

Monitoring tidal flat changes using ERS-1 SAR images and GIS in the Western Wadden sea area, the Netherlands

Yiman Wang
B. N. Koopmans

International Institute for Aerospace Survey and Earth Sciences (ITC)
P.O.Box 6, 350 Boulevard 1945, 7500 AA, Enschede, The Netherlands

ABSTRACT

The tidal flat area of the Wadden Sea along the southern North Sea is an ecologically sensitive area. The bottom configuration is in constant change under semi-diurnal tidal processes. To monitor the topographic changes of the flats and channels, rapid updating of the bathymetric maps is needed. A water line method for topographic mapping in the tidal flat area using ERS-1 SAR satellite imagery was tested to overcome the difficulties met by the conventional survey method. In this article, an improved procedure for increasing the accuracy of the water line method is discussed. The procedure includes automatic delineation of the water lines from radar images, tidal water surface modelling and the evaluation of the accuracy based on an established digital elevation model (DEM) of the flat.

It was found that a proper water surface model is a crucial factor in the accuracy of the water line method. It is especially important in the flat area within the tidal range, but there is a lack of measurement data from the flat. For investigating the tidal water surface on the flats, a measuring campaign was carried out on one of the large flats in the study area for measuring the water level. By using 14 pressure loggers with automatic recording systems along a transect across the flat from the west channel to the east channel, 14 day's data with 1 minute recording interval were obtained. The preliminary study of the data shows that the water surface curvature of the incoming tide causes a water height difference of 30 cm between the flat around the water divide and at the edge of the main channel, within a distance of 3000 m to 3500 m. In the outgoing tide, the curvature is a gentle slope with a smaller height difference, i.e. 12 cm in 3000 m. This insight of the water surface behaviour combined with other influencing factors, such as wind force and wind direction, may prove to be useful for better water surface modelling, thus improving the accuracy of the water line method.

1. INTRODUCTION

The Wadden Sea, including a string of barrier islands, is a tidal flat area of 8000 square kilometres along the north coast of The Netherlands, northwest Germany and southwest Denmark. Under the semi-diurnal tides, the flowing sea water changes the coastal configuration continually. Updating of topographic maps has always been an important task for natural coastal defence, the maintenance of safe shipping lanes, conservation of the environment and the control of the region as an important recreational area.

Conventional mapping methods consist of terrestrial geodetic levelling and ship-borne echo sounding, which are time and money consuming. A "water line procedure" was proposed and tested in the 1960's for measuring the height of the flats by using aerial photos and water level data. This procedure makes use of remote sensing images acquired during different stages in the tidal cycle. The land-water boundaries are mapped from each image and are related to a water level model for the time of image acquisition. From the height values found along the water lines of every image, a height map may be interpolated for the tidal flats between maximum and minimum water levels. Due to the small coverage of the aerial photos and the changing tidal water during one flight mission, the test was not successful (Zee, 1980). Satellite spectral images (Landsat) were then tested for their synoptic view over a vast area. A work procedure was established (Wang et al, 1993). Though the result is encouraging, there are not enough cloudless images available in a relatively short time frame representing the different tidal stages (Spek et al, 1991).

To take advantages of radar system, which is daylight independent and has an all-weather capability, ERS-1 radar satellite data were employed here to investigate their usefulness for the mapping method following the water line procedure.

The direction of the longshore and tidal currents along the Wadden Sea is from west to east. The tidal cycle occurs twice a day with a period of 12 hours and 25 minutes per cycle. The time of high tide at Delfzijl in the east part delays up to 4 hours compared with the time at Den Helder in the west, and the tidal range increases from 1.4 m at Den Helder to 2.7 m at Delfzijl. The tidal waters enter the area through channels separating the barrier islands. These channels may reach a depth of 50 meters, but most gullies in the flat area are only 5 to 10 metres deep.

A pilot project area was selected in the western part of the Dutch Wadden Sea, between the islands of Vlieland and the town of Harlingen (latitude $53^{\circ} 10' \text{ N}$ to $53^{\circ} 20' \text{ N}$ and longitude $4^{\circ} 58' \text{ E}$ to $5^{\circ} 28' \text{ E}$) (Fig. 1).

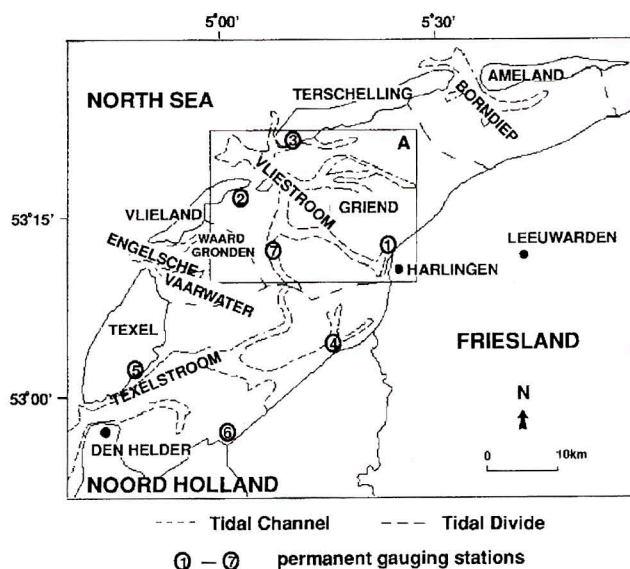


Figure 1 - Location of the Study Area

The average high tide in the project area is + 0.78 m above mean sea level, when most of the area is flooded except a small portion on the high flats of Richel and Griend. The average low tide is -1.07 m, giving a tidal amplitude of 1.85 m. During the outgoing tide, extensive shoals fall dry.

The data used in this study include ERS-1 SAR images provided by ESA, the water surface model (Wadden Model) and echo sounding data provided by Rijkswaterstaat. The work procedure (Fig. 2) comprised three parts: SAR image processing, water level modelling and digital elevation modelling. The combination of parts 1 and 2 yields the height value of the water line, and later was compared with a DEM established from part 3 to evaluate the accuracy of the mapping method. Most of the computer data analysis work was done in ILWIS software developed at ITC.

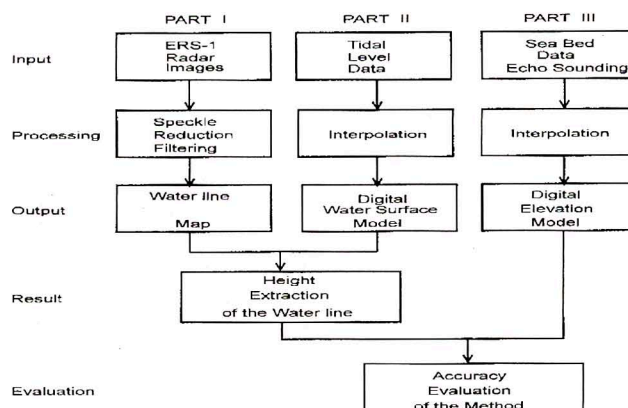


Figure 2 - The Flow Chart of Work Procedure

2. METHOD

2.1 Delineation of the Water Lines of the Tidal Flats using ERS-1 SAR Images

Several ERS-1 SAR PRI images were acquired from this area from 1991 to 1993. Not every image was ideal for this study (Koopmans et al, 1994). The image acquired on 09-Aug-1992, 10:37 GMT, was chosen because the contrast between tidal water area and uncovered flats is clearer than in the other images received (Fig. 3).

The established image processing procedure for delineation of the water lines is reported in above mentioned paper. New approaches for increasing the accuracy were tried since then. Here the emphasis is on the improvement.

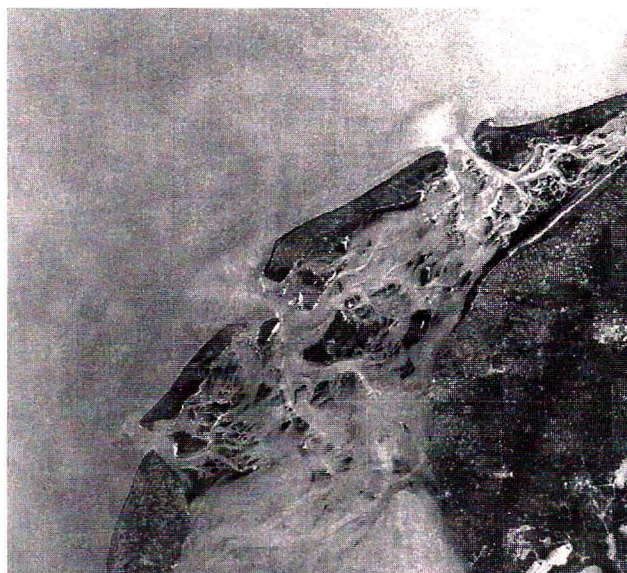


Figure 3 - The ERS-1 SAR Image Acquired on 09 Aug. 1992 (C"ESA, 1992" ERS-1-R)

The received ERS-1 SAR PRI data were in 16-bit format. By truncating the last 1% of the high digital numbers, the image was rearranged into 0-255 byte format. The image was then geocoded to the Dutch RijksDriehoeksmeting (RD) coordinate system which was used in other data provided by Rijkswaterstaat. By selecting the control points from the surrounding permanent land areas on the topographic maps (1:50,000), an affine transformation using nearest neighbour resampling method was performed in geocoding this very flat area. The residual error of the transformation is 0.9 pixel out of 12 well distributed control points.

The digital number of the image is the intensity of the radar backscatter from the ground surface. It is determined mainly by the surface roughness of the target relative to the wavelength of the emission of the radar pulse, the incidence angle relative to the range distance and the local slope of the terrain. In principle, the sea water surface forms a strong backscatter due to the wave motion showing the bright tone in the image. The emerged sandy- and muddy flats show a dark tone because of the mirror reflection at the smooth surface.

Because of the coherent processing of the radar system, a very strong speckle noise occurs from both land area and the moving tidal surface, that makes the water/land classification difficult. Lee's improved filter (in software EASI/PACE, PCI) was applied for the speckle reduction and edge preservation.

With human visual interpretation and histogram analysis, the threshold for separation of these two classes on the basis of the filtered image was chosen at grey levels 27 and 87. The pixel values below 27 dominate the dry flats, where a mirror reflection of the radar signal occurs from the very smooth sand surface in relation with the ERS-1 SAR wavelength 5.3 cm. From the curve of the histogram, pixel number 27 is just at the turning point of the curve direction (**Fig. 4**) which could not be found from the histogram of the original image data. Digital numbers greater than 87 are caused mainly by strong backscatter as the result of the increased local incidence angle at the east-facing slopes of the shoals which is opposite the radar antenna look direction (west). The pixels with grey levels between 28 and 86 represent the tidal water surface. A threshold classified map was produced with values 0 (land, dry shoals) and 1 (water coverage). The existing salt-and-pepper appearance was further treated by a combination of binary filters (Shrink4, Dilate4 and Majority).

The final water line map (**Fig. 5**) was derived from the vectorized boundary of the water/land classification map.

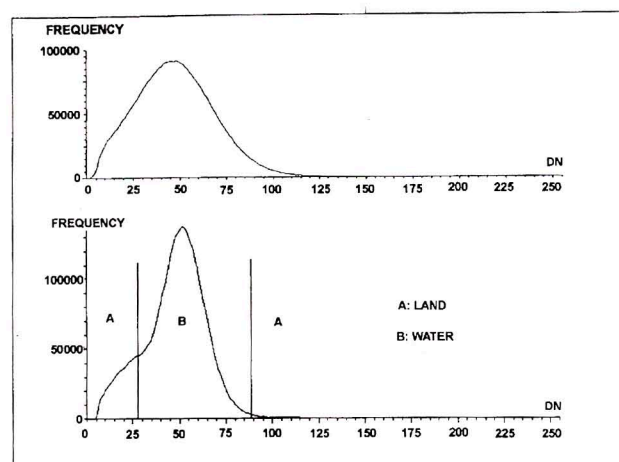


Figure 4 - Histogram of Filtered Image

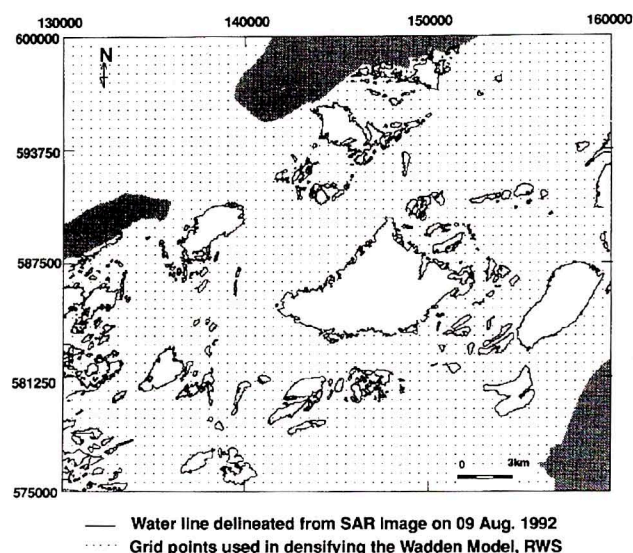


Figure 5 - Water Line Map Delineated from ERS-1 SAR Image

The permanent land areas (the islands of Vlieland and Terschelling, and the mainland area of Harlingen) were masked and the erroneous lines inside the dry shoals were removed.

2.2. Water Surface Modelling with “Wadden Model”

For obtaining the height of the water lines, a water surface model should be derived by interpolation of the available tidal data. There are six permanent gauging stations around this area (see **fig. 1**). The interpolated water surface model derived from gauging records from these stations was too general to be precise for the points on the flats. Another source of tidal data was from a simulation model “Wadden Model” provided by the National Institute for Coastal and Marine Management (RIKZ). A previous study

(Koopmans et al, 1994) has shown that RIKZ's Wadden Model for extracting the water line height yields better results than the interpolated model from six surrounding gauging stations. Therefore the Wadden Model was applied here.

The Wadden Model simulates the tidal movement between the open North Sea and the enclosed Wadden Sea by taking the astronomic, meteorological and topographic influences into the computation (Robaczewska et al, 1991). The whole computation was in a process of many steps in 2 1/2 minute interval until reaching the required time, in this case, 9 August 1992 at 11:40 MET. It was in an outgoing tide situation, 23 minutes before the lowest tidal stage at station West Terschelling. The result of the computation is the tidal current velocity and water level in a 500 metre's grid system for the entire Dutch Wadden Sea. The grid values for the dry flats and the land boundaries are defined as "inactive" points when the velocity values are zero from all the surrounding points. The grid coordinates were converted to the RD system. Interpolation was performed using only active points from the water domain to densify the coarser grid into 12.5 m SAR image ground resolution.

By overlaying the densified Wadden Model with water lines delineated from the SAR image, the tidal water level on the line at the time of image acquisition can be extracted.

2.3. DEM of the Bottom Configuration

A digital elevation model (DEM) is needed in the database as a reference for evaluation of the accuracy of the tested mapping method. The bathymetry of the Wadden Sea has been under surveying every 5 years by Rijkswaterstaat. These data are for verification and evaluation. With a continuous supply of bathymetric survey data by North Netherlands Division of Rijkswaterstaat, a larger coverage for the DEM of 1992 bottom topography in the study area became available. The entire DEM now includes 12 bathymetric map sheets (with some missing parts), each covering an area of 10 x 6.25 km.

The original echo-sounding data were recorded along the survey line at 2 to 5 meter intervals, while the spacing between the survey lines was about 200 m. These irregularly spaced data produced a problem in interpolation of a DEM, which takes very little account of the direction of the cross survey lines.

The TIN (Triangulated Irregular Network) module of Arc/Info was used to improve the interpolation. First, a TIN coverage was created within a polygon covering only the area in which we had data. The distance between points for building a TIN coverage was defined as 12.5 m. The optimized triangles, though very narrow, were built between two survey lines. The second step was to build a regularly spaced lattice by interpolating the height values linearly within three vertices of a triangle. The DEM was created in one run using the remaining 125,492 echo sounding records (**Fig. 6**).

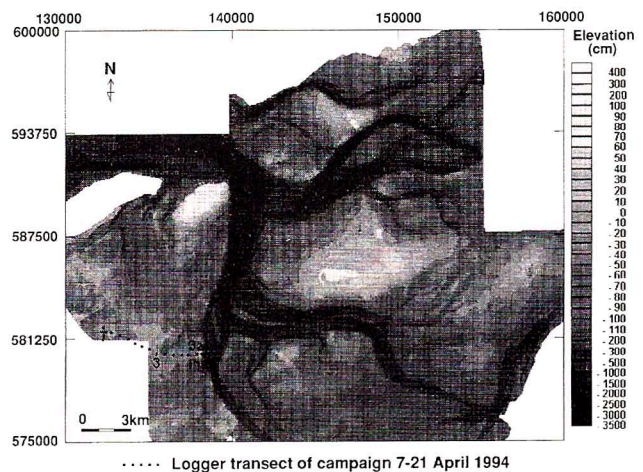


Figure 6 - DEM of the Sea Bottom from 1992

3. RESULT AND DISCUSSION

3.1 Result

Because the data provided by Rijkswaterstaat (water surface Wadden Model and echo sounding data of the bottom bathymetry) were all in the RD coordinate system, the ERS-1 SAR image was also geocoded with the same coordinate system. This makes spatial modelling in a GIS possible.

The height values of the pixels along the water line were extracted from the densified water surface model. These represent the heights of the flat surface along a certain tidal water line. For this case, it was during very low tide, 5.57 hours after the high tide. If more water lines with different heights can be derived during several tidal stages (from low to high tides) in a relatively short period, a new DEM of the tidal flat may be achieved.

The result of the water line height was compared with the DEM of the bottom surveyed in the same year of image acquisition for evaluation of the accuracy of the method.

The difference between the water line height and DEM height is the error. Considering the contour line interval of the output map as 1 m, the acceptable error for height data should be within 30 cm.

The statistics of the error analysis are listed in table 1:

Table 1 - Statistics of the Error Analysis

Total pixels of the image	1,200,000
Total pixels on the water line	22,423
Minimum value of the errors	-364.7 cm
Maximum value of the errors	1010.7 cm
Average of the total errors	-10.55 cm
Median value	-12.5 cm
standard deviation	51.22 cm
Predominant pixel value	-11 cm

After excluding these extreme errors from the minimum and maximum which occupied less than 1% of the total, the average and the standard deviation became -12.3 cm and 35.1 cm, respectively. Our results showed that 87.1% of the pixels were within the -50 and +50 cm error range, 68.1% within -30 and +30 cm, and 27.3% within -10 and +10 cm. Most errors were negative ones, with 69.7% in total and an average of -28 cm of the negative errors. It means, in general, that the extracted sea bottom height from the water surface intersection with the flats was lower than the DEM height. The positive errors accounted for 30.3% with an average of +23 cm.

3.2. Discussion

Errors can be introduced by any one of three major factors involved in the analysis: image interpretation, tidal water surface modelling and the DEM of the bathymetry.

3.2.1. Image Interpretation

For automatic differentiation of water and land, only a simple Lee filtering approach was used to reduce the speckle effect. The backscatter of the radar signal from the moving water surface is mainly determined by the surface roughness which is complicated by many factors. Water surface roughness is influenced by wind speed, water velocity and bottom configuration, etc. An instantaneous change of the local wind may cause a significant change of the backscatter from a patch of water surface.

In addition, for such a large area with tidal water entering from different inlets at different tidal stages and with changeable local winds, a unique threshold for a decision boundary could not yield a good relationship between the digital number and the object for the entire area. Another source of error may come from the abrupt height difference at the steep slope along the channel. The adjacent pixels along this belt have a height difference of tens or hundreds of centimetres. When the water line was drawn here, a large error occurred even though the line was located correctly. Also manual editing of the false water lines from the automatically delineated water line map caused by the remaining water on the dry flat was insufficient. The extreme error values in the statistics were mainly from these kinds of mis-classifications, which cannot be avoided with automatic interpretation.

3.2.2. Tidal Water Surface Modelling

As noted above, the water surface is in fact not a horizontal surface but an undulating one. During the tidal fluctuation, there must be a difference in the water level between the flat and the channel because of a possible time delay (a phase shift of the tidal cycle). No data were available at present to indicate the shape of the surface. To investigate this phenomenon, a measurement campaign was carried out on one of the large flats, Waardgronden, in the western Wadden Sea. It will be described below.

3.2.3. The DEM Built from the Echo Sounding Data

The error analysis of the water line method was based on the DEM of the bottom topography as a reference level. The echo sounding of the water depth conducted on the ship was in turn based on the water level of adjacent gauges during high tide as height reference. It may contain some error. With a survey line spacing as 200 m, some micro-relief such as small gullies may be omitted in the data set and may not be reflected in the interpolated DEM.

4. THE OPERATION LOGGER CAMPAIGN FOR WATER SURFACE MEASUREMENT

Because most permanent gauging stations for tidal measurement are placed in the channel, the behaviour of the water surface on the flats is not well known. To study this aspect, a logger campaign was carried out from 7 to 21 April 1994, on the Waardgronden flat area with the cooperation of Survey Department, North Netherlands Divi-

sion, Rijkswaterstaat. The measuring instrument used in the campaign was the Tirtaharapan Pressure Logger developed at ITC (Hoop de et al, 1992).

With the help of the survey department supplying the ship and personnel, fourteen loggers were deployed at 500 m interval, buried in the sand along a transect over the flat from the west Engelsche Vaarwater channel to the east Inschot channel (for the location of the transect, see **Fig. 7**). The total distance was 6.5 km. Three known points with coordinates and height value provided by Rijkswaterstaat were used as our control points (numbers 7, 3 and 3a). Between 7 and 3 were loggers 71, 72, 73, 74, 75 and 76. Between 3 and 3a were loggers 32, 33, 34, 35 and 36. The permanent gauge (Ins) was in the channel Inschot only 300 m away from logger 3a. The coordinates of the loggers were determined using a Magellan NAV 1000 PRO GPS set.

The loggers automatically registered the total pressure (water and air) above the header at 1 minute interval for 27 tidal cycles in 14 days. A reference "dry" logger was placed on shore to register air pressure, which should be subtracted from loggers' recordings for correct water pressure. The pure water pressure in millibar was then converted to the water depth in centimetre. The water level from the permanent and additional temporary gauging stations of the area and weather conditions were also recorded in the campaign period.

The preliminary findings were shown in the BCRS report (Wang et al, in press). Here we briefly introduce some significant findings in relation with the water surface modelling.

The registered data contain a fluctuation up to 26.8 cm. Ignoring ± 1 cm instrument noise, the fluctuation represents the wave amplitude which is positively related to the tidal water level at a certain tidal stage and the wind force. These fluctuations were eliminated by averaging methods.

The time difference of reaching high tide for 14 logger locations was not significant (a maximum of 20 minutes). But at low tide, time difference for incoming water was large. The incoming tide in the west and east ends of the transect started 1 hour or 1 1/2 hours earlier than in the middle point (**Fig. 7**). For water surface behaviour, let us consider the eastern part of the transect as an example. The curvature of the water surface over the shoal during the incoming tide caused a -30 cm height difference between the water height at the water divide (logger No.75) and the water height at the edge of the channel Inschot(logger 3a), over a horizontal distance of 3,000 m to 3,500 m. This depression in the water surface around the water divide filled rapidly up by the tidal waves when meeting from both directions along the water divide. During the outgoing tide, however, the water surface slopes gently towards the channel. The gradient of the outgoing water slope was about 12 cm over a horizontal distance of 3,000 m (**Fig. 8**).

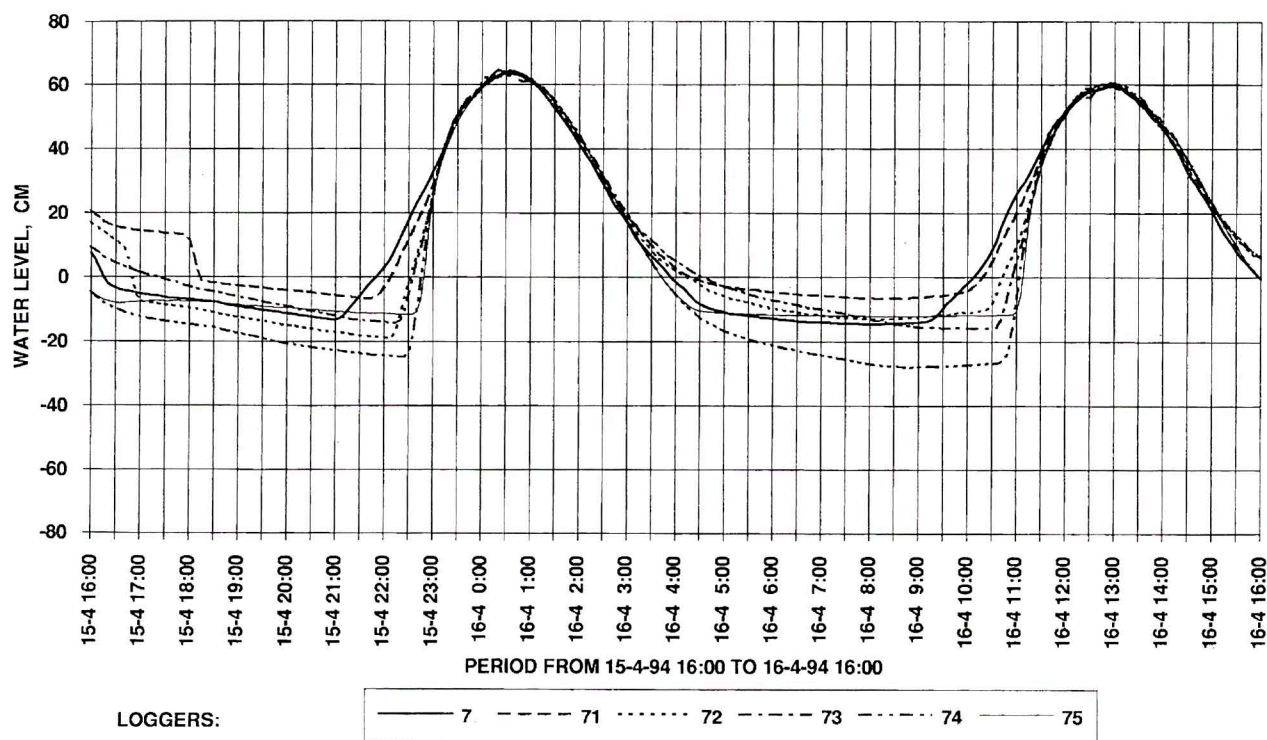


Figure 7 - Simultaneous Tidal Curves at loggers 7 to 75, western part of the transect

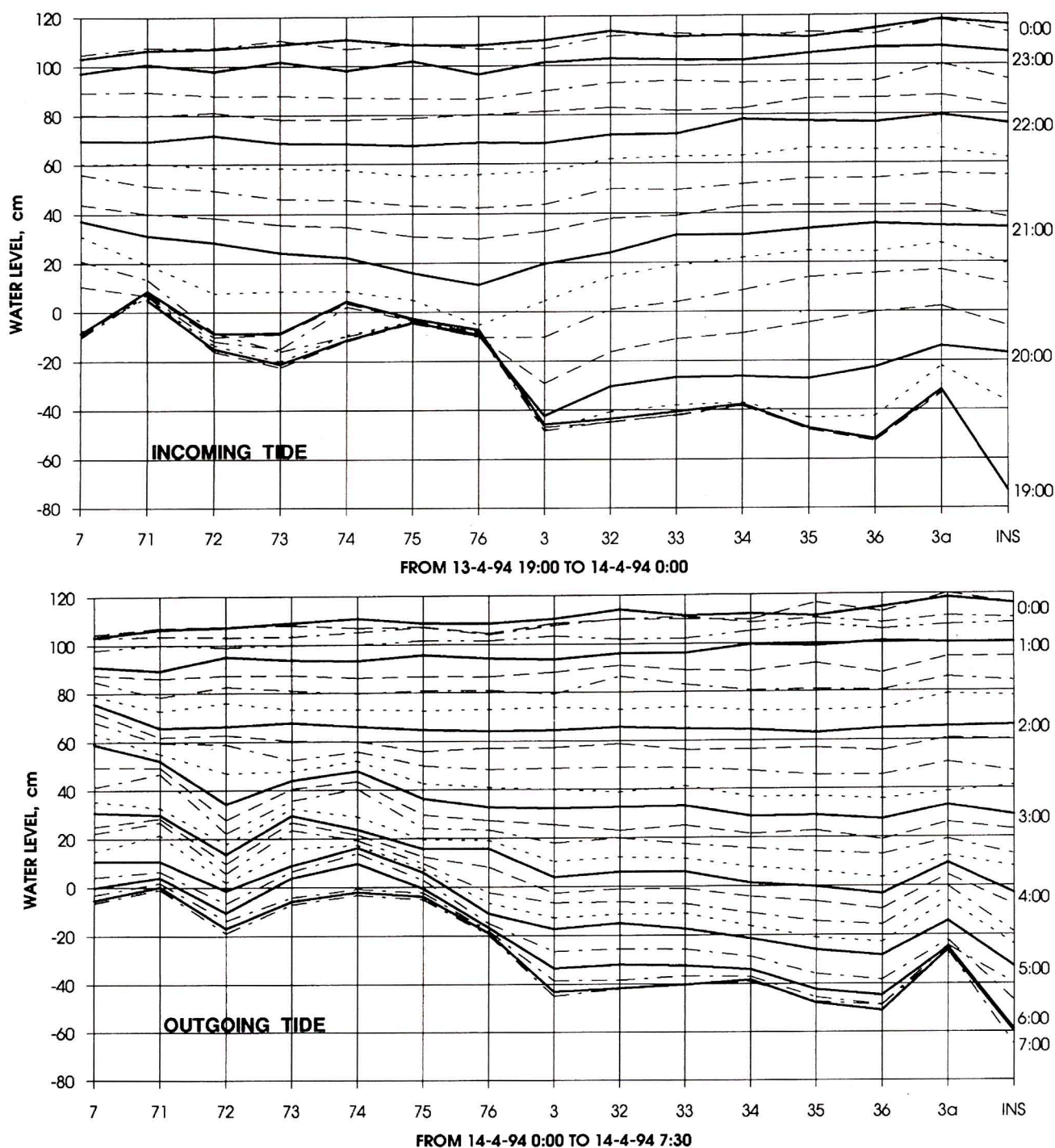


Figure 8 - Curvature of Tidal Water Surface over the flat

The measuring campaign has given us a better insight into the water surface behaviour during the tidal cycle under different weather conditions, which will be a very important factor in improving our water surface modelling when applying either the Wadden Model or using the routine gauging station records. Further analysis of how to utilize the data in water surface modelling will be continued.

5. CONCLUSIONS

5.1. Our study of the ERS-1 SAR image acquired on 9 August 1992 is a good example of using satellite radar data to establish the water line method for rapidly updating topographic maps in the tidal flat area. The automatic classification of water and land based on radar signal return has some difficulties from the radar imaging mechanism.

Human interpretation is still needed. For operational use, the problem is to obtain enough suitable images at certain tidal levels and under certain weather conditions. Longer wavelength radar (L-band) may be more applicable.

5.2. Water surface modelling is the most critical factor, which influences the accuracy of the mapping method. Through a rational interpolation from the coarse grid of the Wadden Model by Rijkswaterstaat, 68 percent of the pixels on the water line contains an acceptable error of less than ± 30 cm, compared with the DEM of the same year. An investigation of water level on the flat using pressure loggers has given a better insight of the water surface curvature. The water surface height difference on the flat compared with that in the channel during the incoming and outgoing tides (gradient of the tidal water surface) will be considered in future water surface modelling.

ACKNOWLEDGEMENT

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