A COHERENT MARINE RADAR FOR MEASUREMENT OF PROPERTIES OF OCEAN WAVES AND CURRENTS

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1. INTRODUCTION

A rotating marine radar offers the capability to image ocean wave fields by virtue of its repetitive and continuous coverage of the same scene. As a result of large area coverage of the order of a few square kilometers, the dynamics and kinematics of ocean wave propagation can be used to determine wave component propagation direction with higher azimuthal resolution than traditional oceanographic instruments, such as buoys or pressure sensors. Using the shallow water dispersion relation for the propagation of shallow water ocean waves in coastal regions, bathymetry maps can be derived on a regular basis. Much research has been done using the traditional non-coherent marine radar that demonstrates this capability [1-5]. The derivation of wave height or wave height spectra from marine radar imagery in this early work has had some success by relating the radar echo intensity variation maps over the wave field to wave height using an empirical approach. These used in-situ sensors for calibrations, and a modulation transfer function (MTF) is derived to empirically scale radar image wave number spectral peak amplitudes to in-situ wave energy spectral amplitudes for each frequency spectral component from both sensors. More recently, using a simple radar scattering model based on the dependence of the radar scattering cross section on long wave slope [6], good results are reported in deep water for shipboard experiments, where winds and waves are typically in the same direction. However, in coastal waters, offshore winds blowing in a direction opposite to the incoming wave field produces an enhanced modulation of the radar wave field image that is not wave height dependent, and thus can present problems with both of these approaches [7]. A coherent radar can overcome these limitations using the direct measurement of the radial component of orbital wave velocity plus Bragg scatter velocity to overcome these limitations. Radial orbital velocity will maximize and minimize at similar positions on long wave profiles as radar echo intensity, so wave patterns should look very similar for the two, and analysis methods used in all non-coherent radar studies should be applicable to coherent radar data as well. The presentation will discuss the design of a new coherent marine radar, and some recent experimental results applied to the retrieval of coastal ocean wave and current properties. A coherent-on-receive modification to a standard marine radar will also be described with similar comparisons.

2. COHERENT RADAR DESCRIPTION

A fully coherent marine radar has been developed for imaging ocean wave orbital wave velocity components in the radial direction with a 4-Hz radar rotation rate and image repetition period. This new capability provides a direct measurement of wave height profiles without relying on the MTF that has been used with previous systems that map radar echo intensity, which is prone to error due to environmental dependencies of the MTF. A standard Koden marine radar was gutted of its non-coherent components and replaced with elements required for a fully coherent radar. The non-coherent 25-kilowatt magnetron is replaced with a 5-watt coherent power amplifier. Pulse compression is used to improve the final output power, with pulse waveform provided by the ISR Quadrapus transceiver PC card, typically using FM pulse swept pulses. In addition, as the waveform transmitted is identical from one pulse to the next, additional signal gain is achieved by summing successive echo waveforms on board the transceiver card before transferring the recorded waveform to storage media. Typical operation uses a 50,000 Hz pulse repetition frequency (PRF) on transmitting, and 2,000 Hz PRF on recording, providing an additional factor of 25 gain with this summing. This combination of pulse compression and waveform summing makes up the factor of 5,000 in peak power output between the two power amplifier approaches.

The recorded signal is the output intermediate frequency of the radar, with a single channel only, providing real data, typically at 1.5-m sample spacing at a 100-MHz sample rate. Signal processing produces complex in-phase (I) and quadrature (Q) outputs at a 3-m spacing. Phase of each sample is determined by taking the arctangent of the I/Q ratio for each range bin. Phase difference, $d\phi$, between adjacent pulses provides a measure of rate of change of phase (rad/sec), or Doppler shift (Hz), $d\phi/dt = f_D$, by dividing the phase difference by the period between pulses. This in turn is related to the radial velocity of an echo by the Doppler equation:

$$V_D = f_D * \lambda/2$$

Position of the pointing direction of the antenna is recorded for each pulse, so that slight variations in rotation speed of the antenna due to local wind forcing can be accounted for in transforming to Cartesian co-ordinate images for analysis.

3. PROCESSING RESULTS

The radar was mounted on a tower at the end of the FRF pier, 600 m offshore, which allows a full 360 deg look onto the ocean waves, providing both approach (offshore incoming) and recede (onshore outgoing) orbital wave velocities. The figure below shows an example of both Intermediate Frequency signal phase difference between pulses as discussed above on the left, and echo magnitude on the right, represented in radial co-ordinates, Range-vs-Azimuth, for a single radar rotation. Linear ocean wave trains appear as hyperbolas in these co-ordinates. Acquisition begins with the radar azimuthal look inward toward shore, along the pier, which appears at the top of each figure across the scene. Breaking waves at the coast are seen at the hyperbolas beginning at ~600 m range at the top and bottom of both figures. The phase difference is gray-scaled between 180 and -120 deg, as inshore shoaling waves have dissipated energy, with lower orbital wave velocities than the deeper approaching waves.

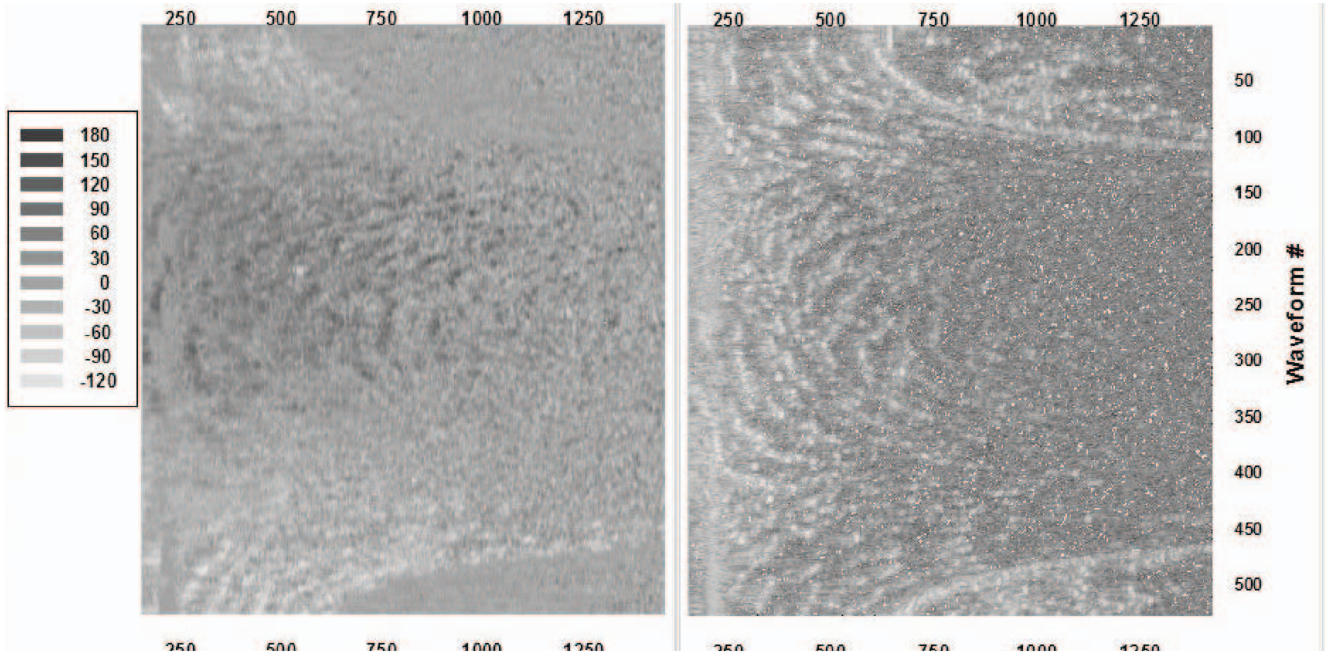

Figure 1. Range-Azimuth (X-Y) plots are shown of phase difference between adjacent pulses on the left, and echo intensity on the right, from a newly developed fully coherent marine radar. Phase difference divided by time between pulses is proportional to radial velocity, the orbital velocity of the waves, plus wind drift current. The latter has a southerly component, accounting for the difference in breaking wave velocity at the coast line at the top and bottom of the figure.

The breaking waves at the shore are seen on the far right as bright while continuous hyperbolas of similar brightness on the right at azimuths 1-100 and 450-510; shoaling waves in shallow water < 8-m depth are seen at these azimuths for ranges shorter than 600 m. Corresponding receding waves are seen in the phase-difference image to the left over this same range-azimuth region, showing up as brighter areas. Incoming waves in water deeper that 8 m are seen in azimuth records 200-350, and the corresponding phase difference is seen as negative (darker), indicating approaching radial wave velocity. The wind drift current, due to northerly winds in this case, causes a slight offset in phase difference measure for the waves breaking at the coast. The receding orbital wave velocity is offset by the wind drift in the northerly look for the top hyperbola, nearly fully canceling it. For the hyperbola at the bottom, for the southerly portion of the sweep, the wind drift adds to the orbital wave velocity and the phase difference is larger. This mean drift current must be removed under such conditions, and examples of this behavior and its correction will be presented at the conference.

4. WAVE HEIGHT MAPS FROM PHASE-DIFFERENCE IMAGES

There has been interest in using shipboard radars as a source of data for real-time initialization of wave propagation models for ship motion prediction and mitigation [6], and data of the type presented here can provide wave height maps directly without the need for 3D-FFT analysis as a first step. A one-dimensional FFT in the direction of propagation defined by the hyperbola axis in Figure 1 provides dominant wave length and propagation direction using just one antenna rotation. Using the equation relating orbital wave velocity and Doppler shift (or phase-difference rate of change), one can immediately transform such an image to wave height directly. Cartesian transformation of such images remains the only step that would allow real time wave height maps for model ingestion application, and programmed FPGA chips for this purpose could be developed with little cost and effort. This new coherent radar technology offers the opportunity to provide such data input, with far faster response times than are currently available with existing methods.

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