimates, and  $\sigma_{\theta\phi}$  is the covariance of the polar and azimuth angle estimates.



**Fig. 1.** Uncertainty in (x,y,z) sounding coordinates. Uncertainties in the time (converted to range  $\Delta R = \pm\sigma_R$ ) and angles of arrival ( $\Delta\theta = \pm\sigma_\theta$ ,  $\Delta\phi = \pm\sigma_\phi$ ) lead to uncertainties in depth ( $\pm\sigma_z$ ) and horizontal position ( $\pm\sigma_x$ ,  $\pm\sigma_y$ ) of the sounding.

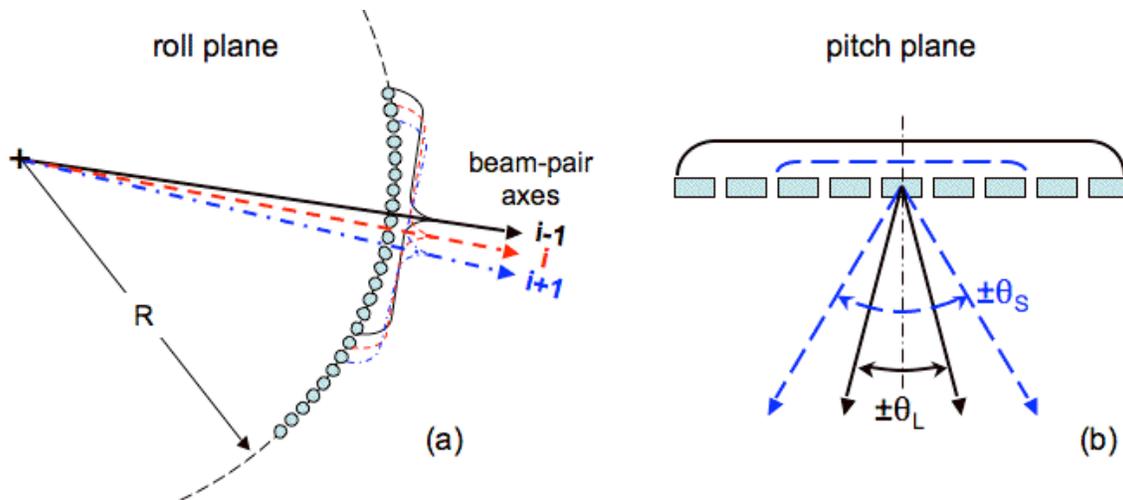
The purpose of this report is to analyze the uncertainties in the estimation of arrival angles (variances  $\sigma_\theta^2$ , and  $\sigma_\phi^2$  above) for bottom echoes received by the Volume Search Sonar (VSS).

We begin with a review of the VSS receive array geometry and beamforming methodologies, and we consider two methods of bottom echo detection:

- (1) a monopulse technique for cophasal beam pairs steered from the same array, and
- (2) a conjugate product technique for pairs of beams, or groups of beams, formed from different subarrays.

## II – Volume Search Sonar (VSS) Receive Array Geometry and Beamforming

The Volume Search Sonar uses a cylindrical receiver array consisting of 40 staves of 9 elements each mounted parallel with the axis of the cylinder. The axis of the cylinder is aligned with the fore-aft axis of the towbody on which it is installed. The staves are spaced at  $7.16^\circ$  increments in the roll plane, covering  $\pm 143.2^\circ$  about nadir, and every other staff is offset fore-aft by half a wavelength to reduce grating lobes.

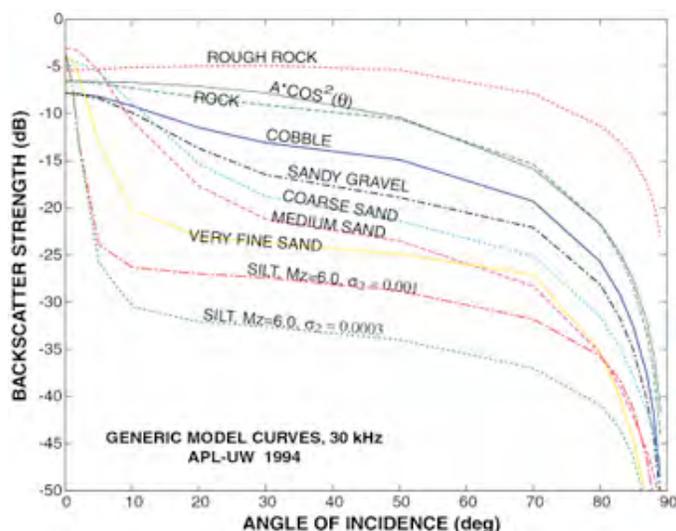


**Fig. 2.** Beamforming geometry of the VSS cylindrical receive array. (a) In the roll plane, the array contains 40 staves spaced at  $7.16^\circ$  intervals on a cylinder of radius  $R = 196.85$  mm. (b) In the pitch plane, each staff contains 9 elements aligned fore-aft. 16 contiguous staves are used to form a fore-aft beam pair, and 27 such beam pairs are formed at  $7.16^\circ$  increments around the cylinder (same angular spacing between beam-pair axes  $i$  and  $i+1$  as between staves). In short-range mode, the central 5 elements in each staff are used to steer the beam pair at  $\theta_s = \pm 8^\circ$  fore-aft. In the long-range mode, all 9 elements in each staff are used to steer the beam pair at  $\theta_L = \pm 4^\circ$  fore-aft.

27 fore-aft beam pairs are formed with 27 sub-arrays of 16 contiguous staves. In the roll plane, the phase centers of these sub-arrays are  $7.16^\circ$  apart, and the axis of each beam pair is broadside to its 16-stave sub-array (Fig. 2-a). In the pitch plane, the beam pair is obtained by steering at either  $\pm 8^\circ$  fore-aft using the 5 centermost elements in each staff in short-range mode, or  $\pm 4^\circ$  fore-aft using all 9 staff elements in long-range

mode (Fig. 2-b). Therefore, each beam pair is obtained with a 3-D array of  $16 \times 9$  elements in long-range mode, or  $16 \times 5$  elements in short-range mode.

Because the array is cylindrical, all the beams have the same nominal beamwidth for a given mode of operation:  $9.5^\circ$  across-track by  $8.25^\circ$  fore-aft in long-range mode, and  $9.5^\circ$  across-track by  $16.5^\circ$  fore-aft in short-range mode. In addition, from about  $20^\circ$  to  $70^\circ$  incidence the angular dependence of seafloor acoustic backscatter is relatively level (Fig. 3), and adjacent beams across-track should have roughly the same signal to noise ratio for any signal arriving from the bottom at an angle halfway between the maximum response axes of the two beams. The same reasoning applies to signals arriving from the bottom halfway between combinations of adjacent beams, however in such cases the signal to noise ratio should decrease in proportion to the reduction in overlap between the beam groups. Conversely, for most sedimentary bottoms (sands and muds in any combination) we should expect variations of 5-10 dB in the backscattered level received by adjacent beams between  $0^\circ$  and  $20^\circ$  incidence, and beyond about  $70^\circ$  incidence.



**Fig. 3.** Angular dependence of seafloor acoustic backscatter. Model curves at a nominal acoustic frequency of 30 kHz from the “High-Frequency ocean environmental acoustic models handbook”, APL-UW TR 9407-AEAS 9501, Oct. 1994.

Previous technical reports by Brogan and de Moustier (2005, 2006) have shown that seafloor echoes received by the VSS could be used to obtain swath bathymetry and seafloor acoustic backscatter imagery. This was achieved with two general methods to determine the time and angles of arrival of seafloor echoes received at the VSS array: (1) a monopulse technique applied to each fore-aft beam pair because beams in such a pair have the same phase center, and (2) a conjugate product technique applied in the roll plane to adjacent beams, or groups of adjacent beams with distinct phase centers.

In both methods, it was initially assumed that the angle of arrival lies exactly halfway between the two beams or groups of beams considered. Then, the corresponding time

of arrival of bottom echoes was estimated with a weighted mean-time technique for fore-aft beam pairs, or with the zero-crossing of the phase difference between adjacent across-track beams (or groups of adjacent beams). However, the assumption that we know the angle of arrival exactly is rarely valid and, as shown in the introduction, uncertainty in the bathymetry depends on the uncertainties in the estimations of both the time and the angle of arrival for each sounding. We examine the angle uncertainties in sections III and IV below.

### III – VSS Beam Pointing Uncertainty In The Fore-Aft Beam Pairs

For each 3D subarray of 16 adjacent staves, the VSS forms fore-aft beam pairs at  $\pm 8^\circ$  and  $\pm 4^\circ$  about broadside in short-range mode, and long-range mode respectively.

Nielsen (1994) provides expressions for the Cramer-Rao lower bounds (CRLB) on the azimuth and elevation angle estimates made with an arbitrary 3D array of omnidirectional sensors, however more time than was available for this work will be required to adapt these expressions to the VSS array geometry. Instead, we simplify the analysis by considering a line array of 9 equally-spaced “elements” for the long-range mode, and the central 5 “elements” of this array for the short-range mode. This simplified geometry ignores the actual staggered staff arrangement with every other staff offset by half a wavelength to lessen grating lobes, but it should not affect the beam pointing estimates.

Nielsen (2001) has compared measurements of the arrival angle of a signal at a uniform line array (ULA) by either (1) conventional DFT beamforming that uses the output from all the elements to form the angle estimate, or (2) forming a set of beams based on the entire array of sensors, and using the outputs of the two beams that encompass the arrival angle. He has shown that the CRLB for the angle estimate obtained with approach #2 is bounded from below by the CRLB from approach 1. We shall adapt here his results to the simplified VSS array geometry described above.

At the outputs of the matched filter for each of the  $M$  array elements ( $M = 9$  or  $5$ ) spaced  $d$  apart, the basebanded quadrature outputs ( $I, Q$ ) of the  $i$ th array element

$$x_I(i) = A \cos \left[ \left( i - \frac{M-1}{2} \right) \frac{2\pi d \sin \theta}{\lambda} + v_0 \right] + w_I(i), \quad i = 0, 1, \dots, M-1$$

$$x_Q(i) = A \sin \left[ \left( i - \frac{M-1}{2} \right) \frac{2\pi d \sin \theta}{\lambda} + v_0 \right] + w_Q(i), \quad i = 0, 1, \dots, M-1$$

where  $\lambda = f_0/c$  is the wavelength at the sonar’s center frequency  $f_0$ , and  $v_0$  is the phase angle at the origin of the array. The array is centered at the origin of the coordinate system, and the angle of arrival  $\theta$  is relative to the broadside of the array.

$w_I(i)$  and  $w_Q(i)$  are the real and imaginary components of the noise, which are assumed to be zero-mean stationary white Gaussian processes with the same variance  $\sigma_w^2$ . Noise sequences received by different sensors are assumed to be uncorrelated.

We form a set of  $N \geq M$  beams equally spaced in  $u = \sin\theta$  using a length  $N$  DFT (padding with zeros for  $N > M$ ). To obtain beams at  $\pm 8^\circ$  and  $\pm 4^\circ$  about broadside requires respectively  $N = 8$  with  $M = 5$  in short-range mode, and  $N = 16$  with  $M = 9$  in long-range mode.

In the following expressions, the signal to noise ratio (SNR) in dB is defined by

$$\text{SNR} = 10 \log_{10}(\eta) = 10 \log_{10}(MA^2 / 2\sigma_w^2)$$

The CRLB for a ULA of  $M$  sensors (approach #1) is:

$$\text{CRLB}_M(\theta) = \frac{M}{2\eta \left(\frac{2\pi d}{\lambda}\right)^2 \cos^2(\theta) \left[\frac{M(M^2 - 1)}{12}\right]}$$

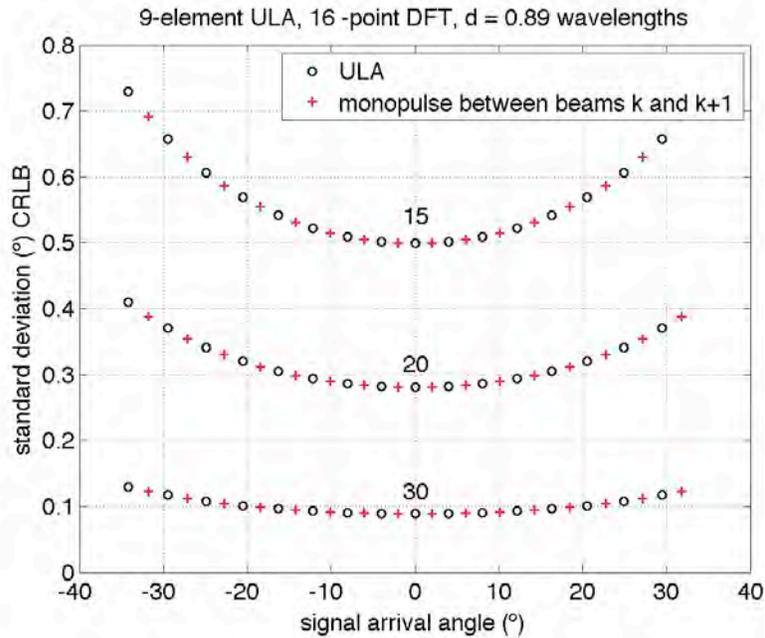
For approach #2, let beams  $k$  and  $(k+1)$  encompass the desired angle  $\theta$ :

$$X(k) = \sum_{i=0}^{M-1} [x_I(i) + jx_Q(i)] \exp\left(-j \frac{2\pi k i}{N}\right) \quad \text{and} \quad X(k+1) = \sum_{i=0}^{M-1} [x_I(i) + jx_Q(i)] \exp\left(-j \frac{2\pi(k+1)i}{N}\right)$$

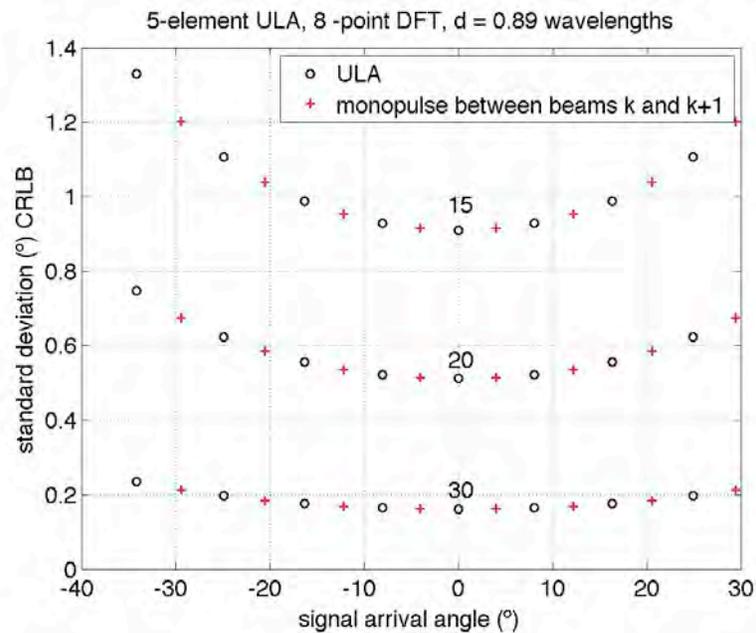
When the signal arrival angle is halfway between beams  $k$  and  $(k+1)$  at  $(k+1/2)$ ,  $\sin(\theta) = (k+1/2)\lambda/Nd$ , and the monopulse CRLB is:

$$\text{CRLB}_{k+1/2}(\theta) = \frac{M \sin^2(\beta) \left[ M - \frac{\sin(2M\beta)}{\sin(2\beta)} \right]}{\eta \left(\frac{2\pi d}{\lambda}\right)^2 \cos^2(\theta) \left[ M \cos(M\beta) - \frac{\sin(M\beta) \cos(\beta)}{\sin(\beta)} \right]^2} \quad \text{with } \beta = \frac{\pi}{2N}$$

These expressions are plotted in Figures 4 and 5 for the long- and short-range modes, respectively and various SNR values. In long-range mode ( $\pm 4^\circ$  about broadside), an SNR of 15 dB or better is necessary for the standard deviation of the angle estimate to remain below  $0.5^\circ$ . In short-range mode ( $\pm 8^\circ$  about broadside) an SNR of 20 dB or better is required to obtain the same angular uncertainty. Such SNR levels should be easily obtainable for fore-aft beam pairs in the near nadir region ( $0^\circ$  to  $\pm 10^\circ$  across-track), but they might more difficult to obtain for fore-aft beam pairs at across-track angle of  $60^\circ$  or more over a flat bottom.



**Fig. 4.** VSS Long Range Mode. Standard deviation of the angle of arrival estimate for a uniform line array (ULA) of 9 elements with 0.89-wavelength spacing. Conventional 16-point DFT beamformer solution compared to monopulse processing between adjacent beams. Signal to noise ratio (dB) value shown at nadir decreases according to Lambert's law ( $\cos^2(\theta_i)$ ), for angles of incidence  $\theta_i$  at the seafloor).



**Fig. 5.** VSS Short Range Mode. Standard deviation of the angle of arrival estimate for a uniform line array (ULA) of 5 elements with 0.89-wavelength spacing. Conventional 8-point DFT beamformer solution compared to monopulse processing between adjacent beams. Signal to noise ratio (dB) value shown at nadir decreases according to Lambert's law ( $\cos^2(\theta_i)$ ), for angles of incidence  $\theta_i$  at the seafloor).

These results are plausible, but they are not directly applicable to the VSS geometry because the fore-aft monopulse processing is done on the  $\pm 8^\circ$  (or  $\pm 4^\circ$  in long-range) beam pair about broadside, which corresponds to beams  $k$  and  $k+2$  (rather than  $k$  and  $k+1$  in the plots). However, the standard deviation of the broadside beam ( $0^\circ$ ) gives an indication of the uncertainty to be expected halfway between the two VSS fore-aft beams. A more extensive analysis is therefore required, and it should include the effects of element amplitude weighting (e.g. Kenefic, 1988), which will mostly broaden the beams and increase the region of overlap between them.

#### IV - Angular Uncertainty In The Conjugate Product Processing

The conjugate product processing method consists in multiplying the complex output of one beam (maximum response axis at  $\theta_p$ ) by the conjugate of the output of an adjacent beam across-track (maximum response axis at  $\theta_{p-1}$  or  $\theta_{p+1}$ ). Beams are spaced at  $7.16^\circ$  ( $0.125$  rad) across-track, which is also the spacing between the phase centers of their respective subarrays of 16 elements. Therefore, the distance between the phase centers of adjacent across-track beams is approximated by the corresponding arc length on a cylinder of radius 196.85 mm:

$$d_{cp} = 196.85 \times 10^{-3} \times 0.125 = 2.46 \times 10^{-2} \text{ m},$$

which is 0.615 wavelengths at a nominal frequency of 37.5 kHz with 1500 m/s sound speed.

Assuming that the bottom signal is received at roughly the same SNR in each beam, the conjugate product yields the phase difference,  $\Delta\phi = \phi_{p+1} - \phi_p$ , between the two beams so that when the phase difference is zero, the arrival angle is halfway between the maximum response axis of each beam ( $\theta_p, \theta_{p+1}$ ).

For narrowband echoes from the bottom, or for single frequency bins in broadband signals, the arrival angle  $\theta$  relative to the “broadside” axis between the beams  $(\theta_p + \theta_{p+1})/2$  is related to the electrical phase difference between the beams  $\Delta\phi$  by:

$$\Delta\phi = 2\pi d_{cp} \sin\theta / \lambda \quad (\text{rad}).$$

When the angle is within  $\pm 4^\circ$  of broadside, the small angle approximation can be applied to  $\sin\theta$  such that  $\sin\theta \approx \theta$  (rad), then

$$\theta \approx \Delta\phi \lambda / (2\pi d_{cp}) \quad (\text{rad}).$$

This approximation is valid here because beams are  $7.16^\circ$  apart and the angle of interest is within  $\pm 3.58^\circ$  of the “broadside” axis between the beams.

The variance of the estimate  $\underline{\theta}$  of  $\theta$  is therefore proportional to the variance of the estimate  $\underline{\Delta\phi}$  of  $\Delta\phi$ :

$$\text{Var}[\underline{\theta}] = (\lambda / (2\pi d_{cp}))^2 \text{Var}[\underline{\Delta\phi}]$$

This problem is equivalent to the target bearing estimation with a split-aperture correlator described by Burdick (1984, Section 13.3.3) who derives the bearing-estimate variance for sinusoidal signals (signal power  $A^2 / 2$ ) in narrowband white Gaussian noise received at each half of the aperture (noise power  $\sigma_w^2$ ). Neglecting beam pattern effects, this derivation is adapted here to the general case of high or low SNR, such that:

$$\text{Var}[\underline{\theta}] = (\lambda / (2\pi d_{cp}))^2 \eta_o^{-1} [1 + 2/\eta_o],$$

with output SNR  $\eta_o = (A^2 / 2\sigma_w^2)$  in each beam (or half aperture).

This expression is consistent with Burdick's result for high SNR:

$$\text{Var}[\underline{\theta}] \approx (\lambda / (2\pi d_{cp}))^2 \eta_o^{-1}$$

For comparison, the uncertainty in the estimation of the angle of arrival for a 2-element array with element separation  $d_{cp}$  is obtained by setting  $M=2$  in the formula of section III:

$$\text{CRLB}_{M=2}(\theta) = \frac{2}{\eta \left( \frac{2\pi d_{cp}}{\lambda} \right)^2 \cos^2(\theta)}$$

At broadside ( $\theta = 0^\circ$ ), the angular uncertainty is inversely proportional to the signal to noise ratio at the array ( $\eta = 2(A^2 / 2\sigma_w^2)$ ):

$$\text{CRLB}_{M=2}(0) = 2 \lambda^2 / [\eta (2\pi d_{cp})^2],$$

which is identical to

$$\text{Var}[\underline{\theta}] \approx (\lambda / (2\pi d_{cp}))^2 \eta_o^{-1}$$

For a bottom echo received between adjacent across-track beams ( $\theta \leq \pm 3.58^\circ$ ), the conjugate processing should yield an rms angular uncertainty of the arrival angle measured relative to the broadside of the two beams given by:

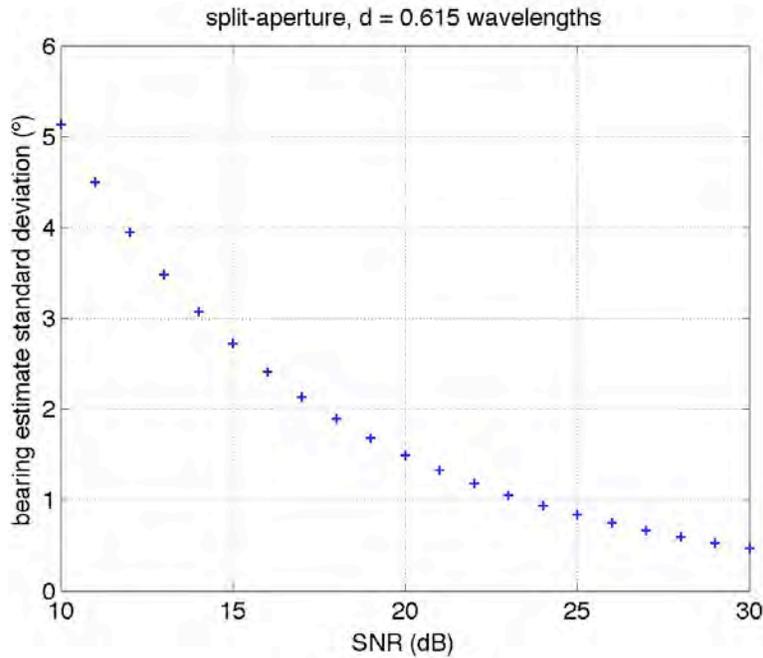
$$\theta_{rms} \approx (\eta_o)^{-1/2} \lambda / (2\pi d_{cp}).$$

This relationship is plotted in Fig. 6 where we see that an SNR in excess of 24 dB is needed to maintain the rms uncertainty in bearing angle below about  $1^\circ$ . However, this analysis is incomplete because it does not take into account the noise reduction achieved while estimating the phase difference by filtering the real and imaginary parts of the conjugate product output (e.g. Masnadi-Shirazi et al, 1992):

$$\underline{\Delta\phi} = \text{atan2} \left[ \frac{\sum_{n=1}^L h^2[n] \text{Im}\{x_{p+1}[n]x_p^*[n]\}}{\sum_{n=1}^L h^2[n] \text{Re}\{x_{p+1}[n]x_p^*[n]\}} \right]$$

which is an unbiased estimate of the phase difference obtained from the conjugate product of the outputs of the two adjacent beams:  $x_p$  and  $x_{p+1}$ , respectively. In this expression  $h[n]$  is the impulse response of a finite impulse response filter (e.g. hanning window) acting on  $L$  data samples, and  $\text{atan2}$  is the four-quadrant arctangent operator.

Computation of the variance of this filtered phase difference estimate requires a more extensive analysis (e.g. Stansfield, 1996) left for future work.



**Fig. 6.** Standard deviation the bearing estimate near broadside of a split-aperture as a function of the output signal-to-noise ratio:  $\theta_{rms} \approx (\eta_o)^{-1/2} \lambda / (2\pi d_{cp})$  with  $\text{SNR} = 10 \log_{10}(\eta_o)$ , and  $d_{cp} / \lambda = 0.615$

## V – Conclusion

The uncertainties associated with estimates of the angles of arrival of bottom echoes received by pairs of VSS beams are primarily driven by the SNR obtained at the output of the chosen processing method. In monopulse processing applied to fore-aft beams with common phase centers, an SNR in excess of 15 dB is necessary for the standard deviation of the angle estimate to remain below  $0.5^\circ$  in long-range mode ( $\pm 4^\circ$  about broadside), whereas an SNR in excess of 20 dB is required to obtain the same angular uncertainty in short-range mode ( $\pm 8^\circ$  about broadside). These SNR values are realistic for near-specular backscattered echoes.

For the conjugate product processing applied to pairs of adjacent across-track beams with phase centers separated by  $d = 0.615$  wavelengths, a relatively high SNR in excess of 24 dB is required to maintain the standard deviation of angle estimates below  $1^\circ$ . Such high angular uncertainty will yield high uncertainties in the corresponding bathymetric values and the resulting bottom maps will appear noisy. Therefore, it is necessary to improve the angular estimates by filtering the real and imaginary parts of the conjugate product output. Details of the corresponding analysis are left for future work.

## VI - References

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## FINAL REPORT

NRL Grant N00173-00-1-G912

Acoustic Signal Processing for Ocean Mapping Applications  
With the Volume Search Sonar (VSS)

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### ABSTRACT

The Volume Search Sonar (VSS) uses a partial cylindrical array populated over a  $286^\circ$  sector to (1) transmit a stepped FM pulse over a  $243^\circ$  vertical fan beam centered on nadir and (2) receive with 27 fore-aft beam pairs steered symmetrically about a plane perpendicular to the axis of the cylinder. The bisectors of these beam pairs are spaced at  $7.16^\circ$  intervals around the cylinder. Up to 52 phasors are formed by conjugate products of adjacent beams across-track (26 phasors forward and 26 phasors aft). These phasors are further combined in groups of two phasors along-track, and two or three phasors across-track to obtain additional soundings between them. For swath bathymetry purposes, 123 of the 153 possible phasor combinations are retained to form three across-track bathymetry profiles per ping cycle in a swath angle of roughly  $\pm 73^\circ$  about nadir. Each ping, a 3D patch of this swath is sampled and continuous bathymetry coverage is possible at survey speed of 25-30 knots. Seafloor acoustic backscatter imagery coregistered with the bathymetry is also obtained through this process, giving the VSS efficient reconnaissance seafloor mapping capabilities.

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## 1. INTRODUCTION

This final report describes work done under NRL-BAA 74-03-03, Section 1 “mapping science research and development via image processing techniques to extract environmental information such as bathymetry, seafloor bottom type, and acoustic provinces from remote acoustic system data”. Specific goals of the work were to design algorithms to extract bathymetry and acoustic backscatter imagery from acoustic data recorded with the Volume Search Sonar (VSS) of the AN/AQS-20 mine hunting sonar system.



Fig. 1. AN/AQS-20 mine hunting sonar system (Raytheon, 1999).  
The VSS is the partial cylindrical array in the forward section of the towbody.

The Volume Search Sonar uses a partial cylindrical array ( $286^\circ$  sector) to transmit and receive. The receiver array consists of 40 staves of 9 elements each mounted parallel with the axis of the cylinder, itself aligned with the fore-aft axis of the towbody on which it is installed. Scientists at the Naval Research Laboratory, Stennis Space Center (NRL-SSC) collected data with this system while it was deployed from a helicopter and towed at speeds of 25-30 knots.

The work reported here was done in collaboration with Dale Bibee and Will Avera at NRL-SSC who provided the VSS data used in the work described here, and the software to read such data.

## 2. TASK OBJECTIVES

Task objectives included:

- A. Model the transmit and receive acoustic geometry of the VSS to help constrain the echo analysis;
- B. Verify the basebanded characteristics of the bottom echoes;
- C. Investigate monopulse techniques to extract time and angle of arrival information from bottom echoes received by the VSS;

- D. Investigate conjugate product techniques to extract time and angle of arrival information from bottom received by the VSS;
- E. Investigate various beam combinations to obtain multiple across-track bathymetry profiles for each sonar ping;
- F. Perform all the necessary attitude, refraction and navigation corrections to produce georeferenced bathymetry swaths;
- G. Assemble acoustic backscatter imagery coregistered with the bathymetry.
- H. Deliver software to NRL-SSC for VSS bathymetry and seafloor acoustic backscatter imagery.
- I. Analyze the uncertainties in depth soundings obtained with the VSS.

### 3. TECHNICAL PROBLEMS

Conventional swath bathymetry sonar systems transmit a vertical fan beam, usually centered at nadir, with a beamwidth that is broad across track and narrow along track. These systems receive with a corresponding fan of partially overlapping individual beams, with narrow across-track beamwidths, that cover the across-track transmit sector. The product of the transmit and receive beam patterns yields an across-track fan of individual narrow beams (usually  $1^\circ$  to  $3^\circ$  along and across track) from which independent soundings are extracted to obtain an across-track profile of bathymetry.

The transmit beam geometry of the VSS is similar to that of conventional swath bathymetry sonars, but its receive beam geometry is not because the VSS forms pairs of fore-aft receive beams steered symmetrically about a plane perpendicular to the axis of the cylinder.

This geometry presents two challenges:

- (1) no beams are formed in the vertical across-track plane, and
- (2) lower spatial resolution than conventional swath bathymetry sonar because the fore-aft beam pairs have relatively broad beamwidths:  $9.5^\circ$  across-track by  $8.25^\circ$  fore-aft in long-range mode with  $\pm 4^\circ$  fore-aft steering about broadside, and  $9.5^\circ$  across-track by  $16.5^\circ$  fore-aft in short-range mode with  $\pm 8^\circ$  fore-aft steering about broadside. Because the array is cylindrical, all the beams have the same nominal beamwidth for a given mode of operation.

### 4. GENERAL METHODOLOGY

The general approaches used in this work to estimate the time and angle of arrival of seafloor echoes come from monopulse radar techniques (e.g. Sherman, 1984; Barton, 1974; Rhodes, 1959). These techniques include using pairs of adjacent beams to estimate the range and bearing of targets that lie in the region of overlap between the beams.

If the beam pair has a common phase center, estimations must be based on magnitude only with various ratio combinations (e.g. difference over sum). If each beam in the pair has a distinct phase center, phase differences between the two beams may be used to obtain bearing information. A more complete solution takes advantage of the magnitude and phase information for beam pairs with distinct phase centers.

## 5. TECHNICAL RESULTS

Technical results have been described in a series of technical reports and in the Master's thesis of UNH Graduate Student Daniel S. Brogan. Abstracts of these technical reports and of the thesis are appended at the end of this final report. Results were presented also at two meetings of the Acoustical Society of America:

\* D.S. Brogan, and C. de Moustier, "3D spatial sampling with a cylindrical multibeam sonar array" (A), *J. Acoust. Soc. Am.*, 117(4-2), 2447, 2005; and

\* D.S. Brogan and C. de Moustier, "Bathymetry and seafloor backscatter imagery with a volume search sonar", (A), *J. Acoust. Soc. Amer.*, 115(5-2), 2547, 2004.

**Task A:** A detailed transmit and receive beam pattern analysis and simulation study were carried out with MATLAB software tools and acoustic array dimensions obtained from the manufacturer, Raytheon Corp. This analysis was done at acoustic frequencies between 35 kHz and 38 kHz and uncovered potential sidelobe interference issues for swath bathymetry and volume search applications, in the transmit beam patterns and the short range volume receive beam patterns. (C. de Moustier and D. Brogan, "Volume Search Sonar (VSS) beam pattern simulations", Progress/Technical Report, Feb. 2003)

**Task B:** The matched filter processing implemented in the sonar was modeled in MATLAB and the results helped explain some of the patterns observable in the data collected at sea, as well as refine the beam pattern simulations. (D. Brogan and C. de Moustier, "Volume Search Sonar (VSS) beam pattern simulations", Progress/Technical Report, Oct. 2003).

**Tasks C, D:** Three monopulse techniques were investigated to obtain time and angle of arrival estimates from fore-aft VSS receive beam pairs and across-track pairs of adjacent beams: (1) conjugate product, (2) difference over sum, and (3) narrow beam. Initially, the narrow-beam technique applied to fore-aft receive beam pairs yielded the most promising results. However, the resulting bathymetry profile was based on 25-27 soundings per ping yielded insufficient along-track coverage to match the 25-30 knots survey speed. (D. Brogan and C. de Moustier, "Bathymetry and seafloor acoustic backscatter imagery with the Volume Search Sonar", Progress/Technical Report, Jun. 2004)

**Tasks E, F, G:** A method was devised to obtain three across-track profiles per ping cycle: a vertical profile and profiles on either side in the fore-aft direction.

This yielded a 3D spatial sampling of the seafloor with up to 123 soundings per ping cycle (41 soundings per profile) in a swath width of about  $147^\circ$  centered at nadir. In principle, up to 153 soundings are obtainable per ping cycle (51 soundings per profile), but soundings beyond  $\pm 75^\circ$  from nadir have low SNR and yield overly noisy bathymetry values. The three bathymetry profiles per ping were obtained by forming phasors from the conjugate product of adjacent across-track beam pairs (26 phasors forward and 26 phasors aft), and by further combining two such phasors along-track, and two or three such phasors across track. Results of Tasks A-G constituted Daniel Brogan's Master's thesis work (D.S. Brogan, "Narrow-beam monopulse technique for bathymetry and seafloor acoustic backscatter imagery with a volume search sonar", University of New Hampshire, MS Thesis, Dec. 2004).

In addition, a final report and the associated MATLAB software were delivered to NRL-SCC. (D. Brogan and C. de Moustier, "3D spatial sampling with a cylindrical multibeam sonar array", Final Report, Jun. 2005).

**Task H:** At NRL-SSC's request, MATLAB software written while performing Tasks A-G was updated and converted to C for improved execution speed. The corresponding software package and its documentation were delivered to NRL-SCC (POC Will Avera). (D. Brogan and C. de Moustier, "Upgraded seafloor detection algorithm for swath bathymetry applications of the Volume Search Sonar", Final Report, Sep. 2006.)

**Task I:** A preliminary analysis of the uncertainties in bearing estimates obtained with the monopulse and conjugate product processing techniques showed that such uncertainties are dominated by the signal-to-noise ratio at the output of the beams. Bearing angle uncertainties of  $0.5^\circ$  or less require an SNR in excess of 15 dB. The time allocated for this task (3 weeks) was not sufficient to quantify fully the effects of averaging on the difference phase estimates, which should be pursued in future work. (C. de Moustier, "Bearing estimation uncertainties for the Volume Search Sonar", Technical Report, Aug. 2009).

## 6. IMPORTANT FINDINGS AND CONCLUSIONS

The most significant result from this work is the ability to obtain 3 profiles of across-track bathymetry per ping cycle (e.g. Fig. 2), which provides full coverage at survey speeds of 25-30 knots. When compared to the output of standard swath bathymetry sonar systems specifically designed for that purpose, the VSS spatial sampling of the seafloor remains sparse and its bathymetry uncertainties are likely to be higher (de Moustier, 2009). However, the VSS seafloor mapping capabilities shown here are adequate for reconnaissance applications with combined bathymetry and seafloor acoustic backscatter imagery (Fig. 3).

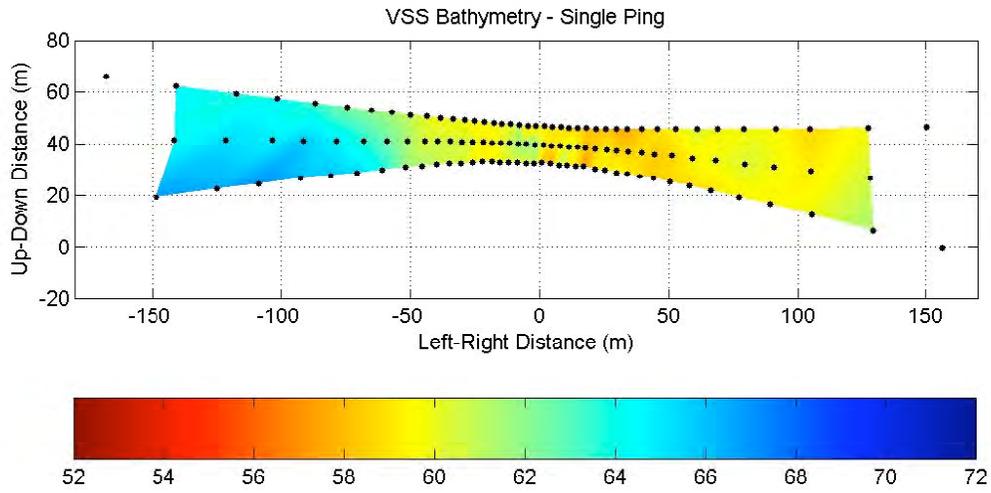


Fig. 2. VSS ping 3897 – Soundings (dots) obtained for one ping and corresponding bathymetry patch. Color bar is depth in meters (Brogan and de Moustier, 2005)

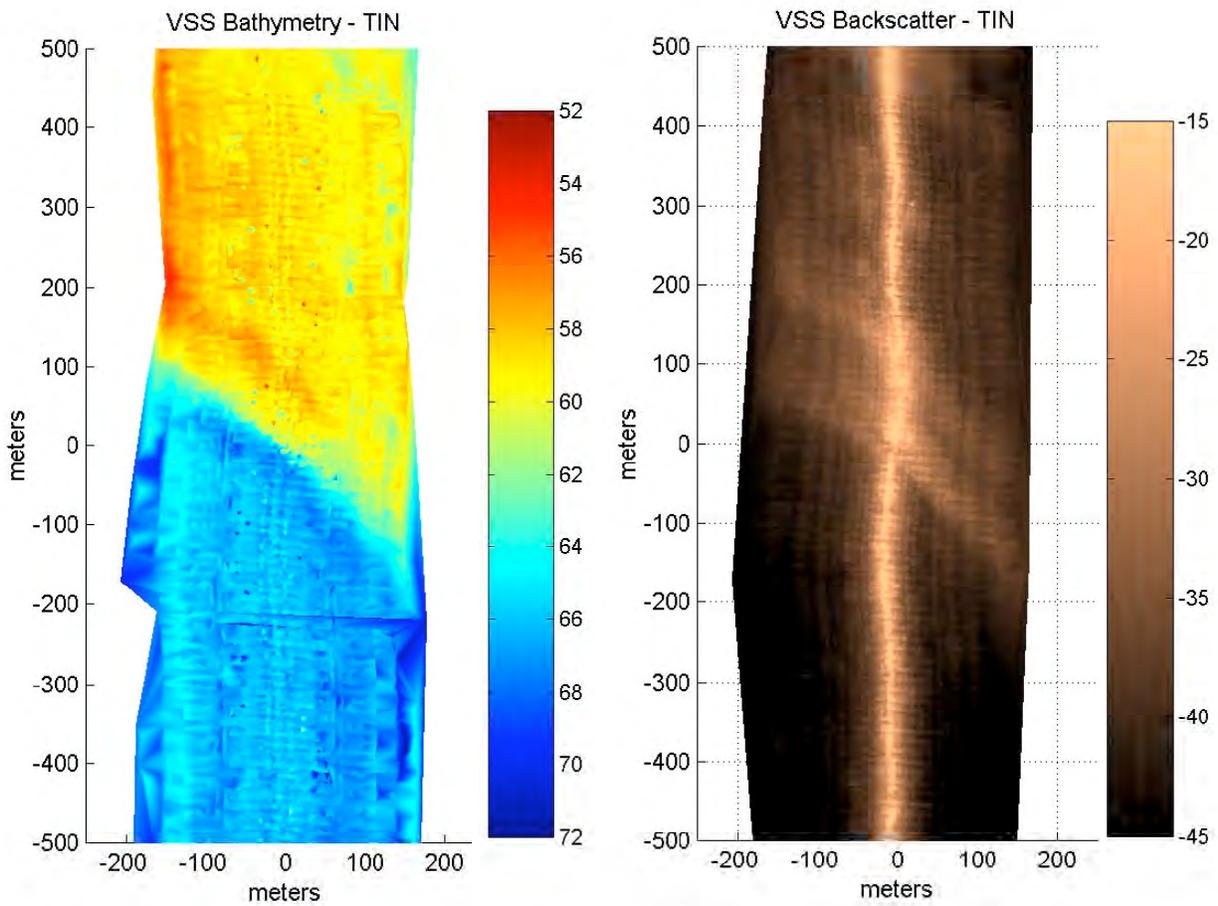


Fig. 3 Triangular Irregular Network (TIN) of (a) one swath of VSS bathymetry (color bar in meters) (a) and (b) locally normalized seafloor acoustic backscatter intensity (grey scale bar in dB). (Brogan and de Moustier, 2005).

## 7. SIGNIFICANT HARDWARE DEVELOPMENT

No hardware development occurred in the context of the work described here.

## 8. SPECIAL COMMENTS

Most of the work described here was the Master's thesis project of Daniel Brogan, Graduate Student in the Electrical and Computer Engineering Department at the University of New Hampshire. Additional funding for this work was provided by NOAA Grants NA170G228 and NAONOS4001153 that supported also Christian de Moustier who served as Thesis director and advisor.

D.S. Brogan, "Narrow-beam monopulse technique for bathymetry and seafloor acoustic backscatter imagery with a volume search sonar", University of New Hampshire, MS Thesis, 228 pp., Dec. 2004.

## 9. IMPLICATIONS FOR FURTHER RESEARCH

Further work is necessary to quantify the accuracy of the bathymetry obtained with the VSS and to streamline the data processing for realtime applications.

A minor modification of the beamforming methodology used to obtain fore-aft beam pairs would improve the usefulness of these beams. Instead of beam pairs with a common phase center, the beams in a fore-aft pair should be formed with different phase centers to be able to take advantage of the phase difference between them while estimating the time and direction of arrival of echoes returning between the pair.

The echo time and angle of arrival estimation techniques developed for this project are not restricted to bottom mapping. They are equally applicable to targets in the water column, potentially leading to more accurate detection and identification of mid-water targets.

## Published abstracts of presentations at meetings of the Acoustical Society of America

D.S. Brogan, and C. de Moustier, "3D spatial sampling with a cylindrical multibeam sonar array" (A), *J. Acoust. Soc. Am.*, 117(4-2), 2447, 2005. 2pEA8.

Various beam pair combinations can be formed with cylindrical multibeam sonar arrays to obtain a 3D spatial sampling of a patch of seafloor for each ping. This capability is explored with a  $286^\circ$  sector cylindrical array transmitting a stepped FM pulse over a  $243^\circ$  vertical fan beam centered on nadir and receiving with twenty-seven beam pairs, symmetrically steered about nadir in the fore-aft direction and spaced at  $7.16^\circ$  intervals across track. Conventional conjugate product techniques yield two across-track profiles of 26 soundings each (52 phasors total) per ping. However, by combining one or two phasors along-track and one, two or three phasors across-track, soundings can be obtained at the spatial bisectors of the angles between the 52 phasors. This yields three profiles consisting of 51 soundings each, for a total of 153 soundings. This effectively creates a 3D patch of detected seafloor for each ping, which may overlap with the patches from adjacent pings depending on the sonar's attitude changes and altitude above the seafloor. [Work supported by NRL-SSC grant N00173-00-1-G912 and NOAA grant NA170G228].

D. S. Brogan and C. de Moustier, "Bathymetry and seafloor backscatter imagery with a volume search sonar", (A), *J. Acoust. Soc. Amer.*, 115(5-2), 2547, 2004. 4aSP6.

Volume search sonars designed for mine hunting applications could be used for environmental sensing, particularly seafloor relief and texture. This capability is explored with a system that transmits a stepped FM pulse over a  $243^\circ$  vertical fan beam centered on nadir. It receives with twenty-seven pairs of beams, symmetrically steered about nadir in the fore-aft direction and spaced at  $7.16^\circ$  intervals across track. The receive beam pair geometry allows simultaneous views of the seafloor in forward, vertical, and aft profiles. Pulse compression, monopulse processing techniques, and temporal and spatial filtering are used to estimate bathymetry and seafloor acoustic backscatter imagery of a sandy bottom and a muddy bottom. Three monopulse techniques have been investigated: conjugate product, difference over sum, and reduced beamwidth, which is the most promising for this application. Results are presented for data collected while surveying at roughly 25 knots, showing the combined effects of acoustic geometry and survey speed on the resolution of the bathymetry and acoustic backscatter imagery and on bottom coverage. [Work supported by NRL grant No. N00173-00-1-G912].

## Technical Reports

C. de Moustier, "Bearing estimation uncertainties for the Volume Search Sonar", Technical Report, NRL-SSC Grant N00173-00-1-G912, 31 Aug 2009.

ABSTRACT: The Volume Search Sonar uses a cylindrical receiver array consisting of 40 staves of 9 elements each mounted parallel with the axis of the cylinder, itself aligned with the fore-aft axis of the towfish on which it is installed. 27 fore-aft beam pairs are formed with 27 sub-arrays of 16 contiguous staves. Previous work (Brogan and de Moustier, 2005; 2006) has shown that time and angles of arrival of seafloor echoes received at the VSS array can be used to obtain swath bathymetry and seafloor acoustic backscatter imagery. This report is a preliminary analysis of the uncertainties in estimation of the angles of arrival of bottom echoes received by pairs of VSS beams. In monopulse processing applied to fore-aft beams with common phase centers, a signal-to-noise ratio (SNR) in excess of 15 dB is necessary for the standard deviation of the angle estimate to remain below  $0.5^\circ$  in long-range mode ( $\pm 4^\circ$  about broadside), whereas an SNR in excess of 20 dB is required to obtain the same angular uncertainty in short-range mode ( $\pm 8^\circ$  about broadside). For the conjugate product processing applied to pairs of adjacent across-track beams with distinct phase centers, an SNR in excess of 24 dB is required to maintain the standard deviation of angle estimates below  $1^\circ$ , highlighting the need to improve such estimates by filtering the real and imaginary parts of the conjugate product output.

D.S. Brogan and C. de Moustier, "Upgraded seafloor detection algorithm for swath bathymetry applications of the Volume Search Sonar", Final Report, NRL-SSC Grant N00173-00-1-G912, 35 pp., September 2006.

ABSTRACT: High processing speed and high detection reliability are desirable attributes for algorithms designed to extract bathymetry and co-registered seafloor acoustic backscatter imagery from the echo time series collected with multibeam sonar systems. However, these are frequently found to be competing constraints. The goals of the work presented in this report were to upgrade the existing seafloor detection algorithm used with the Volume Search Sonar (VSS) of the AQS-20 mine countermeasure system by improving both the processing speed and the detection reliability. Tests conducted with the new algorithm on a VSS data set provided by the Naval Research Laboratory (NRL) showed that processing speed has been increased by a factor of five, with an additional doubling in speed obtained by converting the software from MATLAB to C code. Detection reliability has been improved as well by outlier removal and replacement, allowing a higher number of valid detections to be retained. [Work supported by NRL-SSC grant N00173-00-1-G912 and NOAA grant NAONOS4001153.]

D. S. Brogan and C. de Moustier, "3D spatial sampling with a cylindrical multibeam sonar array", Final Report, NRL-SSC Grant N00173-00-1-G912, 61 pp., June 2005

ABSTRACT: Various beam pair combinations can be formed with cylindrical multibeam sonar arrays to obtain a 3D spatial sampling of a patch of seafloor for each ping. This capability is explored with the volume search sonar (VSS) of the AQS-20. This sonar uses a cylindrical array transmitting a stepped FM pulse over a  $243^\circ$  vertical fan beam centered on nadir and receiving with twenty-seven beam pairs, symmetrically steered about nadir in the fore-aft direction, and spaced at  $7.26^\circ$  intervals across track. Phasors formed from the conjugate products of adjacent beam pairs yield two across-track profiles of 26 soundings each (52 phasors total) per ping. However, by combining one or two phasors along-track and one, two or three phasors across-track, it is demonstrated that soundings can be obtained at the spatial bisectors of the angles between the 52 phasors. This yields three profiles consisting of 51 soundings each, for a total of 153 soundings. This effectively creates a 3D patch of detected seafloor depths for each ping, which may overlap with the patches from adjacent pings depending on the sonar's attitude changes and altitude above the seafloor. This technique has been applied to field data collected with the VSS in the northern Gulf of Mexico with an 90.9% success rate over a swath width of  $149^\circ$ . [Work supported by NRL-SSC grant N00173-00-1-G912 and NOAA grant NA170G228.]

D.S. Brogan, "Narrow-beam monopulse technique for bathymetry and seafloor acoustic backscatter imagery with a volume search sonar", University of New Hampshire, MS Thesis, 228 pp., Dec. 2004.

ABSTRACT: Volume search sonars designed for mine countermeasure applications could be used for environmental sensing, particularly seafloor relief and texture. This capability is explored with a system that transmits a stepped FM pulse over a  $243^\circ$  vertical fan beam centered on nadir. It receives with twenty-seven pairs of beams, symmetrically steered about nadir in the fore-aft direction and spaced at  $7.16^\circ$  intervals across-track. The receive beam pair geometry allows simultaneous views of the seafloor in forward, vertical, and rear profiles. Pulse compression, monopulse processing techniques, and temporal and spatial filtering are used prior to the seafloor detection algorithm in order to improve the temporal and spatial resolution of the data. Three monopulse techniques have been investigated: conjugate-product, difference-over-sum, and narrow-beam. These techniques are used on both along-track and across-track pairs of adjacent beams. A seafloor detection algorithm using the data from narrow-beam monopulse processing applied to along-track beam pairs is derived in order to estimate the bathymetry and seafloor acoustic backscatter imagery. Results are presented for data collected in two test areas while surveying at roughly 25 knots, showing the combined effects of acoustic geometry and survey speed on the derived bathymetry and seafloor acoustic backscatter imagery and on bottom coverage.

D.S. Brogan and C. de Moustier, "Bathymetry and seafloor acoustic backscatter imagery with the Volume Search Sonar", Progress/Technical Report, NRL-SSC Grant N00173-00-1-G912, 18 pp., 4 June 2004.

ABSTRACT: This report summarizes the progress toward assessing the bathymetry and acoustic backscatter imaging capabilities of the Volume Search Sonar (VSS) mounted on the AQS-20 system as it was presented at the spring 2004 Acoustical Society of America meeting. This report describes some of the initial attempts at deriving bathymetry and acoustic backscatter imagery from data collected during AQS-20 sea tests. The beam pattern and transmission signal simulation analyses carried out with MATLAB software tools are covered in a cursory manner since detailed results on these topics can be found in previous reports (Feb. 2003, Oct. 2003). Monopulse processing has been added subsequent to matched filtering as a method of improving angle of arrival estimates by comparing adjacent beams. Three monopulse techniques – conjugate product, difference-over-sum and narrow beam – are described for use with along-track and across-track beam pairs. The initial bathymetry and acoustic backscatter imagery presented here use the narrow-beam approach on along-track beam pairs. The acoustic backscatter imagery shows potential for detecting variations in sediment type in much the same manner that a sidescan sonar detects these variations. However, this data is collected at a towing speed of 25-30 knots (12-15 m/s), which far exceeds that of the standard sidescan system. Finally, the potential of the monopulse techniques to yield three profiles from each ping is considered.

D. Brogan and C de Moustier, "Volume Search Sonar (VSS) beam pattern simulations", Progress/Technical Report, NRL-SSC Grant N00173-00-1-G912, 46 pp., 21 Oct. 2003.

ABSTRACT: The purpose of this work is to assess the bathymetry surveying capabilities of the Volume Search Sonar (VSS) mounted on the AN/AQS-20 system. This report describes initial attempts at deriving bathymetry from data collected during AN/AQS-20 sea tests. Results from a detailed matched filter design analysis and signal simulation study, carried out with MATLAB software tools, are presented and incorporated with results from a previous detailed beam pattern analysis and simulation study. Nominal frequencies of 35 kHz and 38 kHz were chosen for various parts of this study, yielding realistic estimates of the beam patterns and signal characteristics in simulation that agreed with measurements provided by the sonar manufacturer. An initial bathymetry calculation was implemented, which suffered from increasingly noisy estimates towards the outer beams.

C. de Moustier and D. Brogan, "Volume Search Sonar (VSS) beam pattern simulations", Progress/Technical Report, NRL-SSC Grant N00173-00-1-G912, 13 pp., 20 Feb. 2003.

**SUMMARY:** In order to assess the bathymetry surveying capabilities of the Volume Search Sonar (VSS) mounted on the AN/AQS-20 system, a detailed beam pattern analysis and simulation study has been carried out with MATLAB software tools. The goals of this study were to provide visualization tools to describe the main lobe and sidelobe structures of the various beamformed modes of operation used in the VSS. A nominal frequency of 35 kHz was chosen for this study, yielding realistic – though not exact – estimates of the beam patterns. Initial results indicate potential sidelobe interference issues for swath bathymetry and volume search applications, particularly in the transmit beam patterns and the short-range volume receive beam patterns.

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