INTERFEROMETRIC SYNTHETIC APERTURE SONAR FOR SMALL DIAMETER UNMANNED UNDERWATER VEHICLES

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1. INTRODUCTION

Interferometry is a technique used to exploit the principle that coherent energy emitted or scattered by some source traveling along separate paths constructively or destructively interferes when combined. Measurements of the relative phase between the paths give an accurate estimate of the difference in path lengths from the source or scatterer. In the case of interferometric sonar, the receivers are a pair (or more) of vertically displaced hydrophones as seen in Fig. 1. In this diagram, the sea floor is insonified and scatters sound that is subsequently received by a pair of hydrophones. The path difference, Δr, is observed as a time delay or phase shift in the signals recorded by the hydrophones. From this diagram we see that the delay is a function of height above the sea floor. Using the geometry defined in Fig. 1, we can write for the receiver height h,

$$h = r\cos\phi \tag{1}$$

where ϕ is given by the law of cosines as,

$$\phi = \arccos\left(\frac{(r+\Delta r)^2 - B^2 - r^2}{2Br}\right) - \theta \tag{2}$$

and where $\Delta r = c\Delta t = c\frac{\Phi}{f_0}$, where c is the speed of sound, Φ is the measured relative phase shift, and f_0 is the center frequency of the transmitted signal.

By applying interferometric processing to synthetic aperture sonar we are able to estimate the relative bathymetry of a scene. The local bathymetry can be used to remove the "planar bottom" assumption associated with displaced phase center motion estimation. This allows for more accurate estimation of unwanted vehicle motion prior to beamforming. In addition to improving motion estimation routines, bathymetry of sufficient resolution is useful for object detection and classification. Computer aided detection and classifications routines can improve their performance by using the additional information provided by an InSAS.

2. SYSTEM DESCRIPTION

The Bathymetric Reconfigurable Navy Sonar or BaRNS is an interferometric synthetic aperture sonar designed to fit within a 12.75-inch payload housing mounted to a Remus 600. The projector

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will consist of an array with 32 columns of 8 elements. This array will be wired into 8 channels symmetrical about the array center, and each channel will consist of four columns of 8 elements each (2 adjacent columns each to the left and right of center). This design will allow us to broaden the main beam to a suitable width depending on the receive element size. The center frequency of the projector will be 120 kHz and it will be capable of transmitting signals over a 60 kHz bandwidth up to 10 ms in length with a source level of 215 dB re 1μPa at 1 m.

The receive array will consist of a pair of identical four row, eighty element arrays, with 6.35e-3 m square elements. With a total array length of approximately 0.5 m and a vehicle speed of 1.5 m/s, the imaging range of the system is 125 meters. The 640 individual elements will be brought to a wiring board for element grouping before being passed to a 160 channel digitization system. The wiring board allows the user to reconfigure the channels in the receive array between missions. For example, the array pair can be divided into eight rows of 5.08 cm elements, giving 2.54 cm along track resolution at full range and the ability to vertically steer both main arrays. Wiring all elements vertically, while leaving half of the along track unwired permits 1.27 cm 2D resolution out to 60 meters while still maintaining the ability to interferometrically process the data.

A simple schematic of the system is shown in Fig. 2. The current design of the system places the center to center baseline of the main arrays at 0.254 m or 20.3λ. The projector is currently placed on a wedge extending beyond the plane of the receive arrays in order to provide room for the electronics payload. The wedge will provide some baffling against surface multipath for the lower array, while scattering from the wedge may be a problem for the upper array. We are currently simulating this design to ensure the protrusion does not adversely impact the performance of the upper array.

3. PREDICTED PERFORMANCE

Two general methods of height estimation from interferometric sonars exist: interferogram based and correlation based. In the former, the phase difference between a pair of SAS images is calculated on a pixel by pixel basis forming an interferogram. This interferogram, which is a modulo-2π wrapped image of the phase shift, is unwrapped and converted to a height map. By contrast, correlation based processing uses short-time fourier transforms to estimate time delay over a given range window. These delays are then directly converted to a bathymetric map. The correlation based approach is advantageous because image co-registration and phase unwrapping necessary in interferogram based processing are avoided. For this paper, we will only consider correlation-based processing.

The Cramer-Rao lower bound on the estimate of the height obtained in correlation based processing is

$$\sigma_h \approx \frac{r}{k_0 B} \frac{1}{\sqrt{B_w T}} \sqrt{\frac{1}{\rho} + \frac{1}{2\rho^2}}, \tag{3}$$

where k_0 is the wavenumber at the center frequency, B_w is the bandwidth of the system, T is the temporal length of the window used, and ρ is the local signal to noise ratio [1]. In Fig. 3, equation (3) is evaluated with the parameters of BaRNS at a range of 35 m for several SNRs. A simulation was carried out using the Shallow Water Acoustics Tool-set [2] to estimate the

SNR of the system, Fig. 4. The simulation considered multipath, volume reverberation, and baseline decorrelation for a vehicle in 20 m of water at 7 m altitude. Baseline decorrelation is described by Jin and Tang as the effect produced by coherent scattering from multiple targets within a given resolution cell [3]. As the angle of observation changes for a given resolution cell, the complex return will change. For BaRNS the small vertical separation of the receive arrays prevents baseline decorrelation from having a noticeable effect on this system. At short ranges volume reverberation limits the SNR of the system, while at longer ranges multipath is dominant. From Fig. 4 BaRNS will have greater than 15 dB SNR out to 35 m. This should enable us to estimate the bathymetry to within 2.5 cm.

A simulated image for this sensor is shown in Fig. 5 [4]. In this image, a pair of cylinders are shown at two different aspects. The cylinder at -2.5 m along track is 3.25 m long and has a max height above the bottom of 0.57 m while the other cylinder is 2.9 m long with a max height of 0.4m. This scene is processed to 2.54 cm resolution in along track and 1.27 cm in range. The bathymetry of this scene is estimated using 0.5 m windows, and the result is shown in Fig.6. In this estimate of the bathymetry the performance agrees wells with the prediction made by (3).

4. CONCLUSION

We have presented a design for an interferometric synthetic aperture sonar based on a small UUV form factor. Simulations of the SNR and imaging performance of this system show that acceptable performance is achievable even with a reduced baseline. With a user reconfigurable receive array we will be able to experimentally determine the optimal configuration for an interferometric SAS as well as to investigate limitations on standard SAS image formation.

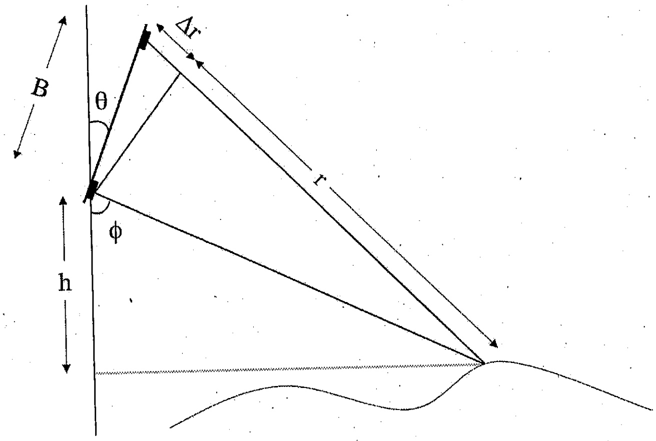

Figure 1: Schematic of an interferometer with parameters defined. Note that we define θ, the array depression angle, relative to zenith.

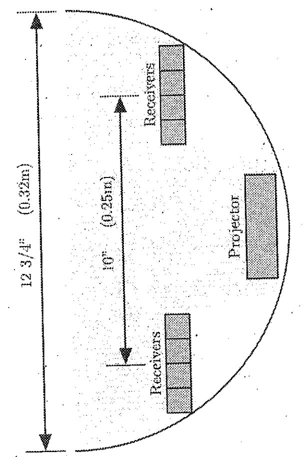

Figure 2: Cross-section of the BaRNS array (not to scale). The system will consist of two identical 4 row by 80 column element receive arrays with 6.35 mm square individual elements. The transmitter will be a single 8 row by 32 column array wired into 8 channels symmetric about the array center with 4 columns per channel with two each to the left and right of center. The system will operate over $90\mathrm{kHz} - 50\mathrm{kHz}$ which give a baseline of 20.3λ at the center frequency

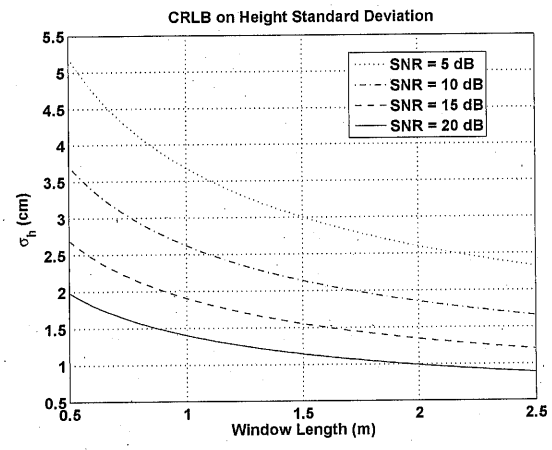

Figure 3: Cramer-Rao lower bound on estimation of height for BaRNS.

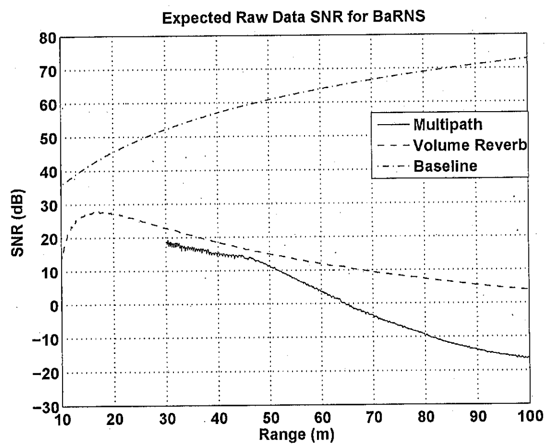

Figure 4: Simulated SNR for BaRNS, including baseline decorrelation, volume reverberation, and multipath.

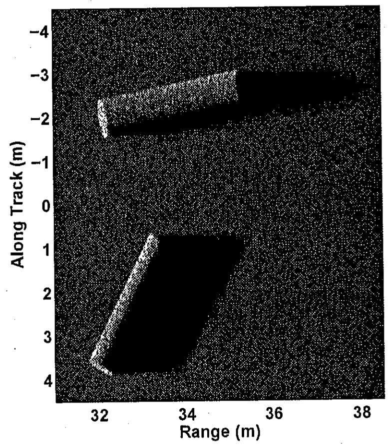

Figure 5: Simulated Image for BaRNS

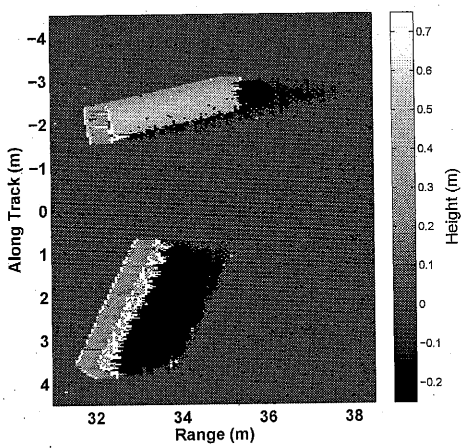

Figure 6: Bathymetry based on image shown in Fig. 5. Point target is highlighted by dashed line.

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