LONG-TERM REMOTE SENSING OF THE WADDEN SEA ECOSYSTEM ON THE GERMAN NORTH SEA COAST

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ABSTRACT

High-resolution multispectral remote sensing data from satellite-borne optical sensors have been used for the classification of sediments, macrophytes, and mussels in the German Wadden Sea. Since the use of those sensors in northern latitudes is strongly limited by clouds and haze, we included synthetic aperture radar (SAR) data, allowing an observation of intertidal flats that is independent of cloud coverage and daytime. The data acquired at different radar bands (L, C, and X band, from ALOS PALSAR, ERS SAR and ENVISAT ASAR, and TerraSAR-X , respectively) have been used to analyse their potential for crude sediment classification on dry-fallen intertidal flats and for detecting benthic fauna such as blue mussel or oyster beds. The information gained from optical and SAR sensors, together with in-situ observations, yields an improved classification of different sediment types, together with mussel beds and seagrass. In addition to the routine sediment classification, for the first time, data from the high-resolution TerraSAR-X are used to demonstrate that residuals of former agricultural areas can still be detected from space. The data are complemented by aerial photographs and in-situ data.

1. INTRODUCTION

The increasing requirements of coastal monitoring, to some extend, can be met deploying remote sensing techniques that allow for relatively cheap surveillance of large coastal areas. Optical sensors are already being used for sediment classification on intertidal flats, and promising results have been achieved through the classification of different sediment types, vegetation, and mussel beds (see Figure 1). However, because of the strong dependence on daylight and cloud conditions, useful optical data (acquired at low tide) from the German North Sea coast are rare. A classification system based on spaceborne remote sensing data would therefore strongly benefit from the utilization of synthetic aperture radar (SAR) data.

Gade *et al.* (2008) suggested to use multi-frequency SAR data for a sediment classification on exposed intertidal flats. However, 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 project DeMarine-Environment (DMU) is particularly devoted to this synergistic approach.

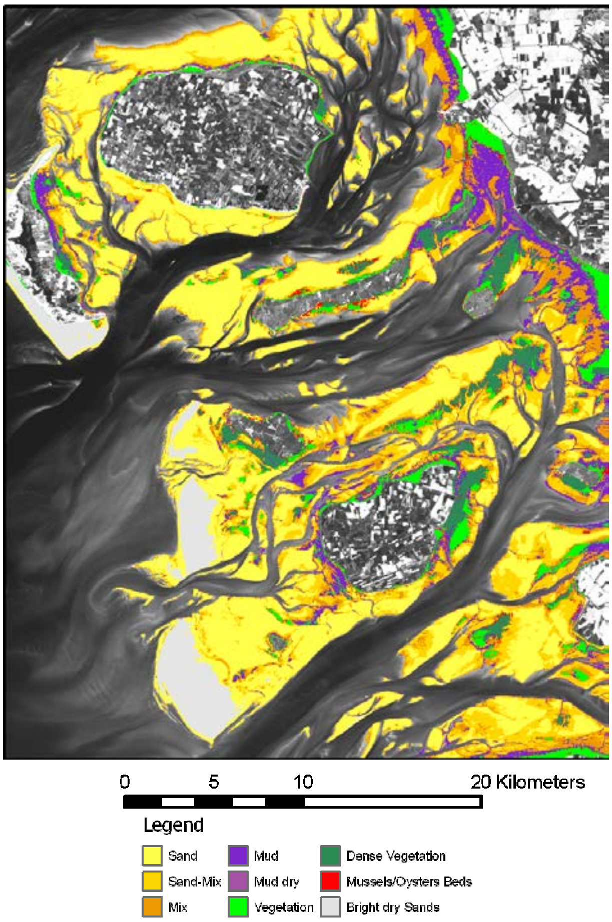

Figure 1. Wadden Sea surface classification for the North Frisian DMU testsite "Halligenwatt", as generated from Spot 4 data from July 28, 2006 (© Brockmann Consult; original data © SPOT Image 2006)

2. RESULTS

2.1. Longterm Radar Remote Sensing

The spatial distribution of sediments, and thus of the dry-falling intertidal flats, and of the various habitats in the entire Wadden Sea is changing severely in the course of only a few decades. Frequent surveillance of Wadden areas is therefore necessary, and is regulated through national and international laws and directives such as the EC's Water Framework Directive and Flora-Fauna-Habitat Directive. As an example, Figure 2 shows two ERS SAR images of exposed intertidal flats on the German North Sea coast, acquired with 16 years in between, on 11 January 1992 (ERS-1; upper panel) and on 24 July 2008 (ERS-2; lower panel).

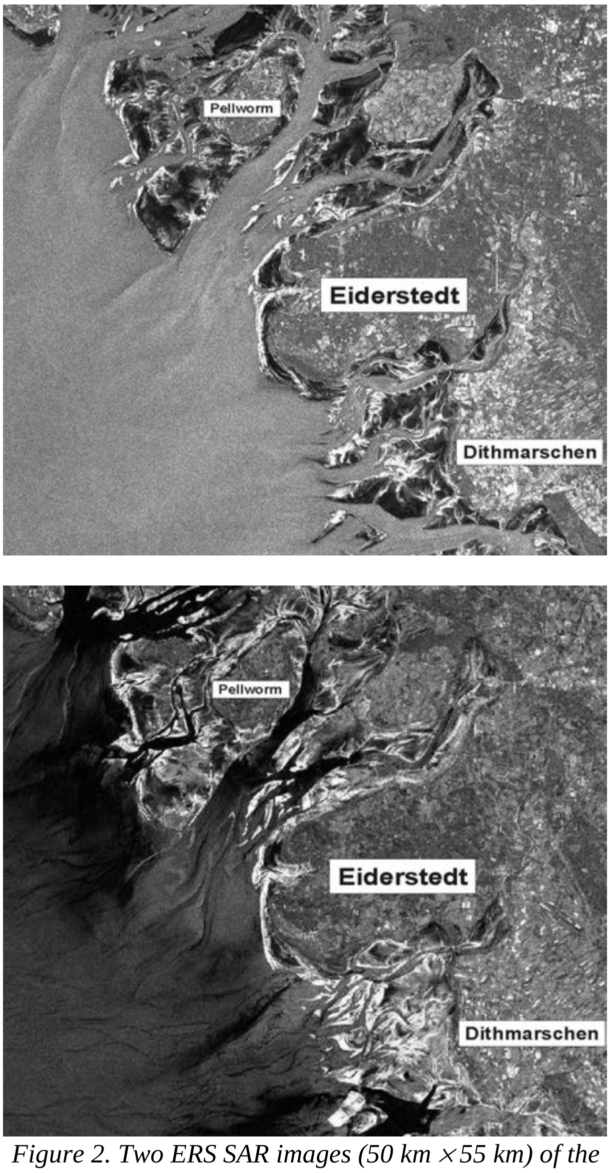

Figure 2. Two ERS SAR images (50 km $\times$ 55 km) of the German Wadden Sea (Dithmarschen peninsula in the image center) acquired (top) on 11 January 1992 and on (bottom) 24 July 2008 (© ESA 1992, 2008)

For the analysis of longterm (i.e., more than a decade) changes in the highly morpho-dynamical Wadden Sea SAR images acquired from board the ERS 1/2 satellites between 1991 and 2008 have been used. In parts of the images the waterline can be inferred through strong local gradients of the image intensity. Depending on environmental (i.e. weather and tidal) conditions, different sediment types may show different radar backscattering (image intensity). However, the location of the main tidal creeks can be easily inferred from both images. A thorough analysis of the two SAR images yields that the "Wesselburen Wadden Sea", the area south of Dithmarschen peninsula in the image center, shows the strongest morphodynamics in the entire area. This is why it was selected as one of the DMU test sites.

2.2. Classification Results

The method used for the classification of optical remote sensing data is based on a linear spectral unmixing and feature extraction from the spectral reflectances (Brockmann and Stelzer 2008). 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 dry and bright sands class. The water coverage, having a strong influence on the spectral reflectance and on the radar backscattering, is considered within the endmember selection for the linear spectral unmixing. Figure 1 shows the result of a classification applied to a Landsat-5 TM scene from July 2, 2007.

The spatial variations of different sediment types, along with the occurrence of mussel beds, see grass, and macro algae, is typical for the test site "Halligenwatt" in Schleswig-Holstein. Figure 3 shows two SAR images of the northern part of the test site, between the German islands of Amrum, Föhr, and Langeness. The images were acquired from different satellites on the same day, during, or shortly after, low tide. The ENVISAT ASAR image in the upper panel was acquired on October 18, 2007, at 09:55 UTC (at low tide), and the ALOS PALSAR image in the lower panel was acquired on the same day, at 10:23 UTC (28 minutes after low tide). Dry-fallen intertidal flats manifest in areas of reduced radar cross section. In general, the radar backscattering from the exposed tidal flats is much lower than that from the surrounding wind-roughened sea surface, because of a strong north-westerly wind (12-13 m/s). Note the different radar contrast of the exposed intertidal flats, which cannot be attributed solely to the different acquisition time (water level).

At the time of both image acquisitions, a strong wind (12-13 m/s) blowing from north-westerly directions was encountered. This explains why the radar backscattering from the exposed tidal flats is much lower than that from the surrounding wind-roughened sea surface, so that they appear much darker.

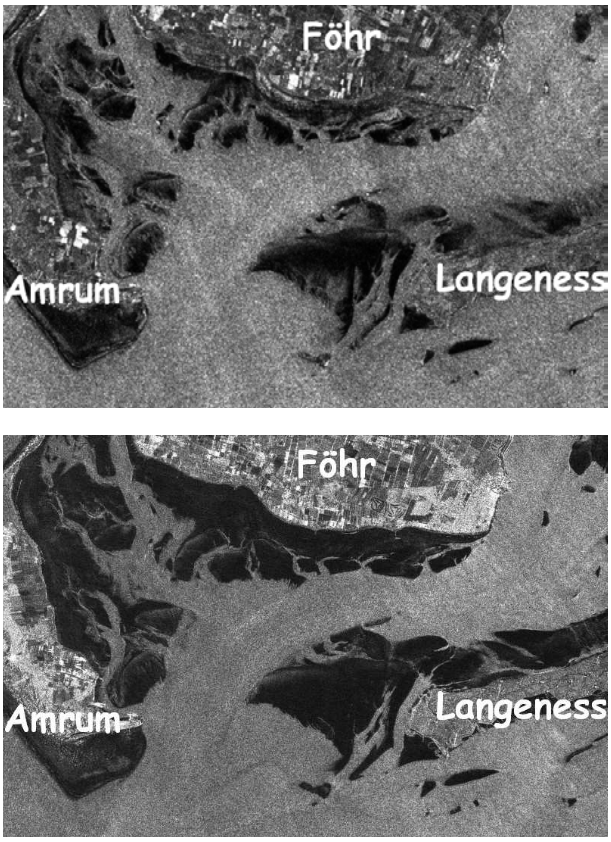

Figure 3. Two SAR images (37.5 km × 25.0 km) of the test site "Halligenwatt", acquired at, or shortly after, low tide. Top: ENVISAT ASAR image of October 18, 2007, 09:55 UTC (© ESA 2007); bottom: ALOS PALSAR image of the same day, but 10:23 UTC (© JAXA 2007).

Some of the exposed intertidal flats show an inhanced C-band radar backscattering. This effect may be due to remaining water, which stays in the sand ripple troughs, or in sinks and small dells, and whose surface is roughened by the strong wind. The map in Figure 4 shows the frequency of water coverage on exposed tidal flats in the test site "Halligenwatt", as derived from two SPOT-4 and five Landsat images. The open sea, islands, and the mainland are colored in dark grey. The red spots denote locations where a spatial water coverage of more than 50% was encountered during field campaigns. Although only a small population of seven images was used to generate this map (through linear spectral unmixing), the results show evidence that remnant water contributes to the radar backscattering at C-band, particularly under high wind conditions. Gade et al. (2008) pointed out that this remnant water may significantly influence the sediment classification they proposed, which is based on the analysis of SAR data and which provides a crude sediment classification through the derivation of the surface's basic roughness parameters. If the sediment surface, as it is seen by the SAR sensors, is flattened by the remnant water, any classification algorithm based on SAR imagery and on the assumption of dry sediments will fail.

The southern test site "Lütetsburger Plate" in Lower Saxony, between the island of Norderney and the mainland, is dominated by a strong spatial variation of different sediment types, along with a high coverage by mussels.

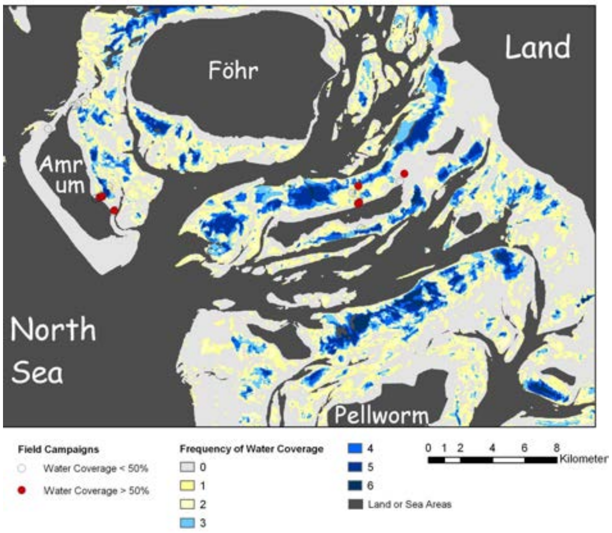

Figure 4. Map showing the frequency of water coverage on exposed tidal flats in the test site "Halligwatt", as derived from two SPOT-4 and five Landsat images.

During summer season, some regions are covered by sea grass and green algae. Thus, a simple classification method that assumes bare sediments cannot be applied in this area.

Figure 5 demonstrates how the test site is imaged by SAR sensors working at different radar bands. The upper panel shows an ALOS PALSAR (L-band) image acquired on April 12, 2008, at 21:43 UTC, 23 minutes after low tide, and the lower panel shows a TerraSAR-X (X-band) image acquired on August 30, 2008, at 17:10 UTC, 34 minutes after low tide. The location of the tidal creeks can be identified through enhanced radar backscattering from the sediment on their edges. This local enhancement of the radar backscatter was already found by Gade *et al.* (2008) who attributed it to an enhanced current-induced surface roughness of the sediments (i.e. sand ripple height).

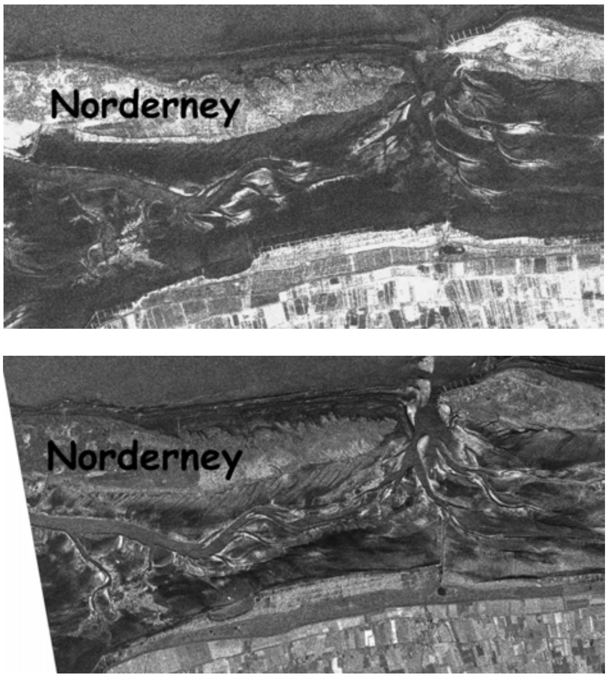

Figure 5. Two SAR images (25.7 km × 13.4 km) of the test site "Lütetsburger Plate", acquired shortly after low tide. Top: ALOS PALSAR image of April 12, 2008, 21:43 UTC (© JAXA 2008); bottom: TerraSAR-X image of August 30, 2008, 17:10 UTC (© DLR 2008).

We also observed some irregular bright patches in the left part of both SAR images in Figure 5, see the respective enhances sections in Figure 6. Those patches are not due to sand ripples, but due to mussel beds mostly consisting of Pacific oysters. The mussel beds manifest as bright patches in the SAR image, because they enhance the surface roughness sensed by the SAR. Note that the mussel beds show up on SAR imagery in both spring and summer, i.e., before and during coverage by green algae, respectively. Moreover, the mussel beds result in enhanced radar backscattering not only at X-band (3 cm wavelength) but also at L-band (30 cm). Both the "effective shell size", i.e. the size of the shell sticking out of the sediment, and the mean distance between adjacent mussels result in an

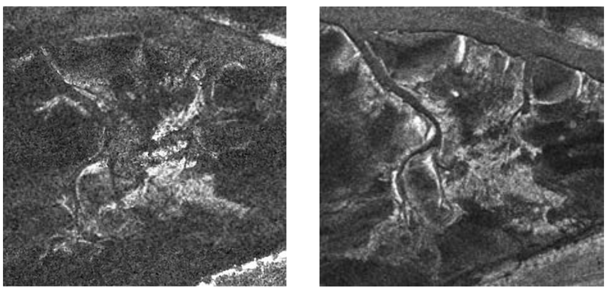

Figure 6. Subsections (5.1 km × 5.1 km) of the two SAR images shown in Figure 5 (left: PALSAR, right: TerraSAR-X). Irregular patches in the image centers are due to mussel beds. (© JAXA 2008; DLR 2008).

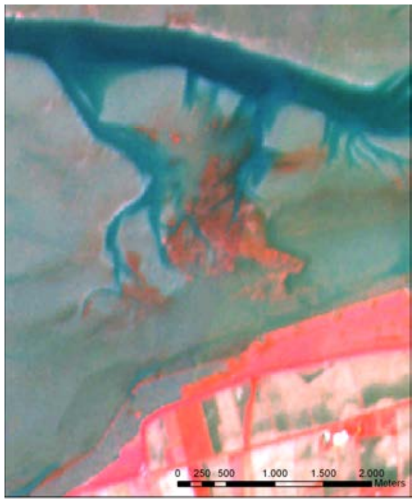

Figure 7. False-color RGB generated from SPOT data (bands 3-2-1) acquired on September 10, 2008. In the image center the mussel bed can be delineated as a brownish irregular patch. © SPOT Image 2008.

enhanced radar contrast at both radar bands. That is, for the first time, benthic fauna on exposed intertidal flats has been imaged by multi-frequency (L, C, and X band) SAR sensors.

2.3. Archeological Observations

In the Middle Ages, farmsteads and villages were built along the German North Sea coast, surrounded by farmland and also floodplain forests. The houses were mostly built on dwelling mounds, protected by small dikes, and ditches were built to take out the water of the farmlands. During a severe storm surge on January 16, 1362, large land areas were lost to the sea, and they haven't been diked ever since. New farmland was structured by a wide-meshed system of ditches, and farmhouses on terps were connected by narrow lanes.

Another major storm surge occurred on October 11, 1634. The big (second) "Manndränke" is still the most known storm surge in history in the area of the North Frisian Wadden Sea. Major parts of the populated area were destroyed and the swampy land changed its face and became the Wadden Sea as it is known today. Figure 8 shows the change in coastline during the past 2000 years, and particularly since the Middle Ages. Over the years, great parts of this former agricultural area have been buried by muddy and sandy sediments, which nowadays form the German Wadden Sea. Under the permanent action of the tidal forces, morphodynamics take place, the muddy and sandy marine sediments are partly driven away, and traces of former peat digging, farmland, and settlements appear again on the bottom of the Wadden Sea. These sedimental structures show distinct biological effects and are often marked by benthic organisms.

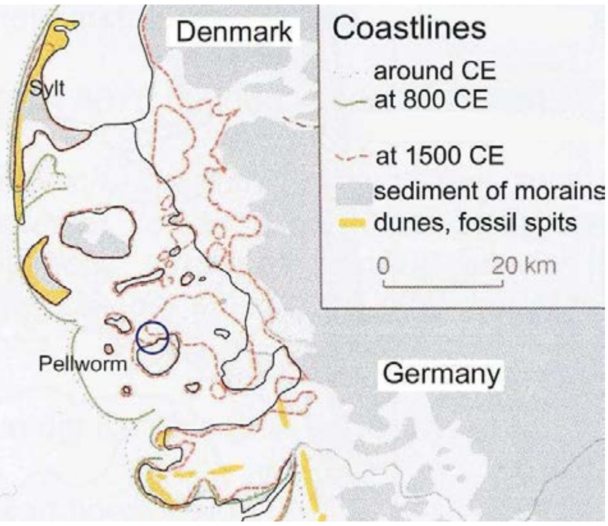

Figure 8. Changes in the Northern German coastline during the past 2000 years, after Behre (2009). The black line denotes the coastline at present, and the dark blue circle off Pellworm denotes the area of interest.

Figure 9 shows an aerial photograph taken in July 2009 from dry-fallen intertidal flats north-east of the German island of Pellworm. Clearly visible are linear structures that witness the historical land use, before the great "Mandränke". Also visible is the sandy sediment, by which those structures were buried, and which is driven away by the action of currents and waves.

Figure 9. Aerial photograph taken on July 29, 2009, at low tide and showing residuals of former settlements in the German Wadden Sea, close to a tidal creek (upper left) Image by Bernd Hälterlein, LKN.

Figure 10 shows a reconstruction of a historical lane, with ditches on either side, which can be found on the intertidal flats north of Pellworm and which caused structures like those shown in Figure 9. Fossil farmland structures, mostly ditches, but also lanes or dykes, cannot be observed through their relief of less than 10 cm. Rather it is the sediments on the lost pastures that are different from those in the linear structures of ditches. Typical wadden sediments on the flat sand banks consist of marine fine sand, which had been the basic compound of the old marsh land and which is still a major part of the marine environment. The surface of the fossil ditches is different. In the center there are pillowy sediments while the ditch edges are often stabilized by fossil roots and other plant material connected with the sediment (Figure 10). This causes narrow ridges of only 10 cm to 20 cm thickness, which can still be observed today.

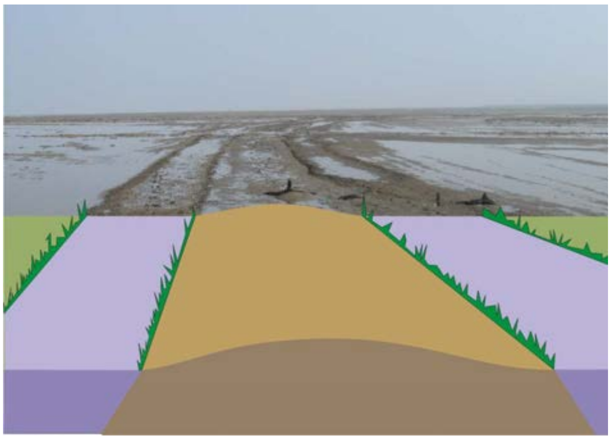

Figure 10. Reconstruction of a medieval lane (Kohlus 2008) crossed by a ditch in the background.

Such linear structures have been found during field campaigns (green and brown measurements) north off Pellworm. Figure 11 shows an aerial photograph of the island's north coast. Superimposed are locations of ditches and one lane and of fossil terps (purple) and field structures (blue), as provided by the State Archeological Department of Schleswig Holstein, Germany (ALSH).

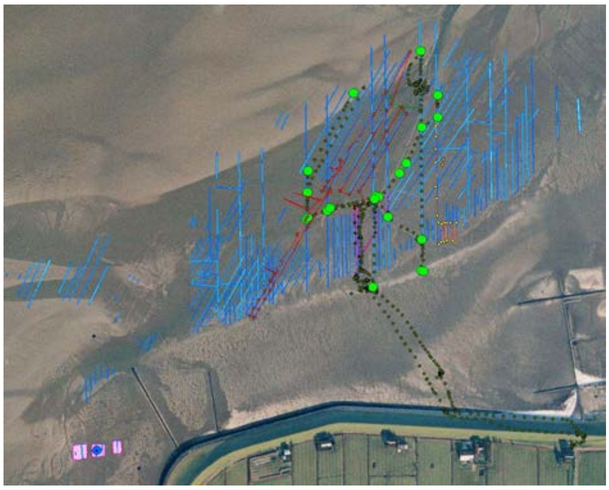

Figure 11. Aerial photograph of dry-fallen intertidal flats north off Pellworm, with the locations of residuals of historical land use superimposed (LKN 2009, ALSH 2008).

The high-resolution X-Band synthetic aperture radar (SAR) aboard the German TerraSAR-X allows for mapping the Wadden Sea surface from space, and SAR images with a pixel spacing of less than 1 m can be used to detect small-scale surface structures if they are linked with a variation of the surface roughness of the Wadden Sea sediments. As an example, Figure 12 shows a small (1630 m × 1730 m) section of a TerraSAR-X image acquired on August 3, 2009, over the same area as shown in Figure 11. The residuals of the historical structures can clearly be delineated as linear bright and dark signatures.

Figure 12. Section (1630 m × 1730 m) of a TerraSAR-X image of dry-fallen intertidal flats north off Pellworm. Residuals of historical land use can be delineated through linear bright and dark structures. © DLR 2009.

For the first time, thus, residuals of historical land use in the North Frisian Wadden Sea are detected by a spaceborne SAR sensor. Moreover, a direct comparison of the SAR image and the available data from aerial survey and field campaigns (Figure 12 and Figure 11, respectively) demonstrates that formerly unknown structures have been identified by TerraSAR-X (cf. the upper image center in both figures).

3. CONCLUSIONS

Within subproject 4 of the national German project DeMarine-Environment (DMU) data from optical sensors and multi-satellite SAR images of exposed intertidal flats are analyzed to improve existing classification systems by including SAR data. For the first time, extensive mussel beds (composed of a mixture of Pacific oysters and blue mussels) have been observed in multi-frequency SAR imagery. However, the strength of their signatures, and thus the capability of SAR sensors to detect and to classify them, may depend on the seasonal change in coverage by brown algae.

During later stages of the project, results from in-situ campaigns will be included, along with further classification results derived using optical remote sensing data. Of particular interest will be to investigate how the observed SAR signatures depend not only on radar frequency and polarization, but also on the season, on weather conditions, and on the tidal phase. A profound knowledge of all main factors contributing to the observed SAR signatures is essential for any improvement of existing classification systems, and our preliminary results show evidence that multi-satellite SAR data can be used for an improved sediment classification on exposed intertidal flats.

High-resolution TerraSAR-X images can be used to complement archeological surveys on intertidal flats on the German North Sea coast. The radar images the former systems of ditches, dating back to the 14th century and to the 16th/17th century. The observed signatures are due to different sediment types, which in turn are due to the very ditch morphology. Moreover, different sediments cause different biological effects and are also often marked by benthic organisms. Thus, the ditch structures containing more biogenic material may be a preferred habitat of certain mussels while sand worms (*Arenicola marina*) are usually found on sandy sediments. Those benthic organisms may cause different surface roughness patterns that can be sensed by the high-resolution X-Band SAR.

4. ACKNOWLEDGMENTS

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