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SAR IMAGING OF ARCHEOLOGICAL SITES ON DRY-FALLEN INTERTIDAL FLATS IN THE GERMAN WADDEN SEA

Martin Gade[1] and Jörn Kohlus[2]

[1] Universität Hamburg, Institut für Meereskunde, Hamburg, Germany
[2] LKN, Nationalparkverwaltung, Tönning, Germany

ABSTRACT

After major storm surges in the 14th and 17th centuries, vast areas on the German North Sea coast were lost to the sea. However, remnants of former settlements and of historical landuse, which were buried by sediments for several centuries, can still be found in the German Wadden Sea, if the surface layer is driven away under the permanent action of wind, currents, and waves. We show that high-resolution SAR imagery with pixel sizes well below 1 m² can be used to complement archeological surveys and that TerraSAR/ TanDEM-X images clearly show remnants of farmhouse foundations and of former systems of ditches, dating back to the 14th century and to the 16th/17th century. In particular, the new high-resolution TerraSAR-X acquisition mode ('staring spotlight') allows for the detection of various kinds of residuals of historical landuse, some of which have been unknown so far.

Index Terms— SAR, coastal remote sensing, intertidal flats, archeological sites, storm surges

1. INTRODUCTION

In the Middle Ages, the German North Sea coast was looking very different from how it looks today (Figure 1) [2]. 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 sometimes built on dwelling mounds, protected by small dikes. Systems of 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 storm, the small dikes broke at many places, thus causing the death of a great number of cattle and men. As a result of that storm surge, huge land areas were lost to the sea, and they haven't been diked ever since (see the upper middle and right panels of Figure 1). Thereafter, it took a long time until new dikes were built to protect the (remaining) marsh land. 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 destroying farmland, farms, and whole villages, and killing cattle and men. The big (second) "Mandränke" 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 by muddy and sandy sediments, which nowadays form the German Wadden Sea (and which fall dry once during each tidal cycle). 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 [1]. 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 historical places [3]. Their use, however, is cost-intensive, which makes high-resolution spaceborne sensors an alternative source of data that can be used by archeologists for their frequent surveillance of the area [5]. A map of our area of interest is shown in Figure 2, with the location of the Synthetic Aperture Radar (SAR) image in Figure 3 inserted.

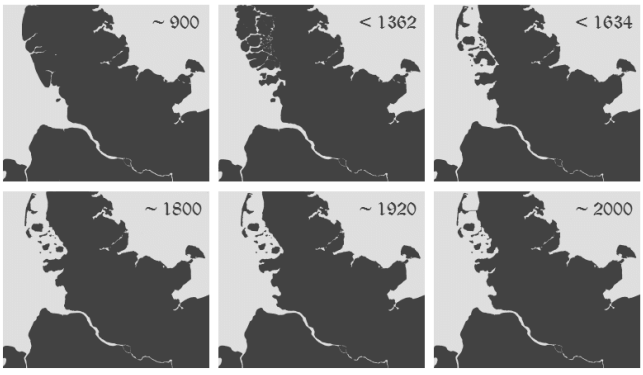

Figure 1. Changes in the German North Sea coastline during the past 1100 years (upper left part of each panel), after [2].

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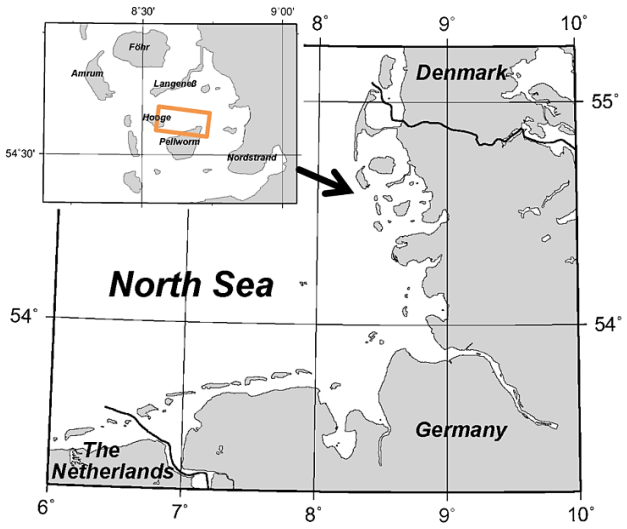

Figure 2. Area of interest on the German North Sea coast. The orange rectangle marks the location of the SAR image shown in Figure 3.

2. TEST SITE AND DATA

The area of interest lies in the center of the Northern Frisian Wadden Sea, i.e. in an area, which was most affected by the major storm surges in the 14th and 17th centuries (see Figure 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 Figure 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 bright features in the right half of the image mark edges of tidal creeks and dry, sandy sediments [4], but are not of interest herein. However, in the two (1.0 km × 1.0 km) areas marked by the orange squares, we found fine, linear structures, which correspond 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 landuse. 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.

3. RESULTS

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. Analyzing the high-resolution SAR imagery we

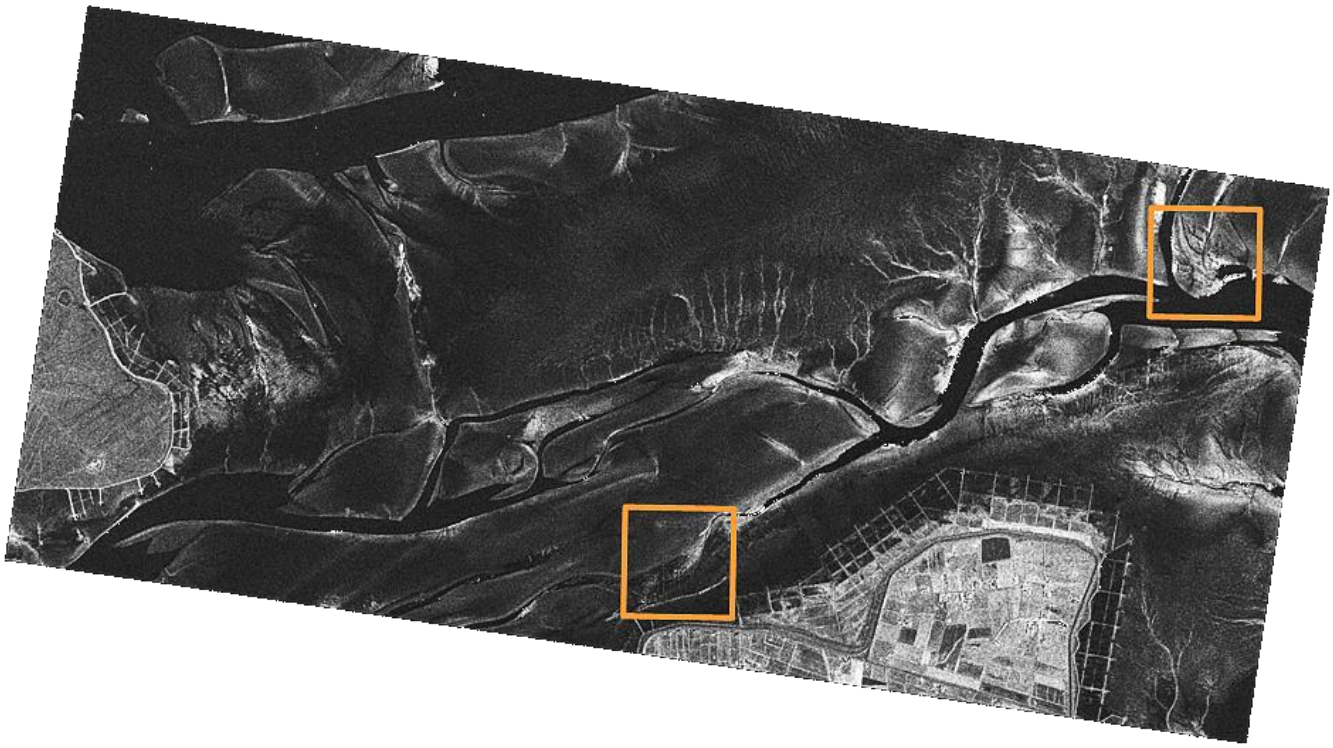

Figure 3. TerraSAR-X image of the area of interest, north of Pellworm and east of Hooge, acquired on 12 December 2012. Orange squares denote the locations of the SAR image details shown in Figure 4 and Figure 6. © DLR 2012.

Figure 4. Subsection (1000 m × 1000 m) of a TanDEM-X staring spotlight scene acquired on November 19, 2014, north of Pellworm island and showing in its lower center the same area as Figure 5. © DLR 2014

found at several places fine linear structures, which are clearly anthropogenic. Figure 4 is a 1000 m × 1000 m detail of a TanDEM-X image acquired in staring spotlight mode on November 19, 2014, at 17:01 UTC (26 minutes after low tide) and shows an example of such structures. The location of this detail is marked by the upper right orange square in Figure 3. The very fine pixel size of 26 cm × 26 cm allows for the imaging of residuals of historical landuse (houses, ditches, lanes), which usually are too narrow to be delineated on SAR imagery of convential resolution (with pixel sizes on the order of 10 m). Clearly visible are linear and rectangular structures in the lower left image center, close to the tidal creek, along with groups of parallel vertical lines at different locations in the upper image center. The mean distance between those parallel lines is about 15 m, thus indicating that they are remnants of former ditches and drainage channels.

Figure 5. 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. Photograph: B. Hälterlein, LKN.

Figure 5 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. Also visible is the sandy sediment, by which those structures were buried for centuries, and which was driven apart by the action of currents and waves. A close comparison of the aerial photograph with the high-resolution SAR image revealed that, during the five years between the two acquisitions, parts of the residuals were already lost, due to the permanent erosion and morphological changes (the tidal creek moved to the east).

Another example is shown in Figure 6. The small section (again, 1000 m × 1000 m, corresponding to the lower left orange square in Figure 3) of a TanDEM-X staring spotlight scene was acquired on November 21, 2014, at 05:41 UTC (low tide) and shows many bright and dark parallel lines all over the image center. The distance of those lines is in the range of 10 m to 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 center of Figure 6).

The upper panel of Figure 7 shows a photograph taken during low tide on May 14, 2009, from a dike on the northern coast of Pellworm island. In the image center 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, which results in a stronger contrast between the parallel bright lines and the dark area in between (Figure 6).

Finally, the lower panel of Figure 7 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. Fossil farmland structures, mostly ditches, but also 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

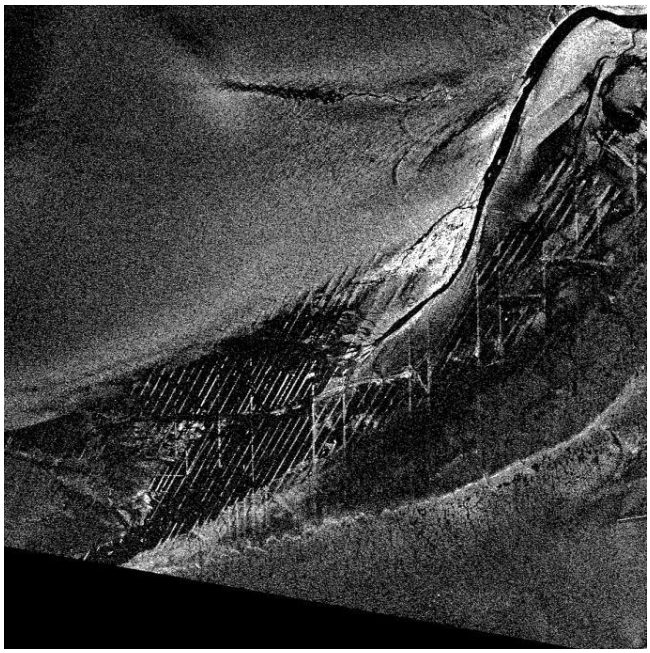

Figure 6. Subsection (1000 m × 1000 m) of a TanDEM-X staring spotline scene acquired on November 21, 2014, north of Pellworm island and showing in its lower center the same area as the upper panel in Figure 7. © DLR 2014

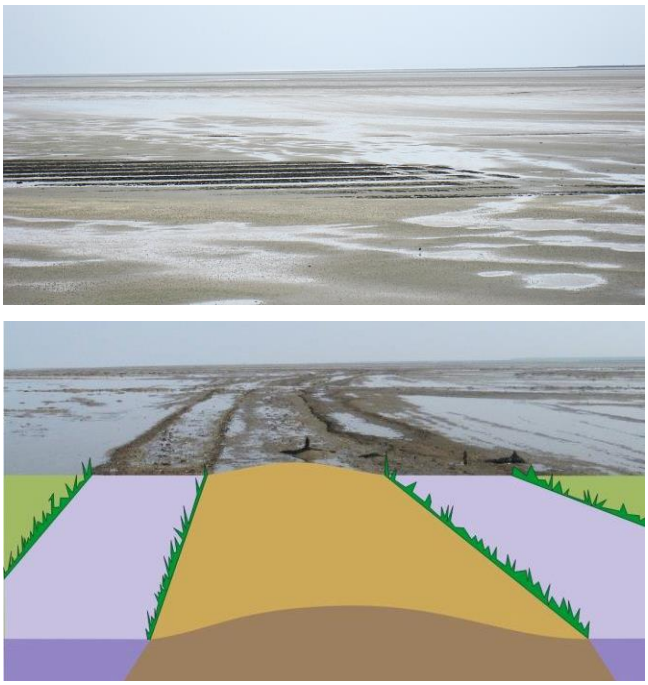

Figure 7. Upper: photograph taken from a dike on Pellworm island and showing manifestations of historical landuse as dark parallel lines; lower: reconstruction of a historical lane with ditches on either sides. Photographs: M. Gade & J. Kohlus.

which is still a major part of the marine environment. In contrast, the surface of the fossil ditches is different: in the center pillow-like sediments can be found, while the ditch edges are often stabilized by fossil roots and other plant material connected with the sediment (Figure 7, lower panel). 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.

4. CONCLUSIONS

High-resolution SAR images can be used to complement archeological 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.

The observed signatures of former ditches are due to different sediment types, which in turn are due to the actual ditch morphology. In addition, different sediments cause different biological effects and also are 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.

In addition to previous studies [3][5] the new high-resolution TerraSAR-X acquisition mode ('staring spotlight') allows for the detection of various kinds of residuals of historical landuse, some of which have been unknown so far.

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