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Implementation of S-band marine radar for surface wave measurement under precipitation

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ABSTRACT

Civil marine radar, which operates at a low grazing-incidence angle and with horizontal polarization in transmitting and receiving, can be modified and used as a primary tool for surface wave monitoring. The high spatial resolutions of sea-clutter image sequences from X-band radar offer a means of deriving individual waves and wave field at low-cost. However, the performance of X-band radar is impaired under rainy conditions, which are usually accompanied by the severe weather at sea. In the present study, we examine the effectiveness of S-band radar for wave measurements under precipitation. The results of comprehensive comparative studies with sea-truth data show that S-band radar is capable of carrying out wave measurements in rainy conditions. Although the longer wavelength of the S-band leads to a coarser resolution of radar imagery, the S-band radar features at least the equivalent performance of the X-band system in non-rainy conditions, in terms of wave height measurement. The results suggest that the S-band and X-band could be complementary systems. In rainy conditions the S-band is more efficient but in the non-rainy periods the X-band gives more confident results. The relationship of significant wave height with radar signal-to-noise ratio (SNR), and the modulation transfer function (MTF) between radar spectrum and wave spectrum for the used X-band and S-band radars are established and discussed in this paper.

1. Introduction

Civil marine radar (CMR), which was originally designed and built for ship detection and tracking at sea or on navigable waterways, and for vessel surveillance from land-based authorities, is the largest radar market. Owing to the business competitions in the CMR market, the outlasted products of CMR have been evolved to be low-cost, easily maintained systems. It is usually non-coherent HH polarization microwave radar used in low-grazing angles. During the last several decades, algorithms have been developed for the extraction of the information of surface wave, current, surface wind and bathymetry using such CMR (Young et al., 1985; Seemann, 1997; Nieto Borge et al., 1998, 1999; Nieto Borge and Soares, 2000; Dankert & Rosenthal, 2004; Dankert et al., 2003, 2005; Bell, 1999; Gangeskar, 2014). For surface wave measurement, typically, the algorithms are applied to the radar images of the sea clutter that generated by Bragg scattering of the radar signal at near-grazing incidence from the high frequency gravity-capillary waves (Valenzuela, 1978). As longer waves become visible in the radar images due to their modulations with the short ripples by non-linear processes, e.g. hydrodynamics modulation, tilt modulation and shadowing, the estimation of wave parameters is viable from the analysis of the nautical radar sea surface image sequences. Comparative and review studies (Nieto Borge et al., 2004; Nieto Borge et al., 2008; Liu et al., 2016) have demonstrated the effectiveness of using the CMR for retrieving information about significant wave height and directional wave spectrum for coastal area. More recently, Trizna (2010) modified the CMR system by replacing the non-coherent magnetron with a solid-state power amplifier, allowing it to detect the phases of transmitted and received electro-magnetic waves. Such coherent radar can provide radial velocity of the sea surface that derived from Doppler shift with high resolutions over the spatial and temporal domain.

As the radars are modified or upgraded based on standard marine radar packages at comparatively low cost, it accounts for high performance-to-cost ratio for the oceanic monitoring station or network. To be the tool for coastal environmental monitoring, the CMR has great potential to play a key role making useful contributions to a diverse range of applications such as harbour navigation safety management, coastal hazard monitoring, and investigation of the mixing, disperse and transport of objects and pollutant in estuaries (Robinson et al., 2000).

Common frequency bands for CMR that are available on the market are X-band (8–12 GHz) and S-band (2–4 GHz). The wavelength of the X-band (2.8 to 3.2 cm in air) is approximately equal to the ripple wavelength existed on the water surface when the wind speed is >3 m/s. Due to the fact that the closer the ripple wavelength and the EM wavelength, the stronger the scatter wave strength, and thus, easier for a radar antenna to pick up the scatter signal. For larger wavelength of S-band (about 12 cm), the scatter waves strength would be weaker, and thus,

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the detectable range would be smaller when comparing with that for the X-band radar. For this reason, X-band radar was chosen for its clear sea-clutter imagery in most of the studies (Maa & Ha, 2005).

However, the drawback of X-band radar is that the performance is significantly reduced by rainfall. Results from European Radar Ocean Sensing Project (EuroROSE) experiments that carried out in 2000 in Norway and Spain demonstrated that heavy rain would downgrade the wave measurement accuracy of the X-band wave monitoring system (WaMoS) (Wyatt et al., 2003). Alamsyah (2008) also suggested that heavy rainfall would increase the background noise and restrain the X-band nautical radar from wave measurement. The hazardous sea states, which are the target phenomena to be monitored, are generated by extreme weather systems such as typhoons, hurricanes, winter storms and the outbreaks of cold fronts. Usually, those weather conditions are accompanied by severe rainfall. For normal weather condition on the other hand, the duration of precipitation is non-negligible, too. The annual rainy days reach approximately 200 days in the northern parts of Taiwan according to the 40 years of statistics from the Central Weather Bureau in Taiwan. The degraded performance during precipitation of the X-band microwave radar is a concern, especially when considering whether it is suitable to be designated as a primary tool for sea-state monitoring in operational mode.

The mask of X-band radar signal by the raindrop is due to the Rayleigh backscattering. As the Rayleigh backscatter intensity is inversely proportional to the fourth power of the wavelength, one of the approaches to reduce the rain mask effect of the radar system could be the shifting from X-band to lower frequency with greater wavelength. Gunn and East (1954) demonstrated that the attenuation factor in heavy rainfall for a 10 cm S-band is two orders of magnitude less than a 3 cm X-band. This result indicated that the use of S-band radar could partly reduce the influence of raindrops. The S-band radar is also commercially available; the use of S-band can be an alternative. However, evidence has yet to show the influences of weaker backscatter and lower resolution of the S-band radar for ocean surface-wave measurements.

The aim of present study is to clarify the feasibility and to assess the performance and corresponding accuracy of an S-band marine radar under rainfall. One X-band and one S-band radar systems were installed at a coastal observatory and run in a synchronized mode. The results of the S-band radar were compared with a well-tested X-band radar system and in situ bottom-mount acoustic wave measurements. The paper is organized as follows. Section 2 describes the experiment setup used to evaluate the performance of S-Band radar. Sections 3 to 4 give an overview about the data processing and radar strength calibration. Section 5 then combines the results from comparative studies. Finally Section 6 presents our conclusions.

2. Field experiment setup

The radar validation campaign was carried out from January 14th to February 1st, 2011. The experiment took place at the National Central University coastal observatory, which was located on the north-western coast of Taiwan (24.966°N, 121.009°E), as shown in Fig. 1. Instrumentation included an X-band and an S-band marine radars, eddy covariance systems for sea surface roughness and meteorological parameters measurements, as well as an array of bottom-mount Acoustic Doppler Current Profilers (ADCPs).

For a pulsed radar, the radial resolution is determined by the pulse length (duration) and the azimuthal resolution by the beamwidth that associated with the antenna length. The radar systems used in this study were X-band (9.41 GHz) FR8251 radar (FURUNO Inc., Japan) and S-band (3.03 GHz) FR2135 radar (FURUNO Inc., Japan). These were the typical CMR in X-band and S-band, and featured nearly identical specifications compared to other manufacturers' products. The pulse lengths were both 0.08 μs (short pulse mode), pulse repetition rates (PRF) were 2100 Hz and 2200 Hz, and the azimuthal resolutions were 0.95° and 1.9° (antenna lengths of 8 ft. and 12 ft) for the X-band and S-band radars, respectively. The pulse length results in a range resolution of 12 m for both radars; while the 0.95° and 1.9° horizontal spreading of the EM waves mean 33 m (X-band) and 66 m (S-band) footprints at 2 km away from the antenna. The rotating speed of both antennas was 45 rpm (revolutions per minute). We used 60 MHz of sampling rate to digitize the radar backscatter intensity and store the signal using 12-bit image depth. X-band and S-band radars were set up on the tower at 10 m and 15 m above the ground, approximately 15 m and 20 m above mean sea level, respectively. The operations were simultaneously implemented every 20 min, together with the measurement of sea-surface roughness by an eddy covariance system and directional waves by ADCPs array. In total, > 1200 datasets were recorded. For each observation, 64 images within a 3 km radius were recorded for both radars, and then interpolated from polar measurement grid to the Cartesian analysis grid.

The sea-truth data were obtained by the upward looking ADCPs (Sentinel 1200 KHz Teledyne RDI Inc. USA), deployed on the inner shelf. The deployed locations of ADCPs are shown in Fig. 1, denoted as Station A, to Station E, with mean water depth ranges from 7 m to 20 m. Three functions of Sentinel ADCP can be used for surface wave measurement: the surface-tracking function, the pressure sensor, and the velocity profile measurement for wave orbital motion estimation. We adopted the surface-tracking function with a sampling rate of 2 Hz in present study. The acoustic chirp signals transmitted from four upward looking transducers on the ADCPs with different angles reached to the sea surface then reflected, and formed four footprints on the surface level. With known distances from the transducers to the sea surface, the positions and elevations of each footprint could be determined according to the ADCP's pitch, roll, and heading angle. The sizes of acoustic footprints on the sea surface and associated position were time-varying and depended on the surface elevations. The sizes ranged from 0.22 m^2 to 0.33 m^2, which were considered sufficiently small compared to the dominant wavelength and the radar resolution in the experiment domain. The temporal variations of the footprint elevations were regarded as the ocean surface vertical displacement. The data together with the geometrics of the footprints were then used as inputs to DIWASP (Johnson, 2008), a directional wave spectra toolbox for MATLAB®, in which the Extended Maximum Likelihood Method (EMLM) was chosen for directional wave-spectrum estimation.

The coastal flux tower was equipped with two eddy covariance systems for the measurements of the friction velocity and sea surface roughness. The wind data were measured by CSAT3 ultrasonic anemometers (Campbell Scientific Inc., USA), which were installed at 10 m and 15 m above mean sea level. Other meteorological factors, such as air-temperature, humidity, rainfall intensity and barometric pressure were recorded at Xinwu weather station, about 5 km northeast of the experiment site.

Fig. 2 illustrates the overview of the sea state background condition during the experiment. Significant wave heights (Hs) ranged from 1.0 m to 3.0 m; wave periods ranged from 6 s to 10 s. Caused by the wave refraction in shoaling bathymetry, the dominant wave directions in the nearshore region were approximately 350° (NNW-N), which exhibited 60° to 70° difference, compared to the wind directions (NE-ENE). Two events of the arrivals of cold surge fronts are indicated in the shaded boxes. Cold surge fronts with sharp temperature drops were produced by the Mongolian high-pressure systems, which occurred periodically in Taiwan from October to next April. Within this period, prevailing winds are directed northeast into areas of Southern China and Taiwan, imposing the major driving force on wave generation. The precipitations were usually intensified during the passages of cold fronts.

Fig. 3 shows the rainfall intensity, measured by tipping bucket rain gauge, and relative humidity during the experiment. The rainfall intensity was 12.5 mm/h on January 29th.

Fig. 4 shows the comparisons of the sea-clutter images of the X-band radar (left panel) and S-band radar (right panel) from January 29th. On