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Multi-frequency SAR data help improving the monitoring of intertidal flats on the German North Sea coast

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A B S T R A C T

We demonstrate that Synthetic Apertur Radar (SAR) data have great potential to improve an existing monitoring system based on optical data for intertidal flats and to complement the classification of sediments, macrophytes, and mussels in the German Wadden Sea. Multi-satellite SAR data acquired at different radar bands (L, C, and X band, from ALOS PALSAR, from ERS SAR, Radarsat-2 and ENVISAT ASAR, and from TerraSAR-X, respectively) were used to investigate whether they can be jointly used for crude sediment classification on dry-fallen intertidal flats and for detecting benthic fauna such as blue mussel or oyster beds. In this respect, we show that both multi-satellite and multi-temporal analyses provide valuable input for the routine monitoring of exposed intertidal flats on the German North Sea coast, the latter already improving the identification of the spatial extent of mussel (oyster) beds. In addition, we demonstrate that high-resolution SAR is capable of detecting residuals of historical land use in areas that were lost to the sea during major storm surges in the 14th and 17th centuries.

1. Introduction

Worldwide, the largest intertidal flats can be found on the German, Danish and Dutch North Sea coast (CWSS, 2008) and on the western coast of South Korea (Kellermann and Koh, 1999), in a distance of up to 10 Km offshore. Those areas fall dry once during each tidal cycle and consist of fine sediments such as (fine) sand and mud, and they are only partly vegetated. Not only because they are impacted by the stress of the global sea level rise and the expected increasing frequency of storm events, a frequent surveillance is of great importance, though this is a difficult task by boat, foot, or land vehicles. This is when remote sensing techniques come into play.

Optical sensors are already being used for sediment and habitat classification on intertidal flats (Dennert-Möller, 1982; Kohlus, 1998; Stelzer et al., 2007), and promising results have been achieved through the classification of different sediment types, vegetation, and mussel beds (Brockmann and Stelzer, 2008). Existing classification systems for the different surface types of intertidal flats are usually based upon optical remote sensing data, since the hyperspectral data allow for a classification of surface types (Brockmann and Stelzer, 2008).

However, because of the strong dependence on daylight and cloud conditions, and because of the short time window around low tide (approx. 3 h), useful optical data acquired at low tide, daytime, and sunny weather conditions from the German North Sea coast are rare. A classification system based on spaceborne remote sensing data would therefore strongly benefit from the additional utilization of synthetic aperture radar (SAR) data. Gade et al. (2008) suggested using multi-frequency SAR data for a sediment classification on exposed intertidal flats. They demonstrated that pairs of simultaneously acquired L-, C- and X-band SAR images from the Spaceborne Shuttle Imaging C/X-Band SAR (SIR-C/X-SAR) campaigns in 1994 can be used for a crude sediment classification based on the inversion of the Integral Equation Model, IEM (Fung et al., 1992; Fung and Chen, 2004). However, whereas SIR-C/X-SAR was providing multi-frequency SAR imagery acquired simultaneously, current spaceborne SAR sensors operate at single frequencies, and as a consequence, SAR data from different satellites have to be used for multi-frequency SAR classification purposes. Because they are usually acquired with a considerable time lag in between, a profound knowledge of the radar backscatter properties of the sediment types, and their dependence on weather conditions, tidal cycle, and imaging geometry is needed, which can only be gained from a joint analysis of multi-satellite SAR data and optical remote sensing data, together with a-priori knowledge gained during in-situ campaigns. The sub-project 4 of the German national joint

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project DeMarine-Environment ("DeMarine-Umwelt", DMU) has been particularly devoted to this synergistic approach.

In addition to optical imagery (see, e.g., Ryu et al. (2008) and literature cited therein) SAR data have already been used for the monitoring of (dry-fallen) intertidal flats. Mason and Davenport (1996) used ERS SAR imagery to develop a semiautomatic method for the shoreline determination on the U.K. east coast between Humber and Wash. Niedermeier et al. (2000) and Heygster et al. (2010) detected waterlines, i.e. the border lines between water-covered and dry-fallen areas, in the Elbe estuary, using a wavelet-based algorithm they applied to ERS SAR imagery. Along those lines, Won (2009) extracted waterlines from TerraSAR-X imagery and compared polarimetric SAR signatures of salt-marsh plants with ground-based radar measurements. The use of polarimetric SAR data was also supported by Lee et al. (2012), who analyzed TerraSAR-X imagery of salt marshes on the South Korean coast and who found that the radar backscatter from wetlands is stronger at horizontal (HH) than at vertical (VV) polarization. This is in line with findings of Choe et al. (2012), who also showed that polarimetric SAR data can be used to detect mussel beds. van der Wal et al. (2005) proposed a regression model for the prediction of surface characteristics (roughness) from ERS SAR imagery. Along with an extensive interpretation of the mechanisms of radar backscattering from intertidal flat surfaces they showed that the roughness decreases with the amount of mud and increases with the median grain size. Additional surface roughness may be caused by biological activity, e.g. burrows of *Arenicola maritima* (van der Wal et al., 2005), while water puddles with a surface coverage ranging from 50% to 80% may decrease the effective surface roughness responsible for the radar backscattering (Kim et al., 2011).

van der Wal and Herman (2007) combined optical and radar data to monitor intertidal flats on the Westerschelde, The Netherlands. They found that the radar backscatter from sandy sediments exceeds that from muddy sediments. From the radar data they inferred a correlation of the sediment grain size and the surface roughness, and from the optical data a correlation of grain size and soil moisture. Recently, Dehouck et al. (2011) used TerraSAR-X data and optical imagery of the Arcachon Bay, France, to detect mussels, salt marshes, and sandy sediments. Similar to Gade et al. (2011) they showed that radar has the potential to complement optical sensors for the routine monitoring of intertidal flats.

The IEM has already been widely used for the interpretation of SAR signatures of bare soils and dry-fallen intertidal flats. Tansey and Millington (2001) analyzed ERS SAR images of arid areas in Jordan and attributed changes in the radar backscatter to changes in soil moisture and surface roughness. van der Wal et al. (2004) used the IEM to explain the relationship between sediment characteristics and the radar backscatter at C band. Baghdadi et al. (2002) compared IEM simulation results and radar backscatter measurements on bare soils in France and found that the IEM overestimates the radar backscatter, but that improved results can be achieved using an empirically derived correlation length. In later (comprehensive) studies, Baghdadi et al. (2004, 2006) calibrated the IEM using data from field campaigns in France and Canada and multi-frequency SAR data from the ERS and SIR-C/X-SAR missions (Baghdadi et al., 2004) and from ENVISAT ASAR (Baghdadi et al., 2006). They compared Gaussian, exponential, and fractal surface correlation functions and replaced the autocorrelation length by a calibration parameter. More recently, Deroin (2012) used ALOS-PALSAR and ERS-2 SAR imagery of the French coast for a thorough analysis and description of the radar backscattering from dry-fallen intertidal flats and for comparisons of in-situ measurements of surface roughness parameters with IEM simulations. Similarly, Choe et al. (2012) measured surface roughness parameters on intertidal flats on the South Korean coast and compared IEM simulations with Radarsat-2 and ALOS-PALSAR imagery.

Alternative radar backscattering models, such as that proposed by Oh et al. (1992) and Dubois et al. (1995), or the Delta Index Model proposed by Thoma et al. (2006), have been compared with the IEM in terms of their use for the simulation of the radar backscattering from dry and wet bare soils, but have not proven to be generally advantageous with respect to the IEM (Baghdadi and Zribi, 2006; Kim et al., 2011).

The aim of our efforts was to build up on the approach of Gade et al. (2008) by using data from different sensors (aboard different satellites), but also to extract information on Wadden Sea surface types from series of single-sensor data and from pairs of dual polarization SAR images, and to investigate if the information gained can enter into existing monitoring systems. After a description of the test areas on the German North Sea coast and of the data basis used herein, we present example results for the use of both multi-sensor and single-sensor SAR data, the latter used to identify the extent of mussel beds. Finally, we demonstrate the use of high-resolution SAR imagery for the detection of signatures that are related to historical land use and that are of interest to archeologists.

2. Test areas and data basis

Within DMU's subproject 4, three main test areas on the German North Sea coast were identified (Fig. 1), which represent areas of typical sediment distribution on intertidal flats, but also include vegetated areas and mussel and oyster beds, as well as residuals of historic land use. All test areas are briefly described hereinafter.

During the summer season, some regions are covered by seagrass and green algae, thus preventing a simple classification assuming bare sediments. The method applied by Brockmann and Stelzer (2008) is built upon linear spectral unmixing and feature extraction from the spectral reflectance. All extracted information from the optical data is combined in a decision tree, which is used to relate each pixel to a class representing different surface types, i.e., five sediment types, two vegetation density classes, one mussel class, and a class representing dry and bright sands (Fig. 2). The water coverage, having a strong influence on the spectral reflectance, is considered within the end-member selection for the linear spectral unmixing. Fig. 2 shows examples of the classification results for three test sites on the German North Sea coast (cf. Fig. 1).

The test area "Lütetsburger Plate" is part of the German National Park "Lower Saxony Wadden Sea", in the south-western part of the

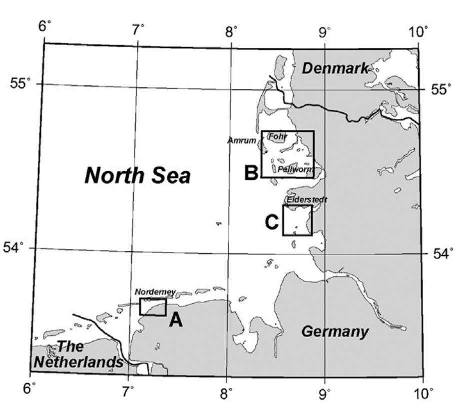

Fig. 1. The test sites of DMU's sub-project 4 on the German North Sea coast. A: "Norderney" is located between the island of Norderney and the mainland; B: "Halligen" is located between the Northern Frisian islands Amrum, Föhr, and Pellworm; C: "Wesselburen" is located south of Eiderstedt peninsula.