Synthetic Aperture Sonar Beam Forming in the Presence of Internal Waves

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LONG-TERM GOAL

The long term goal of our research is to incorporate environmental estimation and compensation methods into the synthetic aperture sonar (SAS) image formation process. Specifically mitigate shallow water environmental effects causing a degradation in image resolution through space/time variations in the sound speed field, e.g., internal waves, turbulence, bathymetry.

OBJECTIVES

The current focus of our research is to develop an algorithm to compensate for the effects of linear internal waves during the formation of a synthetic aperture in a shallow water environment. Internal waves impact the propagation of the acoustic signal and consequently the phase by changing the space time structure of the sound speed field. Our intent is to model this phase change due to internal waves, with the challenge of developing a methodology to remove this internal wave induced phase variation as a part of the formation of the synthetic aperture.

APPROACH

Our research objectives are consistent with the goals of the SAS PRIMER experiment which is affiliated with the overall Coastal and Mixing Optics Experiment conducted during 1996, [1]. The experimental emphasis is on: hi-frequency acoustic propagation through shallow water internal waves and SAS beam formation, characterizing linear and nonlinear shallow water internal waves.

The specific approach we are taking is to first construct a simulation of the phase history of a point target in the presence of an internal wave field, with initial emphasis on linear internal waves. The model is a combination of ray theory using the Gaussian beam method, [2], and generating a realization of a sound speed field perturbed by linear internal waves through which the rays propagate. The primary inputs are sound speed and Brunt-Vaisala (BV) frequency profiles derived from in-situ measurements obtained at the PRIMER SAS experimental site, [3], [4].

We intend to use the synthetic phase history as an aid in developing a simple forward model that comprehends the internal wave phase perturbation and embed the forward model in a beam formation algorithm. The forward model consists of a simplified Gaussian beam ray trace formulation with a depth dependent only sound speed profile as the zeroth order unperturbed propagation model, and a Rytov approximation to include the internal wave effects as a phase perturbation. As an initial test we

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will use the time delay, sensor navigation and angle of arrival series along the synthetic aperture as the synthetic data from which the forward model parameters are estimated.

WORK COMPLETED

We have constructed the simulation of the point target return in the presence of the internal wave field as a generator of synthetic time delay and phase history inputs. An example of the point response functions with no compensation in the azimuth compression is shown in Figure 1 along with the sound speed and BV profiles. The point response functions correspond to the following environments: iso-velocity sound speed profile, depth dependent only sound speed profile, sound speed profile with internal wave effects. The azimuth compression uses the sound speed value at the sensor location. The point response function for the iso-velocity environment is the ideal result with no uncompensated effects in the phase history. The point response functions for the synthetic data inputs with the depth dependent only sound speed profile and the case with internal waves included illustrate the resolution loss due to uncompensated phase variations.

We examined dependencies on internal wave vertical modes, wave number components parallel and perpendicular to the synthetic aperture. Illustrated in Figure 2 is the sensitivity of the autocorrelation function of the residual phase signal and the point response function on the number of vertical modes in the internal wave field. The residual phase signal is a phase function with an argument equal to the difference between the synthetic time delay phase and the phase used in the azimuth compression. The autocorrelation function provides a measure of the coherence across the aperture. From the figure we see the lowest order modes seem to capture the primary features resulting in loss of coherence. With respect to the wave vector components of the internal wave field parallel and perpendicular to the synthetic aperture, we found the point response function and residual phase autocorrelation function are most sensitive to the longer wavelengths with minimum values on the order of 17 % of the synthetic aperture and 25 % of the closest approach distance between the sensor and target. As expected from intuition the longer wavelength internal waves propagating parallel to the synthetic aperture are the most important of the two directions regarding loss of azimuth beam focusing.

We installed and tested an algorithm that estimates the zeorth order sound speed model and internal wave parameters using as input the direct path time delay series, sensor trajectory, and arrival angle for a point target. The algorithm is based on a least squares procedure that includes a search over target location during the estimation of the zeroth order sound speed model parameters. The internal wave parameters are then estimated from the difference between a predicted time delay using the zeroth order model and the synthetic time delay data. Shown in Figure 3 are the point response function and residual phase autocorrelation functions with and without environmental compensation. The compensated result shows a significant increase in resolution, comparable to the ideal calculation.

RESULTS

We made the following observations using the simulation:

- Broadening in the main lobe of the point response function due to environmental mismatch
  - resolution loss from mismatch with depth dependent only sound speed profile
  - internal wave effects significantly amplifies reduction in resolution

- Increased side lobe levels arising from environmental effects

- A subset of the internal wave modes are the primary contributors to resolution loss
  - the lowest order vertical modes determine synthetic aperture coherence loss
  - the longer wavelength components (> 17 % of aperture length from limited tests) propagating along the aperture are most important

We constructed a forward model with sound speed and internal wave parameters to use as a means of compensating the internal wave effects assuming the ideal data input which includes the synthetic time delay series from a point target along the synthetic aperture.

- Tested a forward model estimation concept on ideal synthetic data input consisting of: time delay, receiver location, angle of arrival series for a point target return.
  - simple forward model captures primary structure in time delay series
  - internal wave forward model with a limited number of parameters captures main internal wave features in synthetic time delay series
  - used the forward model estimate to compensate internal wave phase variations in a simple delay and sum azimuth compression scheme with synthetic phase history input from a point target return

IMPACT/APPLICATION

The development of a compensation scheme for environmental effects is important for the situations when moderately hi-frequency sonars are working at longer stand off ranges that require increased resolution for the detection and classification of objects lying on the bottom. We have examined linear internal waves as one environmental source of resolution loss in the formation of a synthetic aperture beam. Continuing development of a compensation scheme can lead to improved beam formation algorithms with increased resolutions and with environmentally adaptive capabilities to estimate and mitigate the defocusing effects of internal waves.

TRANSITIONS

There are currently no actions being taken to transition the results of this work to other projects

RELATED PROJECTS

1) The shallow water internal wave characterization being done by Murray Levine at OSU has provided the initial sound speed and BV profiles used in the simulations along with the initial characterization of the linear internal wave shallow water spectrum

2) The analysis of SAS PRIMER acoustic data by UW/APL to determine the impact of internal waves on beam formation across an array of hydrophones on a tower, and on acoustic wave propagation

3) Analysis of data obtained from a tow fish during the SAS PRIMER experiment by NRL Stennis with the intent of studying synthetic aperture formation in the presence of internal waves.

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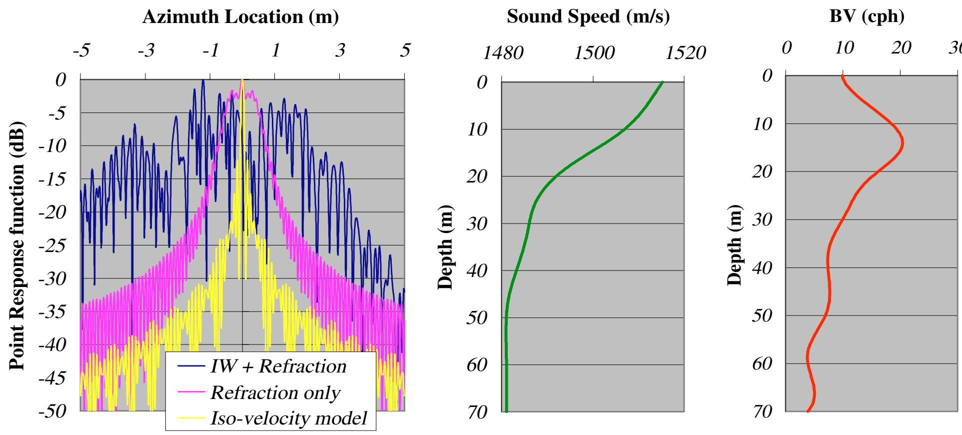

- *internal wave field contains 5 lowest vertical modes*
- *iso-velocity model has no refraction and no Internal Waves, constant sound speed value = 1500m/s*
- *aperture length: 375m, center frequency: 20kHz*
- *receiver depth: 20m, emitter depth: 55m, receiver speed: 1m/s*
- *minimum ground range distance: 500*

Figure 1: point response functions from a SAS simulation illustrating the result of uncompensated environmental effects. The three point response functions correspond to:

1) ***an iso-velocity environment (equivalent to perfect compensation for all variations in the sound speed profile)***

2) ***an environment with a depth dependent only sound speed profile from PRIMER experiment in situ measurements (uncompensated refractivity effects, equivalent to removing internal wave effects)***

3) ***an environment with a sound speed profile including perturbations from simulated linear internal waves (equivalent to no compensation for refractivity or internal wave effects)***

The case shown corresponds to a towed passive SAS at a depth of 20m and a sound source with a center frequency of 20kHz at a depth of 55m. The point of closest approach between the towed receiver and emitter in ground range is 500m. The length of the synthetic aperture is 375m formed over a 375sec time period. The internal wave contributions are modeled from BV and sound speed profiles obtained from the PRIMER experiment and provided by Murray Levine, along with parameters estimated from the pre-experimental numbers contained in reference 1. The depth of the receiver is near the maximum value of the BV profile used in the simulation. As seen in the figure, a refracting environment with or without internal waves can degrade the azimuth resolution of the SAS. The inclusion of internal waves degrades the resolution and can create high side lobes resulting in much higher reverberation. The figure shows the potential improvement in SAS resolution when environmentally induced phase distortions in the echo are compensated for. The significance of the internal wave effects depends on the operating parameters of the SAS along with environmental conditions.

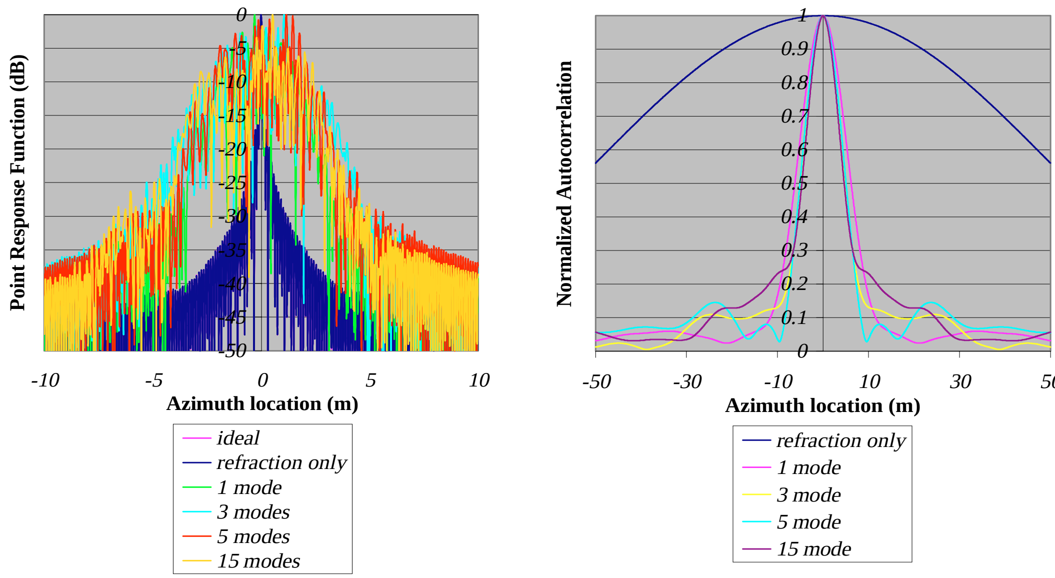

Figure 2: point response functions and normalized autocorrelation of residual phase parameterized by number of vertical modes. 2π/640m < k-horizontal < 2π/20m

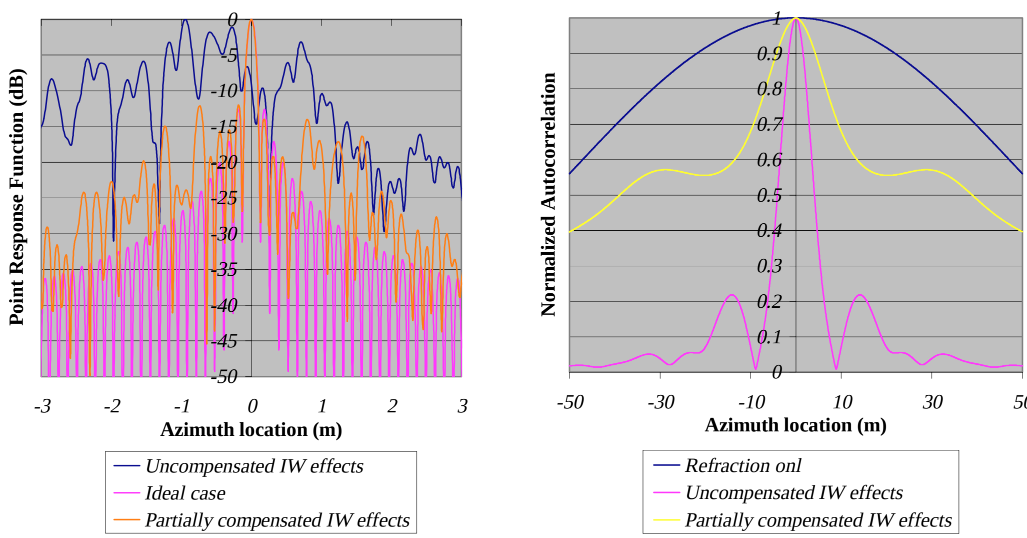

Figure 3: point response functions and normalized autocorrelation of residual phase for refraction only, uncompensated internal wave effects, and partially compensated internal wave effects. Internal wave field contained 5 vertical modes, and 128x128 horizontal wave numbers per mode, 2π/1280m < k-horizontal < 2π/20m. IW field used for compensation contained 1 vertical mode, and 39x9 horizontal wave numbers, 2π/1280m < k-horizontal <