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Study of the polarimetric characteristics of mud flats in an intertidal zone using C- and X-band spaceborne SAR data

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ABSTRACT

The polarimetric characteristics of a mud flat area in the intertidal zone near Jiangsu, China, are analyzed under different environmental conditions using X-band and C-band spaceborne synthetic aperture radar (SAR) data from the TerraSAR-X (TSX) and Radarsat-2 (R2) satellites. The dominant scattering mechanisms of different objects, including mud flats and aquaculture facilities in the intertidal zone, are studied based on the polarimetric target decomposition of fully polarimetric R2 data. The polarimetric characteristics of different objects in the intertidal zone are quantitatively compared using the depolarization parameters derived from the R2 data, which indicate that tides have different effects on the dominant scattering mechanisms of the mud flats and aquaculture farms. Furthermore, comparisons of the C-band and X-band polarimetric characteristics of the mud flats and aquaculture farms in the intertidal zone are analyzed by combining the TSX and R2 data. The results show that surface scattering is the dominant mechanism of the mud flats, whereas different dominant mechanisms occur in the aquaculture areas present during different tides. Interestingly, strikingly similar polarimetric characteristics of mud flats and aquaculture in X-band and C-band SAR are observed, and these novel results were achieved through a depolarization analysis based on the TSX and R2 data in synergy.

1. Introduction

A coastal zone is an intermediate area between the land and sea that hosts interactions between land and ocean systems. Mud flats provide rich and diverse ecological resources and play a critical role in coastal zones. However, field surveys are difficult to perform in mud flat areas because of the large span, weather and tidal conditions and other natural factors. Satellite remote sensing is widely used to monitor mud flats in coastal zones because it provides rapid results and has macroscopic and dynamic advantages. Optical remote sensing technology provides multi-temporal, short-cycle and wide coverage for the classification of mud flats, surveying of resources and extraction of shoreline characteristics (e.g., Chen, 1998; Green, Mumby, Edwards, & Clark, 1996; Murray, Phinn, Clemens, Roelfsema, & Fuller, 2012). However, clouds and fog often limit the usage of optical remote sensing images for these applications. In contrast, spaceborne synthetic aperture radar (SAR) has the unique advantages of high spatial resolution and weather and sunlight independence; thus, spaceborne SAR plays an important role in coastal monitoring. In following, some previous studies on monitoring of intertidal zones using spaceborne SAR data are briefly summarized.

Topographic mapping for monitoring of intertidal zones is a widespread application of SAR. Various algorithms, e.g., the semi-automatic method (Fugura, Billa, & Pradhan, 2011; Mason & Davenport, 1996) and the wavelet-based algorithm (Heygster, Dannenberg, & Notholt, 2010; Niedermeier, Romaneessen, & Lehner, 2000) have been proposed to map waterlines, i.e. the boundaries between water-covered areas and tidal flats, using spaceborne SAR data. In particular, the study of long-term morphodynamics of mud flats can benefit from the mapping of waterlines using time-series of SAR data (Li, Heygster, & Notholt, 2014; Niedermeier, Hoja, & Lehner, 2005).

Spaceborne SAR is also widely used to detect and classify various surface cover types, e.g., sediment, vegetation and mussel beds, of intertidal zones. Compared with single-polarization data, multi-polarization or multi-frequency SAR data contain abundant scattering information regarding surface targets and are particularly useful for classifying land cover types in intertidal zones with complex environmental characteristics. Lee, Park, Choi, Oh, and Won (2012) demonstrated that the combination of co-polarization and cross-polarization SAR data (VH and VV) was better at distinguishing plants in mud flats compared with single-polarization (HH) data. Based on the derived surface roughness parameters of the root-mean-squared height and correlation length of mud flats in the German Bight from the SIR-C/-SAR data using the integral equation model (IEM) (Fung & Chen, 2004), Gade, Alpers, Melsheimer, and Tanck (2008) classified sediments and gave

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results consistent with an existing sediment map. Gade, Melchionna, Stelzer, and Kohlus (2014) used jointly L-, C- and X-band SAR for sediment classification in the German Wadden Sea and demonstrated that the use of multi-frequency and multi-temporal SAR data can provide a valuable complement to routine monitoring of intertidal flats. In addition to using only spaceborne SAR data, the combined use of optical images and SAR data show some advantages in studying tidal flats. For example, Van der Wal and Herman (2007) reported that a combination of ERS SAR, visible and near-infrared (VNIR) and shortwave infrared (SWIR) data can yield better mapping of sediment grain sizes in Westerschelde (southwestern Netherlands). Jung, Adolph, Ehlers, and Farke (2015) took advantage of high spatial resolution TerraSAR-X and RapidEye data to delineate the salt marshes and shellfish beds on the tidal flats in the Wadden Sea of Germany.

The basis for identifying or classifying land cover types in tidal flats using multi-frequency and multi-polarization SAR data is the discrepancies of radar backscatter characteristics of objects at different microwave frequencies and polarizations. Studies of the radar backscatter features of various land cover types in intertidal zones have drawn increasing attention. Lee, Chae, and Cho (2011) studied the radar backscatter features of a mud flat area in various environment conditions and demonstrated it via laboratory experiments. Fully polarimetric SAR data contain four channels (VV/HH/VH/HV) of information of surface scatter. According to the polarimetric target decomposition theorem, the scattering mechanisms and polarization features of surface targets may be studied by taking advantage of fully polarimetric SAR data. Lee, Hong, Kim, Yamaguchi, & Won (2006) found that the scattering characteristics of an exposed oyster farm and mud flats observed with fully polarimetric AIRSAR are significantly different based on the decomposition results. In the oyster farm, surface and double-bounce scattering were dominant, and the intensity of the double-bounce scattering was closely related to the structure of the oyster reef. Chu et al. (2012) used fully polarimetric Radarsat-2 (R2) data to analyze the scattering mechanism of an oyster farm based on the Yamaguchi target decomposition method (Yamaguchi, Moriyama, Ishido, & Yamada, 2005). The decomposition indicated that the oyster farm's double-bounce scattering remained similar when the environmental conditions were the same and showed that strong volume scattering was caused by the massive amount of oyster shells in the oyster farm. With the increased number of spaceborne fully polarimetric SAR sensors, a greater number of studies have focused on the scattering characteristics of mud flats using polarimetric SAR data at different microwave frequencies. Choe, Kim, Hwang, Oh, and Moon (2012) found that the depolarization and volume scattering of oyster farms in the C-band is more significant than that in the L-band.

Most previous studies on the polarimetric scattering of mud flats in coastal zones have been based on single-frequency SAR data, including the widely exploited C-band SAR data. Although studies have focused on the polarimetric scattering of a given surface target using SAR data in different microwave frequencies, studies using multi-frequency polarimetric SAR data in synergy have not yet been conducted; however, such a synthesis was accomplished in this study using high spatial resolution C-band and X-band SAR data, specifically R2 and TerraSAR-X (TSX) data. Mud flat characteristics vary considerably from site to site, which results in significantly variable polarimetric surface scattering. Jiangsu Province has the largest area of mud flats along China's coast. This mud flat area was mainly formed by a unique radiation shoal that is typical of most mud flats in the coastal area of China.Therefore, a goal of this study was to investigate the polarimetric scattering of mud flats along the Jiangsu shoal using two representative sets of new-generation spaceborne SAR, TSX and R2 data. These technologies present high spatial resolution and polarimetric capabilities and provide a better understanding of polarimetric characteristics using C-band and X-band SAR.

This paper is organized as follows. The study area and the spaceborne SAR data are described in Section II, and the study of the dominant scattering mechanisms and depolarization effects of objects in the intertidal zone using the C-band fully polarimetric R2 data is described in Section III. A comparison of the depolarization effect of the mud flat area and aquaculture area is performed using the synergy of C-band and X-band SAR data in Section IV, and a summary and conclusions are presented in the last section.

2. Description of the study area and spaceborne SAR data

The study area is located in Rudong County on the southeastern coast of Jiangsu Province, China. The mud flats in Jiangsu Province are representative of intertidal zones in the East China Sea, where have the unique radiation shoal as shown in an ENVISAT/ASAR image mode image (Fig. 1). The sediments of the Jiangsu mud flats are mainly fine sand, sandy silt, silt, clayey silt and clay (Wang & Ke, 1997).

The spaceborne SAR data used in this study include two scenes of fully polarimetric (HH/HV/VH/VV) R2 data and two scenes of TSX dual polarization (VV/HH) data operating in fine mode and stripmap mode. The white and black rectangles in Fig. 1 indicate the spatial coverage of the TSX and R2 acquisitions is the study area. The technical details of the SAR data are listed in Table 1. The two R2 datasets were acquired on April 10th and 17th, 2014, and they are hereafter referred to as R2-0410 and R2-0417, respectively. The two TSX scenes were acquired on April 10th and 16th, 2014, and they are hereafter referred to as TSX-0410 and TSX-0416, respectively.

The white circle in Fig. 1 denotes the location (Qionggang) where tide predictions are available, which is located approximately 40 km northwest of the study area. The predicated tidal elevations at the Qionggang site at the times of the SAR acquisitions are shown in Fig. 2.

A large number of aquaculture rafts are located in the Jiangsu intertidal zone for cultivating Porphyra from September through April. Recent studies indicate that the cultivated Porphyra there are the likely cause of the frequent green tides in the southern Yellow Sea, China (e.g., Huo et al., 2015). These rafts are composed of bamboo, ropes and nets and measure approximately 3×3 m. Fig. 3a presents a Landsat-8 image of the study area at a spatial resolution of 15 m. The visual interpretation and photos taken during field surveys indicate that seawater, mud flats and aquaculture farms are the three main surface objects in the study area. There are also a dozens of offshore wind turbines located on the mud flats. These objects appear as white dots in the image (Fig. 3b), and their shadows are also evident. The field photo of the mud flats and an offshore wind turbine is shown in Fig. 3c, which illustrates a number of shallow water channels that appear in mud flats during ebb tide. A large amount of regular bamboo grid rafts are observed in the aquaculture area (photo in Fig. 3d), which look like the banded features in the LandSat sub-image in Fig. 3b.

3. Polarimetric characteristics of the mud flats in C- and X-band SAR

This section describes the use of high-resolution R2 and TSX data in studying the polarimetric scattering characteristics of the two major surface objects, namely the mud flats and aquaculture farm, under different tidal conditions in the Rudong intertidal zone.

3.1. Polarimetric characteristics of the mud flats in C-band SAR

In the following, the dominant scattering mechanisms and depolarization effects of the mud flats and aquaculture farm under different tidal conditions are investigated using the fully polarimetric R2 data.

3.1.1. Dominant scattering mechanism

The Freeman–Durden (Freeman & Durden, 1998) and Yamaguchi (Yamaguchi et al., 2005) decomposition methods are widely used to study fully polarimetric SAR data to determine the polarimetric characteristics of targets and derive their classifications. A drawback of both methods is that negative power values appear on the surface and double