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Change detection of ocean wave characteristics

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ABSTRACT

In this paper, a novel feature extraction approach is proposed for identifying ocean wave characteristics in real time. The algorithm was developed through the integration of the fuzzy C-means clustering algorithm, statistics formulation, short-time Fourier transforms, high frequency radar data processing and window function analysis. This method provides new insight into the detection of ocean wave characteristics and provides a more direct and convenient way to detect changes in ocean wave characteristics than the conventional method. To demonstrate the proposed algorithm, two Wellen radar systems were installed in Samcheok City, Gangwon-do on the East Coast of South Korea. A data set was selected for training the proposed algorithm while three other data sets, not used for the training processes, were used to validate the proposed model. The testing results demonstrate that the proposed algorithm is effective in extracting characteristic features from a variety of ocean waves. It is expected that the proposed system will accurately predict natural hazards and provide adequate warning time for people to evacuate from threatened coastal area. Hence this approach will directly contribute to the reduction of injuries and deaths in natural disasters by supplying near real-time data of the environment around coastal areas.

1. Introduction

The real time detection of changes in ocean wave characteristics is a very complex problem which has not yet been definitively resolved. Central to this paper is the development of a novel approach for detecting changes of ocean wave characteristics. This paper presents challenging issues for ocean wave measurement and associated data collection devices. Then, ocean wave spectrum analysis is described, followed by a presentation of the novel ocean feature extraction approach.

1.1. Ocean wave measurement

The monitoring of ocean surface conditions such as wave heights and periods is of high importance to ocean research and a variety of related marine activities, such as physical oceanography, wave forecasting, ship routines, and coastal protection. To obtain ocean wave information, a variety of measurement techniques have been developed. The commonly adopted approaches fall into three categories: wave buoys, acoustic Doppler current profilers (ADCP), and high-frequency (HF) radars. A wave buoy is a floating device that drifts with the sea waves. For wave buoys, the collection of ocean wave data is based on the measurement of buoy motion through mounted sensors such as accelerometers and tilt sensors. However, the wave buoys sometimes lose data because they are vulnerable to accidental or malicious damage from marine traffic. As a hydro acoustic current meter, ACDP devices measure current speed and direction over a range of sea depth, using the Doppler shift of backscattered acoustic signals (Griffiths et al., 1987; Wilson, Lwiza, & Allen, 1997). However, the accuracy of ACDP measurements is sensitive to temperature and salinity. A HF radar is a remote sensing system that is installed on the shoreline and radiates high-frequency radio waves along the sea surface. The radio waves are then scattered back by the ocean waves. These backscattered Doppler waves may result in a strong return of energies at a very precise wavelength and direction. By means of the Doppler spectrum, some information about oceanographic parameters is calculated so that the ocean wave spectrum can be estimated. Because HF radars are installed at the shoreline, damage from various marine activities can be minimized. Thus they tend to be more durable than the other options. In addition, it is reported that the ocean wave measurements of HF radars are more accurate than the ocean wave estimates of ADCPs (Teague, Vesecky, & Hallock, 2001). Hence, this research selected the HF radar system as the main ocean wave measurement device for which the proposed ocean wave change detection algorithm would be developed.

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1.2. High frequency (HF) radar systems

Over the past several decades, HF radars have attracted a great deal of attention in the field of ocean surface wave measurements. Barrick, Evans, and Weber (1977) at the National Oceanic and Atmospheric Administration (NOAA) developed the Coastal Ocean Dynamics Application Radar (CODAR) system, the first HF radar for this use. The system estimated the ocean wave height spectrum using ocean surface currents. Paduan and Roesenfeld (1996) used the CODAR to measure surface currents in Monterey Bay. Independently of the CODAR systems, other systems have also been developed. Prandle, Loch, and Player (1993) developed the Ocean Surface Current Radar (OSCR) system to measure the surface currents in the Straits of Dover. They then used their measurements to conduct tidal analyses. Gurgel, Essen, and Schirmer (1986) developed a new system called Wellen radar (WERA) (Gurgel, Antonischki, Essen, & Schlick, 1999). They utilized WERA to measure surface currents and directional spectra of wave heights. The High-Frequency Ground Wave Radar (HF-GWR), designed and operated by Northern Radar Systems in Canada, was used to estimate surface currents at Cape Race, on the east coast of Canada (Hickey, Khan, & Walsh, 1995). The Courants de Surface MEsurés par Radar (COSMER) at the University of Toulon was deployed in the Normand Breton Gulf to continuously collect sea surface current data (Broche, Forget, Maistre, Devenon, & Crochet, 1987). The Coastal Ocean Surface Radar (COSRAD) at James Cook University in Australia was placed on the Great Barrier Reef (Heron, Dexter, & McGann, 1985) to observe sea-wave spectra, surface currents and boundary-layer winds. Takeoka et al. (1995) observed the sea surface of the Bungo Channel by means of High-Frequency Ocean Surface Radar (HFOSR) at the Okinawa Radio Observatory Communications Research Laboratory (ORO/CRL) in Japan. The Multi-frequency Coastal Radar (MCR) at the University of Michigan, Ann Arbor, was used as part of the third Chesapeake Bay Outflow Plume Experiment (COPE-3) (Teague et al., 2001). It measured the open ocean and then estimated the eastward and northward components of ocean currents. The Ocean States Measuring and Analyzing Radar (OSMAR2000), developed by Wuhan University in China, was employed to measure wave spectra, wave heights and wind fields over the Eastern China Sea (Huang, Wu, Gill, Wen, & Hou, 2002). The PortMap system at James Cook University in Australia was used to map surface currents in Ports and Harbors (Heron, Helzel, Prytz, Kniephoff, & Skirving, 2005). Although the HF radar systems have already widely applied to surface current measurement, research on the real-time estimation of the wave spectrum using HF radar data is still in its early stages.

1.3. Estimation of wave spectra

Several methods have been developed to estimate wave spectra. An ocean wave spectrum can be estimated from first- and second-order Doppler spectra (Lipa, 1977; Wyatt, 1990). Since Crombie (1955) identified the distinctive features of the sea echo Doppler spectrum, Barrick (1972a, 1972b) has derived the theoretical formulations for the Doppler spectrum in terms of the ocean wave spectra. It has been proven analytically and experimentally that the first-order spectrum provides the basis for surface current measurements. Based on the theory of the first-order Doppler spectrum, several commercial systems have been applied extensively to provide detailed maps of surface currents in coastal waters. However, the first-order spectrum requires a wide frequency band of operations and thus has a limited coverage area for remote-sensing per station (Barrick, 1972a).

The second-order spectrum provides the basis for wave measurement by inverting the integral equation related to ocean wave spectra to the second-order Doppler spectrum. The Doppler spectrum is expressed as integral forms of the wave spectrum based on the HF radio wave scattering theory. Many researchers have successfully solved the inversion problems under certain conditions (Gill & Walsh, 1992; Gill, Khandekar, Howell, & Walsh, 1996; Green & Wyatt, 2006; Hashimoto & Tokuda, 1999; Hashimoto, Lukijanto, Yamashiro, & Kojima, 2008; Hashimoto, Wyatt, & Kojima, 2003; Hisaki, 1996; Howell & Walsh, 1993; Lipa, 1977, 1978; Lipa & Barrick, 1986; Lipa, Barrick, Isaacson, & Lilleboe, 1990; Wyatt, 1990, 2000). However, it is still challenging to derive wave spectra from the second-order Doppler spectrum because of the difficulty in inverting the integral equations. It is also because the lower-energy second-order Doppler is closer to the noise level and therefore more likely to be contaminated (Lipa & Nyden, 2005). In particular, when the higher order nonlinear effects in the Doppler spectrum are dominant, the accuracy of wave measurements from the spectra may be limited (Wyatt, 1995, 2000).

In order to address these problems, Hisaki (2005, 2006) developed a new method to estimate ocean wave spectra. He integrated the energy balance equations and regularization constraints with the relationship equations between the Doppler and the ocean wave spectra. However, it is difficult to solve this large-scale nonlinear least squares problem. The solution of the nonlinear least squares formulation employing the iterative optimization algorithm is sensitive to the initial values of design variables and the weighting factors of the objective function (Hisaki, 2009).

Rather than inverting nonlinear integral equations, Vizinho and Wyatt (2001) proposed the use of the modified-covariance method in order to monitor the rapidly varying oceanographic conditions. The results showed that the proposed spectral-estimation method, based on the autoregressive stochastic model, can provide sufficiently stable spectral estimates using short period data sets. Although this method is suitable for the fast-changing sea clutter environment, the resolution is relatively low when the signal-to-noise ratio is low (Tian, Yiying, Yuguan, & Chengyu, 2012). In other words, the quality control of the Doppler spectra and radar-estimated wave data is critical to the accuracy of wave estimations. It is therefore apparent that a much more reliable and accurate method for spectrum estimation of time-varying ocean wave signals should be developed.

1.4. Short-time Fourier transform (STFT)

As an alternative framework for spectrum analysis of ocean wave signals, the use of short-time Fourier transform (STFT) is proposed that transfers random signals to the ordered sum of sinusoids or complex exponentials. STFT was first applied to speech and acoustic signals processing and analysis (Berouti, Schwartz, & Makhoul, 1979; Godino-Llorente & Gomez-Vilda, 2004). Then it was successfully extended to other application areas related to non-stationary signals, such as biomedical signals (De Boer, Karemaker, & Strackee, 1985). STFT is useful in analyzing HF radar data due to fast computation, allowing the real-time monitoring of rapidly-varying ocean wave signals. But there is, to date, no serious study of the application of STFT to ocean wave signals. In this paper, the use of the STFT method is integrated with a real time feature extraction algorithm for wave detection and the classification of ocean wave characteristics.

The proposed approach is a novel integrated model of several algorithms such as STFT, clustering algorithms, statistical analysis, and feature extraction schemes; thus it is difficult to find similar methods in the literature. In general, it is very difficult to develop a robust parametric model that can accommodate numerous unknowns and still predict the complex patterns of ocean wave signals. There are significant uncertainties associated with the parametric model for forecasting varying ocean wave patterns, including the definition of the time-varying ocean waves