LAND-WATER BOUNDARY DELINEATION FROM ERS-1 SAR FOR CONSTRUCTION OF DEM IN THE INTER-TIDAL ZONE

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ABSTRACT

Topographic mapping of the inter-tidal area is very important in the viewpoint of human economic activities and the environmental management in the coastal areas. The ERS-1 radar satellite provides an opportunity for testing the "water line procedure" for rapidly updating of the topographic maps in the Wadden Sea, The Netherlands. Water lines from low tide to high tide can be delineated from sequential SAR images acquired at different tidal stages. The height values along those water lines can be extracted from respective water surface model at the time of image acquisition. The DEM of the inter-tidal flat area then can be constructed by interpolation from those height values.

For land/water classification, the speckle effect on the SAR imagery has to be treated first. Here we present a concept of global classification filtering. By the Global Classification Filter, the speckle is reduced by grouping all the pixels of the image which have the similar characteristics space (variables such as the local mean and variance) with the T-test method. It was proved to be efficient in speckle reduction and edge preservation for accurate water line delineation.

Water surface model was derived from an existing tidal simulation model with corrections according to the real tidal measurements from gauges and the water surface curvature over the flats learnt from our field measurement. The combination of water lines and water surface models yields the height values along the water lines.

Water lines delineated from 9 ERS-1 SAR images acquired during 1993 were used for the construction of a water line DEM (WALDEM). For validation the WALDEM was compared with the DEM obtained by bathymetric echo sounding survey. The height differences between the WALDEM and the bathymetric DEM on basis of pixel-by-pixel comparison give an average of -5 cm and a standard deviation of 28 cm. 73% of the total pixels of WALDEM is within the accuracy of 30cm, and 93% is within 50 cm.

1. INTRODUCTION

Repeated topographic mapping of the inter-tidal flat area is important in respect to ship routing, sound management of ecosystem balance and recreation activities, change monitoring and erosion-sedimentation studies, etc. due to the active morpho-dynamic changes in the tidal area. At present the mapping has been carried out with ship-borne echo sounding and terrestrial leveling. They are constrained by weather and tidal conditions and very time and money consuming.

The ERS-1 radar satellite provides an opportunity for testing a rapid mapping method —water line procedure— using sequential SAR data over the western Dutch Wadden Sea. It requires several SAR images representing different stages of the tidal cycle for the extraction of the water lines, and obtains the height values of these water lines through water surface modeling at the time of the image acquisition. Interpolation between the height points will derive a DEM of the flat area within the tidal range.

The Wadden Sea, including a string of barrier islands, is a tidal flat area of 8000 square kilometres along the North Sea coast of the north Netherlands, northwest Germany and southwest Denmark. The study area was selected in the western part of the Dutch Wadden Sea (figure 1).

The Wadden Sea is one of the most important and highly sensitive coastal tidal areas in the world. This large tidal area provides an important habitat for migration birds and for part or full life cycle of many fish, shrimp and shell fish species.

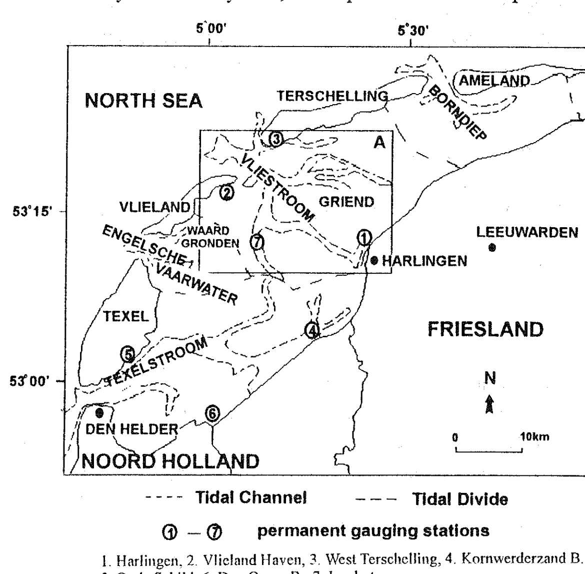

Figure 1. Study area (A) in the western Dutch Wadden Sea.

Under the semi-diurnal tides, the water exchange between the North Sea and the Wadden Sea continuously remodels the coastal configuration and the bottom topography of the channel systems and related ebb and flood deltas. The ecological balance should be carefully maintained.

Disturbance of this fragile ecosystem looms from many sites. Excessive shell fishing threatens to destroy the mussel banks. Toxic discharge carried by Rhine and Meuse into the North Sea enters the Wadden Sea through the inlet channels and gets concentrated here. Drilling for oil and gas exploration carries the danger of environmental pollution. Excessive tourists and recreational activities disturb the tranquillity of the region. For monitoring such a sensitive area, constant updating of topographic and bathymetric maps is required.

Conventional mapping methods consist of terrestrial levelling over the tidal flats and echo sounding over the water covered areas. The survey and mapping of the Wadden Sea has been conducted periodically by the North Netherlands Division, Ministry of transportation and Public Works of the Netherlands (Rijkswaterstaat). These methods are labour intensive, costly and time consuming. The ship-borne echo sounding is carried out during the period of high tide, under the assumption that the water surface in that period is horizontal. The water level at ship's location is on reference of water level measurements from nearby gauging stations. The original echo-sounding data were recorded along the survey line in 2-5 metres interval, while the spacing between the survey lines is about 200 metres. Height approximation between the lines are obtained by interpolation.

2. METHOD

The water line procedure consists of three parts: the image processing for water line delineation, the water surface modeling for height extraction and the evaluation of the accuracy by comparing with the existing DEM.

2.1 Water line delineation and the Global Classification filter. Radar imaging is near weather independent and sun light independent, therefore it can acquire sufficient data in a relatively short period. Variations in the radar backscatter from moving water surfaces due to changes of surface roughness modified by the wind and tide may cause difficulties in the land-water classification.

The following generalizations can be made from the analysis on basis of 20 ERS-1 SAR images over the study area (Koopmans *et al*, 1995):

1). For delineation of the water line, more than 60% of the images acquired can be used.
2). Wind velocity has obvious influence on the differentiation of the water surface with the emerged flats (land). When the wind velocity is higher than 5 m/s, the water surface shows a continuous light grey tone which has strong contrast with the dark toned smooth surface of the flats. However, when the wind velocity is lower than 5 m/s, the water surface varies very much in tone. Patches of dark toned water surface are confused with the flats.
3). The recognition of the channel and gullies is not clearly wind related. Wind velocities between 3.4 and 10 m/s seem to be more favourable. Low and outgoing tides seem to form the best tidal conditions for channel pattern delineation when stream velocities are in the order of 1-2 m/s.
4). For visibility of the ebb tidal delta, no straight forward relationship with the tidal situation or the wind force has been found.

Nine SAR images acquired during 1993 in this area were used for water line delineation. All the images were geocoded to the Dutch national rectangular coordination system (RD system) by ground control points selected from the coastal constructions.

Some images with good contrast between water and dry flats allow automatic classification. The main problem is speckle effect in the SAR image. Several adaptive filters such as Lee, Kuan, Frost and GMAP filters were tested. They are all aiming on the reduction of speckle and preservation of the edges and based on the noise distribution model, which is believed as the multiplicative noise model. The removal of the noise from the observed intensity are derived from calculation referencing to the local window. It was found that for classification it is not sufficient and efficient by using the local window. The local window strategy has problems in selecting the window size for speckle reduction. Using large window size has more capability of reducing speckle but less effective in the edge preservation. The smaller window size has the opposite effect. There is always a trade-off.

The real intensity of the radar return signal is ground object dependent, therefore the estimation of the real intensity should be made from all the pixels of the same ground object. The issue is, how to find those pixels belonging to the same kind of object, that is, how to classify the image?

In our proposed filter, the Global Classification Filter, the global strategy was used. The speckle will be reduced by referencing to a class of pixels of the same object distributed in the entire image. The mean value of the class will be the new pixel value, thus the speckle is reduced and different objects are separated.

The Global Classification filter is performed in two steps. The first step is to define a characteristic space. The space includes one or more characteristic variables. The selection of the variable(s) is determined by the application purpose (segmentation, line detection, etc.). Therefore each pixel of the image will have characteristic vector(s) in a distribution pattern in the characteristic space.

The second step is to group these variables by a classifier. There are many well developed classifiers. The application adaptive classifier is more relevant. For testing the idea, a classifier was designed. Two characteristic variables, the local statistical mean and variance, are chosen for the classifier. Firstly, all pixels of the original image with the same variance value (rounded in integer) are put into one group. Then all groups are arranged according to their variance from small to large. Some neighbouring groups are not significantly different in statistics, therefore they should be combined. For this purpose, the boundaries should be found.

They can be determined by T-test method. Each variance separates all groups into two sets, say set 1 and set 2. T-values of these two sets is calculated by

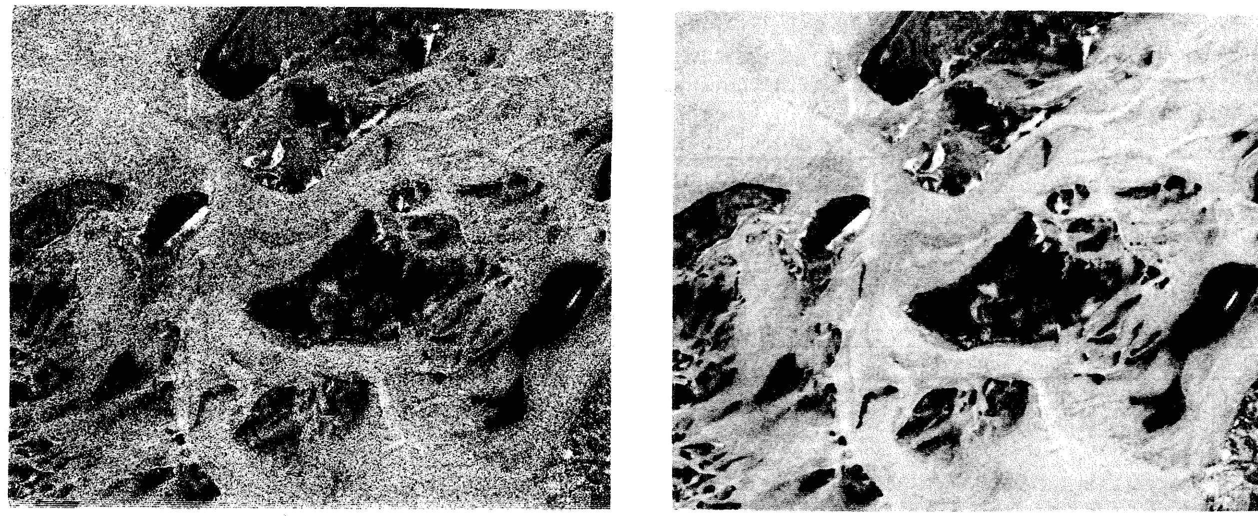

Figure 2. Image 09-08-1992 before (left) and after (right) filtering by the Global Classification Filter

$$T = \frac{\bar{X} - \bar{Y}}{\sqrt{mS_1^2 + nS_2^2}} \sqrt{\frac{mn(m+n-2)}{m+n}} \qquad (1)$$

where $\bar{X}$, $\bar{Y}$ are the mean value of set 1 and set 2, respectively, S_1^2, S_2^2 are the variance of set 1 and set 2, and *m, n* are the number of pixels in set 1 and set 2. Therefore a curve going through the T-values is achieved. The extreme values of the curve are selected as the boundaries. Thus the groups without significant difference are combined. The same procedure is performed for the mean value of the original image, the second variable of the characteristic space, based on the result of the variance grouping.

The reason for choosing T-test method is that the T-values is a good indicator of the selected variables. The bigger the difference in mean value between two sets, the larger the T-value is. And the smaller the variance in both sets, the larger the T-value is. The reason for selecting the extreme T-values as the boundaries is that the intermediate T-values represent gradual changes, but the extreme T-values indicate the abrupt changes of the characteristics of the pixels from one group to another. The filter preserves the edge because if the characteristic variables describe well the difference of the areas on two sides of an edge, the pixels in different areas will be grouped into different classes and get different filtered values.

Different T-values describe different ground objects: in the tidal flat area, the water surface has high mean and high variance because of the alternative bright and dark speckles from the moving water surface; in the dry flats the mean and variance are all low because of the specular reflection from the smooth surface. Grouping the pixels from the same object reduces the speckle and have the edges preserved. After filtering by the Global Classification Filter, the speckle was greatly reduced and the contrast between land and water was enhanced (figure 2).

The real classification of land and water was done by thresholding with the help of , from histogram analysis or density slicing observation. It was proved that the threshold value is easier to be determined from the Global Classification filtered image than that of the Lee filtered image. The continuity of the water or land areas is also improved with our filter. The land-water classification map is a binary map from which the outline of the areas was extracted for the final water lines.

For the images having difficulty in automated classification, the knowledge based screen digitizing was carried out.

At this moment, the mean and the variance are selected as the variables. They may not be the best ones. Later other or more characteristic variables may be considered. For programming such a filter, the speed and memory of the computer system should be well handled because the global strategy requires a large amount of memory and computing time. The present program run very well on PC both in time and memory.

2.2 Water surface modeling. Use has been made of the "Wadden Model" provided by the National Institute for Coastal and Marine Management (RIKZ) (Robaczewska *et. al.*, 1991). This model provides the simulation of the tidal water levels and the tidal current velocities in the Wadden Sea. It is based on calculations involving 26 harmonic components such as tidal and rest currents at the North Sea, the climatic conditions, water stowage or drawdown as the result of strong wind and wave actions, sea floor bathymetry and roughness, the expected current drag and the interaction in time between the different channel systems, etc. The model yields the data in a grid system of 500 m with a temporal resolution of 2.5 minutes and simulates the tidal conditions quite well.

To evaluate the model, the time series data of the Wadden Model were compared with the tidal gauging records over the same period. The differences, which are not constant, are principally a result of local change of wind velocity and wind direction. The model takes the wind influence into account only when the wind velocity exceeds 8 m/s.

To adjust these differences between the Wadden Model and the real measurements, the model was corrected by the gauging data at the time of SAR image acquisition. The differences between measured and modelled values at the gauging stations and the interpolation of these values in the 500 m grid system were added to the Wadden Model. This is the first step in correcting the Wadden model (table 3).

Gauging Stations	Measured	Modelled	Correction
Vlieland	-79	-35	-44
W. Terschelling	-88	-43	-45
Harlingen	-100	-40	-60
Kornwerderzand	-108	-53	-55
Oude Schild	-29	+5	-34
Den Oever	-63	-32	-31

Table 3. The example of correction of the Wadden Model based on gauging records (16-05-1993, in cm)

A second correction was applied further to improve the model with respect to bottom drag which causes a water surface curvature over the flat areas. The knowledge about the water surface curvature was obtained through a measurement campaign carried out during 7-21 April 1994. During this campaign, 14 pressure loggers were placed along a transect of 7 km in 500 m spacing over one of the large flats in the study area. The water levels were recorded during a 14-day full spring tidal cycle with time interval of 1 minute. This experiment gave us an insight into the curvature of the water surface at all stages of the tidal cycle. In general, the bottom drag over the flat causes a water surface gradient of 1:10.000 during incoming tide. During outgoing tide the slope of the water surface declines gently towards the channel in an order of 12 cm over 3000 m, which is not as obvious as in incoming tide. The actual correction of this surface curvature is further adjusted according to the time in the tidal cycle and the distance towards the low tide line. A full description is given in the special ERSWAD report on this experiment (Wang *et al.* 1995).

The corrections have been applied in zones of 500 m from the channel edges (low tide line: -110 cm) towards the central part of the flats. The DEM of the corrected water surface model was then densified to a 12.5 m grid size equal to the SAR pixel size.

2.3 Evaluation of the accuracy of the water line method. The delineated water lines from the SAR image was combined with the corrected water surface model at the time of image acquisition in order to extract the height value of the pixels along the water lines.

As an example, the evaluation of this mapping method was done for the SAR image acquired on 09-08-1992. The height values of the water lines delineated after the Global Classification Filtering were compared with the bathymetric DEM. This DEM was constructed by interpolation of ship-borne echo sounding data surveyed in the Vakloding Program conducted in 1992-1993 by Rijkswaterstaat. The TIN method (Triangulated Irregular Network) in Arc/Info software was applied followed by the bi-linear interpolation of the intermediate points between two survey lines which can improve the interpolation. The comparison between water line height and the bathymetric DEM shows an average of -0.38 cm of differences. Seventy-one percent of total pixels along the water line are within ± 30 cm (acceptable errors) which is very good.

3. RESULTS

The merging of the 9 water line data derived from the SAR images from 1993 with the Corrected Wadden Models (CWM) at the time of each image acquisition gave the height values for multiple water lines from different images.

On the flats, a higher density of height points are found at places where the topographic variation are more apparent. This distribution of height points can be trusted more and will be more useful than a ground survey with a large line spacing, in which the minor depressions and gullies may be easily missed. Of course no values are available in the channels lower than the low tide line.

The interpolation was run on the basis of TIN module in Arc/Info, the same procedure as that used for the bathymetric DEM creation. The resulting Water Line Digital Elevation Model (WALDEM) is shown in figure 4.

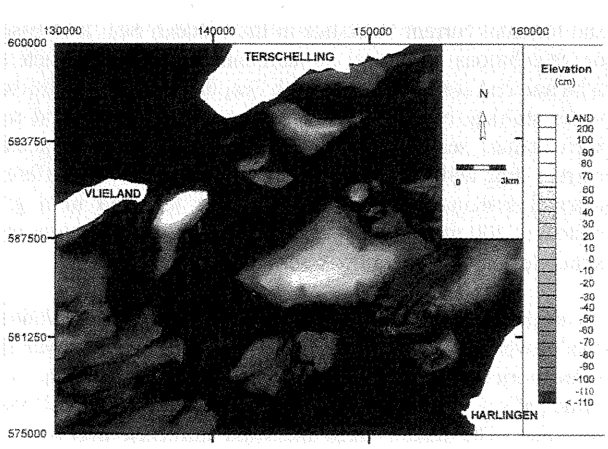

Figure 4. Water Line DEM of the Inter-tidal Area Using Water Line Procedure with Multiple ERS-1 SAR Images (1993.3-1993.10)

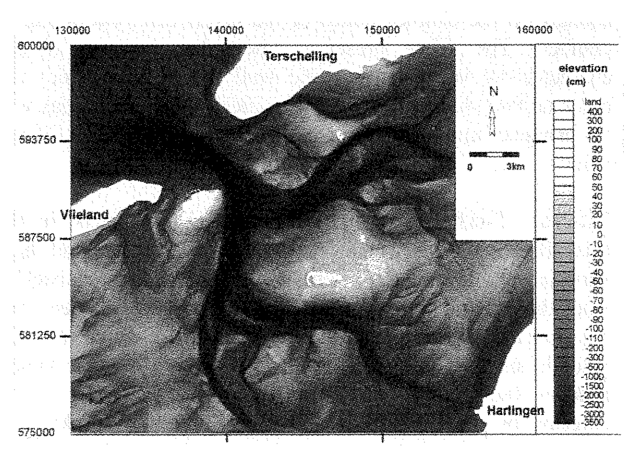

Figure 5. Bathymetric DEM of the western Dutch Wadden Sea using sounding data by Rijkswaterstaat from 1992-1993.

A comparison of the WALDEM (figure 4) with the bathymetric DEM (figure 5) demonstrates the large similarity. The height differences between WALDEM and DEM on basis of pixel-bypixel comparison give a mean difference of -5 cm (WALDEM lower than DEM) and a standard deviation of 28 cm. 93% of the pixels are within the ± 50 cm difference range, 73% within ± 30 cm.

The differences may attribute to:

A. Water line procedure

1) Georeferencing errors: not larger than 1 pixel (12.5 m) in horizontal

2) Water line delineation: several pixels in transitional zone of the land and water due to a thin water film.

3) Water surface modelling: smaller than 20 cm vertically.

4) Selection of the interpolation method.

B. Bathymetric DEM

1) Echo sounding errors: approximately 20 cm in general and up to 40 cm over flats (Calkoen, *et al*, 1995).

2) Omission of the topographic details due to interpolation between large spacing of bathymetric survey lines.

4. CONCLUSIONS

The water line procedure based on satellite radar imagery appears to be a reliable method for precision topographic mapping in the tidal range.

The usefulness of SAR imagery for water line procedure is very much influenced by the wind and tide conditions at the time of acquisition. More than 60% of the acquired ERS-1 SAR images may be used for water line delineation. Wind velocities lower than 5 m/s often preclude a reliable discrimination between water and dry flat surface on the SAR image and the image can not be used. With a 35-day cycle (17-day sub-cycle), sufficient imagery will become available during the year for applying this method.

The Global Classification Filter for segmentation of the speckled SAR image is proved effective by introducing the global concept.
The water surface model (Wadden Model of RIKZ) for the acquisition time of the images is required and should be corrected on basis of actual gauging records and water surface curvature.

The precision of the WALDEM compared with the bathymetric DEM are: for 93% of the pixels in the inter tidal area within $\pm$ 50 cm, and for 73% within $\pm$ 30 cm vertically.

The water line method is suitable for quantitative height measurements over the flats between high and low tide lines. By combination of the two methods —bathymetry over the channels and water line method over the flats— a considerable saving, more than 50% for this flat area, can be made on bathymetric surveying.

The frequent SAR coverage allows for a monitoring on a more regular basis (once every or second year) for determination of the zones of erosion and sedimentation and the changes of the channels and gullies.

The present results are very encouraging and the study on the water line procedure may lead to an operational use of the method for topographic mapping in the inter tidal zone.

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