The use of ERS-1 SAR data to support bathymetric survey

G.H.F.M. Hesselmans, G.J. Wensink, C.J. Calkoen

DELFT HYDRAULICS
P. O. Box 152
8300 AD Emmeloord, the Netherlands

ABSTRACT

A model is presented to extract sea bottom depth information from radar images. This model is able to predict radar backscatter given the bottomtopography and the wind and flow conditions. Inversion of the model is obtained by a technique called data assimilation. The model has been applied in the coastal waters of the Netherlands and of Belgium. Results show that the technique can be used to obtain bathymetric maps with the same accuracy as traditional maps based on sounding data. Costs however are reduced considerably.

1. INTRODUCTION

Knowledge of the sea bottom topography is essential for activities such as shipping, fishing, dredging, offshore construction and pipeline laying, amongst other things. Assessment of the sea bottom topography with present state-of-the-art techniques (ship-based echosounders) may become relatively expensive and it is expected that a combination of traditional methods with remote sensing (RS) techniques may greatly reduce survey costs.

Methods of obtaining bathymetric information from remote sensing (RS) imagery have been developed at DELFT HYDRAULICS, with support from the Netherlands Remote Sensing Board (BCRS) and the European Union (EU). A great step forward has recently been taken in this field by the development of a so-called Bathymetry Assessment System which combines echosounding and Synthetic Aperture Radar (SAR) observations.

Demonstration projects using these rs-based methods have been carried out. The purpose of these demonstration projects is to show that the combined use of ERS-1 SAR and *in-situ* observations is more cost effective than only traditional bathymetric surveys.

Two examples will be presented. The first examples concerns the delta area of Zeeland in the south-west of the Netherlands and the second example concerns the laying of a pipeline from a Norwegian gas field to the Belgian town of Zeebrugge.

2. THEORY: BATHYMETRY ASSESSMENT SYSTEM

Under favourable meteorological and hydrodynamic conditions (moderate winds (3 to 5 m/s) and strong tidal currents), air- and space-borne Synthetic Aperture Radar (SAR) imagery shows features of the bottom topography of shallow seas (Alpers and Hennings 1984, Vogelzang et al., 1989). It is generally accepted that the imaging mechanism consists of three stages (a more detailed mathematical formulation is given in Calkoen et al., 1993): i.e.

(1) Interaction between (tidal) flow and bottom topography results in modulations in the (surface) flow velocity. This relation can be described by several models with an increasing level of complexity: continuity equation, shallow water equations, and the Navier Stokes equations.

(2) Modulations in surface flow velocity cause variations in the surface wave spectrum. This is modelled with the help of the action balance equation, using a relaxation source term to simulate the restoring forces of wind input and wave breaking.

(3) Variations in the surface wave spectrum cause modulations in the level of radar backscatter. To compute the backscatter variations a simple Bragg model can be used, but also available are two-scale and first iteration Kirchoff (Holliday) models.

Based on the above three stage mechanisms, a series of computer models has been developed at DELFT HYDRAULICS. Models with different levels of complexity and physical detail are available for each step. These models describe the flows, waves and electromagnetic scattering and can be used to interpret radar images.

The above package makes it possible to determine the radar backscatter given the depth. In order to invert this depth-radar backscatter relation, a data assimilation scheme has been developed, minimizing the difference between the predicted and the measured radar backscatter by adapting the bottom topography. The structure of this modular system is shown in **Fig. 1**. and explained below.

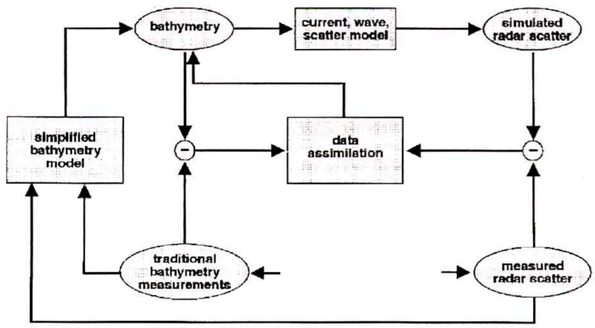

Figure 1 - Bathymetry Assessment System

3. IMPLEMENTATION

Based on the three step radar backscatter mechanism a modular model has been implemented. Each module corresponds with a step in the imaging mechanism: current model, short wave spectral model, and radar backscatter model. These models can be made with different levels of complexity. However, in general very sophisticated two- or even three-dimensional models are not required and simpler models can also be used. The physical processes in the areas considered in this paper are described by one-dimensional models and so the description of the Bathymetry Assessment System will be limited to these one dimensional models. The following sections describe the modules of the Bathymetry Assessment System:

Flow model

The flow model determines the surface current in two steps. Firstly, the mean flow over the total water column or depth-averaged flow is determined by means of the continuity equation. Based on the depth-averaged flow, wind speed and depth the surface flow is calculated by a dynamic flow profile model, allowing for the effects of Coriolis forces and turbulence.

Short wave spectral model

The roughness of the sea surface is described by the energy spectrum or equivalently the action spectrum. The action balance equation [Hasselmann 1960, Willebrand 1975] describes how the action spectrum is modified by wave propagation and the effects of wind input, dissipation and wave-wave interaction. The action balance equation is a partial differential equation, which can be reduced to an ordinary differential equation along a characteristic. The spectrum tends to evolve towards an equilibrium spectrum. The relaxation parameter depends on wind speed, wave velocity and surface current. For the equilibrium spectrum we take the Philips spectrum. The differential equation can be solved analytically and in order to obtain a solution on a discrete grid, we assume that the relaxation parameter is constant between two grid points.

Radar backscatter model

The radar backscatter is based on the Bragg mechanism. The radar backscatter is proportional to the wave energy at the Bragg wave number, which is of the same order as the radar wave number. The proportionality constant depends on the incidence angle, radar wave length and polarization. As for the bathymetry system only backscatter variations in the sar image are relevant, all radar measurements are preprocessed, subtracting empirically-obtained equilibrium values.

Data assimilation

The model train described above simulates the radar backscatter for a given bottom topography. The aim of the data assimilation scheme is to invert this relation and assess a reconstructed bottom topography, given the measured radar backscatter and *in situ* measurements such as soundings. This is achieved in two steps:

1) A first-guess bottom topography is obtained by inversion of a simplified version of the bathymetry model described above, which has been linearized around a best-guess working point. A smoothness condition is imposed in order to reduce the effect of speckle noise.

2) quadratic cost function is constructed from the difference between the measured and simulated SAR image and the difference between calibration and reconstructed depths. Minimization of this cost function yields the reconstructed bottom topography.

3 EXAMPLES

Zeeland

The province Zeeland is a delta area in the south-west of the Netherlands, which is of great public interest. After a large flood in 1953, a number of coastal defence constructions, called the "Delta Works" have been build. These works include stronger dikes, and the closure of tidal inlets by e.g. semi-permeable dams of the Eastern Schedt. Due to these human interventions, current conditions have changed dramatically. As a consequence sedimentation transport has changed and bottom topography is likely to change further in the next decades. Since a large part of the Netherlands is located below mean sea level, any change in bottom topography may change safety levels of the coastal defence works. Therefore, surveys are executed on a regular basis along the whole of the Dutch coast by governmental agencies. A depth based on linear interpolation of sounding data collected along the southern shores of the Netherlands is shown in **Fig. 2**.

For this project ERS-1 SAR data were used to determine the depth. It has to be stated that optical remote sensing data are almost useless due to the high turbidity levels of the coastal waters of the North Sea. The selected ERS 1 imagery was recorded on April 29, 1992. Selection was based on favourable hydro-meteorological conditions (large tidal currents, and wind speed between 2 and 5 Beaufort). The results of the analysis are shown in **Fig. 3**. The estimated bottom topography is in good agreement with the measured bottom topography. The rms depth error is 0.3 to 0.4 m. Some sounding data have been used to calibrate the model and to determine the large scale trends.

Zeebrugge

This project included the execution of detailed multi-beam bathymetric surveys in the southern North Sea to investigate sand wave activity and excavation effectivity for the ZEEPIPE DEVELOPMENT project (1991-1992). The ZEEPIPE DEVELOPMENT included the laying of several pipelines from a Norwegian gas field, including one to the Belgian town of Zeebrugge. The bottom topography of the area in question is characterized by numerous sand waves and bars which together with the strong regional tidal currents provide ideal conditions for the application of sar imagery for bathymetric purposes.

Bathymetric information is vital for the safe and proper routing of offshore pipelines. In general, offshore pipeline projects include five stages within which surveys are executed: reconnaissance survey, route survey, pre-lay survey, as-laid survey, and as-built survey.

The techniques presented in this project are meant to allow future users to design possible routes prior to the performance of the reconnaissance, route and pre-lay surveys.

For the reconnaissance phase, estimates of the sea bottom topography across large areas are required to select the most promising route. Usually, these estimates are based

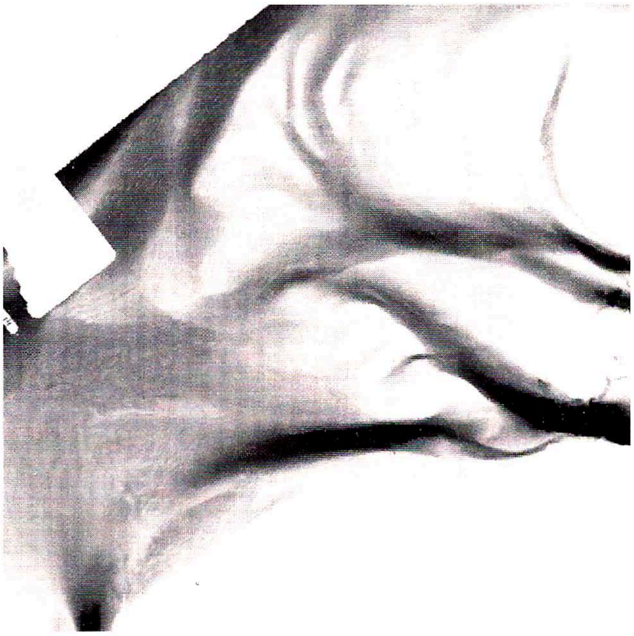

Figure 2 - Linear interpolated sounding data

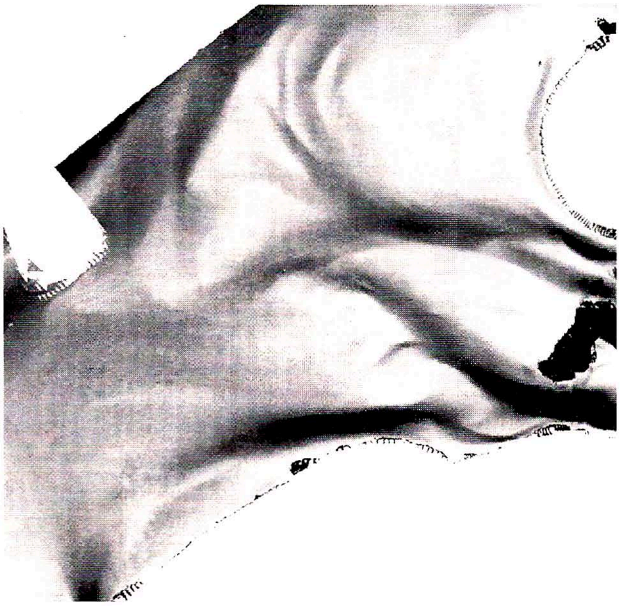

Figure 3 - SAR based bathymetric map. Depth ranges from 0 to 25.5 m

on existing data which may or may not be up-to-date. For the reconnaissance phase, a survey is generally performed along the most promising route. During the route survey phase, additional tracks are being investigated at offsets of a few hundred metres from the proposed route so as to verify the pipelay corridor and to optimize the pipeline track. In the pre-lay survey the selected track is surveyed generally ahead of the lay vessel to once again verify the lay corridor and possibly to assess any required dredging effort.

Reconnaissance survey

In the reconnaissance phase, sar imagery (see **Fig. 4**) and existing depth information from Admiralty Charts were used to provide depth estimates of an area covering about 50 km by 50 km. The Admiralty Chart data were used as boundary conditions by the Bathymetry Assessment System and the end result was the so-called pre-reconnaissance map. The Admiralty Chart data are less accurate than sounding data. Therefore, the weight of the depth difference in the data assimilation system was small relative to the weight of the radar backscatter difference. Effectively, the sar data provided the small-scale depth changes whereas the Admiralty data yielded the average depth and depth modulations.

The Admiralty Chart data were assumed to change only slightly in time and so, in a sense, the sar data were used either to confirm the existing data or to update them. The result was evaluated by comparing the depth estimate with the acquired sounding data along the pipeline track (see **Fig. 5**). The pre-reconnaissance map is clearly better than the Admiralty Chart data. The maximum difference as found near kp 800 was reduced from 11.22 m to 6.44 m. The root mean square error along the pipeline track was reduced from 2.14 m to 1.35 m (see also **Table 1**).

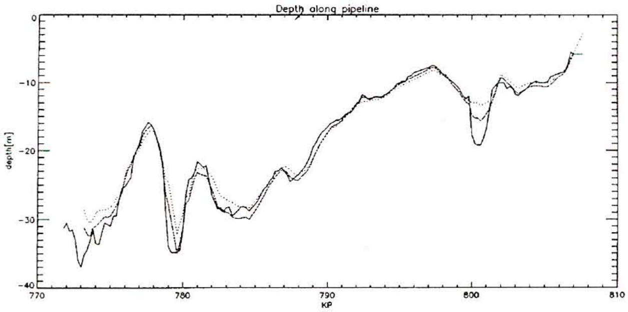

Figure 5 - Comparison of sounding data (solid), pre-reconnaissance depth map (dashed) and Admiralty Chart data (dots)

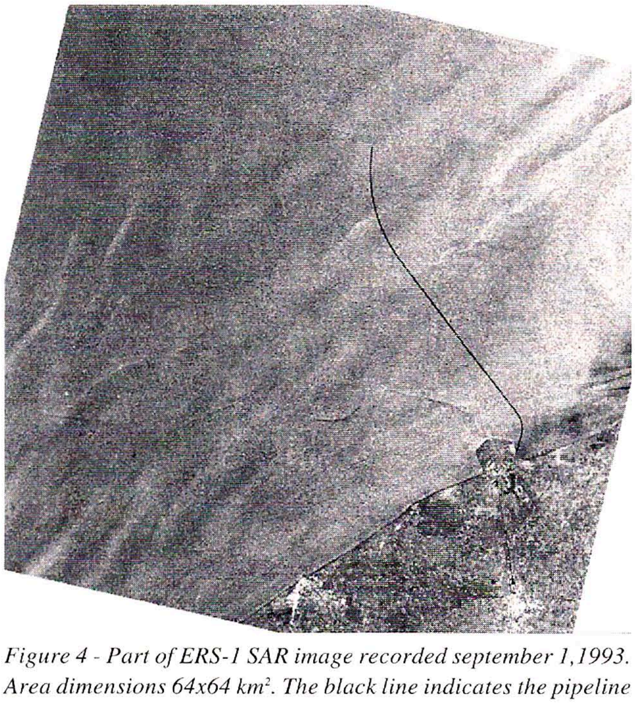

Figure 4 - Part of ERS-1 SAR image recorded september 1,1993. Area dimensions 64x64 km². The black line indicates the pipeline track

Route survey

Prior to the route survey, the single track reconnaissance survey become available and are also included in the boundary conditions of the Bathymetry Assessment System. The resulting depth map is the so-called pre-route map (see **Fig. 6**).

In a sense the survey data are extrapolated perpendicular to the track, the result was evaluated by comparing the depth estimates with existing multi-beam sounding data at a 100 m offset from the central track. The results show a bias of 0.0 m, and a root means square error of 0.39 m (see **also Table 1**). As the multibeam sounding data along the pipe line track were used for calibration, the pre-route depth map at the track equalled the measured depth. At large distances the effect of the sounding data will decrease and the errors are expected to be similar to those found in case of the pre-reconnaissance map.

Pre-lay survey

The distance between section lines measured during the route survey exceeds the beam width of the multi-beam echosounder used during the traditional survey. Therefore interpolation techniques are required to estimate depths between the sailed lines. This interpolation is achieved by including the route survey data in the boundary

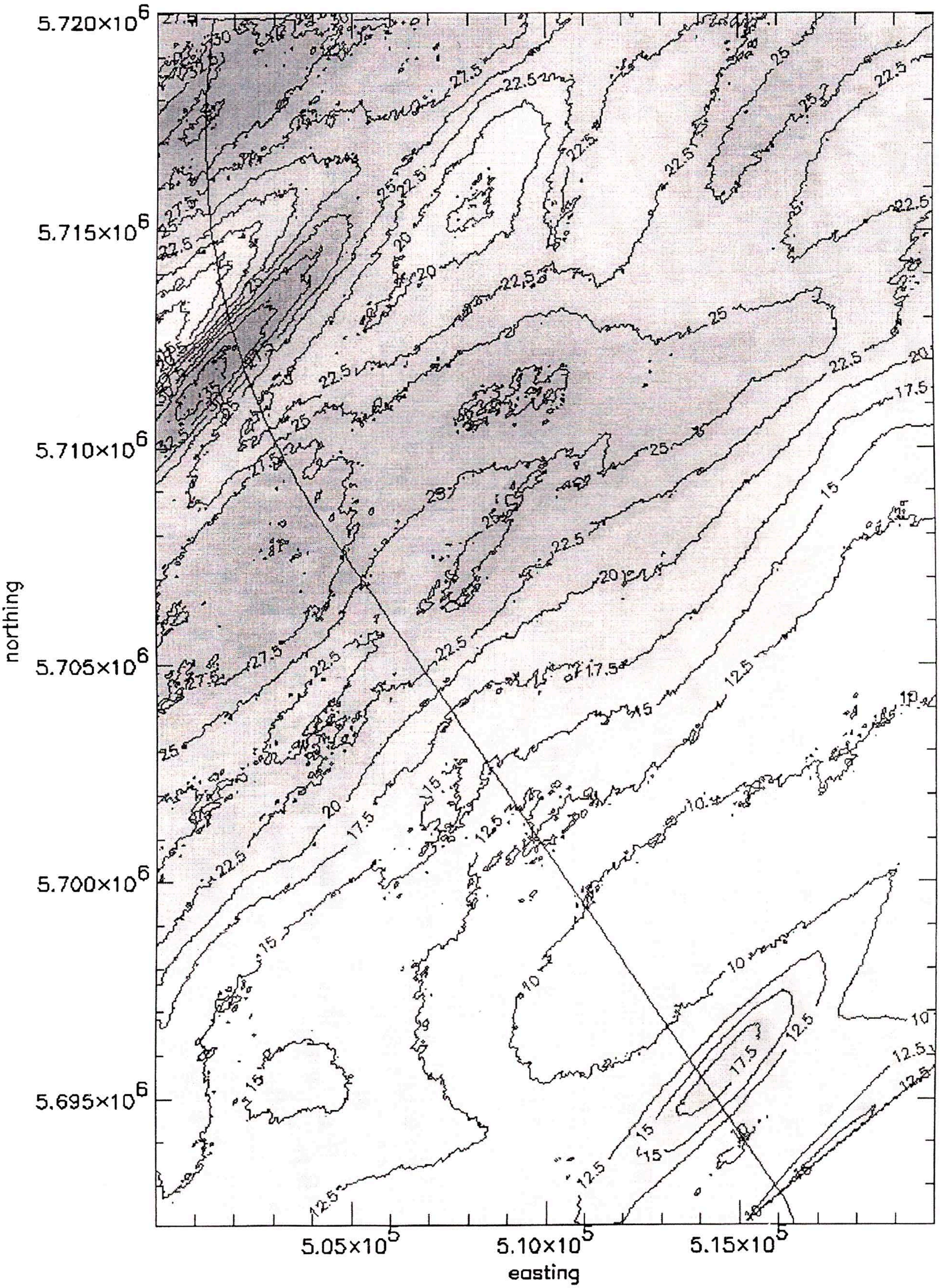

Figure 6 - Pre-route depth map of bottom topography. Coordinates defined within UTM system. Line segment indicates track of pipeline

conditions of the Bathymetry Assessment System. The quality of the interpolation was assessed by comparing results with measurements along the central track (see **Fig. 7**). As expected, errors are smaller than those found for the route survey. The pre-lay depth map uses data of section lines 200 m apart, whereas the pre-route depth map is based on a single sailed track.

To plan the consecutive stages, namely, reconnaissance, route and pre-lay survey, three maps have been made. These maps are based on existing data (such as Admiralty Charts), SAR imagery and sounding data acquired in the previous phase of the pipeline project. The accuracy of each map is determined by taking the difference between the calculated depth and the depth measurements obtained in the subsequent survey of the pipeline project. The accuracies of the maps are compiled in **Table 1**.

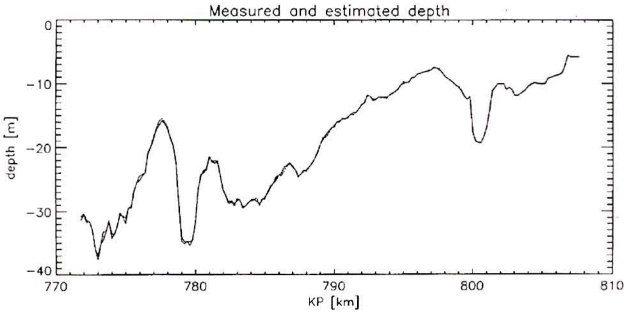

Figure 7 - Depth estimates along the pipeline track. solid: sounding data; dashed: estimated depth based on sar data

Table 1 - Comparison of depth maps and sounding data. Admiralty Chart data and pre-reconnaissance depth map are compared with sounding data at the pipeline track. Accuracy of the pre-route depth map is assessed at a 100 m from the track and the pre-lay depth map is based on section lines that lie at a distance of 200 m

	bias [cm]	rms [cm]	abs [cm]
Admiralty Chart data	75	214	127
Pre-reconnaissance depth map	49	135	90
Pre-route depth map	0	39	28
Pre-lay depth map	0	26	8

4. CONCLUSIONS

It is concluded that:

- ers-1 sar data can be used to construct bathymetric maps of shallow coastal waters, even in complex areas such as the delta in the south-west of the Netherlands.
- It is possible to construct up-to-date large-scale depth maps based on remote sensing data and existing Admiralty Chart data. For example, it was found that the maximum error in the pre-reconnaissance depth map was 4.78 m less than the maximum error in the Admiralty Chart. Based on such a map the reconnaissance survey can be optimized.
- Using the data from reconnaissance survey an improved pre-route depth map can be constructed by extrapolation. This may result in the generation of better alternatives for the route survey.
- Using the data from the route survey the depth map can be improved further by interpolation between section lines.
- Interpolation using sar data yields better results than those achievable by linear interpolation.
- Absolute accuracy achieved by combination of ERS-1 SAR and echosounding was of the order of 30 cm which is comparable to most industry-standard echosounders.

Therefore, it appears technically feasible to optimize survey effort using ERS-1 SAR imagery. In general the effect of ERS-1 SAR imagery on the accuracy of the depth assessment and the potential reduction in survey effort depends on the actual *in-situ* topography. The actual cost savings through the reduction of ship's soundings depend on the user requirements with respect to the desired depth accuracy and survey area.

REFERENCES

Alpers W. and Hennings I., A Theory of the Imaging of Underwater Bottom. Topography by Real and Synthetic Aperture Radar, *Journal of Geophysical Research*, Vol. 89, No. C6, pp 10,529-10,546, November 20, 1984.

Calkoen C.J., Kooi M.W.A. van der, Hesselmans G.H.F.M. and Wensink G.J., *The imaging of sea bottom topography with polarimetric P-, L-, and C-band SAR.* Report BCRS project 2.1/AO-02. Netherlands Remote Sensing Board. Delft 1993.

Hasselmann K., Grundgleichungen der Seegangsvorhersage, *Schiffstechnik*, 7, 191-195, 1960

Vogelzang J., Wensink G.J., de Loor G.P., Peters H.C. Pouwels,H. and van Gein, W.A., 1989, *Sea bottom topography with X-band SLAR*, BCRS report, BCRS-89-25.

Willebrand J., Energy transport in a nonlinear and inhomogeneous random gravity wave field. *Journal of Fluid Mechanics*, 70, 113-126, 1975.