Land/water detection with polarimetric SAR
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Abstract

Knowledge of the geographic position of the waterline, i.e. the transition from water to land, has many applications, in particular related to the study of coastal morphology. The land/water boundary in Dutch estuaries like Waddenzee and Westerschelde is complex and dynamic.

The land/water boundary can be used as additional information to echo-soundings when charting the seabed elevation of the intertidal zone. This is currently monitored by merging echo soundings above sea and airborne laser altimetry measurements above land to generate a Digital Elevation Model (DEM). A series of land/water contour lines might be used to extract a DEM.

An other application is to use the land/water boundary in the Bathymetry Assessment System (BAS). The BAS, developed by ARGOSS to chart the depths of shallow seas in the intertidal zone, generates depth maps from radar images and a limited number of echo soundings in an efficient way. In BAS the land must be masked. A better horizontal accuracy in the land/water boundary will yield a more accurate BAS depth map.

Radar images seem most promising for such an application due to the cloudy conditions in the Netherlands. In the past, detection of the land/water boundary from SAR observations with the ERS satellites was not satisfactory. As ENVISAT offers polarimetric data and thus more than one channel, it allows to detect the waterline with a per-pixel algorithm, using the most contrasting combination of polarimetric channels. This would mean that the horizontal accuracy with which the waterline is determined is not deteriorated like with extracting the waterline by computing the SAR coherence over a number of pixels.

In this project, cofunded by the National User Support Programme Earth Observation (Nationaal Programma Gebruikersondersteuning Aardobservatie, GO), a classification algorithm is developed and applied on images with a variety of polarimetric modes and incidence angles. The images are acquired based on a theoretical and literature survey. The detected land/water boundary is used in the BAS and compared to previous results. Conclusions are drawn with respect to the best polarimetric channels and incidence angles, the geocoding accuracy and the accuracy and applicability of this land/water boundary determination method.
Kennis van de geografische positie van de waterlijn, dat wil zeggen de overgang van water naar land, heeft veel toepassingen, met name gerelateerd aan de studie van kustmorfologie. De land/waterscheiding in Nederlandse estuaria als de Waddenzee en de Westerschelde is complex en dynamisch.

De land/waterscheiding kan worden gebruikt als extra informatie naast echoladingen bij het karteren van de zeebodemhoogte in het intergetijdegebied. In het algemeen zijn dergelijke gebieden moeilijk te karteren met lodingen omdat daarvoor het meetschip voldoende waterhoogte nodig heeft. Deze gebieden worden momenteel in kaart gebracht door echoladingen op het water samen te voegen met vliegtuig-laseraltimetrie boven het land tot een digitaal hoogtemodel (DEM) van het interessegebied.

Een DEM zou kunnen worden vervaardigd uit een reeks van land/watercontourlijnen. Zo kan de detectie van de land/waterscheiding bijdragen tot de studie van de morfologie van ondiepe wateren.


Radarbeelden lijken voor een dergelijke toepassing het meest veelbelovend, gezien de vele bewolking boven Nederland. In het verleden is detectie van de land/waterscheiding met SAR-beelden van de ERS-satellieten niet bevredigend gebleken. Omdat ENVISAT polarmetrische data biedt en dus meer dan één kanaal, maakt het detectie van de waterlijn mogelijk met een algorithme op pixelliveau, waarbij de combinatie van polarmetrische kanalen kan worden gebruikt die het grootste contrast oplevert. Dit zou betekenen dat de horizontale precisie van de bepaling van de waterlijn niet zou worden aangetast door de berekening van de SAR-coherentie over een aantal naburige pixels.

In het project is een classificatiealgoritme ontwikkeld, dat is toegepast op beelden met verschillende polarmetrische modi en invalshoeken.

Het project leed onder een gebrek aan geleverde beelden, maar niettemin kon worden geconcludeerd dat polarmetrische verschilbeelden te veel spikkelruis bevatten om te kunnen gebruiken.
voor land/waterscheidendetectie. We concluderen dat het grote voordeel van ENVISAT ten opzichte van ERS niet zozeer zijn polarimetriscle vermogens zijn, maar dat hij grotere en kleinere invalshoeken biedt. Grote invalshoeken (richting 45°) tonen een groter contrast tussen land en water laten zien, net als de kleinere invalshoeken (richting 15°).

Het kruis-polarisatiekanaal (bijv. HV) biedt geen voordeel boven de co-polarisatiekanalen HH en VV. Het land/watercontrast voor HV is weliswaar minder afhankelijk van de invalshoek, maar het contrast van VV voor grotere invalshoeken is groter dan dat van HV en het contrast van HH is zelfs nog groter.

Het waterlijn-extractiealgoritme dat in deze studie is ontwikkeld, is gebaseerd op een classificatieprocedure en heeft een horizontale precisie van 30–70 m. Ongeveer 30 m van deze fout kan worden toegerekend aan de geocoderingsfout. Voor gebieden met een groot land/watercontrast, bijvoorbeeld scherp gedefinieerde kustlijnen, kan een horizontale precisie van 30 m worden verkregen. Een precisie van 70 m wordt verkregen voor gladde oppervlakken met een laag land/watercontrast.

Voor het testgebied in de Westerschelde laten de bepaalde waterlijnen een fout in hoogte zien van ongeveer 1 meter vergeleken met echolodingsdata. Deze fout van omstreeks 1 meter is te groot om de waterlijnen te kunnen gebruiken als aanvullende calibratiedata in het BAS. Ook voor andere toepassingen, zoals de berekening van een DEM voor het intergetijdegebied, is de bepaalde land/waterscheiding te onnauwkeurig.

De precisie waarmee de beelden gegeocodeerd worden is van cruciaal belang voor de bepaling van de waterlijn. Met recht-toe-recht-aan-algoritmes zoals gebruikt in dit rapport is de precisie typisch in de orde van 2 pixels. Met beeld-op-beeld-coregistratie kan een subpixelprecisie worden verkregen, hoewel het lastig kan zijn deze techniek toe te passen op beelden die nauwelijks land bevatten. Veelbelovender op dit punt zijn toekomstige hogeresolutie-SAR-satellieten als Radarsat 2. Deze satellieten zouden ook kunnen leiden tot de herintroductie van het concept van interferometrische kustlijn kartering door gebruikmaking van de complexe coherentie.
Knowledge of the geographic position of the waterline, i.e. the transition from water to land, has many applications, in particular related to the study of coastal morphology. The land/water boundary in Dutch estuaries like Waddenzee and Westerschelde is complex and dynamic.

The land/water boundary can be used as additional information to echo-soundings when charting the seabed elevation of the intertidal zone. Such areas are generally hard to survey with echo-sounding equipment as this requires sufficient depth for the survey vessel to pass. Presently, they are monitored by merging echo soundings above sea and airborne laser altimetry measurements above land to generate a Digital Elevation Model (DEM) of the area of interest.

A DEM may be extracted from a series of land/water contour lines. In this way detection of the land/water boundary can contribute to the study of the morphology of shallow waters.

An other application is to use the land/water boundary in the Bathymetry Assessment System (BAS). The BAS, developed by ARGOSS to chart the depths of shallow seas in the intertidal zone, generates depth maps from radar images and a limited number of echo soundings in an efficient way. In BAS the land must be masked. A better horizontal accuracy in the land/water boundary will yield a more accurate BAS depth map.

Radar images seem most promising for such an application in the Netherlands due to the cloudy conditions here. In the past, detection of the land/water boundary from SAR observations with the ERS satellites was not satisfactory. As ENVISAT offers polarimetric data and thus more than one channel, it allows to detect the waterline with a per-pixel algorithm, using the most contrasting combination of polarimetric channels. This would mean that the horizontal accuracy with which the waterline is determined is not deteriorated like with extracting the waterline by computing the SAR coherence over a number of pixels.

In the project a classification algorithm was developed and applied on images with a variety of polarimetric modes and incidence angles.

The project suffered from a lack of delivered images, but nevertheless it could be concluded that polarimetric differences (e.g., HH–VV) contain too much speckle to use for land/water boundary detection. We conclude that the main advantage of the ENVISAT ASAR over ERS is not its polarimetric capability, but that it offers larger and smaller incidence angles. Large incidence angles (near 45°) show a larger
contrast between land and water, as the small incidence angles (near 15º) do.

The cross-polarisation channel (e.g., HV) does not provide an advantage over the co-polarisation channels HH and VV. The land/water contrast of HV is less dependent on the incidence angle, but the contrast of VV for large incidence angles is larger than that of HV and the contrast of HH is even larger.

The waterline extraction algorithm developed in this study is based on a classification procedure and has a horizontal accuracy of 30–70 m. About 30 m of this error can be attributed to geocoding error. A horizontal accuracy of 30 m can be obtained for large land/water contrast, i.e. along sharply defined coastlines. An accuracy of 70 m is obtained for smooth surfaces which have low land/water contrast.

For a test area in the Westerschelde, the extracted waterlines show an error of about 1 m in depth when compared with sounding data. This error of about 1 m is too large for the waterlines to be used as additional calibration data for depth charting with BAS. Also for other purposes, like the computation of a DEM of the intertidal zone, the detected land/water boundary is too inaccurate.

The accuracy with which the images are geocoded is of crucial importance to successfully determine the waterline. With straightforward algorithms like the one used in this report this accuracy is typically of the order of 2 pixels. With image to image co-registration a subpixel accuracy may be obtained, although it may be difficult to apply this technique in images that hardly contain any land. More promising in this respect are future high resolution SAR satellites like Radarsat 2. These satellites may also reintroduce the concept of interferometric shoreline mapping using the complex coherence.
Acknowledgement

We would like to thank Jur Vogelzang and Jos Groot for performing the simulations and the literature survey which are included in this report as appendix C.
1 Introduction

1.1 Background

Knowledge of the geographic position of the waterline, i.e. the transition from water to land, has many applications. Many of these applications are related to the study of coastal morphology, either by human interference or by nature itself. The land/water boundary in Dutch estuaries like Waddenzee and Westerschelde is complex and dynamic.

A somewhat challenging application of detection of the land/water boundary is to use it as additional information to echo-soundings when charting the seabed elevation of the intertidal zone. Such areas are generally hard to survey with echo-sounding equipment as this requires sufficient depth for the survey vessel to pass. Hence, these areas can only be surveyed at around high tide, if ever. Presently, they are monitored by merging echo soundings above sea and airborne laser altimetry measurements above land to generate a Digital Elevation Model (DEM) of the area of interest.

A DEM may be extracted from a series of land/water contour lines. In this way detection of the land/water boundary can contribute to the study of the morphology of shallow waters.

Another application is to use the land/water boundary in the Bathymetry Assessment System (BAS). The BAS, developed by ARGOSS to chart the depths of shallow seas in the intertidal zone, generates depth maps from radar images and a limited number of echo soundings. With the BAS, monitoring of the depth in estuaries and shallow seas can be performed more efficiently. Over the last three years enormous progress has been made in the further development of BAS for complex coastal areas like the Waddenzee (c.f. Swart et al., Towards implementation of the BAS within Rijkswaterstaat, and Swart, Kleine kroniek van het BAS). In shallow areas, the BAS needs to separate land pixels from water pixels for proper processing of the radar image.

1.2 Problem definition

Direct detection of the land/water boundary would be very helpful for refining the DEM of the intertidal zone.

For use in BAS, the land must be masked. As shoals generally have small slopes, a small vertical error in the DEM or the measured water level may result in considerable horizontal uncertainty in the land/water boundary. To keep on the safe side, a (too) large area must be masked.
as land, thus generating an unnecessary large gap between the BAS depth map and the radaraltimeter height chart. With a known water level, the land/water level also gives a height contour line which may be incorporated in the BAS as extra depth information.

Radar images seem most promising for such an application in the Netherlands due to the cloudy conditions here. In the past, a number of studies have aimed to extract the land/water boundary from satellite observations. The results so far were not satisfactory. Koopmans & Wang (ERSWAD project, NRSP-2 95-20) tried to classify land and water using pixel intensity. However, these intensities are highly variable and this method has limited applicability. Van Koppen et al. (Interferometric shoreline mapping, USP-2 99-24) tried to distinguish between land and water using the coherence between SAR images. As coherence is a non-local quantity, this method has poor resolution.

In this study, Synthetic Aperture Radar data of the ENVISAT remote sensing satellite have been used. Although optical data may be used for this purpose as well, we have concentrated on SAR data for the reason that the novelty of ENVISAT compared to ERS-1 and ERS-2 is that it delivers polarimetric data. Hence, besides the vertical polarization channel VV of the ERS satellites, the horizontal polarization HH and the cross polarization HV can be studied as well. More importantly, combinations of polarimetric channels can be investigated for waterline extraction from SAR. The main advantage of using polarimetric data would be that having more than one channel allows to detect the waterline with a per-pixel algorithm. This would mean that the horizontal accuracy with which the waterline is determined is not deteriorated like with extracting the waterline by computing the SAR coherence over a number of pixels.

While previous results with airborne polarimetric SAR indicate the suitability of ASAR, the method must still be verified and clearly demonstrated. In particular, the following questions will be answered in this project:

* which polarimetric channels are suitable / optimal (HH/VV, HV/VV, HV/HH);
* which ASAR modes are suitable with respect to incidence angles;
* which basic SAR processing is suitable / optimal, e.g. number of looks of the multi-look image;
* which classification algorithm is optimal;
* how well does this coast line extraction work in conjunction with BAS;
* what is the accuracy and reliability of the detection.

The project was accepted for funding in the National User Support Programme Earth Observation (Nationaal Programma Gebruikersondersteuning Aardobservatie, GO).
1.3 Approach

The project starts with theoretic predictions of the radar backscatter of land and water, as may be expected in SAR imagery. These predictions are derived from model simulations and from a literature survey (chapter 2).

Based on the expected contrast between the backscatter of land and water (which enables the two to be separated and the waterline to be detected), a number of ENVISAT ASAR (Advance SAR) are ordered. Within the Announcement of Opportunity proposal AO-376, a total number of about 20 ASAR images would become available. At the start of the project, we proposed to order and study all images, to use both SLC and PRI images and to generate a different multi-look product for each type of image. The two-channel SAR images, HH/VV and HV/VV, would then be compared with land/water maps, resulting in a choice for a classification algorithm. Because the delivery of the ordered images was problematic, to say the least, we concentrated on a few images ordered via a private company. The accuracy will be assessed, and the best channel combination, radar mode / incidence angle, and multi-look product will be identified.

An algorithm was developed to extract the waterline. The algorithm is discussed in chapter 3.

The area of study was ‘vak 4’ in the Westerschelde, because in a previous project that aimed at comparing bathymetric data acquisition methods (cf. Wiegmann et al., Opnametechnieken vaklodingen), the BAS-processing has already been done and therefore the data was already available. Moreover, a comparison could be made between the BAS results of that project and the current project incorporating the land-water boundary. In chapter 4, the extracted waterlines are used as depth information (calibration data) by the BAS software.

Conclusions on the usefulness of the extracted waterlines from SAR as depth information for charting bathymetry are given in chapter 5.

A short review of the problems and successes of the project and team is given in chapter 6.
2 Land/water contrast in polarimetric SAR imagery

2.1 Introduction

The main purpose of this chapter is to give theoretic predictions of the land/water contrast that may be expected in SAR imagery. These predictions are derived from model simulations and from a literature survey. The radar backscatter ($\sigma_0$) of the sea surface was simulated using the Romeiser-Alpers-Wismann model [Romeiser et al., 1997], whereas that of land is mainly based on the model of [Dubois et al., 1995]. Details on the simulations and literature survey can be found in appendix C. The idea behind the theoretic predictions of land/water contrast is to select about 30 SAR images of varying polarization and incidence angle for this study. In that way, it was hoped to collect an ideal set of images to optimally extract the waterline. Disappointingly, only 3 images were delivered by ESA as part of the ESA Announcement of Opportunity. Six more images were available for the Westerschelde area, which we had to order through commercial channels. Hence, a total of nine images could be evaluated for waterline extraction, which is not much because favourable conditions for a large land/water contrast may depend strongly on the incidence angle and on the weather. Still, as will be motivated in this chapter, the data set contains a number of images that are suitable for extracting the waterline in the Westerschelde.

2.2 Theoretic predictions of land/water contrast

To obtain an idea which polarimetric channels give sufficient land/water contrast to successfully extract the waterline, radar backscatter of land was simulated under varying conditions for soil moisture and soil roughness with the model of [Dubois et al., 1995], whereas radar backscatter of water was simulated with the model of [Romeiser et al., 1997] for various wind speeds. Where needed, the simulations were supported by a literature survey, e.g. for the cross-polarisation channel (e.g., HV) and for incidence angles for which the Dubois model is not valid. Below, the most important conclusions of the simulation results are given, whereas details of the simulations and the literature survey may be found in appendix C.

The most important result of the simulations and literature survey are summarized in figure 2.1. This figure shows the simulated (predicted) radar backscatter for the sea (wind speed of 5 m/s upwind), for a smooth land surface consisting mainly of sand ($0.4$ cm roughness, $29\%$ volumetric moisture, soil composition: $80\%$ sand, $10\%$ clay, $10\%$ silt) and for a rough land surface consisting mainly of sand ($3$ cm roughness, $29\%$ volumetric moisture, soil composition: $80\%$ sand, $10\%$ clay, $10\%$ silt). Backscatter of the sea is given by the blue lines,
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Figure 2.1: Predicted radar backscatter for the sea (wind speed of 5 m/s upwind) and for a smooth land surface (0.4 cm roughness, 29% volumetric moisture, soil composition: 80% sand, 10% clay, 10% silt) and a rough land surface (3 cm roughness, 29% volumetric moisture, soil composition: 80% sand, 10% clay, 10% silt). Backscatter of the sea is given by the blue lines, backscatter of smooth land by the green lines and backscatter of rough land by the red lines. Solid lines represent HH, dashed lines HV and dotted lines VV.

1. The radar backscatter of soil mainly depends on surface roughness and to a lesser extent on moisture. If the roughness is increased from 0.4 cm (very smooth land surface) to 3 cm (rough land surface), the backscatter increased by 5–10 dB for all polarimetric channels. In contrast, if the moisture is increased from 10% to 50% (soaking wet), the backscatter increased by a mere 2 dB.

2. For land of specific roughness and moisture, the backscatter varies by about 3 dB at most if the incidence angle is increased (red and green curves in figure 2.1). Backscatter of the sea on the other hand decreases by 10–20 dB if the incidence angle is increased from 15° to 45°. HH and VV backscatter of a rough land surface are about 10 dB smaller than that of the sea at 15° incidence, equal to that of the sea at about 25° incidence and about 10–15 dB larger than that of...
the sea at 45º incidence. HH and VV backscatter of a smooth land surface are about 15 dB smaller than that of the sea at 15º incidence, equal to that of the sea at about 30º -35º incidence and about 2–4 dB larger than that of the sea at 45º incidence. HV backscatter of a rough land surface is about 10–15 dB larger than that of sea at all incidences and HV backscatter of a smooth land surface is about 3–10 dB larger than that of sea at all incidences. With HV, the contrast slightly increases with incidence angle.

This leads to the important conclusion that if rough land surfaces are expected, large incidences of 45º are preferred which give a contrast relative to sea of 10–15 dB for HH and VV. If smooth land surfaces are expected, small incidences of 15º are preferred which give a contrast relative to sea of −15 dB for HH and VV. With HV, large incidences are preferred to obtain good contrast.

3. In general, for the differences between the polarimetric channels values have been found for land of HH–VV = −5 dB, HH–HV = 10 dB and VV– HV = 10–15 dB. For sea these differences are HH–VV = −5 dB, HH–HV = 15 dB and VV–HV = 15 dB. These means that all the polarimetric differences are less than 5 dB. With regard to the number of looks of 2 (appendix B), the speckle in the SAR images of Alternating Polarization mode and hence in the polarimetric differences is significant. This means that the differences of polarimetric channels are less useful to separate land from water than the channels themselves (10–15 dB difference between land and water as explained above).

4. Wind increases the roughness of the sea and hence the backscatter. Compared to the wind direction of 0º relative to the SAR’s looking direction (upwind) a wind direction of 90º (crosswind) has no significant effect on the backscatter, i.e. about 1–2 dB less. The magnitude of the wind speed, however, has a major effect on the backscatter of all polarimetric channels. If the wind speed is increased from 3 m/s (light breeze) to 15 m/s (gale), the backscatter increases by as much as 10–15 dB. Figure 2.1 has been computed for a wind speed of 5 m/s. For strong winds, the figure and the above discussions may have to be adapted. However, a wind speed of 5 m/s seems quite common in the Netherlands [KNMI, 2006], so that figure 2.1 is useful to explain most of the SAR imagery in this study.

Based on the above discussion it may be concluded that in general the best land/water contrast is obtained at the largest incidence angles of ASAR of 45º. For those incidences, the backscatter of land will ideally be about 10–15 dB larger than that of sea for moderate wind speeds and moderate soil roughness. Note that small incidence angles of 15º may be preferred to separate water from very smooth land surfaces in which case the land/water contrast is reversed, i.e. the backscatter of land now being 15 dB below that of sea in case of HH and VV. However, because the first swath position of ASAR has an incidence range of 15º–23º and the HH and VV backscatter of the sea surface rapidly declines with incidence angle (solid and dotted blue curves in figure 2.1), this contrast for smooth surfaces may only be provided for a relatively small part of the image.
2.3 Acquired SAR images

For this study, ASAR images were obtained as part of an ESA Announcement of Opportunity in which RWS/AGI is involved. Although RWS/AGI were entitled to about 30 image acquisitions, only three image acquisitions were received (image acquisitions 8-9 in table 2.1) in 2004. After a couple of months, no more image acquisitions were received on request, mainly because of conflicts with programming the ENVISAT satellite. Therefore, we decided to order additional images from historical archives through commercial channels. In total six extra image acquisitions were available that were acquired by ENVISAT over the Westerschelde. Three of these image acquisitions are in Alternating Polarization mode (images 1–3 in table 2.1), while the three other image acquisitions are in Image mode (images 4–6). Image acquisitions 1–3 were the only images of the Westerschelde that ENVISAT had acquired in Alternating Polarization mode since its launch. Image acquisitions 1–3 were the only images acquired in Image mode in swath position IS1 (see appendix B, table B.2), which is needed to obtain good land/water contrast, as explained in the previous section.

In figure 2.2 the SAR images are shown in dB units of the radar backscatter $\sigma_0$. The backscatter in each pixel is obtained by applying the calibration constant in the ASAR header files to the data as explained in [Rosich and Meadows, 2004]:

$$\sigma_0 = \frac{DN^2 \sin I}{K},$$ (2.1)

where $K$ is the calibration constant, $I$ is the incidence angle (taken constant over the scene) and $DN$ is the pixel's digital number provided in the data file.

Generally, the backscatter of land and sea in the images in figure 2.2 can well be explained with figure 2.1, as the daily mean wind speed on the acquisition days is 4–6 m/s, similar to the wind speed of 5 m/s for which figure 2.1 was computed. For instance, image acquisitions 1–3 were acquired with small incidence angles of 15°–23°. Hence, for these images, the HH and VV backscatter of sea exceeds that of land, except for image acquisition 3. In case of image acquisition 3, the HH and VV backscatter of sea is below that of land, which is most likely because of heavy rainfall as can be seen in the last column of table 2.1. A total of 15.6 mm rain was collected that day in Vlissingen. As heavy rainfall increases moisture in the top soil this may well explain the larger than expected HH and VV backscatter of land for image acquisition 3.

Note from figure 2.2c that the HV contrast between land and water is only about 5 dB. According to figure 2.1 this means that most of the land areas have a rather smooth surface.

Note that the land/water contrast of HH and VV of image acquisitions 1 and 2 is relatively small. One reason is that part of these images have
a range of incidence angles of 15°–23°, where the contrast becomes less for larger incidence (figure 2.2). Another reason could be that the wind speed at the time of acquisition may have exceeded the daily mean.

With regard to images 4–6, note the very small land/water contrast of the VV channel for these images. Figure 2.1 shows (solid red and blue curves) that the incidence angle of these images is exactly in the range where backscatter of land and sea are about equal.

Finally, as anticipated from figure 2.1 image acquisitions 7–9 have good land/water contrast in HH and VV because of the large incidence angle. In these images, the land/water contrast of the HH channel is slightly larger than that of VV, as was also predicted by figure 2.1 (compare solid red curve with solid and dotted blue curves). Obviously, image acquisitions 7–9 are the most suitable for waterline extraction.

Table 2.1: Acquired SAR imagery for this study. Incidence angle is in degrees. Meteorological data are from the Vlissingen weather station. Wind speed is in m/s and wind direction is in degrees, clockwise relative to north. Daily precipitation is in mm.

<table>
<thead>
<tr>
<th>Image acquisition</th>
<th>Date, time of day</th>
<th>Incidence angle (swath position)</th>
<th>Polarization</th>
<th>Wind speed (direction)</th>
<th>Daily precipitation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>15/02/2003, 10:13</td>
<td>15 – 23 (IS1)</td>
<td>HH/HV</td>
<td>6.2 (59)</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>22/03/2003, 10:13</td>
<td>15 – 23 (IS1)</td>
<td>VV/HV</td>
<td>5.0 (87)</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>26/04/2003, 10:13</td>
<td>15 – 23 (IS1)</td>
<td>VV/HH</td>
<td>4.8 (225)</td>
<td>16</td>
</tr>
<tr>
<td>4</td>
<td>07/02/2003, 10:08</td>
<td>19 – 27 (IS2)</td>
<td>VV</td>
<td>5.0 (217)</td>
<td>1</td>
</tr>
<tr>
<td>5</td>
<td>06/08/2003, 10:08</td>
<td>19 – 27 (IS2)</td>
<td>VV</td>
<td>3.8 (92)</td>
<td>0</td>
</tr>
<tr>
<td>6</td>
<td>10/09/2003, 10:08</td>
<td>19 – 27 (IS2)</td>
<td>VV</td>
<td>6.3 (242)</td>
<td>9</td>
</tr>
<tr>
<td>7</td>
<td>12/08/2004, 21:39</td>
<td>43 – 45 (IS7)</td>
<td>HH/VV</td>
<td>5.9 (173)</td>
<td>7</td>
</tr>
<tr>
<td>8</td>
<td>28/08/2004, 21:36</td>
<td>39 – 43 (IS6)</td>
<td>HH/VV</td>
<td>3.2 (297)</td>
<td>0</td>
</tr>
<tr>
<td>9</td>
<td>16/09/2004, 21:39</td>
<td>43 – 45 (IS7)</td>
<td>HH/VV</td>
<td>4.0 (213)</td>
<td>0</td>
</tr>
</tbody>
</table>
Figure 2.2a: HH backscatter (dB) of image acquisition 1 (15/02/2003).

Figure 2.2b: HV backscatter (dB) of image acquisition 1 (15/02/2003).
Figure 2.2c: HV backscatter (dB) of image acquisition 2 (22/03/2003).

Figure 2.2d: VV backscatter (dB) of image acquisition 2 (22/03/2003).
Figure 2.2e: HH backscatter (dB) of image acquisition 3 (22/03/2003).

Figure 2.2f: VV backscatter (dB) of image acquisition 3 (22/03/2003).
Figure 2.2g: VV backscatter (dB) of image acquisition 4 (07/02/2003).

Figure 2.2h: VV backscatter (dB) of image acquisition 5 (06/08/2003).
Figure 2.2i: VV backscatter (dB) of image acquisition 6 (10/09/2003).

Figure 2.2j: HH backscatter (dB) of image acquisition 7 (12/08/2004).
Figure 2.2k: VV backscatter (dB) of image acquisition 7 (12/08/2004).

Figure 2.2l: HH backscatter (dB) of image acquisition 8 (28/08/2004).
Figure 2.2m: VV backscatter (dB) of image acquisition 8 (28/08/2004).

Figure 2.2n: HH backscatter (dB) of image acquisition 9 (16/09/2004).
Figure 2.2o: VV backscatter (dB) of image acquisition 9 (16/09/2004).
3 Waterline extraction from ENVISAT SAR images

3.1 Introduction

As explained in this chapter, the method to extract the waterlines from the SAR image acquisitions consists of two steps. The first step is to assign geographic coordinates to the SAR image pixels, so that the images can be used in BAS and other applications. The assignment of these coordinates is known as geocoding and the geocoding algorithm developed in this study is discussed in section 3.2. In the second step, the geocoded SAR images are ingested by a waterline extraction algorithm. The algorithm that has been developed (section 3.3) uses all available polarimetric channels of the image acquisition, i.e. one in case of Image mode and two in case of Alternating Polarization mode. Finally, in section 3.4, the accuracy with which the waterline can be extracted is assessed and discussed.

3.2 Geocoding of SAR images

For the waterlines extracted from the SAR images to be used in BAS, geographic coordinates have to be assigned to the image pixels. The assignment of these coordinates is known as geocoding and relies on a transformation between the SAR image coordinates of a point and the ground coordinates of this point in a reference frame attached to the earth. In this study, a backward geocoding algorithm has been developed that for each point in a grid on the earth’s surface looks for the corresponding point in the SAR image. This section briefly explains the geocoding algorithm that has been developed.

With backward geocoding, a map projection grid in UTM (Universal Transverse Mercator) coordinates, i.e. Easting and Northing, is set up. For each point in the grid, Easting and Northing are transformed to ground coordinates \( \vec{r} = (x,y,z) \) in an earth-fixed reference frame. These ground coordinates can be transformed to the corresponding SAR image coordinates if auxiliary information of the satellite platform is available as explained below. By copying the pixel’s backscatter value at the image coordinates to the map projection coordinates, the procedure is completed. Doing this for all points in the map projection grid, the land/water mask is geocoded.

If we denote the satellite’s position and velocity in an earth-fixed reference frame by \( \vec{r}_s \) and \( \vec{v}_s \), respectively, whereas the target point in the map projection grid has ground coordinates \( \vec{r} \) on a flat earth (approximated by an ellipsoid) as shown in figure 3.1, the fundamental equations that relate the ground and image coordinates are the range and Doppler equation [Curlander, 1982]:
\[ R = |\vec{r}_s - \vec{r}_i| \]

\[ f_D = -\frac{2}{\lambda R} \vec{v} \cdot (\vec{r}_s - \vec{r}_i) \]

(3.1)

where \( R \) is the slant range distance, \( f_D \) is the Doppler frequency and \( \lambda \) is the radar wavelength. The satellite orbit is modeled by a number of state vectors, i.e. position and velocity, at equidistant epochs along the acquired SAR image, or in our case the land/water mask derived from the SAR image. If the times of the first and last azimuth positions of the image, \( T_{\text{start}} \) and \( T_{\text{end}} \), are known and similarly the slant range distances of the SAR image at near range and at far range, \( R_{\text{near}} \) and \( R_{\text{far}} \), the problem that remains is to determine the time at which the target point was imaged. Hence, with the aid of equation (3.1), the orbit is searched for the satellite position and velocity that give the value of \( f_D \) that was used in the SAR processing. For all ENVISAT SAR images used in this study \( f_D \) has a value of zero (zero Doppler processing). Assuming a linear approximation of the Doppler curve in between two satellite states, the time of imaging \( t \) is found by linear interpolation in between the two consecutive orbit states with epochs \( t_i \) and \( t_{i+1} \) and Doppler frequencies \( f_i \) and \( f_{i+1} \) that obey the relation that \( f_i > f_D \) and \( f_{i+1} < f_D \):

\[ t = t_i + \frac{f_D - f_i}{f_{i+1} - f_i} (t_{i+1} - t_i) \]

(3.2)

Assuming a constant satellite velocity along the orbit, the azimuth pixel coordinate \( i_{Az} \) in the image corresponding with \( t \) is:

\[ i_{Az} = \frac{t - T_{\text{start}}}{T_{\text{end}} - T_{\text{start}}} np_{Az} \]

(3.3)

where \( np_{Az} \) is the number of image pixels in azimuth direction. With the use of equation (3.1), the interpolated satellite position at time \( t \) determines the slant range pixel coordinate \( i_R \) in the image:

\[ i_R = \frac{R - R_{\text{near}}}{R_{\text{far}} - R_{\text{near}}} np_R \]

(3.4)

where \( np_R \) is the number of image pixels in slant range direction and where it is assumed that the terrain is flat and thus can be represented by an earth ellipsoid.
3.3 Method to extract waterlines

As discussed in section 2.2, the polarimetric channels themselves are preferred over channel differences for extracting the waterlines. Because the backscatter of land and sea depends on the incidence angle and on weather conditions, mainly rainfall and wind speed but possibly on the time of year, we believe that a classification procedure to separate land from water is the best approach to follow. With this approach, the land/water contrast in each of the polarimetric channels is conveniently combined, the resolution of the SAR image is retained in the extracted waterlines if the imagery are classified per pixel, and the classifier is trained on the acquired image. The latter makes this approach less sensitive to changes in backscatter as the training areas of the classifier change along with the backscatter.

According to [Duda and Hart, 1973], the discriminant function $D$ on which the classification is based is given by:

$$D_k(v) = (v - \mu_k)\Sigma_k^{-1}(v - \mu_k) - \ln|\Sigma_k|$$

(3.5)

In the above equation, $\mu_k$ and $\Sigma_k$ are the mean and covariance matrix of class $k$ computed from a selected training area of $N$ samples in the image (in our case $k$ is water or land):

$$\mu_k = \frac{1}{N} \sum_{i=1}^{N} v_i$$

(3.6)

$$\Sigma_k = \sum_{i=1}^{N} (v_i - \mu_k)(v_i - \mu_k)$$

(3.7)
while $|\Sigma_k|$ denotes the determinant of $\Sigma_k$. The vector $v$ in (3.5) contains the polarimetric channels of a pixel:

$$v = \begin{pmatrix} HH \\ HV \\ VV \end{pmatrix}$$ (3.8)

where in our study based on ASAR data, $v$ will contain one (image mode) or at most two (Alternating Polarization mode) of the three channels. The pixel is assigned to the class (water or land) that gives the smallest value of (3.5).

After the per-pixel classification the result was filtered to remove isolated pixels as much as possible. For each pixel that was declared land it was tested if at least 7 out of 10 pixels to the north, south, east or west of test pixel were also classified as land. If this was not true the test pixel was changed into water.

### 3.4 Waterline results

Figures 3.2–3.4 show the results of the extracted waterlines from the classification procedure, corresponding to image acquisitions 7–9. The result is obtained by using both polarimetric channels, HH and VV, in the classification algorithm. If only one of the two channels was used, the results did not differ very much, the reason being that the HH and VV channels are strongly correlated. The classification result of image acquisitions 1–6 did not give meaningful waterline results, regardless of which polarimetric channels were used or combined. The reason is that the land/water contrast in these images is insufficient, as already anticipated in section 2.3. The waterline results of figures 3.2–3.4 were provided to ARGOSS. The inlay show part of the Westerschelde that are used for depth charting with ARGOSS’ BAS in this study, as discussed in chapter 4. In the next section, the waterlines results are compared with a land map to assess the horizontal accuracy with which they have been computed.
Figure 3.2: Waterline extracted from image acquisition 7. The inlay show part of the Westerschelde that will be used for depth charting in this study.
Figure 3.3: Waterline extracted from image acquisition 8. The inlay show part of the Westerschelde that will be used for depth charting in this study.
Figure 3.4: Waterline extracted from image acquisition 9. The inlay show part of the Westerschelde that will be used for depth charting in this study.
3.5 **Horizontal accuracy of extracted waterlines**

Errors in the horizontal position of the extracted waterlines are the combined result of errors of the geocoding algorithm and errors of the waterline extraction algorithm.

To assess the accuracy of the geocoding algorithm, all SAR images geocoded onto the WGS84 ellipsoid (UTM zone 31) were compared with a land map. A total of about 25 check points in the SAR images were identified, mainly cross roads and railway crossings. At these check points, the differences between the geocoded image coordinates and the land map coordinates were determined. A mean of 30 m (approximately two pixels) for the vector difference of the Easting and Northing coordinates was found, which may be taken as a measure of the accuracy of the geocoded SAR images. In figure 3.5, one of the SAR images is laid over the land map for the south-east part of the Oosterschelde Estuary. The dam structure in the middle of the plots is the Oosterschelde dam whereas the city in the top-half is Bergen op Zoom. Note at the yellow arrows how well the geocoded SAR image and hence the geocoded land/water mask matches with the land map at cross roads and railways (top plot) and at the dam structures (bottom plot).

Regarding the accuracy of the waterline extraction algorithm, results were found to depend strongly on the type of land/water boundary. In case of a well-defined shoreline or permanently dry flats, horizontal errors of about 30–40 m were found (two to three pixels). Accounting for the geocoding error of about 30 m, this means that the waterline of these types of boundary can be detected with an accuracy of about 15 m, i.e. one pixel. Examples are shown in figure 3.6. The top plot of this figure shows part of the island of Overflakkee and to its south the delta-shaped flat Hompelvoet. The bottom plot shows part of the Veerse Meer on the island of Zuid-Beveland. In both plots, it can be seen how well the detected waterline matches with the land map.

In contrast with permanently dry flats, the waterline of shoals (flats that become flooded during high tide) are determined with much less accuracy. Although no detailed comparison of the waterlines with e.g. tide gauge data have been performed, experiments with different training areas for the land/water classification have shown horizontal variations in the detected waterline of about 2–3 pixels, i.e. 30–40 m. These variations indicate that the backscatter of parts of the shoals that had been flooded does not show sufficient contrast with the backscatter of the water surface. Apparently, with these shoals, the sand is too moist and the roughness of the sand surface too small to obtain a reliable land/water classification results. Figure 3.7 gives an example of the Roggeplaat shoal below the island of Schouwen-Duiveland during low tide. In the top plot of this figure, the human eye seems quite capable to detect the waterline, mainly by "visually interpolating" the contour of the shoal. However, if we magnify the land/water boundary as shown in the bottom plot of figure 3.7, the
difficulty to separate land from water using radar backscatter becomes quite apparent, especially for a numerical algorithm.

Based on the results in this section we believe that the horizontal accuracy of the waterline is 30–70 m, where about 30 m of this error can be attributed to geocoding error.
Figure 3.5: Comparison of geocoded image with land map. Note how well the geocoded image matches with the land map at cross roads and dam structures (yellow arrows).
Figure 3.6: Comparison of extracted waterline with land map.
Figure 3.7: Roggenplaat shoal below the island of Schouwen Duiveland during low tide
4 Use of extracted waterlines for depth charting

4.1 Introduction

One possible application of land/water classification of SAR images is charting the seabed elevation of the intertidal zone, which is the main goal of this study. Such areas are generally hard to survey with echo-sounding equipment as this requires sufficient depth for the survey vessel to pass, so they can only be surveyed at around high tide, if ever.

The Bathymetry Assessment System (BAS) software, developed by ARGOSS, uses SAR imagery to chart the depths of shallow seas, based on the principle that depth-induced variations in the tidal current interact with surface waves to create roughness variations, which can be measured by radar [Vogelzang et al., 2004]. This principle works only over the submerged part of the area but not over dry shoals or over very shallow water where numerical flow simulations are not very reliable. Addition of depth (calibration) data in the form of waterlines with known elevation detected in SAR images could therefore improve BAS charts in the intertidal zone.

This chapter discusses a test of the use of waterline data extracted from SAR images in the BAS software. For the test area, part of the Westerschelde has been selected as already briefly presented in figures 3.2–3.4.

4.2 Waterlines and auxiliary data

Waterlines determined from the Envisat ASAR image acquisitions 7–9 were received from TNO Defense, Security and Safety. These three images covering most of the province of Zeeland, were the best ones for classification of land and water, as concluded in chapters 2 and 3.

<table>
<thead>
<tr>
<th></th>
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<td>0.24</td>
<td>–1.92</td>
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<td>–2.51</td>
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<tr>
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<td>5699182</td>
<td>1.06</td>
<td>–0.09</td>
<td>–2.15</td>
</tr>
</tbody>
</table>

Table 4.1: Measured water surface elevations [m] relative to NAP at four tide gauge stations. Positions of the stations (Easting and Northing) are in UTM zone 31 coordinates on the WGS84 ellipsoid.
In addition, we have auxiliary data, i.e. (single-beam) sounding data acquired by Rijkswaterstaat at around the same time as the ASAR images in the Westerschelde Estuary (we have used the sounding data obtained in April 2004 in this study) and water surface elevation measurements obtained from Rijkswaterstaat through the www.waterbase.nl website as listed in table 4.1.

4.3 Methods

Two methods were considered to extract elevation data from the extracted waterlines:
1. levelling with tide gauge data
2. interpolation of known depth values along the contours

The first method has been attempted before in the Waddenzee [Koopmans and Wang, 1995] using sophisticated methods and data to correct for sea surface curvature.

If there are a sufficient number of intersections between sounding transects and waterlines from images acquired at around the same time as the soundings, then a more direct approach to determine elevations along waterlines is to interpolate the soundings along the contours. Irrespective of water surface curvature due to bed friction or streamline curvature, depths along water lines should be smooth and exhibit relatively small variations.

In the present study we tested the potential of waterlines from SAR images in the following manner:

a) Waterlines from the images were cleaned up, removing some noise and inconsistencies: "land" over depths larger than 4 m (from a 2004 depth chart ) was changed into "water", "land" in image acquisition 7 has to be "land" in image acquisition 8, "land" in image acquisition 8 has to be "land" in image acquisition 9.
b) Waterline contours were extracted using a Matlab routine developed for BAS which identifies "islands" and the associated boundary pixels using a matrix permutation technique.
c) Seabed elevation was determined at the intersections of the waterline contours with sounding transects.
d) Tide gauge measurements coincident with the images were interpolated onto the waterline contours.
e) Elevations along the waterlines from tide gauge data and from soundings were compared.
f) Test runs with BAS were made with and without elevation data from waterline contours and tide gauge data to assess the impact on the chart.

4.4 Results

The figures 4.1–4.3 show in colours:
• the waterline contours extracted from the three image acquisitions after cleaning up;
• the elevation of the waterline contours interpolated from tide gauge data;
• the elevations from sounding data at intersections with transects.

Figure 4.1: Waterline contour from image acquisition 7 (curves) and intersections of waterline contour with sounding transects (squares). Colour indicates elevation: for waterline contour, derived from tide gauges, and for intersections, derived from sounding data.
Figure 4.2: Waterline contour from image acquisition 8 (curves) and intersections of waterline contour with sounding transects (squares). Colour indicates elevation: for waterline contour, derived from tide gauges, and for intersections, derived from sounding data.
Figure 4.3: Waterline contour from image acquisition 9 (curves) and intersections of waterline contour with sounding transects (squares). Colour indicates elevation: for waterline contour, derived from tide gauges, and for intersections, derived from sounding data.
The elevations from interpolation of tide gauge data show very little variation along the contours. This is expected. In reality, there may be more variation due to "dynamic sea surface topography", mainly related to increased friction over shoals, and the curvature of streamlines in channels. The order of magnitude of these effects can be a few decimetres at most.

The elevations from soundings show a much larger variation along the contours. For example, for image acquisition 9 acquired during low tide, the elevation from soundings varies from about $-3\, \text{m}$ to $-1.4\, \text{m}$ along a contour. Possible explanations are:

1. Bed steepness. During low tide, the water line is not on the smooth central part of a shoal but on the steep channel slopes surrounding the shoal. Therefore, a small error in horizontal position can lead to a large error in elevation.
2. Classification errors. Separating water from land in a radar image is not free of errors, due to varying backscatter properties of e.g. sand and mud, and the strong dependence on water content of the soil surface.
3. Waterline interpolation errors. We think that despite the large distances separating the tide gauges, this error is still rather small, as can be assessed by leaving out a tide gauge from the interpolation.
4. Local curvature of the sea surface due to friction and streamline curvature (see above).
5. Image geocoding errors. A uniform shift in the positions of the pixels could lead to errors in elevations, especially during low water when the waterline is on the steep channel slopes.
6. Morphological changes between the dates of the depth survey and the acquisitions of the images.

For image acquisition 9 acquired during low tide, the clear distinction in values between the eastern and western boundaries of the Platen van Ossenisse (the big shoals in the western part of figure 4.3) could indicate an image geocoding error, as a shift can lead to such systematic errors. However, a more likely explanation is misclassification which may give rise to a similar pattern if the bed surface material is different on both side of the shoal.

The figure 4.4 below shows the result of assimilation of the tide-gauge based elevations along the waterlines in a depth interpolation with BAS. In this test, no SAR image was used to reconstruct the seabed elevation. By only using the soundings data of April 2004 and the elevations along waterlines retrieved from the 3 images, the situation is easy to interpret. Figure 4.4(a) shows a chart based on interpolation of sounding data only, figure 4.4(b) shows the chart obtained using also elevations along water lines, and 4.4(c) shows the difference. Note that some parts of the shoal were not charted; they are uniformly grey (zero difference) in figure 4.4(c).

The inconsistency between the soundings and the elevations along the waterlines is clearly seen in 4.4(b), where depth contours deviate close to intersections with sounding transects. Also in the central part of the
southern shoal (Platen van Ossenisse), the waterline-based chart gives much lower elevations than the chart based on soundings only. The most likely explanation of this is misclassification of land as water. The large magnitude of the differences is no doubt also caused by the steepness of the channel slopes.

Figure 4.4: Seabed elevation charts determined from (a) sounding data only, (b) a combination of sounding data and elevation data along contours from SAR imagery, and (c) the difference, i.e. (b) minus (a).
5 Conclusions

Because of the relatively small number of looks of 2, the speckle in the SAR images of Alternating Polarization mode and hence in the polarimetric differences (e.g. HH–VV or HH–HV) is significant. This means that the differences of polarimetric channels are less useful to separate land from water than the channels themselves.

To obtain a large land/water contrast for waterline extraction, ASAR incidence angles should be used that are either small (near 15º) or large (near 45º). Incidence angles of 20º–30º, as with the ERS satellites, are to be avoided as they give very small land/water contrast. We conclude that the main advantage of the ENVISAT ASAR over ERS is not its polarimetric capability, but that it offers larger and smaller incidence angles.

The cross-polarisation channel (e.g., HV) does not provide an advantage over the co-polarisation channels HH and VV. The land/water contrast of HV is less dependent on the incidence angle, but the contrast of VV for large incidence angles is larger than that of HV and the contrast of HH is even better.

The waterline extraction algorithm developed in this study is based on a classification procedure and has a horizontal accuracy of 30–70 m. About 30 m of this error can be attributed to geocoding error. A horizontal accuracy of 30 m can be obtained for large land/water contrast, i.e. along sharply defined coastlines. An accuracy of 70 m is obtained for smooth surfaces which have low land/water contrast.

For a test area in the Westerschelde, the extracted waterlines show an error of about 1 m in depth when compared with sounding data. This error of about 1 m is too large for the waterlines to be used as additional calibration data for depth charting with BAS. Also for other purposes, like the computation of a DEM of the intertidal zone, the detected land/water boundary is too inaccurate.

The accuracy with which the images are geocoded is of crucial importance to successfully determine the waterline. With straightforward algorithms like the one used in this report this accuracy is typically of the order of 2 pixels. With image to image co-registration a subpixel accuracy may be obtained, although it may be difficult to apply this technique in images that hardly contain any land. More promising in this respect are future high resolution SAR satellites like Radarsat 2. These satellites may also lead to re-introduction of the concept of interferometric shoreline mapping using the complex coherence.
6 Project progress

The project start was succesfull: a theoretical elaboration led to a set of simulations, a literature survey was done and a set of 30 images was ordered in the framework of an ESA Announcement of Opportunity.

However, within a few months the project suffered from two major disappointments. First, only three (!) of the ordered thirty images were delivered by ESA. Apparently other ENVISAT ASAR modes, presumably wide swath mode over the North Sea, had priority over our required modes. This shows a major disadvantage of a multi-modal instrument. Moreover, no information is available to customers concerning the criteria for the trade-off between modes.

The second disappointment was the leave of the project leader Jur Vogelzang from Rijkswaterstaat AGI. The handing over of the project management hampered the project even further.

With only three images, it would not be possible to verify the predictions on incidence angle and polarisation channels or combinations of them, let alone a valid conclusion based on several images per case. Wide swath was considered, but these images do not only have a much lower resolution (see appendix B, table B.1), but are not polarimetric, hampering the starting point of the project. In the end, we searched the ENVISAT archive and ordered six more suitable images.

Even then, ESA was not able to deliver the requested archive images. The project team ordered them succesfully via Geoserve, a Dutch commercial provider.

Thanks to the dedication of Arthur Smith (TNO) and Cees de Valk (ARGOSS) the project concluded with valuable conclusions.
Bijlage A  Contributing organisations

NATIONAL USER SUPPORT PROGRAMME (NUSP)
2001-2005
http://www.ao-go.nivr.nl

The National User Support Programme 2001-2005 (NUSP) is executed by the Netherlands Agency for Aerospace Programmes (NIVR) and the SRON Netherlands Institute for Space Research. The NUSP is financed from the national space budget. The NUSP subsidy arrangement contributes to the development of new applications and policy-supporting research, institutional use and use by private companies.

The objectives of the NUSP are:

• To support those in the Netherlands, who are users of information from existing and future European and non-European earth observation systems in the development of new applications for scientific research, industrial and policy research and operational use;

• To stimulate the (inter)national service market based on space-based derived operational geo-information products by means of strengthening the position of the Dutch private service sector;

• To assist in the development of a national Geo-spatial data and information infrastructure, in association with European and non-European infrastructures, based on Dutch user needs;

• To supply information to the general public on national and international space-based geo-information applications, new developments and scientific research results.
Organisation

The Directorate-General for Public Works and Water Management (Rijkswaterstaat/RWS) is the executive branche of the Ministry of Transport, Public Works and Water Management (V&W). Under the command of a departmental Minister and State Secretary, it constructs, manages, develops and maintains the Netherlands' main infrastructure networks.

Rijkswaterstaat’s core tasks

- To ensure safe and unimpeded movement of traffic
- To construct, manage and maintain the main roads and waterways
- To protect the Netherlands against flooding
- To ensure an adequate supply of good quality water for all users
- To generate reliable information in a user friendly format

Geo-information and ICT Department

Rijkswaterstaat has six specialist departments, which provide technical and scientific information and support for preparation of Ministry policies and planning and implementation of tasks of the regional departments. The Geo-information and ICT Department (Adviesdienst Geo-informatie en ICT, AGI) serves Rijkswaterstaat with accurate geo-information and delivers the generic ICT infrastructural needs and systems.
ARGOSS is a privately owned company developing and providing innovative solutions on environmental issues to the offshore, coastal and harbour sector. Close links with research institutes, universities and being backed up by the maritime industry ensures that the latest techniques and services are available for our clients.

Our staff include highly qualified physicists, mathematicians, information technology engineers and coastal engineers, having many years of experience in the coastal and oceanographic sector.

ARGOSS is at the leading edge of coastal mapping and marine information services for planning and design of activities and of infrastructures in ports, coastal and offshore areas. With many years of experience in projects and in-house developed global databases of observations and models of wind, waves, sea level and currents ARGOSS is well placed to respond to needs of clients worldwide.

ARGOSS is specialised in processing radar, optical and acoustics measurements, numerical modelling, assimilation of measurements in models and the development of marine environmental information services and decision support systems.

Amongst others, the services of ARGOSS include

- Web based Marine Environmental Information and Decision Support
- Forecasting and hindcasting
- Mapping and monitoring
- Consultancy, Product Development and Research

ARGOSS was founded in 1995 and is located in the Geomatics Business Park in Marknesse, the Netherlands.
TNO, the Netherlands Organization for Applied Scientific Research, is a knowledge organization for companies, government bodies and public organizations. The daily work of some 5,000 employees is to develop and apply knowledge. We provide contract research and specialist consultancy, as well as granting licenses for patents and specialist software. We test and certify products and services, issue an independent evaluation of quality, and we set up new companies to market innovations.

TNO is active in five core areas: TNO Quality of Life, TNO Defence, Security and Safety, TNO Science and Industry, TNO Built Environment and Geosciences, and TNO Information and Communication Technology.

TNO Defence, Security and Safety provides innovative solutions to enhance the general security of our society and is a strategic partner of the Ministry of Defence. Research at TNO Defence, Security and Safety focuses on: observation systems, policy studies and information provision, protection, munition and weapons, biological and chemical protection, and human factors. There are three research locations: The Hague, Rijswijk and Soesterberg.
Compared to the single-channel (VV) SAR onboard of ERS-1 and ERS-2, Envisat’s ASAR employs two improvements. First, instead of a passive radiator array, the ASAR antenna uses an active phased array which means that the radar beam can be steered electronically within the swath thus resulting in a large coverage of incidence angles. Second, ASAR has the possibility to switch between polarization channels which allows scenes to be imaged with a combination of horizontal and vertical polarizations. Because of the active array and the possibility to switch between channels, the ASAR instrument can be operated in five modes, which are mutually exclusive (see figure B.1 and table B.1) and are operated on request. Given below is a brief description of each of the ASAR modes. A more detailed description can be found in [ESA, 1998]. Note that in this study, no other images than Image mode and Alternating polarization mode are used.

**Medium spatial resolution modes**

There are three modes, i.e. image mode, alternating polarization mode and wave mode, in which ASAR operates at medium resolution of better than 30 m.

Figure B.1: ASAR operating modes [ESA, 1998].
Table B.1: ASAR operating mode parameters [ESA, 1998]. The values for the spatial resolution in this table refer to azimuth and groundrange resolution.

<table>
<thead>
<tr>
<th>Polarization</th>
<th>Image Swath Width (km)</th>
<th>Incidence Angle Range</th>
<th>Worst Case Noise Equivalent Sigma Zero</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polarization</td>
<td>Spatial resolution</td>
<td>Wave</td>
<td>Swath width</td>
</tr>
<tr>
<td>HH or VV</td>
<td>&lt; 30 m (4 looks)</td>
<td>HH or VV</td>
<td>&lt; 100 km</td>
</tr>
<tr>
<td>HH or VV</td>
<td>&lt; 30 m (2 looks)</td>
<td>HH or VV</td>
<td>5 × 5 km</td>
</tr>
<tr>
<td>HH or VV</td>
<td>&lt; 150 m (12 looks)</td>
<td>HH or VV</td>
<td>&gt; 400 km</td>
</tr>
<tr>
<td>HH or VV</td>
<td>&lt; 1000 m (7 looks)</td>
<td>HH or VV</td>
<td>&gt; 400 km</td>
</tr>
</tbody>
</table>

Table B.2: ASAR image mode swaths (for satellite altitude of 786 km) [ESA, http://envisat.esa.int].

In image mode, ASAR collects data from a relatively narrow single swath, nominally 100 km wide, in HH or VV polarization. The swath can be selected anywhere within a viewing area of approximately 500 km. Seven swaths are defined within this area called IS1–IS7 (see table B.2). Data in this mode are multilooked in azimuth direction to obtain images with 4 looks and 9 (slantrange) × 24 (azimuth) m resolution. With incidence angles of 15°–45°, this means that the groundrange resolution varies from approximately 34 m at near range to 13 m at far range. Hence, a spatial resolution of better than 30 m (azimuth and groundrange) is obtained almost everywhere in the swath.

The alternating polarization mode provides images in HH/HV, HH/VV or HV/VV polarization with the same resolution and swaths as image mode but with a number of 2 looks. The images are obtained by interleaving the polarizations along track within the synthetic aperture, which results in two images of the same scene in the requested two different polarization combinations.

In wave mode, ASAR uses the same facilities as in image mode to image small areas of the ocean surface. Imaging is carried out for a single-look spatial resolution of 9 (slantrange) × 6 (azimuth) m in HH or VV polarization. Vignettes of 5×5 km size are generated, spaced 100
km apart in along track direction. The position of the vignettes across track, i.e. in the range direction, can be selected either as constant or alternating between adjacent subswaths over the full swath range.

Image and alternating polarization mode require high data rates and, therefore, are limited in operation time up to 30 minutes per orbit by data relay satellite visibility or by ground station visibility. Wave mode is performed with low data rate and hence an operation capability of 100% of the orbit can be obtained.

Low spatial resolution modes
In these two modes, i.e. wide swath and global monitoring mode, ASAR operates at low spatial resolution (150 m to 1 km) but with relatively wide swath (more than 400 km).

Wide swath mode provides continuous coverage over a swath of 400 km, which is divided into five subswaths of approximately 100 km in width. In this mode, ASAR uses a ScanSAR technique, which means that pulses are transmitted to each of the five subswaths in turn in such a way that a continuous along track image is built up.

In global monitoring mode, images are taken with the same swath and subswaths as in wide swath mode, again using ScanSAR. The difference is that this mode has a resolution of 1 km.

Like the medium resolution modes, wide swath mode requires a high data rate so that an operation capability of 30 minutes can be achieved. Global monitoring mode is performed with low data rate and hence the data are stored onboard for later dump so that an operation time of 100% of the orbit is achieved.
Bijlage C  Simulation results of radar backscatter for sea and land

C.1 Simulation results for sea

The radar backscatter ($\sigma_0$) of the sea surface was simulated using the Romeiser-Alpers-Wismann model [Romeiser et al., 1997]. Figures C.1–C.4 show the results at HH, VV, and HV polarization together with the polarization difference of the two co-channels HH/VV. Each figure is for four different wind directions, $0^\circ$, $30^\circ$, $60^\circ$, and $90^\circ$, respectively, while the radar look direction was set equal to $0^\circ$. The wind speed ranges from 2.5 m/s in figure C.1 to 15 m/s in figure C.4. The radar wave number was 110.97 rad/m (C-band).

Note that the simulated radar cross section is symmetric around a wind direction of $90^\circ$ due to the fact that the wave spectrum occurs always as the sum of the values at plus and minus the Bragg wave number.

The wind direction has little effect on the results, notably at low wind speeds. At higher wind, 5 m/s or more, the effect of wind direction becomes discernable in figures C.2 - C.4. The polarization difference HH/VV varies between 0 and −10 dB for incidence angles between $15^\circ$ and $60^\circ$ at all wind speeds. It is insensitive to the wind direction, also at high wind. The HV cross section varies between −30 dB and −50 dB at low wind, and between −20 dB and −40 dB at high wind. Note that the HV cross section and the polarization difference vary less with incidence angle as the HH and VV cross sections.
Figure C.1. Simulated radar cross sections of the sea surface at a wind speed of 2.5 m/s.
Figure C.2. Simulated radar cross sections of the sea surface at a wind speed of 5 m/s.
Figure C.3. Simulated radar cross sections of the sea surface at a wind speed of 10 m/s.
Figure C.4. Simulated radar cross sections of the sea surface at a wind speed of 15 m/s.
C.2 Simulation results for land

Given below is quantitative information on the backscattering coefficient ($\sigma_0$) for bare soil surfaces. The backscattering of a bare soil surface depends on these quantities:

- Frequency (5.33 GHz for ASAR)
- Incidence angle (15–45 degree for ASAR)
- Polarisation (HH, HV or VV)
- Soil roughness $s$ (RMS roughness in cm)
- Soil moisture $m_v$, in cm$^3$/cm$^3$ (the water volume per volume)

Using these parameters as input to a model, $\sigma_0$ (model) data for HH, VV and HV for several incidence angles can be computed. Where possible, the model data are verified against literature. Sometimes the data of different literature sources was found to be not completely consistent. This is probably caused by the variability of $\sigma_0$ due to different environmental conditions.

Dubois model results

[Dubois et al., 1995] derived an empirical backscatter model. It predicts HH and VV backscatter (no HV) with the following limitations:

- Moisture $m_v < 0.4$
- Incidence angle in the 30°–65° range
- Frequency in L-, C- (ASAR) or X-band
- Wavelength > 2.5s (2.5 times the roughness)

We computed the HH and VV backscatter with this model for the ASAR parameters and pure sand (figure C.5). The incidence angle range is the intersection of the ASAR range with the model’s validity range, i.e. 30°–45° (the steeper incidence angles of 15°–30° are not covered by the model). The soil roughness ranges from 1 to 4 cm, where 4 cm can be considered as very rough. The soil moisture is in the 0.1–0.5 interval, where 0.5 corresponds to soaking wet soil. Note that the results for 3 cm and 4 cm are crossed in the figure because they are an extrapolation from the Dubois model (wavelength < 2.5s) and hence less reliable. The $s = 1–2$ cases cm (no extrapolation) show a backscatter that drops by ~5–6 dB (HH) and ~3–5 dB (VV) over the incidence angle range. The HH and VV backscatter differ by at most 1–3 dB (at equal incidence angles).
C.3 Literature survey

As a result of our literature survey, four references were found especially useful. These are briefly discussed below along with a number of figures that can be found in these references.

Reference [Henderson and Lewis, 1998]
We reproduce and discuss here four figures from [Henderson and Lewis, 1998]. These produce information for incidence angles not covered above, and information about HV. The exact soil type is not given in the reference.
Figure C.6: Figure 8-16 from [Henderson and Lewis, 1998].

This figure shows the HV/VV backscatter ratio for three different incidence angles. The ratio appears not to depend systematically on the incidence angle. The horizontal axis is $k_s = 2\pi s/\lambda$. For ASAR this boils down to the pencil written roughness $s$. The soil moisture was $\sim 0.3$. An empirical model gives the solid line. Above a roughness of $\sim 2$ cm HH/VV is independent of the roughness.

Figure C.7: Figure 8-17 from [Henderson and Lewis, 1998]. The like-polarised ratio HH/VV plotted as a function of surface roughness at 50º incidence angle (horizontal axis the same as above).

The dashed and solid lines are empirical models. The wet condition is $m_v \sim 0.3$, the dry condition $m_v \sim 0.15$. The HH/VV ratio stabilises again above a roughness of $\sim 2$ cm. It does not exceed 8 dB.
Figure C.8: Figure 8-18b from [Henderson and Lewis, 1998]. Semi-empirical model compared with measured data for a surface with $s = 0.4$ cm (very smooth) and $m_v = 0.29$. Solid VV, dotted HH, dashed HV.

The measurement frequency 4.75 GHz is below that of ASAR but close enough to give comparable results. The difference between HH and VV increases with increasing incidence angle. The HV curve has about the same shape as that of VV, but is ~13 dB below VV.

Figure C.8: Figure 8-19b from [Henderson and Lewis, 1998]. Semi-empirical model compared with measured data for a surface with $s = 3.0$ cm (rough) and $m_v = 0.29$. Solid VV, dotted HH, dashed HV.

The measurements in this figure were done at a larger roughness than in the former one, while all other parameters are the same. Three differences appear: all backscatter levels are higher, HH and VV now
coincide and the HV curve is a little less below the VV curve: ~10 instead of ~13 dB.

Reference [Ulaby and Dobson, 1989]
This book contains backscatter data compiled from different sources. In the figures below (the range of) C-band HH-, VV- and HV data is plotted for soil and rock surfaces. The 5 % smallest $\sigma_0$ values are below the 5 % level. Analogously, the 5 % highest $\sigma_0$ values are above the 95 % level. Hence the majority (90 %) of the values falls between the 5 % and 95 % levels, which are about 15 dB apart at incidence angles above 15\(^\circ\).

Figure C.9: Mean and range of soil and rock surface $\sigma_0$. 

![Graph showing backscatter data for different incidence angles and polarization modes for soil and rock surfaces. The graphs display the mean and range of $\sigma_0$ values with 5% and 95% occurrence levels indicated.](image)
Reference [Notarnicola et al., 2003]
This paper analyses C-band data of bare soil obtained with several scatterometers. Linear models are fitted for $\sigma_0$ as a function of the incidence angle, and $\sigma_0$ as a function of soil moisture. A quick comparison with the Dubois model of above learned that the results are not very different from the Dubois model and hence are not discussed here.

Reference [Ulaby et al., 1986]
This standard work contains a chapter on “Active microwave sensing of land”. However, not much C-band data is presented.


