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High frequency radar and its application to fresh water

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ABSTRACT

High frequency (HF) radar has become an important tool for remotely mapping the spatial distribution and temporal evolution of waves and currents of the nearshore coastal ocean. Its acceptance along ocean coasts has resulted in the development of several commercially available systems and a planned nationwide coastal network to routinely measure coastal currents. Because HF radiation is known to propagate less efficiently over fresh water than seawater, it has been largely overlooked as a viable tool for freshwater application. However, its potential utility in freshwater was clearly demonstrated by a deployment along Lake Michigan as part of the 1999–2001 Episodic Events Great Lakes Experiment. As part of this experiment, the University of Michigan Multi-frequency Coastal Radar consistently produced reliable near surface current measurements to a range of approximately 25 km offshore showing strong correlation with both in-situ measurements and numerical hind-casts. This paper provides background on HF radar technology, a summary of the current state of the art with respect to freshwater and describes the results of a recent experiment to measure the propagation of HF radar signal over freshwater using CODAR Ocean Sensors SeaSondes, operating at 5 and 42 MHz with 21 W and 90 W average radiated powers, respectively. The effective offshore range for these radars was found to be 18 km at 5 MHz and 4–5 km at 42 MHz. These findings are consistent with currently available models for the prediction of propagation loss, verifying that they can reliably be used to estimate ranges in freshwater settings.

Introduction

The coherent backscatter of high frequency (HF) radar waves (10 to 100 m wavelengths) at grazing incidence from the ocean surface was first observed by Crombie (1955). He found that the peak in the backscattered Doppler spectrum was located approximately at the frequency of ocean surface gravity waves with wavelengths on the order of one half the radar wavelength. These findings indicated that radio waves reflected from the sea obey Bragg scattering in which the ocean surface acts as a diffraction grating. To first order, the strong HF echo arises from a Bragg scattering interaction with ocean waves traveling radially with respect to the radar and having a wavelength of one half the radar wavelength.

Observed Doppler spectra, as shown in Fig. 1, reveal the dominant, first order Bragg echo peaks as described by Barrick (1971) at a Doppler shift corresponding very nearly to the phase velocity of the radially advancing and receding waves. The Doppler shift, Δf, can be approximated by

$$\Delta f = (2fc)/c_{em}, \tag{1}$$

where f is the transmit frequency of the radar, c is the radial velocity of the Bragg resonant waves and c_{em} is the speed of light in free space and $c \ll c_{em}$. In the absence of an underlying current, these first order Bragg peaks, visible in Fig. 1 at $\Delta f \sim \pm 0.72$ Hz, correspond directly to the first order phase velocity of Bragg-resonant surface gravity waves traveling radially toward or away from the radar.

The presence of near-surface currents perturbs the phase speed of the surface gravity waves. Stewart and Joy (1974) estimate the influence of near surface currents U on wave phase speed via

$$c = c_p + \partial c(k) \tag{2}$$

in which

$$\partial c(k) = 2k \int_{-\infty}^{0} U(z) e^{2kz} dz. \tag{3}$$

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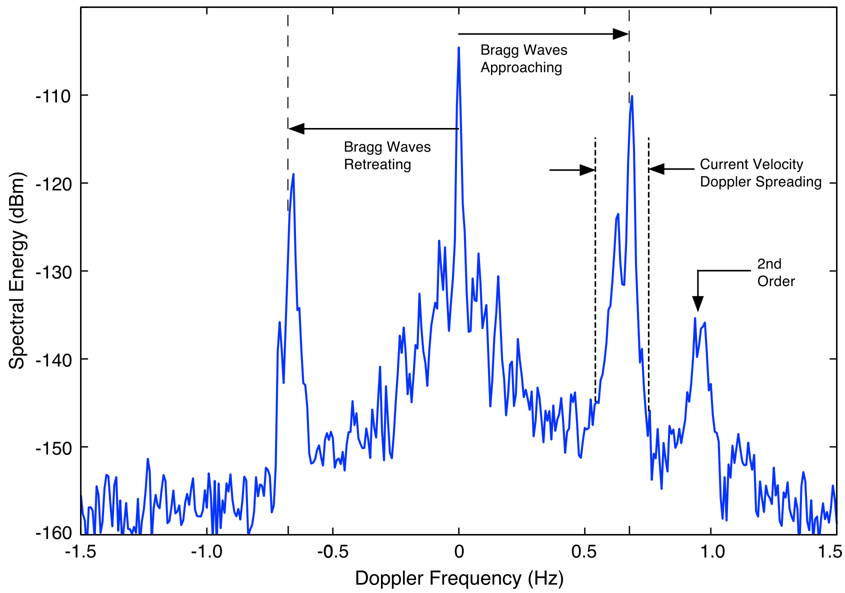

Fig. 1. Typical HF (high frequency) ocean surface Doppler spectrum at 25 MHz (Harlan et al., 2010) with first order Bragg peaks from surface waves that are half the radar wavelength traveling toward (positive Doppler) and away (negative Doppler) from the radar. A second order peak from longer waves modulating the Bragg wave is visible to the right.

Here, $U(z)$ is the horizontal current velocity profile as a function of depth z (negative downwards) and $U \ll c_p$. Given a measurement of c from the Doppler spectrum observation of Δf (Fig. 1), and knowing the theoretical wave phase speed, c_p, as derived from the dispersion relation for deep water gravity waves:

$$c_p = (g/k)^{1/2} \tag{4}$$

in which g is the acceleration due to gravity and k is the radar wavenumber, Eq. (2) yields a value for $\partial c(k)$. Stewart and Joy (1974) estimate that this value is approximately equivalent to the current at a depth of 4% of the Bragg resonant wavelength.

Since a single system is only able to retrieve the radial component of near surface current velocity, it is typical to pair systems and retrieve two different radial components over a footprint in order to construct the full vector field.

HF radar applications

In addition to surface currents, primary and secondary HF spectra have been used to determine surface wind speed and direction (Vesecky et al., 2005), track sea-going vessels and other hard targets (Fernandez et al., 2001), determine wave field characteristics (significant wave height, dominant wave period and direction), as well as wave spectra (Wyatt, 2011) and with limited success in tracking ice flows (Potter and Weingartner, 2010). These products have been used to inform such diverse and important applications as search and rescue operations, water quality monitoring, marine navigation, rip current prediction, harmful algal bloom forecasts, ecosystem and fisheries management, oil spill response and hydrodynamic modeling. Because of this significant utility for a broad scope of measurements and applications, HF radars have seen a ten-fold increase from 2004 to 2008, along with the development of a national network of HF systems for coastal surface current monitoring in the US ocean coasts (Harlan et al., 2009). Approximately 95% of HF radars operating in the U.S. are the compact cross-loop direction finding type. It is noteworthy that operational HF radar networks have to date been deployed exclusively for use over salt water with typical ranges of 15–20 km for VHF systems in the 42 MHz band up to 180–220 km for the lowest frequencies in the 5 MHz band. We consider here the impact on radar performance of operation over fresh water.

HF radar measurement range

The range over which any radar is capable of making measurements is a function of the signal-to-noise ratio (SNR) of the received signal scattered by its targets. In the case of HF radar for current mapping, the targets are the surface waves. The equation for determining the SNR for any target is given as:

$$SNR = P_T \frac{G_T D_R F^4 \lambda^2 \sigma_t \tau}{(4\pi)^3 R^4 kTF_a} \tag{5}$$

where P_T is the average radiated power, G_T the transmit antenna power gain, D_R the receive antenna directivity, λ the radar wavelength, τ the coherent FFT processing time, σ_t the radar cross section of water surface within the radar cell, R the range to the radar cell, kT the internal receiver thermal noise spectral density (4×10^{-21} W/Hz), F_a the factor by which external noise exceeds internal receiver noise, and F the normalized one-way field strength attenuation factor. The last parameter, F, is the only term in the expression for SNR that changes between freshwater and seawater. F depends on transmit frequency, water dielectric permittivity and conductivity, distance and surface roughness (sea state) and it includes the effects of diffraction over the spherical earth. The normalization is such that this factor is unity for a flat, perfectly conducting surface and/or at very short distances. Values of F for freshwater and seawater can be calculated accurately from GRWAVE, the program recommended by ITU/NATO and the accepted standard for 40 years (Rotheram, 1981). A comparison of freshwater to seawater range performance for three different frequencies is shown in Fig. 2. Typical values for transmit power, antenna gain and wave state account for the range of distances plotted on each curve. The difference in values between freshwater and seawater is primarily due to the difference in salinity, which primarily affects the conductivity.

To achieve range distances beyond the horizon, the electromagnetic signal must couple with the surface and propagate via groundwave mode. For typical ocean surface water with salinity over 30 ppt, the higher conductivity favors HF coupling to the sea surface and allows the signal to travel significantly farther than over land or freshwater.

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