MODELLING PULSE-TO-PULSE COHERENT DOPPLER SONAR

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1. INTRODUCTION

Pulse-to-pulse coherent Doppler sonar can provide current profile information over ranges of order 1 m with sub-cm resolution, see for example (Zedel et al. 2002, Vagle et al. 2005). The analysis of the data is however complicated by the occurrence of range and velocity ambiguities (Brumley et al. 1990). These complications greatly restrict the general use of coherent Doppler to situations where one or both of the ambiguity problems can be constrained. Given the difficulties of working with coherent Doppler, design for any application is critical. A valuable tool in the design process is the ability to accurately model the system before committing to hardware. This paper reports on a computer model that can generate pulse-to-pulse coherent backscatter data. The model is used to simulate data that is compared to calibration data from a 1.7-MHz coherent Doppler sonar.

2. SONAR OPERATION

The phase of acoustic backscatter is determined by the geometric configuration of scatterers relative to the acoustic source and receiver. In coherent sonar, backscatter phase is compared between successive pulses. Coherent motion of the scatterers leads to a deterministic change in phase that is related to the speed of the scatterers. For backscatter geometry, the velocity radial to the transducer is given by

$$V = \frac{\Delta\phi}{\Delta t} \times \frac{C}{4\pi f}, \qquad 1$$

where $\Delta\phi$ is the change in phase, Δt is the time between pulse transmissions, C is the speed of sound, and f is the operating frequency of the sonar.

Equation 1 is only valid if the backscatter from successive pulses is coherent. The presence of turbulence (leading to incoherent scatterer motion) and the motion of the scatterers through the acoustic sample volume lead to decorrelation.

3. MODEL DESIGN

In order to simulate coherent sonar operation, it is necessary to accurately reproduce backscatter that retains a coherent component but one that also accurately represents those processes that act to de-correlate the backscatter. The approach taken here is to model individual scatterers as randomly arranged point targets each assigned a velocity from a prescribed velocity structure. A similar approach has been used in modelling backscatter from blood in medical Doppler applications (see for example Mo et al. 1992). The velocity structure allows for both a deterministic (time dependent) and random component to be included. The point targets are introduced into a (three dimensional) domain that is larger than the region sampled by the sonar (see Figure 1). Targets eventually drift out (down-stream) of the sample domain and are then replaced by new particles introduced on the upstream side: the total number of targets in the domain remains constant.

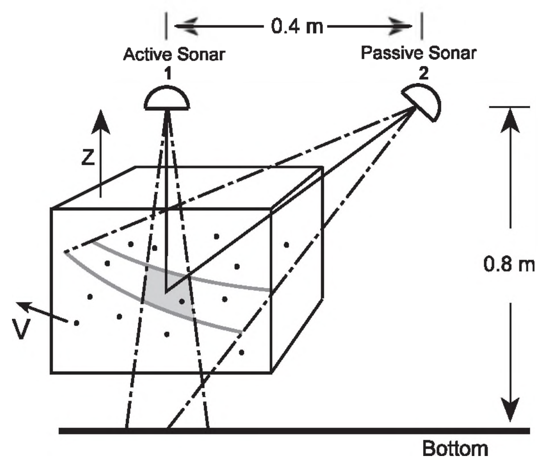

Fig. 1. Model rectangular domain is shown as it might be arranged with a bistatic sonar system. The dot-dash lines indicate sonar beams; point target scatterers are indicated as dots.

The acoustic backscatter is constructed by adding up contributions from each target in the domain accounting for the source-target-receiver geometry and transducer beam-patterns. Each target contributes a return pulse that is an amplitude-scaled replica of the (bandwidth limited) transmit pulse. The total return is given as

$$S(t) = \sum a_i s\left(t - \frac{(r_{si} + r_{ri})}{C}\right), \qquad 2$$

where the summation is over all particles in the model domain, a_i is the backscatter amplitude of the i'th target, $s(t)$ is the transmit pulse template, t is the time since the pulse transmission, r_{si} and r_{ri} are the source-target and target-receiver distances, and C is the speed of sound in water. A simplification incorporated into Equation 2 is the absence of any time scaling associated with the Doppler shift of the moving particles. The backscatter signal from each scatterer is therefore the same saving a great deal of computation. Coherent Doppler is concerned with the changes between successive acoustic returns so that the absence of a Doppler shift on a single return does not affect the results (see discussion by Bonnefous and Pesque 1986).

Once the backscatter signal is generated, it is processed through simulated analog receiver circuitry and digitised to create the final (simulated) sonar data.

4. MODEL VALIDATION

The reliability of the model was validated both by assessing its performance relative to expected backscatter characteristics and also through comparisons with calibration test data for a 1.7-MHz coherent sonar.

Backscatter Statistics

The statistics of acoustic backscatter are such that phase should be uniformly distributed and amplitude should follow a Rayleigh distribution. Figure 2 shows phase and amplitude statistics for a model realisation accurately reproducing the expected statistics.

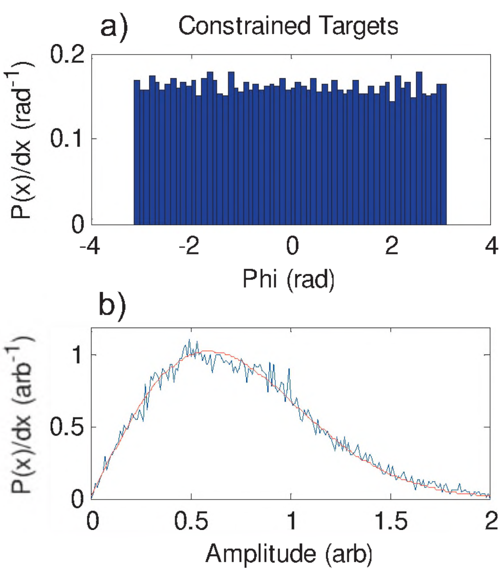

Fig. 2. Model backscatter statistics: a) backscatter phase, and b) backscatter amplitude. The solid (red) line represents a best-fit Rayleigh distribution.

Data Comparison

Calibration data collected with a 1.7-MHz coherent Doppler sonar was available to provide a reference with which to compare model output (Zedel et al. 1994). In coherent Doppler sonar, the quality of velocity estimates is determined by the correlation in backscatter between successive pulses. Aside from system noise and real velocity turbulence at scales below the resolution of the sonar system, decorrelation is determined by the beam patterns and flow geometry (see Zedel et al. 1994). The model was configured to reproduce the geometry of those calibration tests and the excellent agreement between model and experiment is shown in Figure 3.

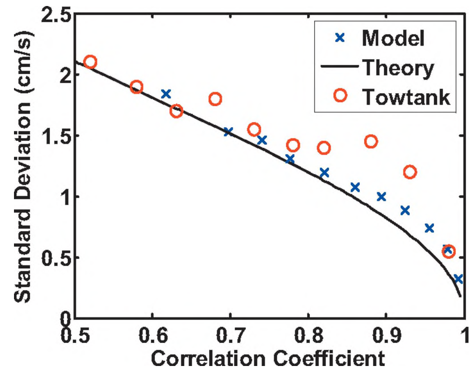

Fig. 3. Comparison of model output, towtank trials and theoretical predictions for the relationship between velocity standard deviation and pulse-to-pulse correlation coefficient.

5. CONCLUSIONS

A model of acoustic backscatter based on point targets that reflect an amplitude scaled copy of the transmit pulse can reproduce volume backscatter that retains the critical characteristics of pulse-to-pulse coherent sonar. This model provides a valuable tool in developing a new generation of coherent Doppler sonar.

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