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Turbulence Measurement with Coherent Doppler Sonar

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1 Project Narrative

1.1 Introduction

The ocean has been described as Earth's "final frontier" in a vision statement on ocean exploration (National Oceanic and Atmospheric Administration, 2000). The search for new insight is motivated by the fact that our environmental and economic security depends critically on the ocean and the freshwater bodies that drain into it. As the vast majority of the ocean is unknown and unexplored, there is great potential for scientific discovery beneath the sea surface (McNutt, 2002). The development of remote and *in situ* sensors forms a cornerstone of this vision for exploring ocean dynamics at new scales.

Pulse-to-pulse coherent Doppler sonar has been widely used to study transport and mixing processes in the ocean. Examples include tidal flows, surface boundary layer processes, surface wave breaking, internal waves, sediment transport, and turbulence measurement. High frequency (1 to 10 MHz) coherent Doppler sonar is a promising tool for obtaining near-bed profiles of shear stress and sediment flux in the ocean bottom boundary layer (Thorne and Hanes, 2002). Recent studies have focused on the estimation of bottom friction from acoustic Doppler measurements of near-bed turbulence profiles (Hay, 2008).

The performance and limitations of coherent Doppler sonar have been explored through numerical simulations and in the laboratory. Measurement errors have been found to be caused by pulse-to-pulse backscatter decorrelation from: (i) scatterer advection through the sample volume, (ii) velocity shear and turbulence within the sample volume, (iii) phase distortion of the transmitted wave, and (iv) electronic noise in the receiver circuitry. Coherent Doppler sonar measurements are also limited by the existence of velocity ambiguity when the radial component of scatterer velocity exceeds one quarter wavelength per pulse-to-pulse interval. Measurement errors introduce biases when calculating turbulence statistics from the fluctuating component of velocity measurements. Therefore, to further develop coherent Doppler sonar as a tool for turbulence measurement, it is necessary to suppress measurement noise while resolving velocity ambiguity.

This project aims to improve instrumentation for studying near-bed turbulence and sediment dynamics by developing an optimal velocity estimator for coherent Doppler sonar.

An optimal algorithm would extract all of the information available in multi-frequency and multi-transducer Doppler measurements while simultaneously resolving velocity ambiguity and suppressing measurement noise. Optimal velocity estimation would be especially useful for measurements in highly turbulent flow exhibiting backscatter decorrelation and velocity ambiguity. The anticipated long-term benefits of this research are: (i) a better understanding of the physical processes that affect sediment transport; and (ii) improved tools for monitoring shoreline erosion, sedimentation of waterways, and siltation of benthic habitats in coastal and riverine environments. Velocity ambiguity and measurement noise are also present in Doppler weather radar, coherent Doppler lidar, and medical ultrasound. New methods for Doppler signal processing may benefit these related fields as well.

1.2 Results

Existing methods for Doppler velocity estimation have considered noise suppression and velocity ambiguity resolution separately. However, the presence of measurement noise complicates ambiguity resolution, and vice versa, velocity ambiguity presents a challenge for noise suppression methods. Maximum A Posteriori (MAP) estimation was applied to estimate velocity for coherent Doppler sonar for the purpose of suppressing noise and resolving velocity ambiguity simultaneously, rather than separately. The estimation algorithm optimally combines multi-frequency and multi-transducer measurements. Data fusion has been achieved using a probabilistic approach, whereby measurements are combined numerically to derive a velocity likelihood function evaluated on a discrete grid.

The MAP velocity estimator shares many similarities with a Kalman smoother: (i) the estimator processes a time series sequentially using a recursive formulation, (ii) a model is used to provide prior statistical knowledge, (iii) the estimator produces its own performance measure, and (iv) estimator lag is eliminated via forward and backward filtering. However, unlike the Kalman smoother, the MAP velocity estimator makes use of non-Gaussian probability density functions and is inherently nonlinear. The motivation for using MAP estimation is that velocity ambiguity causes the velocity likelihood function to be multi-modal; thus a Gaussian representation is inappropriate. Also, secondary peaks in the likelihood function would bias a minimum mean square error estimator, whereas MAP estimation correctly selects the most likely peak of the posterior distribution.

The estimation framework accommodates commonly used sonar geometries such as one-dimensional single beam systems, acoustic Doppler current profilers (ADCPs) with divergent beams, three-dimensional velocity point sensors, and profiling sonars. The estimation algorithm depends solely on the physical parameters of the sonar and is free from empirically determined instrument-specific and application-specific thresholds and constants. While the focus of this work has been on multi-frequency coherent Doppler sonar, the results are equally applicable to single-frequency and staggered pulse repetition frequency (PRF) systems.

The MAP velocity estimator has been evaluated using numerical simulations of flows with known velocity and laboratory experiments under realistic and challenging operating conditions. Numerical simulations with the coherent Doppler sonar model described in Zedel (2008) were used to validate the probability distributions for autocorrelation phase and magnitude, and to evaluate performance of the MAP velocity estimator using simulations of steady and oscillating flow. Simulations of steady flow produced statistically stationary time series that confirmed the validity of a theoretical model based on a complex Gaussian backscatter distribution. For oscillating flow, the MAP velocity estimator was shown to resolve velocity ambiguity resolution while suppressing measurement noise caused by scatterer advection through the sample volume.

A series of laboratory experiments were undertaken to evaluate the performance of the MAP velocity estimator in increasingly challenging measurement environments. Measurements from the sonar described in Hay et al. (2008) were collected in steady uniform flow in a towing tank. As the towing carriage speed was varied between zero and 3.0 m s^{-1}, velocity ambiguity was introduced gradually until autocorrelation phase wrapping was present on all frequency channels, with some channels experiencing multiple wraps at $\pm\pi$ radians. Analysis of the experimental data showed that the MAP velocity estimator correctly resolved velocity ambiguity for all towing carriage speeds.

Next, additional backscatter decorrelation was introduced with a turbulence-generating grid installed upstream of the towing carriage, resulting in a data set where velocity ambiguity and measurement noise were present simultaneously. Time series and turbulence spectra from MAP velocity estimation were compared to those obtained with conventional Doppler signal processing. In addition to robustly resolving velocity ambiguity, the MAP velocity estimator was shown to lower the noise floor in turbulence measurements.

Finally, a very challenging data set was obtained in a turbulent jet experiment where low scatterer concentration and high turbulence intensity resulted in weak pulse-to-pulse correlation. Velocity was measured simultaneously with multi-frequency coherent Doppler sonar and particle image velocimetry (PIV). Time series and turbulence spectra from PIV were compared to those obtained with conventional Doppler signal processing and MAP velocity estimation. It was shown that optimally combining multi-frequency measurements results in improved velocity estimates in a highly turbulent flow with low signal-to-noise ratio, i.e. conditions in which coherent Doppler sonar does not normally perform well.

The MAP velocity estimator combines measurements according to their probability distributions. A key aspect of this project has been to quantify the distribution of velocity measurement error in terms of the magnitude of a pulse-to-pulse autocorrelation coefficient. The coefficient is calculated from a finite ensemble of backscatter samples and is similar in form to the expected value in the definition of autocorrelation. A new formula was derived for the asymptotic form of the autocorrelation coefficient. The autocorrelation coefficient was shown to be a biased estimator in the limit of infinite ensemble length. Numerical simulation of a Gaussian random process was used to verify the asymptotic formula and to show that a bias persists for finite pulse-pair averages. Validity of the asymptotic formula was also confirmed using the high fidelity coherent Doppler sonar simulation described in Zedel (2008), and from sonar measurements in the towing tank experiment. It was shown that the distribution of observed autocorrelation coefficients is well-predicted by a Gaussian random process once the autocorrelation bias has been removed.

1.3 Research Significance

A new signal processing algorithm has been developed to address the problems of measurement noise and velocity ambiguity that are encountered when measuring near-bed turbulence with coherent Doppler sonar. The results from this project make it possible to effectively use coherent Doppler sonar under challenging conditions where both backscatter decorrelation and velocity ambiguity may be present, such as in a turbulent wave boundary layer.

Shear stress in the near-bed region is responsible for lifting sediment into suspension where it may be transported and deposited elsewhere (Newgard and Hay, 2007). Sediment transport and shear stress also govern the formation, migration, and decay of ripples on the seafloor (Hay, 2008). Sand ripples have been shown to affect the penetration of high-frequency underwater sound into the seabed (Jackson et al., 2002). Numerical prediction of ripple dynamics is presently limited by a paucity of shear stress measurements in the near-bed region. The expected impact of this work will be to improve the accuracy of measurements of shear stress in the lower 10 to 20 cm of the bottom boundary layer, a region that is otherwise inaccessible to *in situ*, optical, and electromagnetic sensors.

1.4 Future Work

The long-term goal of this work is to develop improved signal processing for oceanographic and hydraulic instrumentation that will contribute to new insights into the dynamics of near-bed turbulence and sediment transport. During the fellowship year, the MAP velocity estimator has been evaluated using numerical simulation and laboratory tests in steady and turbulent flows. The next logical step is to collect sonar measurements in the ocean bottom boundary layer. A field experiment involving the multi-frequency coherent Doppler sonar described in Hay et al. (2008) is planned for Spring 2011 in the Bay of Fundy. MAP estimates of velocity and shear stress will be compared with conventional Doppler signal processing, boundary layer theory, and other sensors.

The estimator has been coded as a proof-of-concept in MATLAB® with an emphasis on ease of implementation rather than computational efficiency. For example, the velocity likelihood function is evaluated on a discrete grid of evenly spaced points. A more efficient approach would be to use an adaptive mesh, coded in C or FORTRAN, with elements concentrated in the region of highest likelihood. If the results from the field experiment are promising, and if there is sufficient demand, it may be worthwhile to develop a commercial software package for post-processing of coherent Doppler sonar measurements.

2 List of Publications

This section lists all journal articles that are expected to be published from research performed during the 2009–2010 fellowship year. All of the publications listed below either acknowledge or will acknowledge support from the Link Foundation.

The following manuscript was submitted on September 27, 2010:

[1] **Dillon, J.**, Zedel, L., and Hay, A. E. Asymptotic properties of an autocorrelation coefficient for coherent Doppler sonar. Submitted to the *Journal of Atmospheric and Oceanic Technology.*

The following manuscript is presently in preparation and will be submitted later this fall:

[2] **Dillon, J.**, Zedel, L., and Hay, A. E. On the distribution of velocity measurements from pulse-to-pulse coherent Doppler sonar. To be submitted to the *IEEE Journal of Oceanic Engineering.*

The following manuscripts are expected to be completed and submitted by March 2011:

[3] **Dillon, J.**, Zedel, L., and Hay, A. E. Maximum a posterior velocity estimation for multi-frequency coherent Doppler sonar. Part I: Theory and simulation. To be submitted to the *Journal of Atmospheric and Oceanic Technology.*

[4] **Dillon, J.**, Zedel, L., and Hay, A. E. Maximum a posterior velocity estimation for multi-frequency coherent Doppler sonar. Part II: Experimental methods and results. To be submitted to the *Journal of Atmospheric and Oceanic Technology.*

[5] **Dillon, J.**, Zedel, L., and Hay, A. E. Simultaneous velocity ambiguity resolution and noise suppression for coherent Doppler sonar. To be submitted to the *IEEE Journal of Oceanic Engineering.*

3 Disbursement of Funds

The stipend of \$21,500 was paid in bi-weekly installments from August 2009 to July 2010. The amount of \$2,500 for research expenses was used to purchase a high-end laptop computer and productivity software for performing numerical simulations, analyzing experimental data, preparing conference presentations, and writing journal articles. The remaining \$1,000 is expected to cover publication costs associated with the submitted article [1]. Based on page charge rates for the Journal of Atmospheric and Oceanic Technology, the estimated publication expense will be \$1,120.

4 Fellowship Impact

The Link Foundation fellowship has positively affected my professional development since without this financial support, it would not have been possible to temporarily leave the workforce and return to full-time studies to complete my doctoral degree. Previously, my employment duties required that I perform a supporting role in the research and development process. The fellowship has given me the opportunity to identify a research problem, propose a solution, conduct the necessary numerical and laboratory experiments, analyze the data, and report on the results. In other words, financial support from the Link Foundation has helped me to develop the necessary skills to become an independent research scientist. I look forward to applying these skills throughout the rest of my career.

References

Hay, A. E. (2008). Near-bed turbulence and relict waveformed sand ripples: Observations from the inner shelf. *Journal of Geophysical Research*, 113(C04040), doi:10.1029/2006JC004013.

Hay, A. E., Zedel, L., Craig, R., and Paul, W. (2008). Multi-frequency, pulse-to-pulse coherent Doppler sonar profiler. In *Proceedings of the IEEE/OES 9th Working Conference on Current Measurement Technology*, pages 25–29.

Jackson, D. R., Williams, K. L., Thorsos, E. I., and Kargl, S. G. (2002). High-frequency subcritical acoustic penetration into a sandy sediment. *IEEE Journal of Oceanic Engineering*, 27(3):346–361.

McNutt, M. (2002). Ocean exploration. *Oceanography*, 15(1):112–121.

National Oceanic and Atmospheric Administration (2000). Discovering Earth's final frontier: A U.S. strategy for ocean exploration. `http://explore.noaa.gov/media/http/pubs/pres_panel_rpt.pdf`. The Report of the President's Panel on Ocean Exploration.

Newgard, J. P. and Hay, A. E. (2007). Turbulence intensity in the wave boundary layer and bottom friction under (mainly) flat bed conditions. *Journal of Geophysical Research*, 112(C09024), doi:10.1029/2006JC003881.

Thorne, P. D. and Hanes, D. M. (2002). A review of acoustic measurement of small-scale sediment processes. *Continental Shelf Research*, 22(4):603–632.

Zedel, L. (2008). Modeling pulse-to-pulse coherent Doppler sonar. *Journal of Atmospheric and Oceanic Technology*, 25(10):1834–1844.