Improved Estimation of Ocean Wave Fields from Marine Radars Using Data Assimilation Techniques

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ABSTRACT

Real-time sea state measurements can be used to greatly enhance the safety and efficiency of offshore operations. In this paper, a variational data assimilation scheme is developed to improve ocean wave field estimates from marine navigation radars. The assimilation scheme minimizes the cost function which is defined as the difference between radar observations and predictions from a nonlinear wave evolution model over the assimilation interval. An adjoint method is used to calculate the gradient of the cost function with respect to control variables, and the descent direction for minimization is obtained from tangent linear model. The proposed assimilation scheme is validated using synthetic and field data.

KEY WORDS: Variational assimilation; adjoint method; offshore; minimization; marine radars; wave model.

INTRODUCTION

Many offshore operations can be carried out only if the wave heights remain at a reasonably low amplitude for the duration of the operation and the period of the swell is sufficiently different from the natural periods of oscillation of the vessels involved. Shortly before or during such offshore operations, decisions need to be made regarding suspension of work based on expected risk of damage or loss of life. These decisions must be based upon accurate short and medium-term wave forecasts. Recent advances in remote sensing techniques allow for measurement of the ocean wave fields using marine radars in near-real time. Assimilation of real-time observations into a short-term wave forecasting model can greatly enhance the safety and efficiency of offshore operations. Given an estimate of the present state of the sea surface (initial condition), wave forecast models simulate the short-term evolution of the sea surface subject to imposed boundary conditions. The quality of the forecast strongly depends on the accuracy of both initial/boundary conditions. Given the imperfections in numerical models as well as inherent noise in radar observations and the complexity of the nonlinear radar imaging mechanisms, data assimilation is considered as an extremely important tool to improve estimates of the sea state.

In the past two decades, increasing interest has been paid to the application of conventional marine navigation radars for imaging the sea surface. The use of such radars was first reported by Oudshoorn (1960), Ijima et al. (1964), Wright (1964), Willis and Beaumont (1971),

Evmenov et al. (1973), and Mattie and Haris (1979). These studies assumed that the fundamental interaction between radar and sea surface is Bragg scattering and the longer surface gravity waves become visible by several mechanisms such as hydrodynamic modulation of the short waves by the long waves, shadowing effect, tilting modulation, wind drift, and straining effect of long waves' orbital velocity.

Young and Rosenthal (1985) for a full time series of radar images, each taken at a successive revolution of the radar antenna, and using these series of images, found a three dimensional energy density spectrum through a three dimensional Fourier transform in wave number-frequency space. A modulation transfer function was later proposed from the radar wave spectrum to surface wave spectrum in Fourier space, based on tilting, shadowing and hydrodynamic effects, and nonlinear influence in transfer function was found to be mainly due to shadowing (Ziemer and Rosenthal, 1987). Nieto Borge (1999) used X-Band marine radars to find the characteristics of the sea state such as directional spectrum and significant wave height.

Real-time assimilation of radar measurements requires a fast and efficient numerical wave model that can still capture basic nonlinear interactions. Pseudo-spectral models are increasingly used to model surface waves and can meet both these criteria. Pseudo-spectral methods for free surface problems were initially established using the time-dependent Fourier-series method of Fenton and Rienecker (1982), where instead of using a boundary integral formulation, the solution of the three dimensional Laplace equation was written in terms of Fourier series. In this method, series truncation was the only approximation. It was shown that free surface boundary conditions can be reduced to a pair of evolution equations for the two free surface variables (Zakharov, 1968). This closed set of equations is written in two horizontal coordinates reducing the dimension of the problem by one. Efforts to use this approach have been made by West et al. (1987), Matsuno (1992), Craig and Sulem (1993), and Choi (1995) among others.

Although a number of physics-based modulation transfer functions (MTF) have been proposed to relate the radar backscatter intensity to the sea surface elevation, it is still difficult to obtain reliable estimates of the wave field due to the amount of noise present in the radar data and an inadequate understanding of all radar imaging mechanisms. Wave models are also far from perfect, so data assimilation could potentially improve the estimates of the wave field from marine radars, by combining radar measurements and model predictions. A variational