International Hydrographic Review, LXXV(2), September 1998

THE USE OF RADAR IMAGERY TO ASSESS THE BOTTOM TOPOGRAPHY OF SHALLOW SEAS

by C.J. CALKOEN, G.H.F.M. HESSELMANS and G.J. WENSINK [1]

Abstract

Under favourable conditions features of the bottom topography of shallow seas are visible in radar images, which are nowadays obtained from satellites on a routine basis. A Bathymetry Assessment System (BAS) was developed to use these images in order to produce depth maps. This paper describes the principles behind the system, indicates for what type of applications it might be useful, notes on the accuracy and gives an example of an application.

INTRODUCTION

The state-of-the-art technique to map the sea bottom topography in bathymetric surveys is to use shipborne echosounders, single- or multi-beam. This technique gives high accuracy results, but is expensive and time consuming. Remote sensing mapping techniques may provide useful alternatives, especially when large areas are mapped and a limited accuracy is required.

Remote sensing methods have the advantage that they provide a synoptic overview over a large area at relatively low costs. A typical Synthetic Aperture Radar (SAR) image, as taken by satellites on a routine basis, measures about 100 km x 100 km. These images contain a wealth of information which can be used to get a first impressing of the bottom topography of areas for which no (recent) depth measurements are available. The existing archive of SAR imagery already covers a large part of the coastal areas of the world and also contains historic data which may be used to detect morphological changes.

[1] ARGOSS, Marknesse, The Netherlands.

The Bathymetry Assessment System (BAS) was developed to extract quantitative depth information from SAR images. Radar images have a number of advantages over optical images: they are not blocked by clouds, they can be taken at night time, and the method does not rely on reflection of signals on the sea bottom, so that also turbid waters can be mapped. On the other hand, this method requires a strong (tidal) current and fair wind conditions at the time when the SAR image is taken.

To obtain reliable results BAS needs depth data calibration, either from existing charts or from conventional depth soundings. When BAS is used for the production of accurate depth maps, the remote sensing mapping technique can be viewed as a kind of intelligent interpolation in between depth soundings at ship's tracks using the information contained in the SAR images. Because of this intelligent interpolation, the tracks may be further apart, leading to considerable savings in costs and time.

BATHYMETRY ASSESSMENT SYSTEM

Under favourable meteorological and hydrodynamic conditions (moderate winds of 3 to 10 m/s and significant tidal currents of about 0.5 m/s or more) Synthetic Aperture Radar (SAR) imagery shows features of the bottom topography of shallow seas (ALPERS and HENNINGS 1984, VOGELZANG et al., 1989). The basic physical mechanisms responsible for this are now understood as a three stage mechanism:

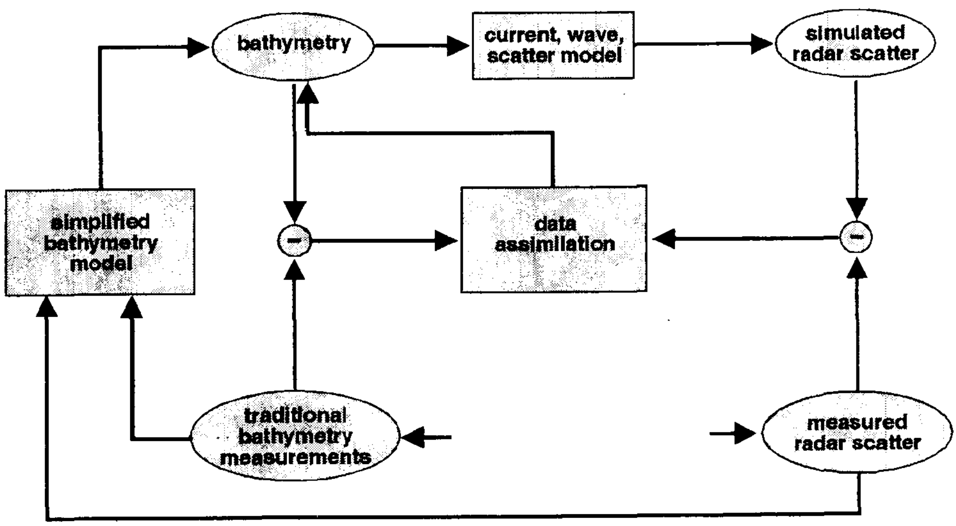

FIG. 1.- Bathymetry Assessment System.

1. Interaction between (tidal) flow and bottom topography results in modulations in the (surface) flow velocity.
2. Modulations in surface flow velocity cause variations in the surface wave spectrum. Variations in the surface roughness cause modulations in the level of radar backscatter.
3. The imaging model, which simulates a SAR image for a given bottom topography, consists of a suite of three models: a flow model, a wave model and a radar backscatter model. Inversion of these models make it possible to extract depth information from SAR imagery of coastal areas. Due to the natural high speckle noise level in the images, inversion is not an easy task and requires sophisticated data assimilation techniques. The Bathymetry Assessment System (BAS) was developed to accomplish this.

The schematic structure of BAS is shown in Figure 1.

To produce a depth map, BAS needs one or more SAR images and a limited number of conventional depth measurements for calibration purposes. The depth measurements are also used to determine an initial depth map to start the data assimilation procedure. In this procedure the imaging model suite is used to simulate a SAR image from the depth map and this simulated image is compared with the "true", measured image(s). Deviations between simulations and measurements are squared and summed and form one part of a so called cost function. Another contribution to the cost function comes from deviations between the depth map and the depth measurements, and also steep depth variations are penalised in order to suppress noise and obtain smooth maps. From the observed deviations depth corrections are deduced which are used to construct an updated depth map with lower deviations and therefore a lower cost function. The updated map is then re-inserted in the data assimilation procedure and this goes on until a minimum is found for the cost function. The depth map which corresponds with this minimum is most consistent with all available measurements and therefore the best estimate for the real depth.

The imaging model consists of a suite of three models: a flow model, a wave model and a radar backscatter model. For the flow model two one-dimensional simplifications of the shallow water model equations are available. One is designed for situations such as sand waves, in which depth variations are oriented mainly perpendicular to the tidal flow. In that case the depth averaged mass flux, *i.e.* water depth times flow velocity, is taken constant along a stream line. The other flow model is designed for situations such as in channels, in which depth variations occur mainly parallel to the tidal flow. For these situations it is assumed that the flow velocity along a stream line is determined by the bottom friction, which means that the velocity is proportional to the square root of the depth. The wave model describes the dynamic behaviour of very short water waves, of the same length scale as the radar waves which means between 1 and 50 cm. These waves lie far in the tail of the wave spectrum and are under stationary conditions in equilibrium with the wind. When a wave package encounters an acceleration or deceleration in the tidal flow, the wave action of the package is conserved but the wave length is changed. This means that the wave package is no longer in equilibrium. In the wave model it is assumed that the wave action relaxes exponentially to its equilibrium value. This is formulated mathematically in the action balance equation with a relaxation source term. To determine the radar backscatter a Bragg model is used. In this model the intensity of the radar waves scattered on the water surface is proportional to the spectral energy of the Bragg water waves. These are waves with a length equal to half the radar wave length, divided by the sine of the radar incidence angle. For satellite SAR systems the Bragg wave length is about 5 cm.

Inversion of the imaging model with data assimilation methods amounts to finding a minimum of a cost function *J*. For a depth map d_{ij} on a grid the cost function consists of three terms:

$$J = w_1 \sum_{i,j} (r_{ij}\, s_{ij})^2 + w_2 \sum_{i,j} (d_{ij}\, l_{ij})^2 + w_3 \sum_{i,j} (\partial d_{ij})^2$$

In the first term the modelled radar backscatter r, computed from the given depth *d*, is compared with the measured image *s*. The second term compares the depth *d* with the depth measurements *l*, where the summation is taken only over locations at which such measurements are available. In the last term ∂d is the slope of the bottom topography. The purpose of this term is to suppress the effect of speckle noise in the image and produce smooth depth maps. The smoothness of the map can be controlled with the weight w_3. The weight w_1 depends on the quality of the used SAR image and w_2 on the accuracy of the depth measurements.

The simplified one-dimensional imaging models in BAS are designed to compute contrasts in the intensity of radar backscatter due to variations in the bottom topography with high computational efficiency. The accuracy of the used models appears to be sufficient for this application. The two one-dimensional models in BAS, one for sandwave-like situations and one for conditions like in channels, are complementary. With the combination of the two models, complex coastal bottom topographies can be mapped.

VALIDATION

The accuracy of a depth map made with BAS depends on the flow and wind conditions, which determine the suitability of the used SAR image(s), and the accuracy and density of the depth measurements used for calibration. It is not possible to estimate the mapping accuracy from first principles. Therefore, BAS has been applied to various sites along the coast of the Netherlands in a few dozen demonstration projects in order to validate its performance and determine the accuracy that can be reached with the system.

To determine the accuracy of the depth maps, the results of BAS on a grid *of typically 25 m were compared with ship's soundings measured along tracks at* intervals of about 3 m. For this purpose, BAS depth values along the tracks were calculated using bilinear interpolation of the assessments on the grid. Part of the ship's soundings were used as calibration during the map generation; these soundings were not used in the statistical accuracy analysis. Using more ship's soundings in the map generation improves the accuracy. As the purpose of BAS is to reduce the amount of required traditional depth measurements, the accuracy of the depth assessments is considered as a function of the interval between ship's tracks used as calibration data.

It is difficult to find reliable measures for the accuracy of two-dimensional depth maps. In the neighbourhood of steep channel slopes a small error in position (or round-off error due to the representation on a grid) can result in large errors in the depth. Moreover, the ship's measurements themselves show a noise level of the order of 20 cm. In the accuracy analysis the most relevant statistical error measures are the bias (the average value of the difference between depth values computed by BAS and depth measurements) and the rms error (the root of the mean of the squared depth difference). These averages are computed over large areas, at least several squared kilometres.

Based on the experience gained in demonstration projects it was found that BAS maps typically have a bias of 1 cm or less and an rms error of around 30 cm. These results were obtained for a variety of bottom topographies along the coast of the Netherlands with a typical depth of about 10 m, but ranging from shoals of a few metres or less to channels deeper than 30 metres. To obtain these results echo soundings were used along ship's tracks at intervals of 500 - 1000 m.

The SAR sensor of the ERS satellite, which is most often used for BAS applications, provides data at a grid of 12.5 m. The actual resolution of the sensor is 25-30 m. This resolution is further degraded because BAS smoothes the depth map to mitigate the effect of speckle noise in the SAR image, and because of the limited accuracy with which the images of coastal areas can be geo-referenced. The resolution of BAS maps in practice is estimated to be 50-100 m. However, sharp elongated features like channel walls have been positioned with an accuracy of about 25 m.

The accuracy of BAS maps can be improved by using more than one SAR image during the data assimilation processing. The reason for this is that use of an increased number of SAR images reduces the effect of speckle noise and that SAR images taken under different tidal conditions show other features of the bottom topography so that a combination of images provides a more complete picture. Another method is to use airborne SAR sensors, which have a resolution of 3 m and a better signal-to-noise ratio.

APPLICATIONS

The strength of remote sensing mapping methods is that they can give an extensive synoptic picture of the bottom topography in a coastal area in a short time and at relatively low costs. Below are some applications for which these advantages are important, while the accuracy limitations are less relevant.

Engineering and dredging projects in coastal areas are carried out in phases and each phase has its own information requirements. In the pre-feasibility phase often very little is known of the project area. Maps of limited accuracy are sufficient to select optimum locations for supporting units, choose supply routes and plan a bathymetric survey to obtain maps of increased accuracy in selected areas. Such maps can be made with BAS from available SAR imagery and Admiralty charts. In the planning phase, when more accurate information is required, the depth soundings obtained during a bathymetric survey can be combined with SAR images to produce depth maps more swiftly and cost-effectively.

Another potential application is to support (inter)national and regional governmental authorities in charge of management, monitoring and maintenance of coastal areas. These organisations require periodic updates on the bottom topography, especially in morphologically (very) dynamic areas. BAS maps can fulfil part of these information requirements and can also be used to optimise bathymetric surveys when more accurate maps are required by concentrating ship's tracks in areas which exhibit strong depth variations or large morphological changes and planning sparser track patterns in smooth, stable areas.

Finally, BAS can provide a good alternative in situations in which traditional surveys are less suited, for instance in very shallow areas and in ecologically sensitive areas.

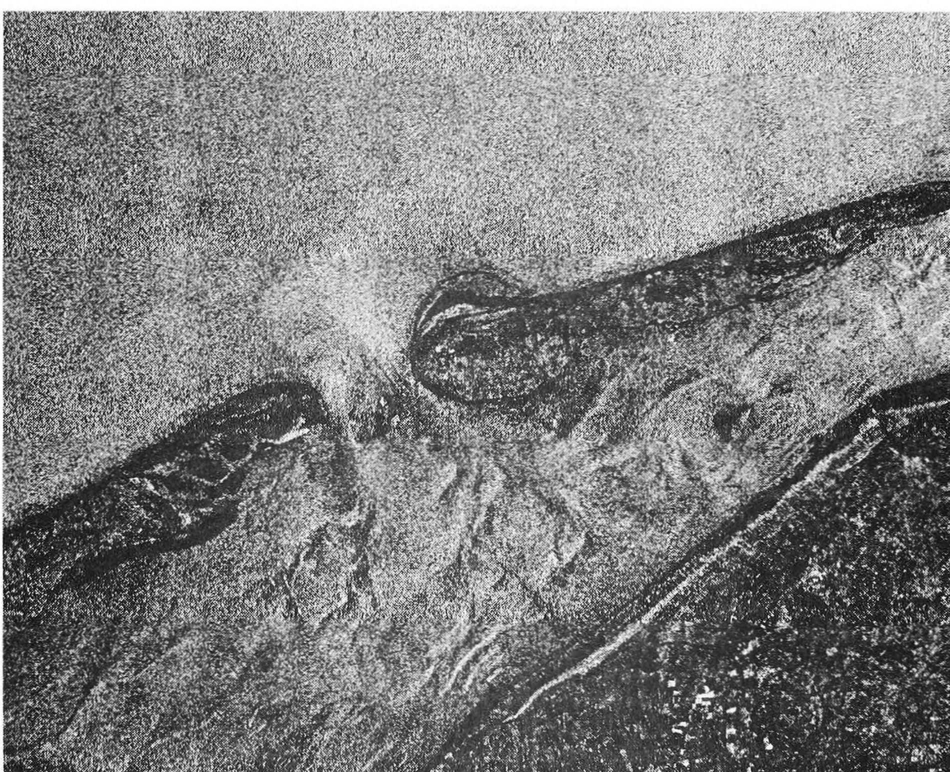

FIG. 2.- ERS SAR image of May 9, 1996.

EXAMPLE

As a recent example of a BAS application, the mapping of the Bornrif area is presented. This area is located north of the Netherlands, measures 35 by 25 km and is morphologically very dynamic. It contains a tidal inlet in between the islands of Terschelling and Ameland, an outer delta and a flood basin with many channels. This BAS application was carried out for Rijkswaterstaat, National Institute for Coastal and Marine Management/RIKZ, in support of morphological modelling of the area.

Figure 2 shows a SAR image of the area made by the ERS satellite. This was one of the four images used to produce the depth map shown in Figure 3. For calibration echo soundings were used along tracks at intervals between 600 and 3000 m . The rms accuracy of the BAS depth map was found to be approximately 25 cm.

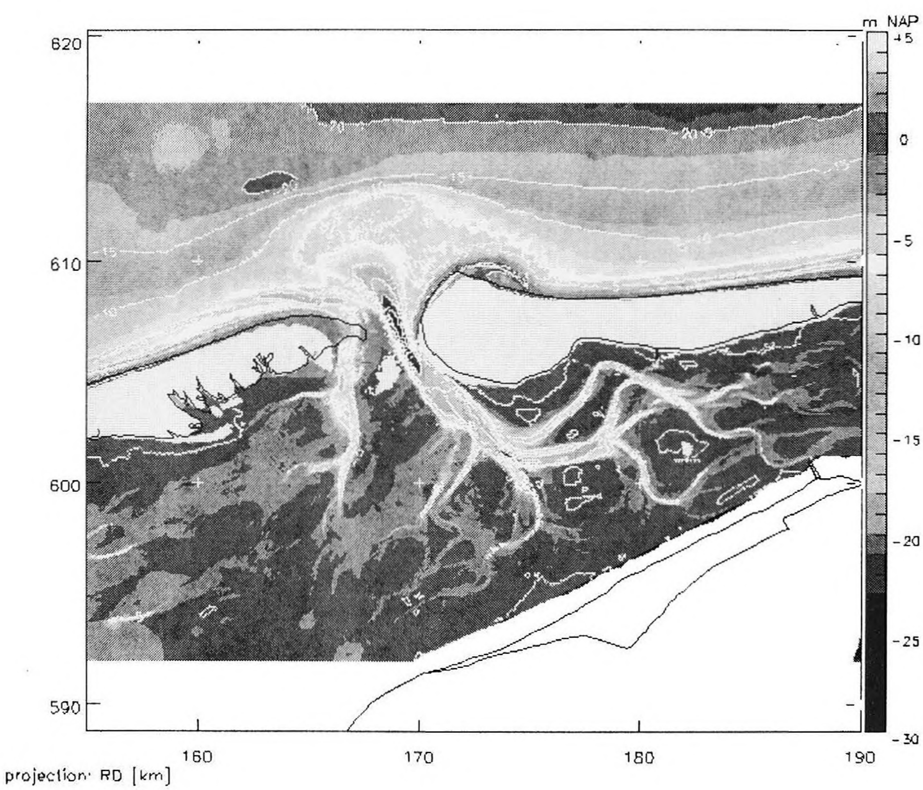

FIG. 3.- Map of the Bornrif area.

Conclusions

Radar images taken from space can be used to make depth maps of shallow seas. In this way a large area can be covered in a short time and at relatively low costs. This technique is complementary to echo sounding surveys and requires a limited amount of traditional depth measurements for calibration. As most promising applications for this new technique are envisaged the production of synoptic maps for engineering and dredging projects in the pre-feasibility and planning phase, and monitoring of (morphologically dynamic) coastal areas for management and maintenance.

References

ALPERS, W. and I. HENNINGS, (1984), A theory for the imaging of underwater bottom topography by real and synthetic aperture radar, *Journal of Geophysical Research*, **89C**, 10,529-10,546.

CALKOEN, C.J., G.H.F.M. HESSELMANS, G.J. WENSINK and J. VOGELZANG, Efficient depth mapping in shallow seas using radar images, submitted to *International Journal of Remote Sensing.*

DE LOOR, G.P., and H.W. BRUNSVELD VAN HULTEN, (1978), Microwave measurements over the North Sea, *Boundary Layer Meteorology*, 13, pp. 113-131.

HENNINGS, I, (1990), Radar imaging of submarine sandwaves in tidal channels, *Journal of Geophysical Research*, 95C, pp. 9713-9721.

HESSELMANS, G.H.F.M., G.J. WENSINK, C.J. CALKOEN and H. SIDHU, (1993), Application of ERS-1 SAR data to support the routing of offshore pipes, *Report BCRS-93-34*, Netherlands Remote Sensing Board, Delft, the Netherlands.

VAN DER KOOIJ, M.W.A., J. VOGELZANG, and C.J. CALKOEN, A simple analytical model for the modulation of sand waves in radar imagery, *Journal of Geophysical Research*, 100(C4), 7069-7082.

VOGELZANG, J. (1989), The mapping of bottom topography with imaging radar: a comparison of the hydrodynamic modulation in some existing models, *International Journal of Remote Sensing*, 10, pp. 1503-1518.