Internal Wave Signal Processing: A Model-Based Approach

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INTERNAL WAVE SIGNAL PROCESSING: 
A MODEL-BASED APPROACH

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A model-based approach is proposed to solve the oceanic internal wave signal processing problem that is based on state-space representations of the normal-mode vertical velocity and plane wave horizontal velocity propagation models. It is shown that these representations can be utilized to spatially propagate the modal (depth) vertical velocity functions given the basic parameters (wave numbers, Brunt-Vaisala frequency profile etc.) developed from the solution of the associated boundary value problem as well as the horizontal velocity components. These models are then generalized to the stochastic case where an approximate Gauss-Markov theory applies. The resulting Gauss-Markov representation, in principle, allows the inclusion of stochastic phenomena such as noise and modeling errors in a consistent manner. Based on this framework, investigations are made of model-based solutions to the signal enhancement problem for internal waves. In particular, a processor is designed that allows in situ recursive estimation of the required velocity functions. Finally, it is shown that the associated residual or so-called innovation sequence that ensues from the recursive nature of this formulation can be employed to monitor the model's fit to the data.

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I. INTRODUCTION

When operating in a stratified environment like the upper ocean with relatively sharp density gradients, then any excitation that disturbs the pycnocline (density profile) will generate internal waves that propagate away from this region (Apel []). Internal waves are volume gravity waves having maximum vertical displacement at a plane where the density gradient are largest and is detectable far above and below this interface (Clay []). They can be generated from tidal flow against islands, sea mounts and continental shelf edges, or atmospheric forcing via barometric wave changes and surface stress, or surface/internal wave interactions created displacements in the pycnocline. For instance, a ship traveling along the surface of a stratified ocean creates various visible wakes: the turbulent or centerline wake, the Kelvin wake and, of most interest in this work, the surface generated internal waves. Internal waves have been measured experimentally both in controlled environments as well as the open ocean (Robinson []) and observed using synthetic aperture radar processing techniques from satellite imagery [Alpers, ]; Thompson, ]). From the scientific viewpoint, it is of high interest to understand the effect of internal waves on acoustic propagation in the ocean [] as well as the ability to measure their effect directly using current sensor technology. Military applications are obvious, since a submerged body moving through the ocean environment disturbing the pycnocline generates internal wave signatures.

The inclusion of a propagation model in any oceanic signal processing scheme provides a means of introducing environmental information in a self-consistent manner. Recent work in ocean acoustics (Candy and Sullivan []) has shown that a propagation model can be imbedded into a signal processing scheme to solve various enhancement, localization and detection problems. In their approach a normal mode propagation model is selected and parameters such as ocean depth, sound velocity profile, and the ocean bottom conditions are introduced along with acoustic measurements from a vertical array which are combined with the model. For instance, this is sufficient information to provide an estimate of the coordinates of the acoustic source that is providing the field measurements on the array.

In this paper, we propose a model-based approach to the internal wave signal processing problem founded on a state-space representation of the normal mode and plane wave models of propagation. Specifically, using the normal mode model of the wave velocity field, the vertical velocity modal functions and the horizontal velocity current meter measurement can be estimated from noisy sensor array measurements in the following way. First, the propagation model is cast into state-space form. It is shown that this representation can be used to propagate the vertical velocity functions, given the basic parameters (wave numbers etc.) developed from the solution of the associated boundary value problem. There are basically two sets of equations in this representation: the state equation and the measurement equation. The state equation describes the evolution in space of the vertical velocity modal and horizontal velocity functions, whereas the measurement equation relates the states to the actual array measurements. In the stochastic
case, an approximate Gauss-Markov representation evolves. The Gauss-Markov representation includes the second order statistics of the measurement noise and the modal noise. In our case, the measurement noise can represent the ambient noise field, flow noise on the sensors and electronic noise, whereas the modal noise can represent Brunt-Vaisala profile errors, errors in the boundary conditions, sea state effects and ocean inhomogeneities.

Once this framework is established, as will be shown in what follows, we are in a position to investigate model-based solutions to the signal enhancement and related parameter estimation problems, since we are able to take advantage of existing systems theory (observability, identifiability, etc.) and processors (Kalman state estimators). We characterize a realizable, recursive processor (see Figure 1) which is, in fact, the minimum variance estimator in the linear case (Candy [], Jazwinski []). Also, since the process is recursive in the sense that the estimators are of the “predictor/corrector” type, the residual or so-called innovations sequence that ensues, which is the sequence of differences between the estimated value of the parameter of interest and its subsequent measured value, can be used to monitor the performance of the processor. By observing the whiteness of this sequence, information concerning how faithfully the model is representing the ocean propagation is available. This in turn presents the opportunity of correcting the model during the processing in an adaptive manner.

In the next section the state space representation of the internal wave propagation model is developed. The so-called “forward propagator” is defined and the measurement equations are developed. The state-space model is then explicitly formulated for the case of all model parameters known where estimates of the velocity field and the modal functions are made and various noise models can be exercised in order to simulate different sources of modal and measurement noise. In Sec. III an internal wave model-based processor is designed. This processor is tested by using simulated data and it is shown that the internal wave can be estimated in terms of the modes and the measured wave field. Sec. IV constitutes a discussion of the results and proposes further problems that can be treated within the framework of the approach developed in this work.

Figure 1. Basic Internal Wave Model-Based Processor.