Exploring coastal morphodynamics of Ameland (the Netherlands) with remote sensing monitoring techniques and dynamic modelling in GIS

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CHAPTER 3

MULTITEMPORAL RADAR SATELLITE IMAGERY ILLUSTRATES COASTAL DYNAMICS IN THEIR SPATIAL CONTEXT

ABSTRACT

Coastal geomorphological processes and tides cause continuous changes in the appearance of coastal areas. Mapping and monitoring these changes can help to understand these processes and can assist in sustainable management of coastal zones. Remote sensing data provide an overview of an area without interfering with the system itself. C-band radar remote sensing allows continuous data acquisition both day and night and is practically independent of weather conditions since it penetrates cloud. Therefore, radar imagery is available for analysis whenever a radar satellite passes the study area. This is particularly useful for coastal environments, in view of their dynamic characteristics.

This chapter discusses the value of multitemporal and multi-tidal synthetic aperture radar (SAR) imagery fused to form an image map. This map is a colour composite based on three images acquired at different tidal stages and on different dates. The changes, or, actually, the differences between the images, appear as distinctly coloured features on the image map. These maps can be of interest to coastal managers because they illustrate coastal dynamics: they can show the areal extent of tidal influence and of geomorphological processes (erosion and accumulation). The images used to construct this particular image map of Ameland were selected according to the tidal differences during image acquisition; this selection obscured possible geomorphological differences. The large number of images that have recently become available will facilitate the analysis because they will allow a reduction of variables: it will be possible to focus on either tidal or geomorphological changes.

1 INTRODUCTION

Radar satellites are observing the earth. Radar sensors transmit pulses of microwave energy to the ground. These pulses are partly backscattered to the receiver, the extent depending on the incidence angle and the properties of the terrain. Within the marine context, Synthetic Aperture Radar (SAR) data are used for mapping and monitoring of:

- surface wind waves and swell,
- the upper ocean, sea ice and oil spill detection,
- shipping traffic,
- and processes in the atmospheric boundary layer (Guyenne, 1995).

Radar data are used for management of the Dutch coast. This is stimulated by the Survey Department of Rijkswaterstaat, which develops remote sensing applications for the local, regional and national managers of the Ministry of Transport, Public Works and Water Management in the Netherlands.

- Firstly, SAR images are used as a monitoring tool. Examples of this application are, for example, the monitoring of ice coverage of the Dutch Wadden Sea, and oil spill detection.

- Secondly, radar imagery is used for bathymetric mapping, for which two methods are in use. One is the 'water line method' (Wang, 1997), for the determination of height values of the intertidal area. Water lines from images acquired at different stages of the tidal cycle have been mapped. They were subsequently correlated with modelled water surfaces for the times of image acquisition. The heights obtained along water lines were TIN interpolated (i.e. interpolation by creating a triangular irregular network), resulting in the digital elevation model 'WALDEM'. The other is the 'Bathymetry Assessment System (BAS)' (Hesselmans et al., 1994), for quantitative bathymetric research. Modulations of the water surface flow, which result from movement over the bottom topography, can be detected on the images and serve as an indicator for bathymetry. Changes in surface roughness through wave-current interactions are used by BAS for bathymetric interpolation of echosounding data (Calkoen et al., 1995; Calkoen et al., submitted).

- In the future, the use of radar interferometry for the detection of deformation (subsidence due to gas extraction), and mapping of water flow (measurement of current fields) will increase. Radar interferometry is a new technique for the determination of terrain height for which technical and application aspects are developing rapidly (Gens & Van Genderen, 1996; Massonnet, 1997). Across track radar interferometry from satellite SAR data relies upon the measurement of phase differences between pairs of coherent radar images acquired on near-repeat orbits of the satellite. The phase difference at a given point in the image pair can be related via the orbital geometry of the satellite to terrain height. A complication with repeat pass interferometry is that it places a high demands on the accuracy of the orbit of the satellite and on the temporal coherence of the scattering surface imaged (Wright et al., 1995). In coastal zones there are a number of factors that might change the scattering surface in time, like moisture differences on the beach and movement of the tops of the vegetation caused by the wind. Therefore the use of radar interferometry for the assessment of coastal erosion (in a sandy coastal system) is limited. Differences in coherence can be used to distinguish the waterline between relatively
coherent land and incoherent water. Recently, airborne SAR interferometry has been used to study deformation of dikes.

Yet another use of radar imagery, related to its usefulness for registration of coastal dynamics, is presented in this chapter. A multi-temporal ERS-1 SAR image map of the Wadden Sea near Ameland resulted from a study of the geometric aspects of multisensor image fusion (Pohl, 1996). The aim of this chapter is to identify the features that can be extracted from a multi-temporal radar image map and to evaluate the usefulness of this image map for the illustration of coastal dynamics.

First, some background information is provided on the research area and on the characteristics and benefits of radar data for the study of coastal environments. Then, a short description of the image fusion process is given. This is followed by a presentation of interesting features and aspects offered by the image map. In the analysis of the image map attention was paid to tidal dynamics and geomorphological changes. Finally, the advantages and disadvantages of radar imagery and the image map as information sources for management of coastal zones are discussed.

1.1 Study area

Figure 1 shows the Wadden Sea and the barrier islands along the North Sea coast. The image map, in Figure 2 (p. 39), shows the study area in more detail. From west to east, the Borndiep (or Ameland Inlet), the island of Ameland, the Pinkegat, Engelmansplaat, and the Zoutkamperlaag (Frisian Inlet) can be seen. The centre of the map shows the Wadden Sea, a shallow tidal sea consisting of tidal flats and channels. The mainland, in particular the reclaimed coast of Friesland, forms the southern boundary of the study area.
The inlets

The study area comprises three inlets: Borndiep, west of Ameland, which has a tidal prism of $478 \times 10^6$ m$^3$ and an estimated net transport of sediment to the tidal flats of $3.8-5 \times 10^6$ m$^3$ per year; and two inlets to the east, Pinkegat and Frisian Inlet, between Ameland and Schiermonnikoog. Borndiep is the deepest of the inlets with a maximum depth of about 25 m. Pinkegat has a tidal prism of $100 \times 10^6$ m$^3$ and an estimated net transport of sediment to the tidal flats of $2-2.7 \times 10^6$ m$^3$ per year. For the Frisian Inlet these figures are $200 \times 10^6$ m$^3$ and $3-4.3 \times 10^6$ m$^3$ per year (Louters & Gerritsen, 1994). However, since the reduction of its backbarrier channel area due to the damming of the Lauwers Sea in 1969 the configuration of the inlet has changed (Biegel & Hoekstra, 1995; Van de Kreeke, 1996). Lauwers Lake is located just southeast of the research area.

Ameland

The island of Ameland consists of three old dune cores: the Hollum-Ballum complex in the west, the Nes-Buren complex in the centre, and Het Oerd in the east. The island’s present shape is the general result of the old dune cores being connected by stuif-dikes in the nineteenth century (Bakker et al., 1979).

Various geomorphologically active areas on the island of Ameland can be indicated.

- In the northwest, an actively changing beachplain with an attached swashbar, which is due to shoal and/or channel migration on the ebb-tidal delta of the Borndiep. To some extent the hard structures on the western end of the island prevent erosion by eastward migration of Borndiep to some extent. Beach nourishments were carried out in 1979, 1994 and 1997 to counteract minor erosion. Furthermore, the foredunes retreated 75 m after being managed as ‘rolling foredunes’ in 1985. In the southwest, accretion formed flats and a saltmarsh area (Vrijheidsplaat).

- The central North Sea coast of the island is rapidly eroding. It is characterised by multiple nearshore bars, a small beach and steep semi-artificial foredunes. The beach and foredunes were replenished along various parts of this coast in 1980, 1990, 1992 and 1996. The total amount of sand deposited was $6.34 \times 10^6$ m$^3$. Going eastwards, the Kooiduinen close the island from the foredunes and Buurderduinen in the north to the Wadden dike in the south. The Kooiduinen close the sea defence for the western, inhabited part of the island.

- Management measures were reduced at the eastern end of this Wadden island. As a result of a more flexible management of the dike to the Wadden Sea, an ecologically interesting saltmarsh with a well developed intertidal creek system (the Nieuwlandsreid) has developed south of the Kooioerdstuifdijk. Blowouts occur in the stable old dune core Het Oerd. Northeast of Het Oerd, an offshore platform in the North Sea and a gas collection station on the island are present. It is estimated that the recent gas extraction will cause a maximum subsidence of about 18 cm close to this platform (Begeleidingcommissie monitoring bodemdaling Ameland, 1995), but it became recently known that this figure might be a bit higher. In the outer east, an extensive beachplain gradually passes into a
saltmarsh landscape. Here, eyedunes are formed and washing over occurs incidentally. This natural area is known as De Hon.

The Wadden Sea

The Wadden Sea is a tidal sea with flats and channels. Virtually all flats are covered by the sea at high tide; they are revealed as separate entities, sticking out above the water, at low tide (see Fig. 3c & b, respectively). The Wadden Sea has a continuous sediment demand, which is primarily satisfied by transport from ebb-tidal deltas and island coasts. Channel migration as a result of local erosion and silting up is the most obvious geomorphologic activity occurring in the Wadden Sea. A historic relict of a landward migrating channel is the Ballumer Bocht on Ameland. The construction of a dike, the 'stroomgeleidedam', in 1847 stopped this process (Bakker et al., 1979). Nowadays, dredging for shipping is one of the few management activities in the area. There is increased interest in monitoring the flats and saltmarshes as possible indicators of climate change (Louters & Gerritsen, 1994).

The Frisian mainland

The Frisian mainland has for centuries expanded northwards as a result of land reclamation. The land gained was mainly used for agriculture. On the Frisian coast, average siltation rates of 18mm/year occur (Louters & Gerritsen, 1994).

1.2 Coastal setting

Wind, waves, tides and currents are the main agents influencing sediment transport, and they also determine the information content of radar images.

Average wind speeds on Ameland range from 6 to 7 m/s. Wind speeds are generally higher during autumn and winter and winds from westerly directions dominate: 70% of the time the winds come from SW-W-NW at speeds of 6-15 m/s (Eisma, 1980). Wave directions generally correspond to wind directions (Van Straaten, 1961; Eisma, 1980). In the shallow areas the waves are redirected. The waves that influence Ameland's North Sea coast advance mostly from the northwest.

Tides are semi-diurnal and their amplitude is about 2.3 m near Nes. Therefore, tides on Ameland can be classified as meso-tidal (Wright & Short, 1984). The incoming tidal current from the North Sea moves along the Wadden islands from west to east and enters the Wadden Sea through the inlets. The tidal divide south of Ameland is located in the Wadden Sea somewhat east of the middle of the island. Eisma (1980) mentions that tidal currents in the Wadden Sea are strongly influenced by the wind.
1.3 Radar imagery of coastal zones

The data consist of ERS-1 Synthetic Aperture Radar images. Radar transmits pulses of microwave energy to the ground, which are partly backscattered to the receiver, depending on the effective incidence angle, the dielectric constant and the roughness of the terrain. Since radar provides its own energy source, it can operate both day and night. The C-band wavelength (of 5.66 cm) can penetrate cloud. These characteristics make radar ideal for coastal zone monitoring. Unfortunately, another characteristic of radar images is its large pixel-to-pixel intensity variation (speckle), due to phase interference effects. This poses a problem for human and automated interpretation.

On land, vegetation structure, land use and substrate determine the backscatter received. Flat areas, e.g. sandy beaches on the North Sea side of the Wadden islands are dark-toned in the C-band radar, due to their high dielectric constant and their smooth surface. Medium tones refer to a relatively rough surface e.g. forest canopy. Human settlements are shown as patches of bright spots produced by buildings functioning as radar corner reflectors (Dallemand et al., 1993). Under favourable conditions different dune types, and their active and inactive parts, can be discriminated (Blumberg, 1997).

At sea, radar backscatter is determined by the interference of radar waves and waves on the water surface; radar hardly penetrates water. The inherent sea surface structure results from tidal waves and low-frequency waves generated by wind, upon which smaller gravity and capillary waves, foam and spray are superimposed. Water surface roughness is influenced by many additional factors, e.g. current modulation due to the bottom topography, water circulation due to density differences, and wave damping effects due to foam, surfactants, oil pollution or rain. According to Wang (1997), the local wind is probably the controlling factor determining the surface roughness of water for the backscatter in the radar images. Radar backscattering from a moving water surface frequently shows striping. Stripes of alternating bright and dark tones indicate flow lines in a tidal channel system. The velocities, directions, temperature and salinity of the currents in a channel may be different depending on whether they are convergent or divergent. The differences in wave-current interactions cause differences in roughness of the water surface and thus cause different responses to radar waves. Foam lines and slicks are also responsible for these line patterns.

Ebb-tidal deltas are often visible on radar imagery as an expression of the bottom topography, due to changes in subsurface currents and resulting changes in water surface roughness. Other factors influencing this change of wave pattern are water depth (related to the tidal situation) and energetic wave conditions.

At the land-sea interface, the amount of land exposed depends on tidal stage and wind. The relative dielectric constant of the sediment is related to the water content of the surface material. The relative dielectric constant of pure water is 18.6 times higher than that of quartz. This determines the proportion of the radar signal that can be backscattered or reflected to the part that penetrates the medium. Wet sediments therefore appear lighter in tone than dry material, if other conditions are the same.
Under ideal conditions, the water surface in SAR imagery is characterised by light greyish tones, possibly with wind streaks and channel patterns. Landwards of the water line the radar signal penetrates the dry sand. The remainder of the signal will reflect, because the surface roughness of drying sandy and muddy flats is much less (the flats are smoother) than the C-band wavelength. The backscattering to the sensor will, therefore, be minimal; the flats appear mainly black and dark grey in tone. An image with a similar high contrast between water and land can result from strong wind conditions. In that case the water surface can appear uniformly bright due to Bragg resonance of the radar signal from the ripples (with a wavelength of about 7.3 cm).

The situation is not always this simple, however. The sea surface can appear very smooth (even locally) if the wind is very weak causing a decreased signal return, thus producing dark-toned specular reflection. In addition, the land surface might be moist, and have sandy ripples or steeper slopes, which produce high backscatter (Wang, 1997).

Based on a study of 18 ERS-1 SAR images of the Wadden Sea, Wang (1997) concluded that:

- Moderate wind speed (>5.7 m/s) is favourable for water line delineation because it provides good contrast between light-toned water surfaces and dark-toned dry land surfaces on radar images.
- Low wind speed (<5.7 m/s) seems to favour channel patterns to be shown on SAR imagery. The stripes in the channel patterns are mainly formed by water converging with high velocity from several directions. The outgoing low tides, when the ebb current velocity is highest (1-2 m/s), form the best tidal conditions for discerning channel patterns.

2 MATERIALS AND METHOD

2.1 Data collection

Processing and analysis was performed on three processed PRI images. Precision Image Products (PRI) are standard images produced from ERS-1 raw data using a SAR processor. They are multilook (3 directions), ground range format images, which have been corrected for some system errors, such as antenna gain and range spreading loss. The processing parameter-settings might influence the image contents in terms of, for example, resolution and intensity (Curlander & McDonough, 1991). ERS-1 SAR PRI imagery has 12.5x12.5 m pixel spacing (nominal pixel resolution 30 m) and covers 100x100 km. A subset that covers the area of interest has been created for this study.

2.2 Description of the three images and the tidal and weather conditions during their acquisition

In Figure 3 (p.40 & 41), three quicklooks of the subsets of the SAR images are presented. The images were originally selected to represent different tidal stages: high, low-outgoing and low-incoming tide. The tidal conditions and wind characteristics during acquisition are given. The colour assigned to each image in the colour composite is indicated per quicklook. Selected maps with mean directions and rates of tidal streams in the layer 0-5 m below the
surface, similar to the tidal situations during image acquisition, are presented as well (source: Atlas of the Dutch Hydrographic Service, 1992).

For the interpretation of the image map a few additional quicklooks from March and July 1993 have been used. Additional meteorological data, on temperature and precipitation were used as well (source: Monthly reports of the weather in the Netherlands issued by the Dutch Meteorological Institute, 1993). In addition to Figure 3, a short description per image is given below.

The first image (3a) was acquired on 30 March 1993 during an incoming tide (rising water) and under moderate wind conditions. Additional meteorological data show that an extremely dry and cold period preceded the 30th. Frost occurred from the 27th until the early morning of the 30th. On the 30th the cloudiness increased and the temperature rose because of an approaching warm front from England. The colour red was assigned to this image.

The second image (3b) was acquired on 1 June 1993. The wind was moderate in force and came from the west. The tide was low in the northwestern part of the study area, and outgoing in the Wadden Sea. The weather reports show that the weather was unstable during the last few days of May with alternating sunny periods and rain showers. On the 31st of May a strong southwesterly wind was blowing. The average temperature was about 15 °C. On the first of June, clouds and sunny intervals appeared. An abating west to southwesterly wind was blowing. The June image was assigned the colour green.

The last image (3c) was acquired on 6 July during high tide and under strong wind conditions. In general, July 1993 was very wet. On the 5th a cold front passed the Netherlands from northwest to southeast. This resulted in much rain and in a decrease in maximum temperature from 23 to 17°C. From the 6th till the 10th the weather remained rather unstable. This image was assigned the colour blue.

2.3 Radiometric correction

For the visual and digital interpretation of SAR images it is often necessary to reduce the speckle. In this case PRI products were used, which are 3-look processed images. Therefore, the speckle is already reduced by averaging, in comparison with single look complex (SLC) data. In addition the images of this example had been speckle-filtered by using an adaptive filter called GMAP (gamma maximum a posteriori) with a 3×3 window. This filter proved to be very useful for visual interpretation of the features concerned. The data were reduced from 16 to 8 bits to make them compatible with the display device for visual interpretation. A linear scaling was applied to the original data using mean and standard deviation.

2.4 Geometric correction

A further pre-processing step prior to image fusion is the co-registration and geometric correction of the images. Remote sensing data contain geometric distortions, which are introduced due to the sensor acquisition and viewing geometry, in addition to platform
movements and the rotation and curvature of the earth. In SAR imagery, additional effects introduced by terrain height variations occur due to the side-looking nature of the sensor (i.e. foreshortening, layover and shadow). For the Ameland case this aspect did not have to be taken into account because the area is very flat. This facilitated the co-registration of the images. A second-order polynomial model based on identified tie-points evenly distributed over the entire area resolved the transformation problem and resulted in sub-pixel accuracy. This level of accuracy is required for pixel-based image fusion to avoid fusing data from different objects and creating incorrect information.

2.5 Image fusion

Image fusion is a valuable tool in multisensor image manipulation. The possibilities and techniques to fuse images are manifold. In this study the multitemporal SAR images were used to form a colour composite using the additive colours red, green and blue of a standard display. This facilitates the interpretation of multitemporal images and the detection of changes because they occur in colour. High digital numbers (white pixels) in an image will contribute more colour to the composite than small values. Differences between the images in terms of digital numbers will contribute to distinctly coloured features, whilst images with similar digital numbers result in black (low backscatter), greyish/brownish and white (high backscatter) structures (Pohl, 1996). Further considerations on image fusion techniques can be found in Pohl (1997) and Pohl and van Genderen (1998).

2.6 Image interpretation

Features can be recognised because they exhibit a certain colour, texture and structure. Colour and texture are covered by the presentation of sample areas (cut-outs) in the legend boxes. Structure will be used frequently in the descriptions. The information given by the image map is described in the next sections. In addition, an explanation is given as to why certain features appear. This is not an easy task because of the many factors influencing the final radar image, and because of the lack of ground truth at acquisition time. Therefore, this exercise should be seen as educated guess-work, and not as absolute truth. It does, however, illustrate how to interpret the image map and how to look at radar imagery.

3 RESULTS

3.1 Features shown in the image map

The main units that are immediately recognised on the map include: the inlets, the island of Ameland, the shallow Wadden Sea and the northern coast of Friesland. Within these larger units many different landforms and types of land use can be distinguished.
Streamlines in the inlets are perceived as lineaments. A distinction can be made between the Borndiep, west of Ameland, which shows various shades of red, and the Pinkegat and Frisian Inlet, east of Ameland, which are shaded green. A difference between the western and the eastern inlets is that the Borndiep is more deeply incised. An explanation for the difference in backscatter observed was explored by reverting to the individual quicklooks with tidal information (Figs 3a & b). The red March image was acquired when the tide was incoming; water is flowing towards the Wadden Sea in both the western and the eastern inlets. Water flows faster in the deeper Borndiep and over the shallow areas of its associated ebb-tidal delta than in the other two inlets. This could explain the high backscatter in the Borndiep. During the acquisition of the green June image the water level was falling rapidly in the east. The low water conditions and the strong tidal current flowing over the gentle slopes of the inlets in the east caused water surface rippling in a wavelength that supports a high backscatter. The differentiation between reddish colours in the Borndiep and greenish shades in the Frisian Inlet also applies to the channels in their respective backbarrier areas.

Ameland

The sandy beaches on the North Sea side of the island are mainly dark-toned in the C band radar due to their very smooth surface and low dielectric constant. Vegetated natural sand dunes are recognisable as a mixed brown/green unit. The elongated features in the dune area are stuif-dikes. The polders with pasture appear mixed red/brown. Actually, both dune vegetation (consisting of trees, shrub and grassland and herbs) and pasture appear to be intermediate backscatterers, but the pasture came out brighter then the dune vegetation in the red March image. A check with additional quicklooks from March and July seems to point to a seasonal effect. The increase in roughness of the dune vegetation seems to occur later in spring and in early summer. In some cases, the radar images would allow a distinction within the dune vegetation to be made (e.g. in the classes trees, shrub and grassland and herbs).

The Wadden Sea

An indication of flood-tidal deltas with superimposed structures consisting of channels and tidal flats can be perceived in the shallow Wadden Sea. Flow lines can be discerned in the channels. The area located just southeast of the middle of Ameland, which does not seem to be intersected by channels, is the tidal divide. It separates the backbarrier influence of the western and eastern inlets. The tidal flats appear red to pink where high backscattering occurred at incoming tide. The tidal flats appear dark blue to purple when the land was covered by a shallow water layer at high tide. The dark blue to purple colour is caused by the high backscatter of the sea in the blue image (under the influence of the relatively high wind speed) and the low backscatter in the red and green images. The colours pink and the dark blue to purple do not reflect absolute height distinction over the area. In the eastern part of the image an area (Engelmansplaat) can be seen where the blue unit is situated higher than the pink unit; in the western part the reverse can be seen (Vrijheidsplaat).
The yellow area bordering the north coast of Friesland represents recently reclaimed outer dike land. The yellow colour results from an extremely high backscatter in March, intermediate in June and low in July. Various factors could explain this result. Firstly, seasonal influences could play a role; e.g. an increase in roughness at a certain stage of the growing season of the saltmarsh vegetation. Additional quicklooks show that the difference in backscatter is not solely related to seasonal influences, but that seasonal influences cannot be excluded either. Secondly, a difference in moisture content as a result of tidal influence, or recent deposition of mud could be a possible explanation for the backscatter received. These processes influence the dielectric constant and the roughness. Inundation and subsequent deposition could occur; the mean absolute height of this unit is about 1.4 m and the mean high tide reaches about 1.2 m. Thirdly, the differing weather conditions during image acquisition could also explain the difference in backscatter received. The weather conditions varied from extremely dry and cold, possibly with some remains of frost (in March), to wet and warm (in July).

Agricultural land use differences can be perceived behind the dikes. The higher lands in the north, which were silted up for a longer period, are cultivated with crops, whereas predominantly pasture can be perceived in the south. The cultivated fields give a higher backscatter in the March (and July) image(s) than the pasture. The low backscatter in the red March image, which allows the cultivated field to appear clearly in green, might be an exception; these fields have a higher backscatter on an additional quicklook of March. Dokkum (a town in the SE of the map) is shown as patches of bright spots produced by buildings functioning as radar corner reflectors.

3.2 Coastal dynamics

The dynamic aspects of the coast are of special importance for its management. The image map shows dynamics in various bright colours, whereas areas with a more-or-less constant surface roughness and dielectric constant appear in black, greyish/brownish, or white. The individual images that construct the image map were obtained during different tidal stages and at different dates, and therefore the map might show tidal dynamics as well as geomorphological dynamics.

The relatively gently sloping to flat areas within reach of the sea register the largest differences in land or sea covered area. These areal differences determine the coverage of the dynamics in the image map. Gently sloping areas within reach of the sea occur in the Wadden Sea and on the extensive beachplains at the extremities of the islands. The Wadden Sea is a tidal sea, the surface areas of the Borndiep and Pinkegat tidal basins that are exposed at mean low water are 165 and 42 km², respectively (Louters & Gerritsen, 1994). Additionally, the tidal currents slowly but continuously remodel the coastal configuration, and thereby change the channel systems (which can shift rapidly) and the bottom topography of flats. For the purposes of this chapter, however, it has been assumed that the tidal flats of the Wadden Sea are mainly influenced by tidal differences within the time scale of this study, and that the geomorphologically most active areas develop on the high-energy open North
Sea coast. Locally, a retreat of the North Sea coastline of tens to hundreds of metres per year has been reported (Louters & Gerritsen, 1994). The following sections show whether these geomorphological changes can be perceived in a period of only three and a half months; i.e. the maximum difference in acquisition date of the three original SAR images.

**Tidal Dynamics**

A sequence of colours from bright turquoise (sea), to purple, pink and red (flats) can be discerned in the Wadden Sea. This sequence can be explained by reverting to the individual images. Blue was assigned to the image acquired at high tide with strong wind conditions, resulting in a uniform moderately high backscatter from the dissipative sea. The influence of the colour green, which is associated with low-outgoing tide, is missing on the flats because they give a very low backscatter at low tide. Red is associated with low-incoming tide, and shows low backscatter on the beach and at the beachplains, and high backscatter where the waves break on the flats. In addition, individual white patches occur on the flats if there is high scattering in all three bands; along these shallow areas currents seem to pass at all tidal stages, which causes rippling or breaking of waves and results in this high backscatter.

Under ideal circumstances, the full tidal sequence comprises bright turquoise (sea, a mix of blue green and red), purple-pink (flats, a mix of blue, high tide and red, associated with low-outgoing tide), blue (high tide) and finally black or brown (land)(see Fig. 4, p. 42). The absence of the latter stages indicates that the Wadden Sea contains few supra-tidal areas.

**Geomorphological changes**

**Ameland's beachplains**

In a landwards direction on the beachplains, at the outer ends of the islands, (parts of) the following sequence of colours can be distinguished: bright turquoise (sea), pink, white, pink, dark blue, green, yellow, red and black or brown (land). A distinct difference between the flats in the tidal Wadden Sea and the geomorphologically active beachplains bordered by the North Sea becomes apparent. Green, which is perceived on the beachplains, is practically absent on the tidal flats in the Wadden Sea and in the ideal full tidal sequence (Fig. 4), while the imaged objects (water and sand) are more-or-less similar.

**Ameland's north-western beachplain**

- Green colours occur, i.e., where the waves are breaking at low-outgoing tide in June, on the outer boundary of Ameland's northwestern beachplain and its attached swashbar. The original radar images show that the same area appears as land on the high tide blue image of July (see Fig. 3). Therefore the green could indicate some accumulation in this area.
- The green area present within the beachplain, results from relatively high backscatter from the beach. Here, the green colour does not indicate accumulation or erosion processes; it might instead be caused by small moist sand ripples on the beachplain.

**Ameland's eastern beachplain**

- The colour green appears also within Ameland's eastern beachplain. Possibly the high backscatter there can also be attributed to moist sand ripples (see above).
Terschelling's eastern beachplain

At the eastern end of Terschelling (Ameland's westerly neighbouring island), the colours on the image map reflect the backscatter received where channel and saltmarsh meet. Landwards, a sequence with bright turquoise (sea), pink, white, pink, purple, green, red and finally brown (land) can be seen. The difference between this (actual) sequence and the ideal tidal sequence (Fig. 4) does not, however, necessarily ensue from geomorphological changes such as channel movement. This difference could also be related to exposition of the beachplain; the southern part of the beachplain is sheltered from the north-northwesterly wind (which influences the blue colour, Fig. 3).

4 DISCUSSION AND CONCLUSIONS

4.1 Features shown on the map

Since the launch of SEASAT-1 in 1978, the earth is being observed with radar satellites. Ever since, there has been an increase in the availability of radar images for coastal applications. This article describes the features which have been extracted from a multitemporal radar image map. These features vary from main units (such as the Wadden Sea) to smaller units (such as stuif-dikes on Ameland). Reasons for their appearance in the image map are given, and their appearance is also placed in a geomorphological framework.

In practice, individual (and combined) radar images are difficult to interpret because the same feature can have a different appearance on different images and even within an individual image. This became apparent in the distinction between 'red' and 'green inlets'. The feature 'inlet' is similar; it just appears in different colours, i.e., 'red' or 'green'. On the other hand, the construction of an image map also required differences between images; combining the differences allowed units to become apparent in the image map. The colour composite (which is the image map without the legend) has increased interpretation capabilities compared to those for a set of three individual radar images; e.g. for location-bound comparison. Nonetheless, the colour composite has to be presented as an image map with a legend to the manager, because of the difficulties just mentioned in the interpretation of the image map.

4.2 Coastal dynamics

In flat areas within reach of the sea, relatively large surfaces can be present as land at one time and are covered by the sea at another. The difference between land and sea could be distinguished quite clearly on the individual radar images used in this study. This agrees with the reported possibilities of coastline extraction from radar imagery (Mason & Davenport, 1996; Wang, 1997; Schwäbisch et al., 1997). In this study, however, the radar data were used for the determination of coastal dynamics.
In the Wadden Sea, a sequence of colours separated areas that were permanently inundated (channels) from areas that are occasionally subaerial (tidal flats). The map did not convincingly show possible geomorphologic changes along the high energy North Sea coast, for the following reasons.

- First of all, it is not absolutely sure that large-scale geomorphological changes took place in the period covered by the acquisition dates of the three images. The areal extent of the geomorphological changes is sure to be much smaller than the extent of the tidal dynamic illustrated.
- Second, geomorphological changes at the land-sea interface might be obscured by tidal effects.
- Finally, the image map presents data from all three images acquired during different tidal stages and at different dates. The interpretation of such a data set (the combined data) is difficult. An alternative approach may be to classify the individual images (in the classes land and sea), and then to interpret a presentation of three overlaid classified images.

The use of the image map has some advantages and some disadvantages for the illustration of coastal dynamics. One advantage of the use of multitemporal radar satellite remote sensing data is that it provides a spatial overview of coastal dynamics. Moreover, it enables highlighting the dynamics of the area in colour. A disadvantage is that both the single radar images and the colour composite are difficult to interpret, due to the complex factors influencing the radar returns from a dynamic environment. For example, this became apparent when the occurrence of the green areas within Ameland's beachplains was related to moist ripples (dynamic features) on those beachplains during the acquisition of the green June image. This agrees with the reported lack of coherence within coastal environments, which was encountered by Wright et al. (1995).

4.3 Future developments

The image map contains the data of all three images. Therefore, an overview of the entire area from three data sets is available. However, the data have to be selected carefully. Nowadays, four radar satellites are available: ERS-1, ERS-2, J-ERS (which is less favourable for marine applications) and Radarsat. In addition, Envisat will be launched in 1999. The large supply of images will facilitate the analysis because it will allow a reduction of variables; it will be possible to focus on either tidal or geomorphological changes. Theoretically there is a higher chance of image acquisition under similar tidal conditions and water levels, but at different dates. This would allow geomorphological changes to be detected. A second option would be to collect the data at (almost) the same date but under different tidal conditions so that tidal dynamics can be visualised.

In conclusion, radar is already being used in coastal zone management for a number of applications, varying from oil spill detection to bathymetric mapping (Guyenne, 1995; Calkoen et al., submitted). This article is an example of opportunities to expand the applied use of radar.
Tide: Low-incoming, -3.07 hrs (Te)
Wind: 8.2 m/s 150° SSE (Te)
6.7 m/s 140° SE (La)

Tide: Low-outgoing, +5.49 hrs (Te)
Wind: 5.7 m/s 260° W (Te)
5.1 m/s 260° W (La)

Tide: High tide, +0.48 hrs (Te)
Wind: 11.3 m/s 280° W (Te)
11.8 m/s 290° NWW (La)

With data from meteorological stations of Terschelling (Te) and Lauwersoog (La).
Tidal stage in hours before (-) or after (+) high tide with respect to the gauging station at West Terschelling (Te).

Figure 3. The individual radar images and the tidal conditions during their acquisition.
Figure 3. (continued.)
Figure 4. The full tidal sequence under ideal conditions.

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Additional sources

In the analysis additional use was made of topographical maps (Topographical Survey of the Netherlands) and extra quicklooks (ESA).