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Radar Imaging of Archaeological Sites on Intertidal Flats

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Abstract

After major storm surges in the 14th and 17th centuries, vast areas on the German North Sea coast were lost to the sea. What was left of former settlements and historical land use was buried under sediments for centuries, but when the surface layer is driven away under the permanent action of wind, currents, and waves, they appear again at the Wadden Sea surface. However, the frequent flooding and, thereby, the strong erosion of the intertidal flats make any archaeological monitoring a difficult task, so that remote sensing techniques appear to be an efficient and cost-effective instrument for any archaeological surveillance of that area. We show that high-resolution space borne Synthetic Aperture Radar (SAR) imagery with pixel sizes well below 1 m² can be used to complement archaeological surveys and that SAR images from the German TerraSAR/ TanDEM-X satellites clearly show remnants of farmhouse foundations and of former systems of ditches, dating back to the 14th and to the 16th/17th centuries. In particular, the new high-resolution TerraSAR-X acquisition mode ('staring spotlight') allows for the detection of various kinds of residuals of historical land use, some of which have been unknown so far.

Introduction

In Medieval times, the German North Sea coastline was very different from how it is today (Fig. 1): the North Frisian islands did not yet exist, but were still what was called the 'Uthlande' (outer lands) and what was part of, or connected with, the mainland (Behre, 2009). Vast areas along the coast were dominated by swamps, marshes, and swamp forests, which often made any settlements difficult or impossible. In the sparse settlements on the German North Sea coast houses were often built on dwelling mounds, protected by small dikes (the latter being called 'summer dikes', because they could effectively provide protection against high water only during summer, when there are usually no storms). Systems of drainage ditches were built to remove the water from the farmlands, thereby allowing for any kind of agriculture.

On January 16, 1362, after more than 24 hours of severe westerly storm, an immense storm tide flooded the coast, causing the small dikes to break at many places, and eventually causing the death of a great number of cattle and men. As a result of that storm surge, which is known in history as the Saint Marcellus' flood or 'Grote Mandrenke' ('great drowning of men'), huge land areas were lost to the sea, and they haven't been diked ever since (see the upper middle and upper right panels of Fig. 1). Thereafter, it took a long time until new dikes were built to protect the remaining marsh land. The new farmland was characterized by a dense system of ditches, the dikes enclosed larger polders than in the centuries before, and farmhouses on terps were connected by narrow lanes.

Another major storm surge occurred on October 11, 1634, again killing cattle and men, after the dikes had broken at many places. This second 'Grote Mandrenke'(also known as Burchardi flood) hit the area of North Frisia in an

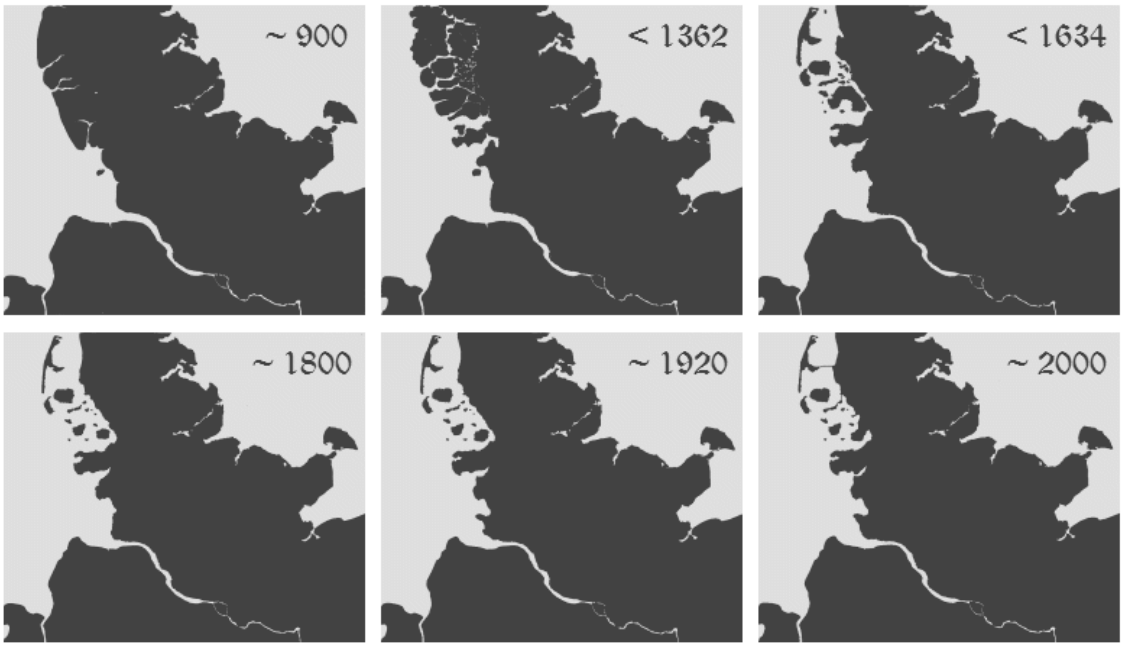

Fig. 1: Changes in the German North Sea coastline during the past 1100 years (upper left part of each panel), after Behre (2009).

economically weak period, after the plague had caused many deaths only about 30 years before. The island of Strand, in the centre of the North Frisian coast, was cut into parts by the flood (cf. the upper right and the lower left panels of Fig. 1), thereby destroying farmland, farms, and whole villages. The Burchardi flood is still the most-known storm surge in history in the area of the North Frisian Wadden Sea.

Over the following centuries, great parts of this former agricultural area have been buried under muddy and sandy sediments, which nowadays form the German Wadden Sea. This area is being flooded, and falls dry, once during each tidal cycle, thereby making archaeological excavations very difficult. However, under the permanent action of the tidal forces the muddy and sandy marine sediments are partly driven away, and traces of former peat digging, drainage systems, and settlements appear again on the surface (Bantelmann, 1967). Since those areas are difficult to reach, and thus to observe from ground, airborne sensors have proven to be advantageous for a systematic observation of the residuals of those historic places (Gade and Kohlus, 2011, 2015). Their use, however, is cost-intensive, which makes high-resolution space borne sensors an alternative source of data that can be used by archaeologists for their frequent surveillance of the area (Gade et al., 2014). A map of our area of interest is shown in Fig. 2, with the location of the Synthetic Aperture Radar (SAR) image in Fig. 3 inserted.

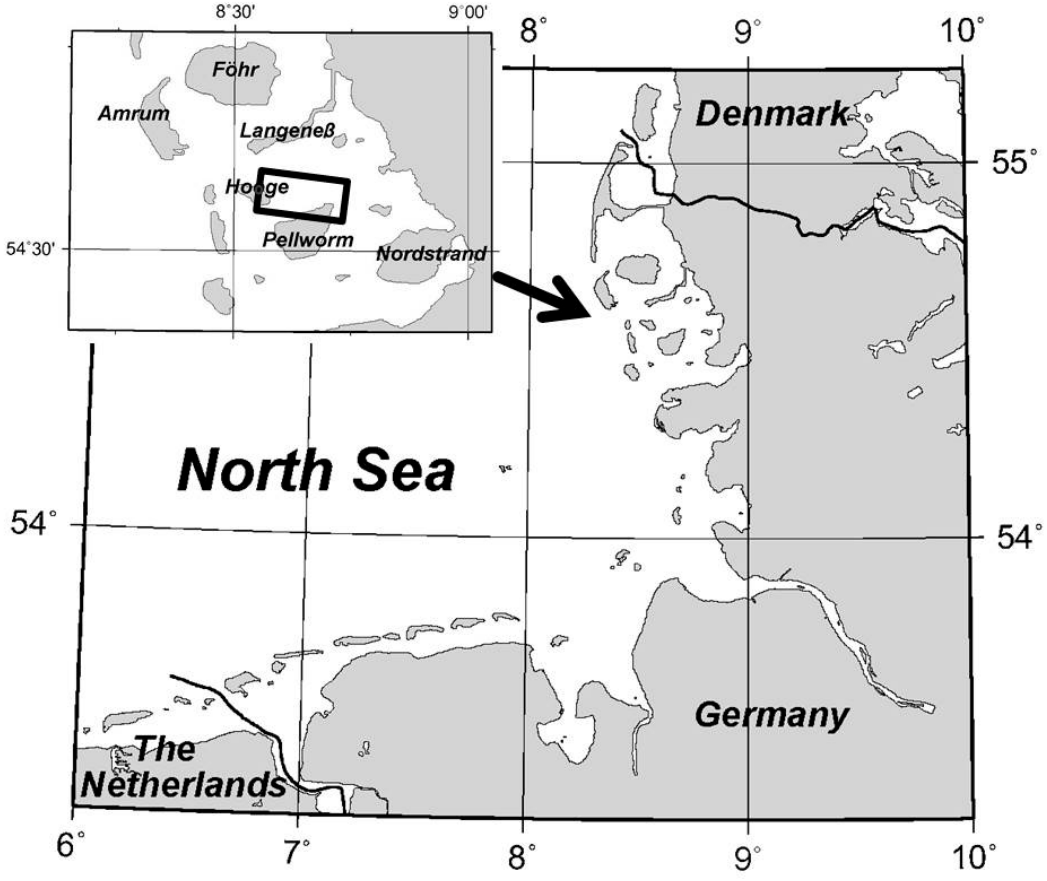

Fig. 2: Area of interest on the German North Sea coast. The black rectangle in the close-up on the upper left marks the location of the SAR image shown in Fig. 3.

Test Site and Data

The area of interest lies in the centre of the North Frisian Wadden Sea, i.e. in an area, which was most affected by the major storm surges in the 14th and 17th centuries (see Fig. 1). A TerraSAR-X image (11.6 km × 5.2 km) of that area, acquired on December 12, 2012, (at 05:33 UTC, 18 minutes after low tide), is shown in Fig. 3. The islands of Pellworm and Hooge can be seen in the lower and left parts of the image, respectively, and tidal channels and creeks show up dark, because of the low wind speed during image acquisition (4 m/s, blowing from SE; the radar backscattering mainly depends on the roughness of the water surface; therefore, a flat surface at low wind speeds causes low radar backscatter and, thus, dark image areas). The bright features in the right half of the image mark edges of tidal creeks and dry, sandy sediments (Gade et al., 2008), but are not of interest herein. However, in the two (1.0 km × 1.0 km) areas marked by the white squares, we found fine, linear structures, which are due to to remnants of former landuse (before the storm surge of 1634).

A total of 26 TerraSAR-X/TanDEM-X images acquired in high-resolution spotlight mode between 2008 and 2014 form the basis for our systematic analyses of SAR signatures of historical land use. The pixel sizes of all images were on the order of 1 m², or even below, thereby allowing for the detection of fine structures that can be attributed to remnants of narrow ditches or settlements. Those images are complemented by Terrasar-X/TanDEM-X acquisitions in the new ‘staring spotlight’ mode, with extremely fine pixel sizes of 0.3 m × 0.3 m and below.

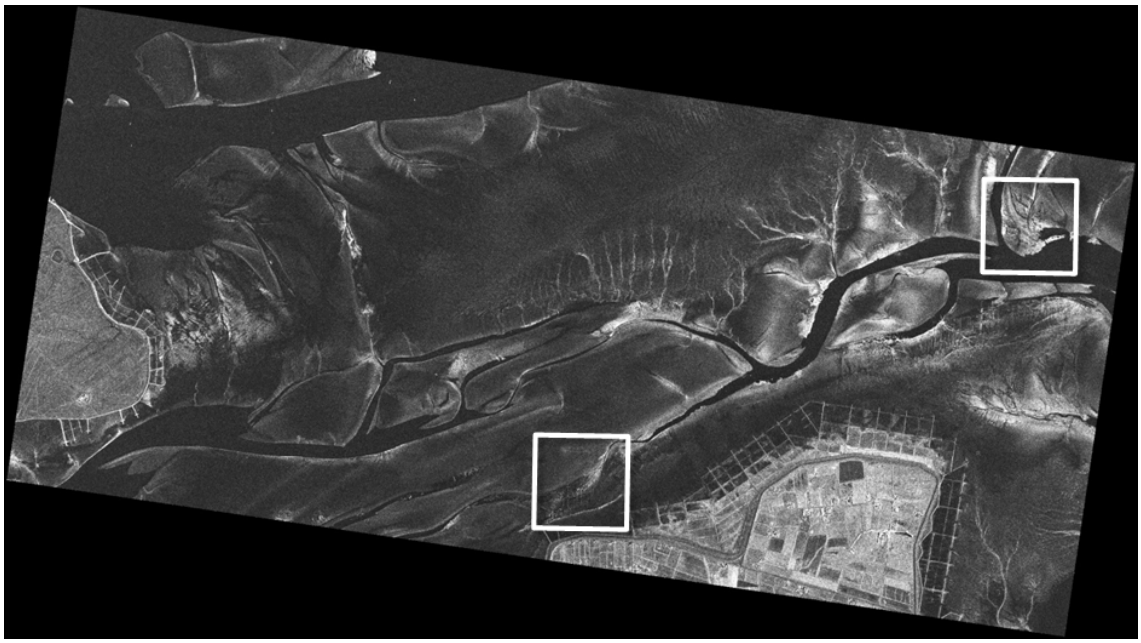

Fig. 3: TerraSAR-X image of the area of interest, north of Pellworm and east of Hooge, acquired on 12 December 2012. The white squares denote the locations of the SAR image details shown in Fig. 4 and Fig. 7. © DLR 2012.

Examples of Cultural Traces Found on SAR Imagery

Intertidal flats are highly morphodynamic, and when the muddy and sandy marine sediments of the flats' upper layer are moved away, banks of peat, old clay, and remnants of farmland and settlements appear again on the dry-fallen surface. Moreover, the deposition of fine sediments along those morphologically harder structures can help pronouncing them, thereby making them (better) visible in aerial and satellite imagery. Analysing the high-resolution SAR imagery we found at several places fine linear structures, which are clearly anthropogenic. Fig. 4 and Fig. 5 are the same 1000 m × 1000 m details of two TanDEM-X images acquired in staring spotlight mode on November 19, 2014, at 17:01 UTC (26 minutes after low tide, 3 m/s wind from easterly

Fig. 4: Subsection (1000 m × 1000 m) of a TanDEM-X staring spotlight scene acquired on November 19, 2014, north of Pellworm island. The linear structures are cultural traces, i.e., remnants of former settlements and land use. The letter (A) is included for comparison with Fig. 5. © DLR 2014

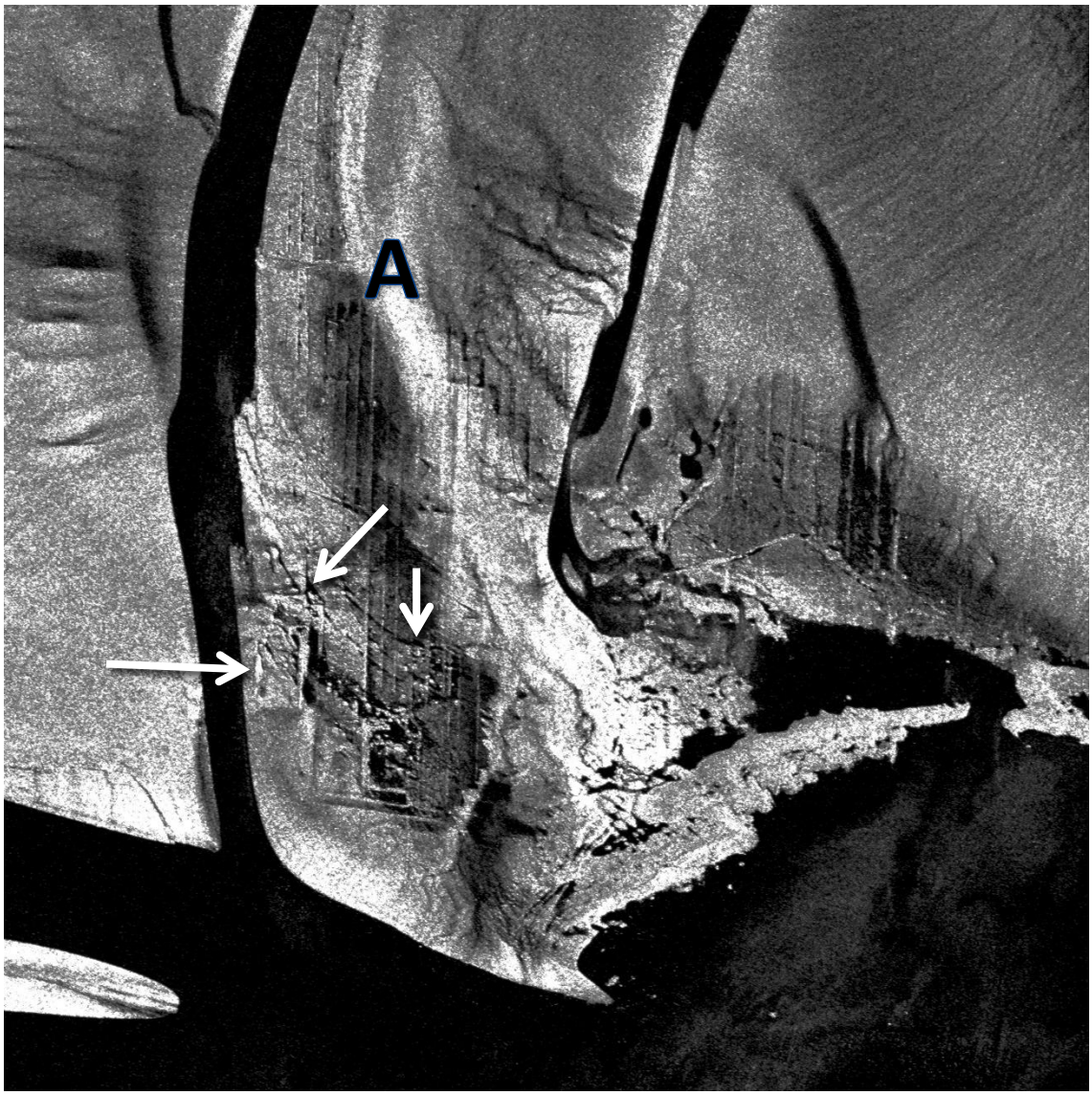

Fig. 5: Same as Fig. 4, but TanDEM-X staring spotlight scene acquired on January 20, 2015. © DLR 2015. The letter (A) marks the same area as in Fig. 4, the arrows were included for easier comparison with the aerial photograph shown in Fig. 6.

directions) and on January 20, 2015, at 05:50 UTC (37 minutes before low tide, 1.3 m/s wind from easterly directions), respectively, and show examples of such structures. The location of these 1 km² details is marked by the upper right square in Fig. 3. The very fine pixel sizes of 26 cm × 26 cm and 28 cm × 28 cm, respectively, allow imaging of residuals of historical land use (houses, ditches, lanes), which usually are too narrow to be delineated on SAR imagery of conventional resolution (with pixel sizes on the order of 10 m).

Clearly visible are linear and rectangular structures in both lower left image centres, close to the tidal creek, along with groups of parallel vertical lines at different locations in both image centres. The mean distance between those parallel lines is about 15 m, thus indicating that they are remnants of former ditches and drainage channels. In both SAR images the letter (A) marks the same location; note that the parallel vertical lines to the south and south-west of this location are visible only in the younger SAR

image (Fig. 5), whereas a diffuse bright band in the older SAR image (Fig. 4), left of (A), indicates that this area was still covered by sandy sediments in November 2014. This comparison illustrates the strong morphodynamics on intertidal flats, and also demonstrates the need for a frequent monitoring of those archaeological sites.

Fig. 6 shows an aerial photograph of the same intertidal flat north-east of Pellworm, taken on July 29, 2009, at low tide. Here, it is obvious that the linear structures origin from foundations of former settlements. In addition, several dark spots are visible, which origin from former wells, pits, cisterns, etc. Those spots can also be found on SAR imagery (as bright spots, though; see Fig. 4 and Fig. 5), if the spatial resolution is high enough (in SAR images of lower resolutions they could easily be confused with speckle noise typical for SAR imagery). For an easier comparison with the above SAR images three arrows marking the same spots have been included in both the aerial photograph (Fig. 6) and the second SAR image (Fig. 5). Also visible is the sandy sediment, by which those structures were buried for long, and which was driven apart by the action of currents and waves. A close comparison of the aerial photograph with the high-resolution SAR images reveals that, during the (more than) five years between the two kinds of acquisitions, parts of the residuals were already lost, due to the permanent erosion, sedimentation, and morphological changes.

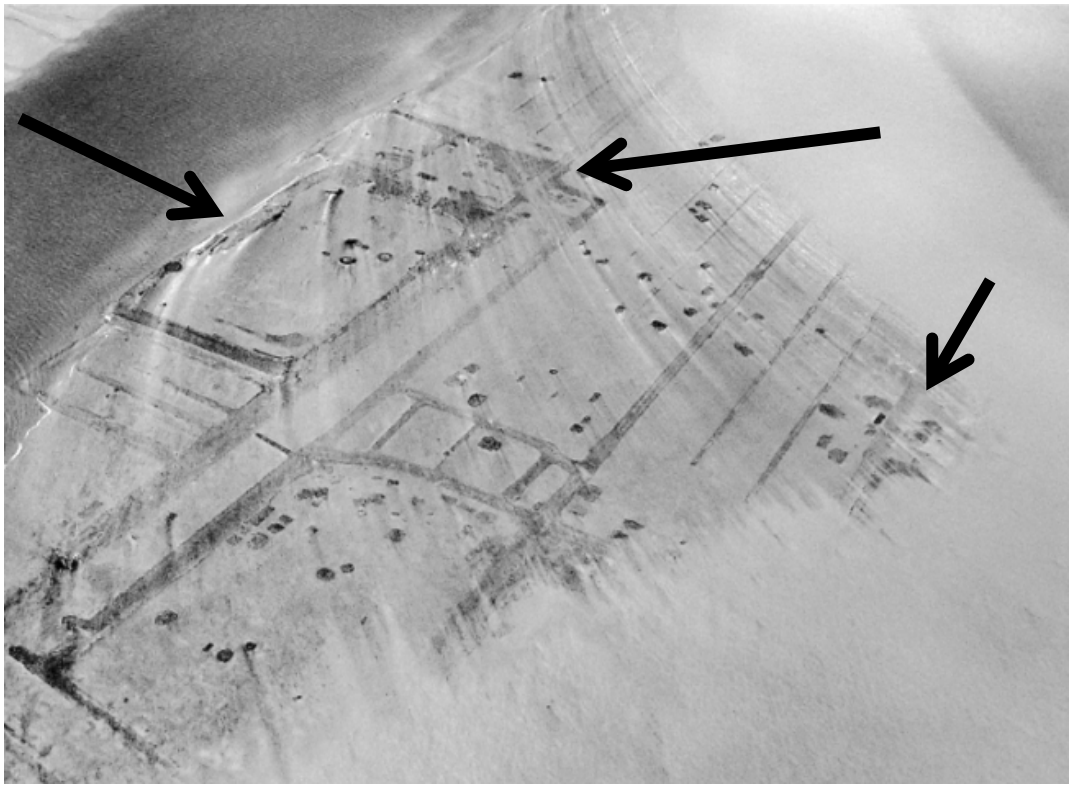

Fig. 6: Aerial photograph of exposed intertidal flats north of Pellworm, taken in July 2009. Residuals of former settlements, close to a tidal creek (upper left), can be clearly seen. The arrows were included for easier comparison with the SAR image shown in Fig. 5. Photograph: B. Hälterlein, LKN.

Another example of very high resolution SAR imagery of archaeological sites is shown in Fig. 7. The small section (again, 1000 m × 1000 m, corresponding to the lower left square in Fig. 3) of a TanDEM-X staring spotlight scene was acquired on November 21, 2014, at 05:41 UTC (low tide; 2 m/s wind from easterly directions) and shows many bright and dark parallel lines all over the image centre. The distance of those lines is between 10 m and 20 m, again, indicating that they are remnants of a former mesh of ditches built for the drainage of the farmland. The ditch residuals are marked by denser (harder) sediment causing higher surface roughness which, in turn, results in higher radar backscattering. However, we also note that, once the space in between is partly filled with sandy sediments, some of the lines may also appear dark (seen in the image centre of Fig. 7).

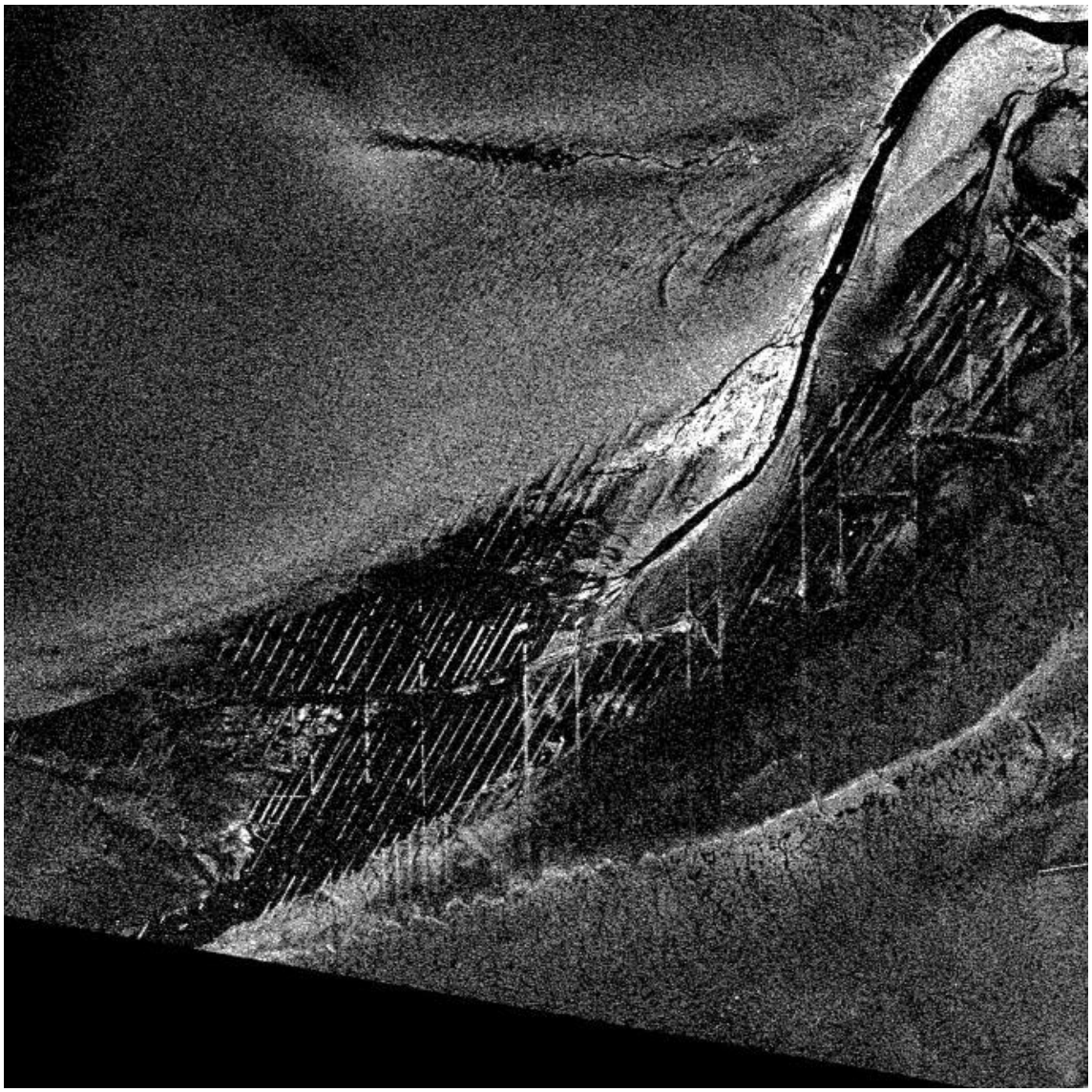

Fig. 7: Subsection (1000 m × 1000 m) of a TanDEM-X staring spotlight scene acquired on November 21, 2014, north of Pellworm island and showing in its lower centre the same area as in Fig. 9. © DLR 2014

Fig. 8 shows a photograph taken during low tide on May 14, 2009, from a dike on the northern coast of Pellworm island. In the image centre dark parallel structures can be delineated, which correspond to those seen on the SAR images. Clearly visible are the differences in sediment composition of the linear structures and the surrounding sandy flats. Also visible is remnant water in between the dark lines (and in several puddles all over the place), which results in a stronger contrast between the parallel bright lines and the dark area in between (Fig. 7).

Finally, Fig. 9 shows a reconstruction of a historical lane, with ditches on either sides, which can be found on the intertidal flats north of Pellworm and which may cause structures like those observed in the SAR imagery. Residuals of fossil farmland structures, mostly of ditches, but also of lanes or dikes, cannot be observed through their relief of less than 10 cm. Instead, 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 coastal environment. In contrast, the surface of the fossil ditches is different: in the centre pillow-like sediments can be found, while the ditch edges are often stabilized by fossil roots and other plant material connected with the sediment (Fig. 9). This causes narrow ridges of only 10 cm to 20 cm width, which can still be found today and which show up on SAR imagery, if its spatial resolution is high enough.

Fig. 8: Photograph taken from a dike on Pellworm island and showing manifestations of historical land use as dark parallel lines. Photograph: M. Gade.

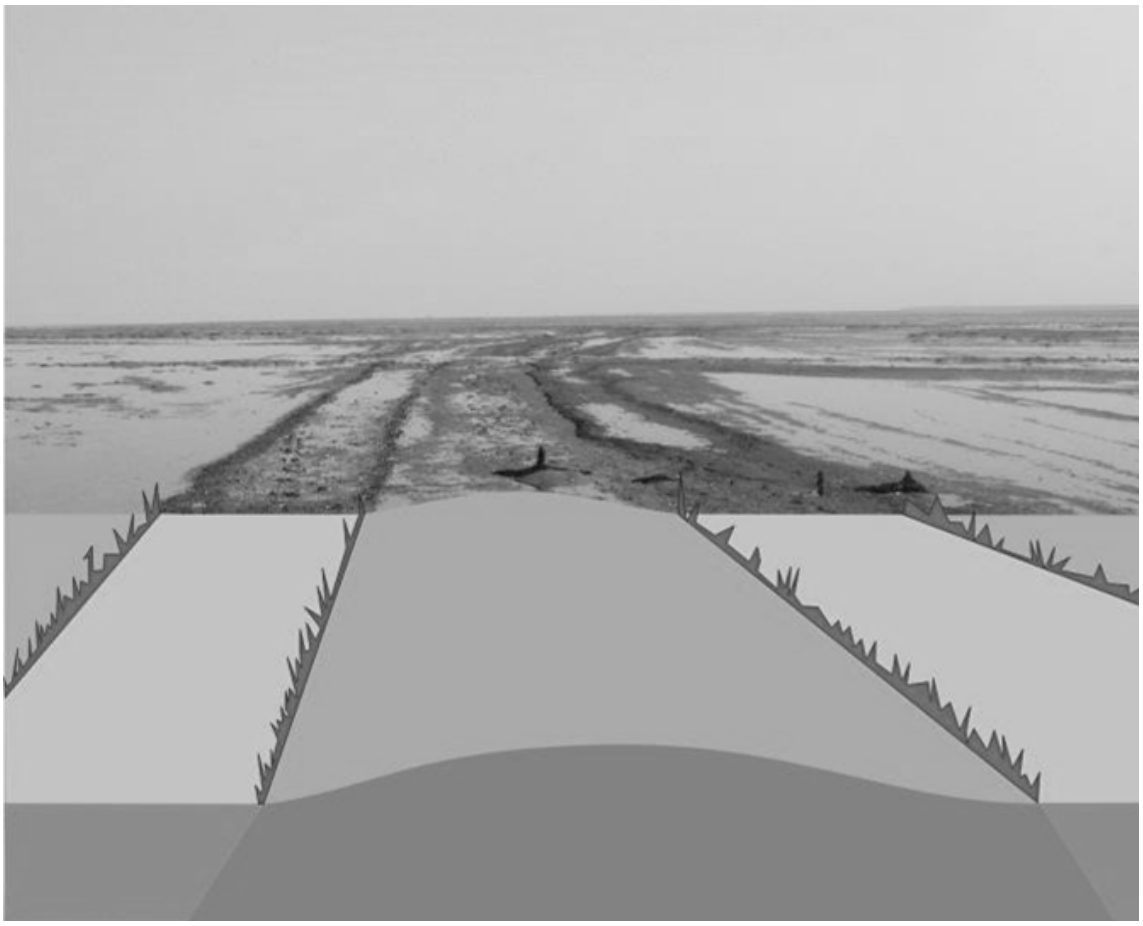

Fig. 9: Reconstruction of a historical lane with ditches on either sides. Photograph and sketch: J. Kohlus.

Conclusions

High-resolution SAR images can be used to complement archaeological surveys on intertidal flats on the German North Sea coast. Here, signatures of both former settlements and remnants of former systems of ditches and of peat cutting, dating back to periods before major storm surges in the 14th and 17th centuries, can be found on high-resolution TerraSAR/TanDEM-X images. In this respect, best results were obtained (i.e., strongest and clearest signatures were found) when SAR images acquired in the new 'staring spotlight' mode, with pixel sizes on the order of 0.1 m², were used.

In many cases, the observed signatures of former ditches are due to different sediment types, which in turn are due to the actual ditch morphology. Fossil roots and other organic material may result in denser and harder sediments, which may be directly sensed by the space borne SAR, or which may cause additional sedimentation (i.e., deposition of sandy sediments) that can be seen on SAR imagery. We also note that different sediments may cause different biological productivity, and are therefore often marked by benthic organisms, which may cause different surface roughness patterns. It is those patterns that are sensed by the high-resolution X-Band SAR.

The archaeological sites presented herein have already been subject to previous studies (Gade and Kohlus, 2011, Gade et al., 2014). However, the new high-resolution TerraSAR-X acquisition mode (‘staring spotlight’) allows for the detection of various kinds of residuals of historical land use, some of which have been unknown so far.

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