Development of automated tools for detailed monitoring of mussel and oyster beds using satellite data: spatial, temporal and vertical development

Narangerel Davaasuren, Johan Stapel, Norbert Dankers, Jeroen Jansen.

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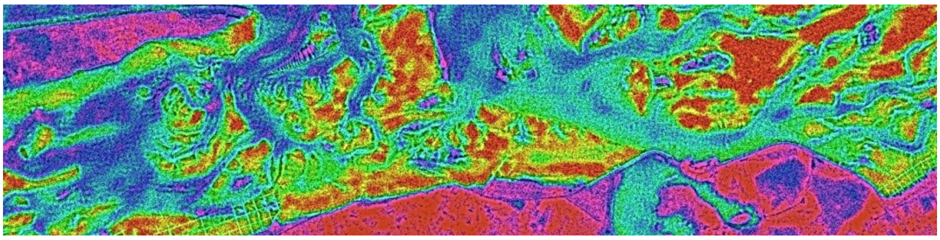

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P.O. Box 68
1970 AB IJmuiden
Phone: +31 (0)317 48 09 00
Fax: +31 (0)317 48 73 26
E-Mail: imares@wur.nl
www.imares.wur.nl

P.O. Box 77
4400 AB Yerseke
Phone: +31 (0)317 48 09 00
Fax: +31 (0)317 48 73 59
E-Mail: imares@wur.nl
www.imares.wur.nl

P.O. Box 57
1780 AB Den Helder
Phone: +31 (0)317 48 09 00
Fax: +31 (0)223 63 06 87
E-Mail: imares@wur.nl
www.imares.wur.nl

P.O. Box 167
1790 AD Den Burg Texel
Phone: +31 (0)317 48 09 00
Fax: +31 (0)317 48 73 62
E-Mail: imares@wur.nl
www.imares.wur.nl

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Summary

Remote sensing is a cost-effective tool, able to provide information on spatial distribution (location and size) and temporal development (changes over time) of mussel and oyster beds.

The advantage of Remote sensing and satellite technology is repeated imaging over one spot, recording spectral information (the reflectance of the sun light) and, independent from weather and cloud condition (radar satellite), structural information which can be used in distinguishing and mapping surface features, including mussel and oyster beds.

The historical data from the ERS-1 and ERS-2 satellites provide information to a resolution of 12.5 meters, and historical coverage dating back to 1999 assisting in tracking long-term changes, applicable for mussel and oyster beds. After the termination of the ERS-1 and ERS-2 satellite program in 2002, the RADARSAT-2 radar satellite started to continue providing information independent from weather (rain and cloud) conditions, with the same capability of imaging day and night, in 25 meters resolution. In addition, radar satellites can record information concerning vertical height and the topography, which can be retrieved using the interferometry technique. The multi-spectral FORMOSAT-2 satellite records information in red, blue, green and near-infrared spectrum in precision to 8 meters, useful to detect mussel and oyster beds surrounded by sediments, and areas covered by algae.

The novel idea of this research is to combine information from different platforms, radar and multi-spectral, and to use it in detecting location and estimation of size of mussel and oyster beds on intertidal flats in the Wadden Sea. The study also explored a technique to estimate the vertical development (changes in height) of mussel and oyster beds. Such a technique is new and has never been applied before for intertidal mussel and oyster beds.

Overall, the results indicate promising applicability of remote sensing which can be integrated into the present mussel and oyster monitoring programs at IMARES. These novel technological tools may in the future be extended into the trilateral framework of Wadden Sea science and monitoring.

The research aims to support the objectives of the Delta Programme Wadden Sea, and the Building with Nature program, exploring the potential applicability of including the ecological functions of mussel and oyster beds (i.e. wave energy reduction, erosion protection of intertidal flats, and sediment capturing capacity) in coastal defence management, contributing to the protection of the natural environment of the Wadden Sea.

This research is performed within Kennisbasis Onderzoek (KB) / Beleidsondersteunend onderzoek (BO) / Wettelijke onderzoekstaken (WOT) of the EL&I-program with a contribution from the Netherlands Organization for Scientific Research NWO, through the National Programme Sea and Coastal Research – Changing Capacity ZKO program.

1. Introduction

Mussel and oyster beds are important biogenic structures in the Wadden Sea, playing an important role in building and stabilising intertidal flats, reducing wave energy and possibly protecting the coast from erosion by increasing the level of the flats surrounding the mussel beds (Dankers et.al, 2004). The significance of the mussel and oyster beds to overall development of the Wadden Sea and their contribution to coastal protection needs more quantitative assessment, e.g. by assessing changes and developments over time in their size, location and height (i.e., elevation or vertical development).

Monitoring of mussel and oyster beds in the Wadden Sea is carried out on a regular basis in the Netherlands and Germany. The several monitoring programs supervised by IMARES are monitoring benthos and making inventories of mussel and oyster beds every spring. Although monitoring of mussel beds is carried out according to similar protocols agreed upon in the trilateral TMAP framework, no mussel bed monitoring is carried out in the Danish part of the Wadden Sea. In Germany and the Netherlands the mussel bed monitoring is time consuming and in Germany not all mussel beds are monitored. Existing mussel bed monitoring does not include changes in elevation of mussel and oyster bed. Establishment of a coherent monitoring program over the entire Wadden Sea is one of the important tasks to be implemented in the future. This may be facilitated with novel techniques such as remote sensing.

The main focus of this report is to develop the application of a novel technique in mapping of mussel and oyster beds using Remote sensing, which can be combined with regular field monitoring to obtain an optimal monitoring strategy.

Vertical development in the Wadden Sea is a big issue. Sea level rise and gas extraction are considered serious threats that could potentially lead to “drowning” of the Wadden Sea in the future, with adverse effects for its ecology and coastal protection of the mainland. It is not without reason that nature organisations, mining companies and policy makers are very interested in tools that could monitor vertical development.

Analysis of the vertical development of mussel and oyster beds in sufficient resolution and areal coverage is not yet readily available. It is therefore difficult to assess what the quantitative contribution of these ecosystems is or could be in relation to the development of intertidal areas and coastal protection. Yet, the promotion of mussel and oyster bed development in the Wadden Sea could represent a promising Building with Nature (Ecoshape, 2013) solution for erosion prevention, tidal flat build-up and coastal protection, integrating engineering tools and natural processes and ecosystem services.

There are indications that mussel and oyster beds play an important role in sediment accumulation and stabilisation of tidal flats, contributing to vertical development of tidal flats, hydrodynamic energy absorption and coastal flood protection. Information about this contribution is important for policy and management development within the framework of the Delta Programme Wadden Sea. At the same time, interest is increasing over using natural structures and ecosystem services in coastal development, serving multiple ecological and socioeconomic purposes and cost effective coastal defence strategies. This is the main objective of the Building with Nature programme.

The application of Remote sensing can be merged with other available and currently used tools and integrated into a sustainable coastal defence strategy. New developments in Remote sensing techniques and new satellites to be launched in very near future, such as Sentinel-1 and Landsat-8, will offer possibilities to continue monitoring using satellite data.

Intertidal areas between Ameland, Schiermonnikoog and the main land were selected for a study to optimise classification of mussel and oyster beds from satellite images and to search for techniques to determine the elevation of mussel and oyster beds from satellite images (Figure 1), and to detect changes over time.

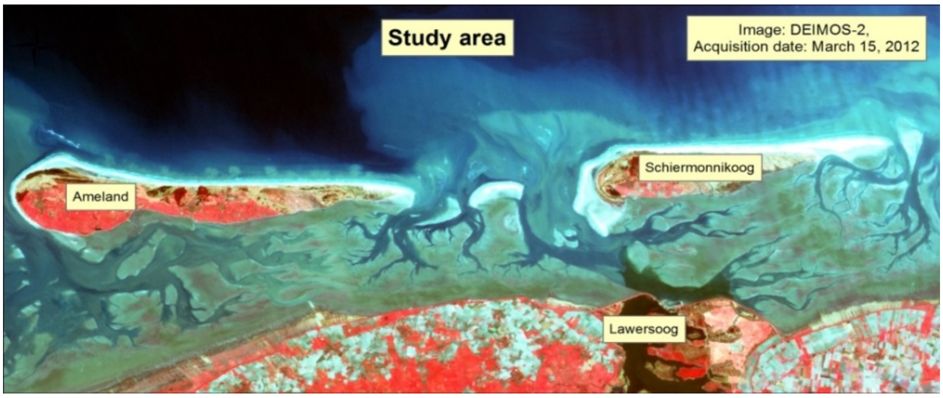

Figure 1-Study area in the Dutch Wadden Sea. Satellite image: DEIMOS-2, acquisition date: March 15, 2012. Resolution: 22 meters. Bands combination in false color composite: land in red, intertidal flats in brown-green, water: blue.

The area was chosen because of its relatively undisturbed environment (closed for fishing since the 1990s), the presence of surveyed mussel and oyster beds and on-going field monitoring programmes, the availability of radar ERS-1 and ERS-2 and multi-spectral satellite data, links to previous IMARES projects (Delta Programme Wadden Sea) and potential interest from IMARES partners and the Netherlands government. It is assumed that the selected area is sufficiently representative for the entire Wadden Sea and that results and developed techniques can be extrapolated for application in other parts of the Wadden Sea.

Results from interpretation of processed satellite images were calibrated using expert knowledge, scientific literature and field data collected by IMARES during field campaigns in 1995, 2001 and 2009.

1.1 Research objective

1.1.1 The general objective

The proposed research is multi-disciplinary in combining satellite data from different platforms (i.e. multi-spectral and radar) with current knowledge and expertise on mussel and oyster beds monitoring in the field. The project will serve as a first step in developing an automated, novel tool producing continuous up-to-date and accurate information on location, size and height and changes thereof over time of the mussel and oyster beds in the Wadden Sea. Ground verification will be needed in order to filter out false positive and/or false negative classifications, but that was not part of this research. The project contributes to the Delta Programme Wadden Sea and Building with Nature as it aims to determine the occurrence and development of mussel and oyster beds in the Wadden Sea in space and time; it may be used to assess the total Wadden Sea area covered with mussel and oyster beds; and as such may be used to assess the (potential) capacity of these systems to support the intertidal areas in the Wadden Sea growing with sea level rise.

1.1.2 The specific objectives- research questions

The specific objective of the current research is to develop and propose automated tools for detailed mapping of mussel and oyster beds in the Wadden Sea using radar and multi-spectral satellite data by providing answers to the following research questions:

- Can temporal and spatial development of the location and size of mussel and oyster beds (horizontal development) be mapped and estimated using ERS-2 radar and multi-spectral FORMOSAT-2 satellite data?
- Can vertical development of the beds be measured using radar ERS data?

The research combines multidisciplinary science and technology tools, using modern image processing and analysis tools and field monitoring data, and applying the scientific concepts of marine ecology and the ecology of mussel and oyster beds.

The expected results of the project are: 1) mapped locations of mussel and oyster beds in selected areas of the Wadden Sea using ERS-2 radar and multi-spectral FORMOSAT-2 satellite data; 2) estimated area (in hectares) of mussel and oyster beds; 3) assessment of the prospective of developing a remote sensing based method to monitor vertical development of mussel and oyster beds from radar ERS data; 4) evaluation and assessment of the uncertainties of the results and products and 5) field validation using survey data.

The main deliverable is a project report describing the developed algorithms and methods used. It is expected that the developed method will be applicable and can be extended to other parts of the Wadden Sea.

1.2 The scope of the research

The scope of the research is to develop an algorithm and methodology to detect location and estimate size and elevation of intertidal mussel and oyster beds and to assess developments thereof over time. The satellite images were processed using methods and algorithms provided by scientific institutions, commercial companies and members of the European Space Agency.

To illustrate the usability of historical satellite data in detecting changes over time, we analysed differences before and after a storm event in 1995. Providing advice on improving regular monitoring programmes for mussel and oyster beds in the Wadden Sea in order to make these more cost effective, allowing improvement of and more and better targeted qualitative measurements during ground verification inventories is also within the scope of the current research.

1.3 The limitations of the study

Time and budget constraints limited the study area to a selected part of the Wadden Sea between Ameland, Schiermonnikoog and the mainland.

The availability of useable FORMOSAT-2 data was limited to daytime clear sky and low tide co-occurring at the time of the satellite passing over the study area, leading to a maximum of two images per month. The availability of radar data are independent from weather and cloud conditions, have imaging capability day and night and are limited only by low tide conditions during the satellite's passing.

Considering the frequency of satellite data availability and the mostly seasonal controlled developments of mussel and oyster beds, it can be concluded that the availability of satellite data will not limit the applicability of the proposed monitoring tool.

1.4 Research methodology

The research methodology followed different steps in image processing and analysis for ERS SAR, RADARSAT-2 and FORMOSAT-2 data, because of differences in data format and data structure, requiring specially tailored pre-processing and processing algorithms. For radar ERS-2 SAR and RADARSAT-2 data, some steps were similar, because of similarities of the data structure (recorded radar pulses).

The processing of radar data followed basic steps for data pre-processing, including corrections for the satellites' antenna pattern; applying orbital information; image enhancement using speckle Gamma frost filtering; and co-registration and projection to geographic latitude and longitude. Similar steps were followed during pre-processing of the Formosat-2 data, in addition to atmospheric correction and projection to geographic latitude and longitude. The new, advanced Imagine Objective tool was used to classify the multi-spectral FORMOSAT-2 data.

The field validation is an essential component in assessing the quality of the information derived from remotely sensed data (Congalton and Green, 2008). The assessments can be fairly complex and the most commonly used is a method of comparison between classfied satellite data and visual interpretation of the satellite images with the field data.

1.5 Novel features of the research

The research contributes to traditional knowledge and tools on mussel and oyster bed monitoring, providing new insight about advanced concepts of satellite data processing and tools, and scientific concepts of the ecology of mussel and oyster beds. The developed procedure can be wrapped into a standard operational framework, and integrated into a long-term monitoring program.

The attempt to detect and monitor vertical changes of mussel and oyster beds using remote sensing is a completely new concept. Only few studies were previously conducted in relation to mapping of intertidal flats and mussel and oyster beds using satellite data (but see research by (Fey *et al.*, 2010), (Hommersom *et al.*, 2010), (Van Der Wal *et al.*, 2005), (Wal *et al.*, 2008). The challenges to map the intertidal mussel and oyster beds using satellite data lay within the complexity and high spatial and temporal variability of intertidal ecosystems, which requires advanced knowledge and tools and finding innovative ways to overcome technical limitations.

1.6 The benefit for IMARES and for the client

The direct benefit for IMARES of this project is new knowledge, which can be used to advance present monitoring protocols, and assist the improvement of the efficiency and quality of the monitoring programmes. In other applications, Remote sensing has proven to be a very time efficient method for areal mapping, which currently makes up most of the investment of monitoring mussel and oyster beds. Efficient mapping and identification of locations showing significant temporal changes may be a powerful tool to specifically target field monitoring activities making it possible to shift the focus towards a more quality assessment of the mussel and oyster beds and increasing our knowledge about the (ecological) functioning of mussel and oyster beds. In the long run it will certainly contribute to the objectives of the Building with Nature programme and the Delta Programme Wadden Sea (Delta Commissioner, 2013) on developing coastal defence policy and strategies.

1.7 Structure of the report

The report consists of an Introduction in Chapter 1; in Chapter 2, a description of the Approach with the state of the art on effects of a storm event and detection of mussel and oyster beds, with respect to temporal and spatial development of location and size of mussel and oyster beds (horizontal development) and temporal development of mussel and oyster bed elevation (vertical development). Chapter 3 presents results of radar and multi-spectral data processing in finding the storm effect and detecting the location of mussel and oyster beds, followed by Discussion in Chapter 4 and the Conclusion in Chapter 5.

2. Approach

2.1 State of the art

It was previously known that radar and multi-spectral satellite data can provide synoptic and repeated coverage over time for any location on the globe, including the Dutch Wadden Sea. Several studies on sediment mapping (type and grain size) and location of mussel and oyster beds (Hommersom *et al.*, 2010), (Sørensen *et al.*, 2006), (Van Der Wal *et al.*, 2005), (Van Der Wal and Herman, 2007) show considerable limitations when using single satellite platform data and to identify sediments and mussel and oyster beds and that successful mapping, classification accuracy and sufficient resolution requires ground truth sampling. However, (Hennig *et al.*, 2007) and (Klonus *et al.*) discussed application of high resolution multi-spectral RapidEye data in resolution of 5 meters and radar TerraSAR-X data in one meter resolution using hybrid classification algorithms to classify the location and size of mussel and oyster beds. They concluded that a highly efficient integration of data and tools, using the advanced concepts of image processing algorithms, is necessary because of the high nonlinearity of sediment transport and gradients in sedimentation processes, patterns of high temporal and spatial variability, and tidal asymmetries (Stanev *et al.*, 2007), (Hommersom *et al.*, 2010).

2.1.1 Temporal and spatial development of the location and size of mussel and oyster beds (horizontal development)

Traditionally, in optical Remote sensing, detecting the spatial location and size of mussel and oyster beds has been done by analyzing the spectral property of the object, which is reflected in different wavelengths of the electromagnetic spectrum. Mussel and oyster beds have a very distinct spectral signature, compared with surrounding sediments, based on their color and spatial coverage, which greatly depends on the resolution of the image. Indirectly, during the summertime, the location of large mussel and oyster beds in known locations, combined with ground truth data can possibly be predicted by occurrence of algae or other green biomass covering them. However, in areas where mussel and oyster beds were not encountered in the past, the areas with algae not necessarily indicates the presence of the mussel and oyster beds underneath and needs to be ground checked.

2.1.2 Temporal development of mussel and oyster bed elevation (vertical development))

The radar processing technique known as interferometry and coherence in detecting the location, size and vertical (height) development of the objects is one of the advanced techniques employed in various land applications. In addition, the information from the intensity of radar images can be used in classification and in computing images of mean and standard deviation, which can provide additional information about the texture and surface structure of the objects.

Interferometry is a technique for generating an interferogram using two Single Look Complex (SLC) images, acquired over the same area from two slightly different look angles (Cloude and Papathanassiou,

1998) and (Papathanassiou and Cloude, 2001). The interferogram is used to calculate the coherence (change) image and in the computation of the Digital Elevation Model (DEM). To produce an interferogram, a sufficient number of Ground Control Points (GCP) is needed, to precisely co-register two SLC images.

2.2 Acquisition of satellite data- radar and multi-spectral

Radar

The ERS-2 radar satellite instrument, the name of which is abbreviated as SAR (Synthetic Aperture Radar), is a side-looking, microwave imaging system, capable of sending and receiving signals. It is termed Synthetic Aperture because of antennas positioned on its side. The SAR images are panchromatic (black and white) recorded in two dimensions- vertical (VV) and horizontal (HH), to a (horizontal) resolution of 12.5 meters. The ERS-2 SAR system transmits a signal in C-band, in amplitude of 8.0 to 4.0 GHz. The C-band has the ability to penetrate clouds, rain and the water surface up to 1.5 meters deep. The vertical and horizontal dimension of the SAR system can be used to measure the heights of the objects and ERS-2 SAR images acquired over the course of one day are used to compute elevation.

To demonstrate the usefulness of the ERS-2 SAR imaging for the detection of spatial changes in mussel and oyster bed, two images from 1995 were selected from before and after a storm event. The image from 08 February 1995 presents the situation before the storm and the image acquired on 25 May 1995 the one after the storm (Table 1). The image from 20 August 2010 presents recent developments in location and size of mussel and oyster beds.

Table 1-Single ERS-2 images used in the classification of mussel and oyster beds (ground resolution: 12.5 meters)

Image acquisition dates	Acquisition time (CET)	Tide level (in meters), Lauwersoog station, Netherlands	Image type
08 February 1995	21:38:39.28 (21 min before Low Tide)	21:59 PM 0.62 meters Low Tide* (NAP) 4:04 AM 2.45 meters High Tide (NAP)	ENVISAT format Amplitude, intensity images
25 May 1995	10:34:37.65 (2h 07 min before Low tide)	8:27 AM 2.52 meters High Tide (NAP) 14:24 PM 0.35 meters Low Tide (NAP)	ENVISAT format Amplitude, intensity images
20 August 2010	10:35:00.00 3h 12 min before Low tide)	7:23 AM 2.59 meters High Tide (NAP) 13:48 PM 0.72 meters Low Tide (NAP)	ENVISAT format Amplitude, intensity images

**- the tidal predictions are taken from David Flater. XTide. http://www.flaterco.com/xtide/. 2005-07-04. The predictions are generated by BASIC pseudocode made by David Flater, using the principle on generating the tide height or current velocity for a specified time point. The tide information is relative to NAP in meters.*

To assess the vertical development of mussel and oyster beds, three pairs of ERS SAR images were chosen (Table 2) in Single Look Complex (SLC) format, containing records on phase, amplitude and slant range (baseline), in an attempt to compute the interferometry and Digital Elevation model (DEM). 2-ERS interferometry pairs (resolution: 12.5 meters) are selected to generate the interferogram.

The ERS interferometry pairs were selected from the EOLISA, the European Space Agency (ESA) system. The EOLISA system specifically provides ERS image pairs which are suitable for interferometry. In our case, one ERS-2 scene, acquired on 2009-08-16 (Table 7) was recorded 1 (one) hour 50 minutes before the high tide, whereas the ERS-2 scene acquired on 2009-05-03 was recorded 1h 4 min before low tide. Because this pair is specifically suitable for interferometry due to matching in baseline and other parameters, it was nonetheless selected for analysis, despite differences in water levels.

Table 2-ERS interferometry pairs, (resolution: 12.5 meters)

Mission	Sensor	Track	Orbit	Date and time of acquisition (CET)	Tide level (in meters), Lauwersoog station, Netherlands
ERS-2	AMI/SAR/Image	380	31296	1996-02-11 10:31:49.86 (2h 18 min after Low tide)	8:13 AM 0.31 meters Low Tide (NAP) 14:18 PM 2.61 meters High Tide (NAP))
ERS-2	AMI/SAR/Image	380	33801	1996-04-21 10:31:49.11 (3h 10 min after Low tide)	7:21 AM 0.10 meters Low Tide (NAP) 13:21 PM 2.82 meters High Tide (NAP)
ERS-2	AMI/SAR/Image	380	73380	2001-04-15 10:31:34.00 (46 min after Low tide)	9:45 AM 0.45 meters Low Tide (NAP) 15:58 PM 2.54 meters High Tide (NAP)
ERS-2	AMI/SAR/Image	380	74883	2001-10-07 10:30:17.70 (2h 35 min after Low tide)	7:55 AM 0.41 meters Low Tide (NAP) 13:53 PM 2.88 meters High Tide (NAP)
ERS-2	AMI/SAR/Image	380	4242	2009-05-03 10:32:42.13 (1h 4 min before Low tide)	5:50 AM 2.35 meters High Tide (NAP) 11:36 AM 0.57 meters Low Tide (NAP)
ERS-2	AMI/SAR/Image	380	5244	2009-08-16 10:33:03.32 (1h 50 min before High tide)	5:59 AM 2.51 meters High Tide (NAP) 12:23 PM 0.68 meters Low Tide (NAP)

The RADARSAT-2 is a Canadian satellite launched in December 2007, daily covering the entire globe in a resolution of 25 meters. The RADARSAT-2 is a continuation of the RADARSAT-1 program of the Canadian Space Agency. Since March 2012, the Netherlands Space Office (NSO) has provided free access to Dutch organizations to use the RADARSAT-2 data of the Netherlands. The data can be obtained at the satellite data portal of the NSO office.

The RADARSAT-2 satellite images the earth in C-Band, in a signal frequency of 5.405 GHz. The system is similar to that of the ERS SAR, the Synthetic Aperture Radar system. The RADARSAT-2 images are acquired in two polarization modes – vertical (VV) and horizontal (HH) (Figure 2).

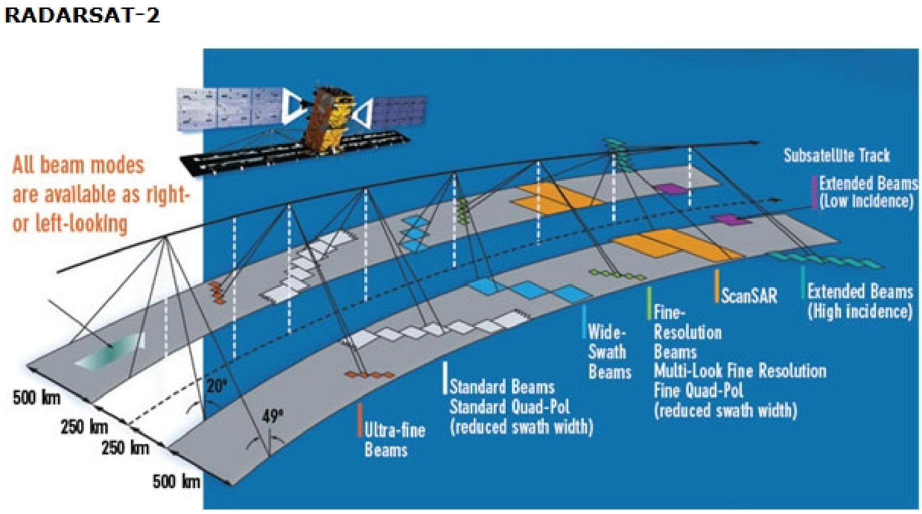

Figure 2-RADARSAT-2 satellite imaging system (Reference: Canadian Space Agency 2012, http://www.asc-csa.gc.ca).

From available data set one, RADARSAT-2, an image was acquired on 20 August 2012 during low tide (Table 3).

Table 3-RADARSAT-2 image (ground resolution: 25 meters)

Image acquisition date	Acquisition time (CET)	Tide level (in meters), Lauwersoog station, Netherlands	Image type
20 August 2012	10:24 (3h 21 min after Low tide)	7:03 AM 0.28 meters Low Tide (NAP) 12:59 PM 3.04 meters High Tide (NAP)	SAR (vertical VV polarization) intensity image

<u>Multi-spectral</u>

The FORMOSAT-2 is a Taiwanese satellite (Figure 3), providing daily coverage of the Netherlands and the Dutch Wadden Sea (Figure 4) in 4 multi-spectral bands- Blue, Green, Red and Near-infrared (Table 4).

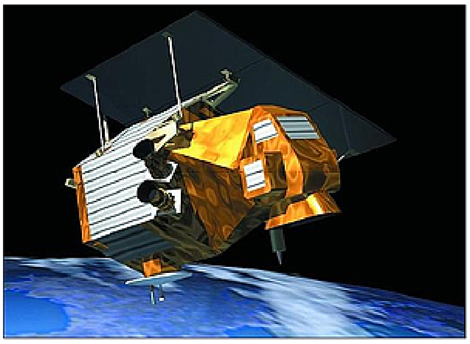

Figure 3-View of FORMOSAT-2 satellite

Figure 4-FORMOSAT image over Ameland, date of acquisition 08 August 2012.

Table 4-Spectral bands of FORMOSAT-2 satellite

Band	Spectrum	Resolution
Blue	0,45 – 0,52 µm	8 meters
Green	0,52 – 0,60 µm	8 meters
Red	0,63 – 0,69 µm	8 meters
Near-infrared	0,76 – 0,90 µm	8 meters

The selected images were acquired on 08 and 13 August 2012 (Table 5). Usage of FORMOSAT-2 data is limited to cloud free conditions and low tide scenes.

Table 5- FORMOSAT-2 images

Image acquisition date	Acquisition time (CET)	Tide level (in meters), Lauwersoog station, Netherlands	Image type
08 August 2012	10:24 am 1h 18 min after Low tide)	9:06 AM 0.24 meters Low Tide (NAP) 15:18 PM 2.80 meters High Tide (NAP)	GeoTIFF converted from original DIM format
13 August 2012	10:24 am (3h 03 min before Low tide)	7:21 AM 2.50 meters High Tide (NAP) 13:29 PM 0.88 meters Low Tide (NAP)	GeoTIFF converted from original DIM format

2.3 Processing

Radar

To analyse the radar images, the precise orbit needs to be applied first, to obtain well matched collocation of the satellite images. The orbit information for ERS SAR and other radar images can be downloaded from the website of the Technical University of Delft, the Netherlands. The next step is to image the co-registration and choose the Master (main) and the Slave (secondary) images. The step after that is generation of the interferometric phase which is the measurement of the relative terrain altitude (Bhattacharya *et al.*, 2012), (InSAR Principles, 2007). From the interferogram the coherence (change) image is computed. The coherence image shows changes in white and no change in black. Finally comes the phase of unwrapping and generation of the Digital Elevation.

The Next ESA SAR Toolbox (NEST) is an open source (GNU GPL) toolbox for reading, post-processing, image analysis and visualization of data from ESA SAR missions, including Level 1 data (basic processed, raw data), other levels of ERS-1 and 2 data, ENVISAT, and in the future Sentinel-1. In addition, NEST supports satellite products from third party missions including JERS-1, ALOS PALSAR, TerraSAR-X, Radarsat-2 and Cosmo-Skymed. NEST has been built using BEAM Earth Observation Toolbox and Development Platform from Brockmann Consult (Germany).

The ERS-2 SAR images were ordered from the EOLISA system, the platform of the European Space Agency (ESA) that was designed to access and order satellite images from the ESA catalogue, including third-party missions. The selected ERS-2 SAR images were amplitude and intensity images, corrected for geometric and radiometric errors and projected to geographic latitude and longitude.

The ERS-2 data were processed using the NEST tool box, with the InSAR tool to apply orbit corrections, co-registration of images and generation of interferogram and computing the coherence images.

The Focal analysis tool used to compute images of variance (mean) and skewing from radar images. The result is presented in Figure 5. A detailed description of the tool can be found in the ERDAS IMAGINE Field Guide (2011).

The formulas to calculate images of variance (mean) and skew images are:

$$Mean = \frac{\Sigma x_{ij}}{n}$$

, where : xij = DN value of pixel (i,j)
n = number of pixels in a window
M = Mean of the moving window (3 by 3 pixel size).

$$Skew = \frac{\left|\Sigma(x_{ij} - M)^3\right|}{(n-1)(V)^{\frac{3}{2}}}$$

, where: : xij = DN value of pixel (i,j)
n = number of pixels in a window
M = Mean of the moving window (3 by 3 pixel size). V = Variance

The analysis of images before and after Focal analysis shows improvement to the quality of the images, presented in a histogram (Figure 5). After Focal analysis, all outliers (exceptional high values) (the image on the left) were removed (the image on the right).

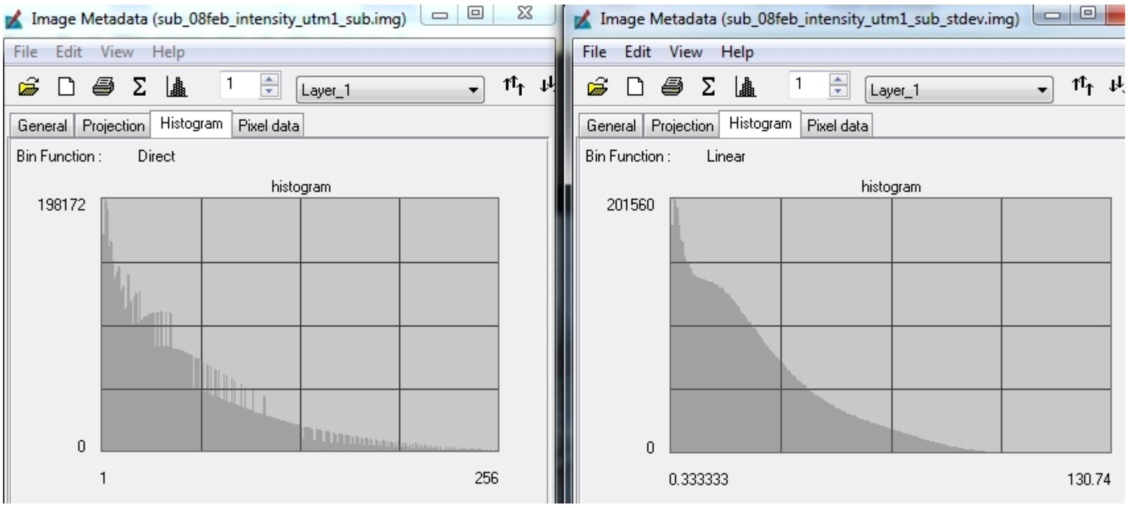

Figure 5- The histogram of the ERS SAR image before the Focal analysis (left) and after (right).

Removal of the exceptionally very high values (outliers) is very important, as such outliers will affect the accuracy of classification.

ERS SAR-1 and 2 satellites had a repeating cycle of revisiting the same area every 35 days. When both satellites were active, the images were acquired over a one day difference. Such images can be used to compute change (coherence). In this case high coherence will indicate no change and images with low coherence indicate that change has occurred. However computing coherence (change) for intertidal flats can be challenging, because the satellite camera can only record the specific "momentum" of intertidal flats and their specific non-correlated pattern of temporal and high spatial variability, further complicated by the periodicity of the tidal wave (Davaasuren, Stapel et.al, 2012). It is also not clear, whether the computation of coherence in intertidal flats will produce highly correlated images, because intertidal flats by their nature already have large dissimilarities in water and moisture content during each tidal cycle.

The RADARSAT-2 image was downloaded from the NSO data portal and it contains geometric corrections, and a correction for antenna pattern, slant and range. The selected RADARSAT-2 image is geometrically corrected, HDF format image.

The RADARSAT-2 images in different polarization can be used to produce a synthetic color composite (Figure 6 image, which is similar to the color image of the multi-spectral FORMOSAT-2 satellite).

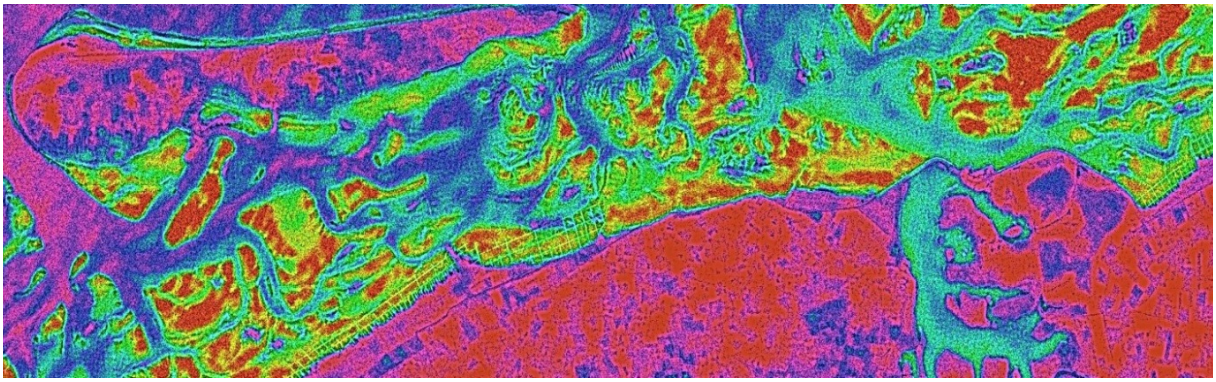

Figure 6- RADARSAT-2 image, date of acquisition 20 August 2012, synthetic colour composite, combination of horizontal (HH) and vertical (VV) polarization modes.

The difference in moisture and water content in Figure 6 is shown in different colors, from red for dry land, blue for wet land and very wet areas, green for low turbid waters around Lauwersoog and yellow for mixed sand and muddy places. The intertidal flats are in green.

Multi-spectral

The FORMOSAT-2 data was processed using ERDAS IMAGINE 2013 tools. The pre-processing algorithms used a basic raster processing tool, atmospheric correction ATCOR, spectral (Principal component analysis) and Object oriented classification, and the Imagine Objective tool.

The FORMOSAT-2 images were downloaded from the NSO satellite data portal. The images were pre-processed resulting in images of Level 1A containing the radiometric corrections and removal of distortions due to variations in sensitivity of elementary detectors in the imaging sensor.

The FORMOSAT-2 images were checked for positional accuracy, using as a reference a topographic map of the Netherlands, scale 1:100 000. The positional accuracy was found to be within acceptable limits (the shift was less than 1 pixel). The next step was to apply an atmospheric correction, the process of conversion of digital DN values to Top-of-Atmosphere Radiance (TOA), based on the approach described in (Liu *et al.*, 2010) and (Kamei *et al.*, 2012). The conversion removes and reduces the atmospheric effect, which blurs the visibility of the mussel and oyster beds. The whole process starts from Top-of-Atmosphere-Reflectance and accomplished by a conversion to Top-of-Atmosphere-Radiance.

The following steps are taken during Top-of-Atmosphere Radiance conversion:

1. Top-of-Atmosphere-Reflectance:

$$L_{RSI}\ (bRSI) = DN_{RSI} * PG_n\ (bRSI)$$

Where-

- L_{RSI} - estimated recalibrated TOA radiances;
- DN_{RSI} - average DN values within the image;
- PG_n - physical gain for each spectral band of FORMOSAT-2 image;
- bRSI- spectral bands of FORMOSAT-2 image, depending on gain number n (1 to 10).

2. Top-of-Atmosphere-Radiance:

$$\rho = \frac{\pi L_{RSI}}{E_s\ \mu_s\ D}$$

Where-

- μ_s - cosine of the sun zenith angle (90^0- (minus) sun elevation angle);
- D- Earth to Sun distance at day of acquisition (Table 6), and calibration coefficients, as defined in Lavender et.al, 2005: $D = (1 + 0.0167 \cos \frac{2\pi(d-3)}{365})^{\ 2}$

Table 6-Calibration coefficients

Band	Calibration coefficients (for gain 1)
Panchromatic	1.928409
Blue	1.881574
Green	2.006462
Red	2.040042
Near-infrared	1.732235
Cosine of the sun zenith angle	0.722338725
Earth to Sun distance D	1.032445
∏ number	3.141593

It is also possible to use the ATCOR tool from ERDAS IMAGINE, to do the atmospheric correction of the images. The results from both tools were similar: the FORMOSAT-2 image corrected by the ATCOR tool is used in the classification. Figure 7 shows the results from atmospheric correction. The left hand image presents the effect from the atmosphere appearing as noise spread in digital DN values across the entire image, especially disturbing band 3, the red wavelength (the irregular sharp peak on the image on the left). In contrast, the histogram of the corrected image presents a normalised curved distribution of DN values and increased reflectance in the near-infrared band 4, probably because of the strong reflectance of vegetation (the image on the right).

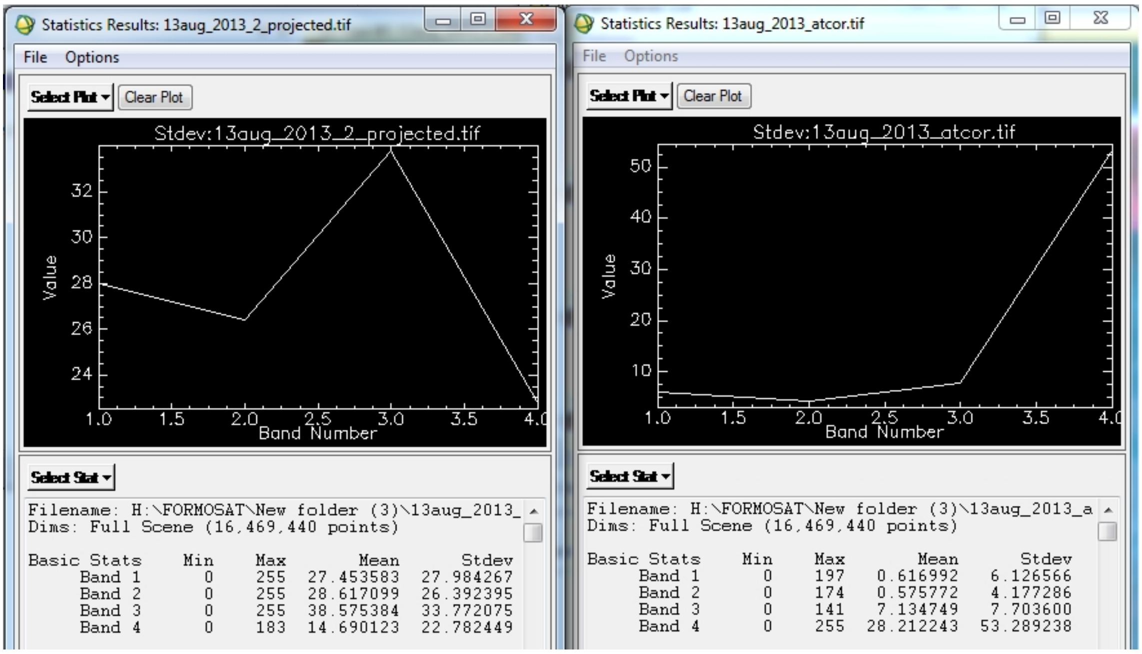

Figure 7- Histogram of uncorrected image (left) and atmospherically corrected (right)

The image processed by ATCOR visually shows exceptional visibility for the intertidal flats and mussel and oyster beds, which appeared in a dark brown-greenish colour (Figure 8). The two selected FORMOSAT-2 images were presented in mosaic using the Mosaic tool of ERDAS IMAGINE 2013, merging the spectral information of both images to produce one image with similar colors for land and the intertidal flats (Figure 9).

The FORMOSAT-2 image, after atmospheric correction, was classified using the Imagine Objective classification tool. The tool did straight differentiation between mussel and oyster beds and the rest of the features. Related with the fact, that before 2004 there were no oyster reefs in the eastern Wadden Sea and only mussel beds, the term “mussel” beds is used for historical ERS data and for RADARSAT-2 and FORMOSAT-2 the description of beds refer to “mussel and oyster beds”.

The classification of FORMOSAT-2 image using the Imagine Objective classification tool was first followed by a step on identification of known location of mussel and oyster beds using IMARES survey data, by overlaying the shape file from the field survey over the satellite image; and secondly by choosing the classification parameters, such as the probability filter (selecting from known location the spectral property, color and shape of the objects identified as mussel and oyster beds). Finally, the the image was segmented, using the selected classification parameters, to produce the classification. The result from classification is a shape file, showing the location of the mussel and oyster beds.

It was decided not to mix the classification of sediments and mussel and oyster beds, but to follow the single feature classification approach, instead.

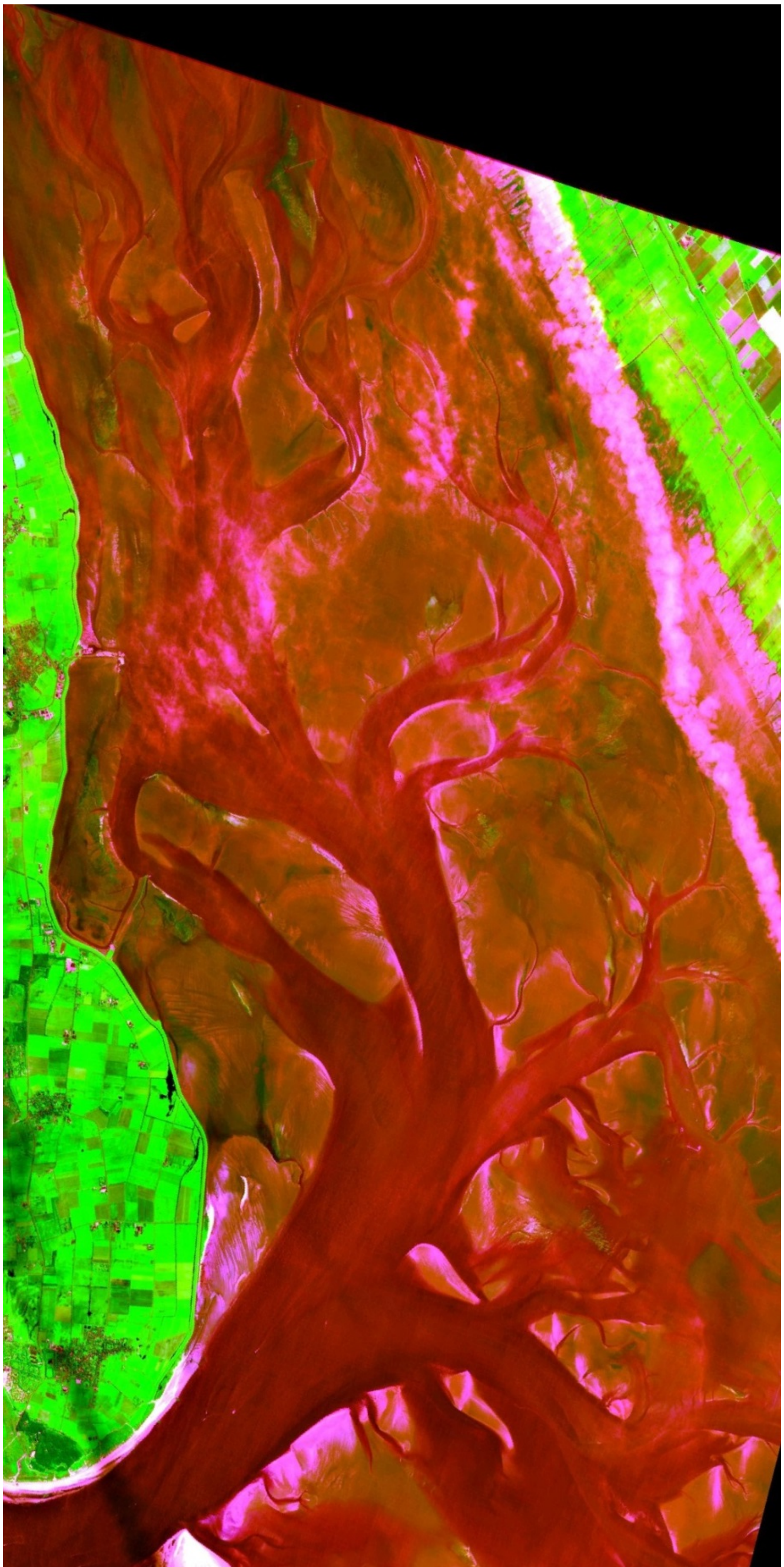

Figure 8- FORMOSAT-2 image, date 08 August 2012, Ameland. Colors - light green: land, greenish and brownish patches on tidal flats: mussel and oyster beds, pink strips along the coast and tidal flats: clouds and haze, dark red-deep color: water, light red: shallow depth areas.

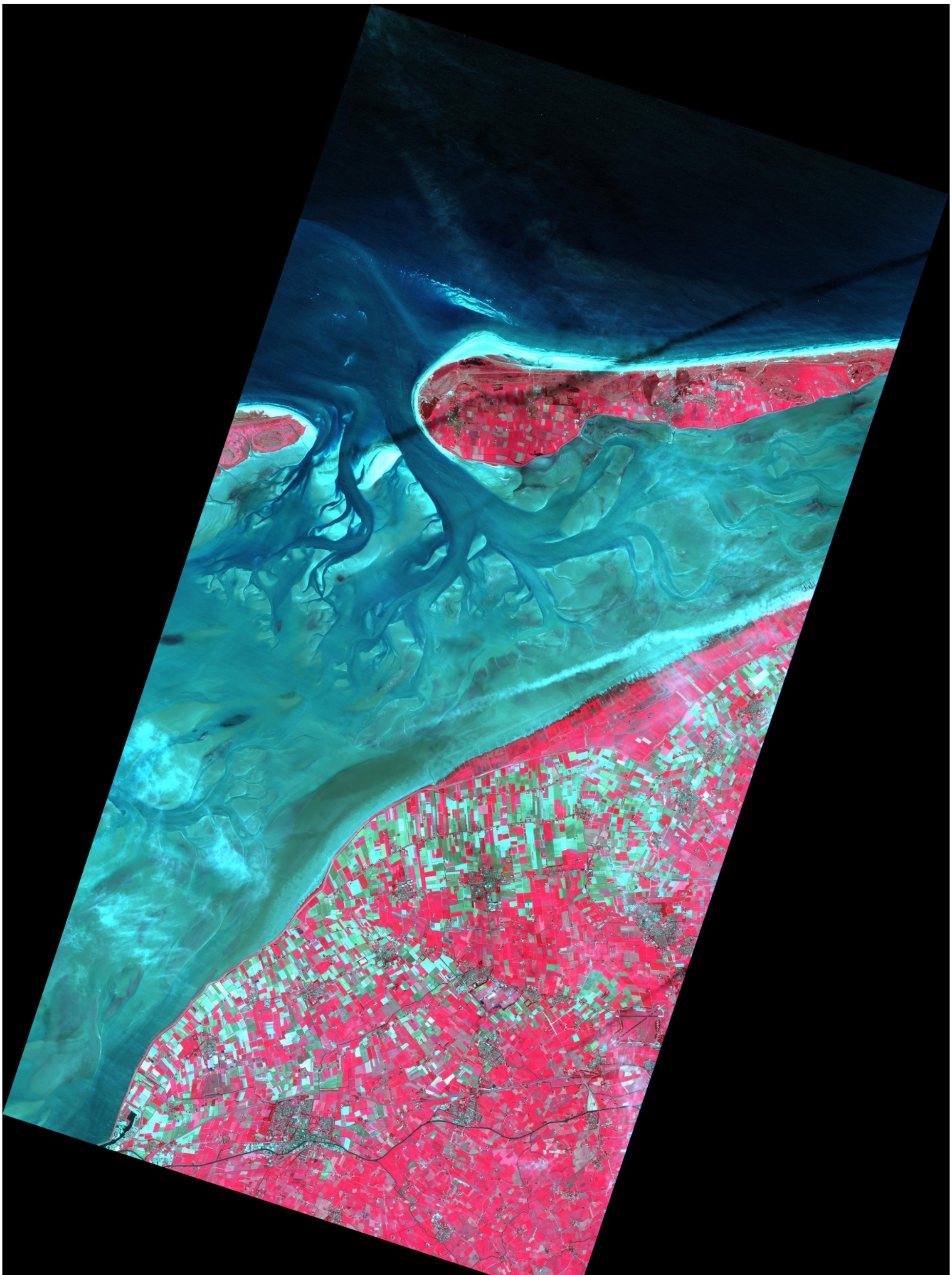

Figure 9-Two FORMOSAT-2 images in mosaic, Ameland, dates- 08 and 13 August 2012. False color composite (vegetation areas in red, water in blue). The red colors on land show crops, white strips along the coast are clouds and haze, greenish areas on the land and on the intertidal flats- areas without vegetation and submerged intertidal flats. The dark blue is water and shallow depth areas are light–greenish blue.

2.3.1 ArcGIS Model Builder tool

The Python script can be integrated into the ArcGIS Model Builder tool. The tool can be uploaded in Arc Toolbox in ArcGIS program (Figure 10).

The advantage of using the Model Builder tool is the ability to merge all operations using one interface, which is convenient and time saving.

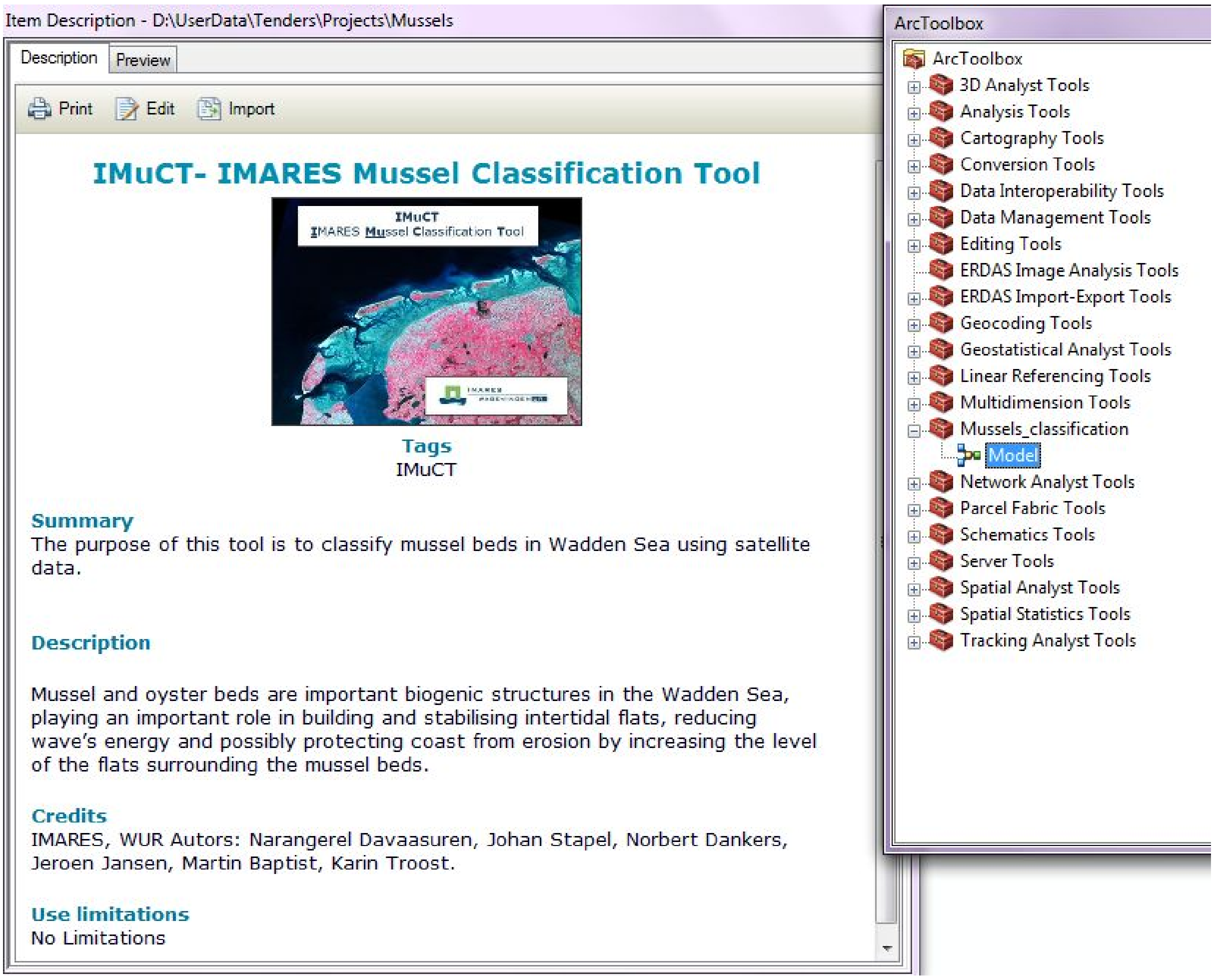

Figure 10-Proposal on mussel classification tool (IMuCT), integrated in ArcGIS.

2.3.2 Image texture and Moran's I statistical analysis

To find the degree of pixel covariance on images before and after the storm, a Moran's I statistical analysis was computed by using an R program. The Moran's I statistical analysis measures the correlation in texture between images from different dates. Computing Moran's I started from sampling, and was completed by calculating the degree of covariance (autocorrelation). For Moran's I analysis two images were used- one image before and second image after the storm. The high Moran's I values in this case indicate areas where changes occurred. A low Moran's I values indicates that no change had taken place.

3. Results

3.1 Temporal and spatial development of location and size of mussel and oyster beds (horizontal development)

Two SAR images from 1995 were selected with the purpose to detect the temporal and spatial development of the location and size of mussel and oyster beds. Before the storm, about 2500 ha of mussel beds in the entire Wadden Sea were recorded. After the storm, which occurred on February 28, 1995 and on March 2-3, 1995 almost half of the mussel beds disappeared. Recovery started in 1997.

A similar event happened during the winter of 2001-2002. More than a half of the young mussel beds disappeared during a winter storm in 2001 (Dankers *et al.* 2004), with poor recovery and continuous mussel bed disappearance and hardly any or no new development of mussel beds in 2002.

3.1.1 Mussel and oyster beds on ERS SAR images

To see the storms' effect, a comparison between two radar images from February 08, 1995 (before the storms) and 25 May, 1995 (after the storms) was made. However, extending a similar comparison to images from 2001 and 2002 was not possible because the images were covering other parts of the Wadden Sea.

The ERS SAR intensity images were used to compute the images of mean and standard deviation, using the ERDAS IMAGINE Focal Analysis tool. The data on mussel and oyster beds, from 1996 and 2000 from IMARES survey (Ende *et al*. 2012) was used to detect the location of mussel and oyster beds on satellite images. For this purpose, the survey data was overlaid with the ERS SAR mean and standard deviation images. The mussel and oyster beds which were clearly identifiable on images, were digitized and their area was calculated. To analyse the change, the areas from both images were compared in size (Figures 11 and 12).

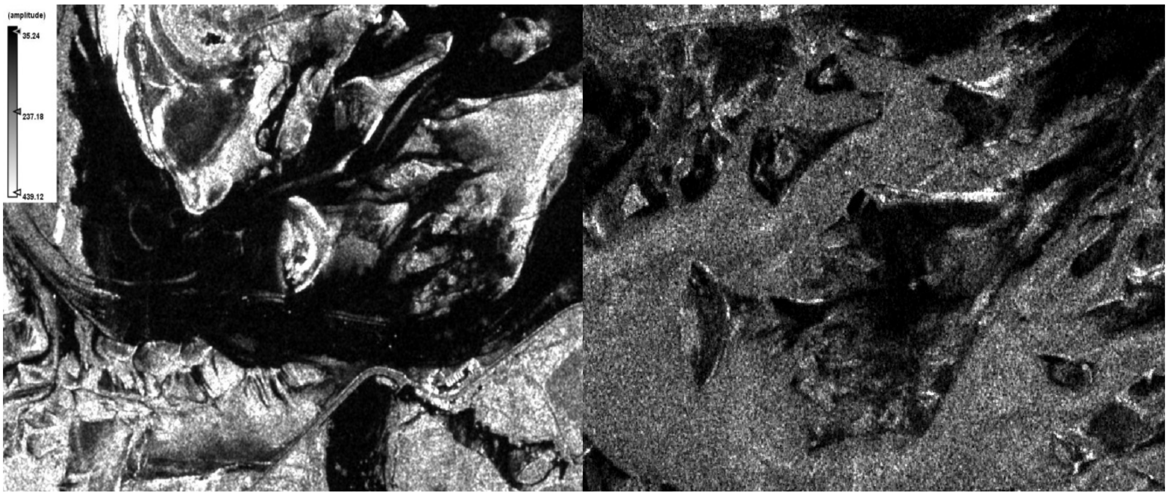

Figure 11-Images from 08 February 1995 before the storm (left) and 25 May 1995 after the storm (right).

Both images before and after the storm represent the actual mussel bed coverage on their respective dates of recording. Comparing image before the storm with survey data recorded in 1995 presents quite well- distinguishable mussel beds (Figure 12- (1) and (2)), while in image after the storm, some mussel beds were missing and mussel bed area was reduced, compare with survey data collected in 1999 (Ende *et al*. 2012) (Figure 13).

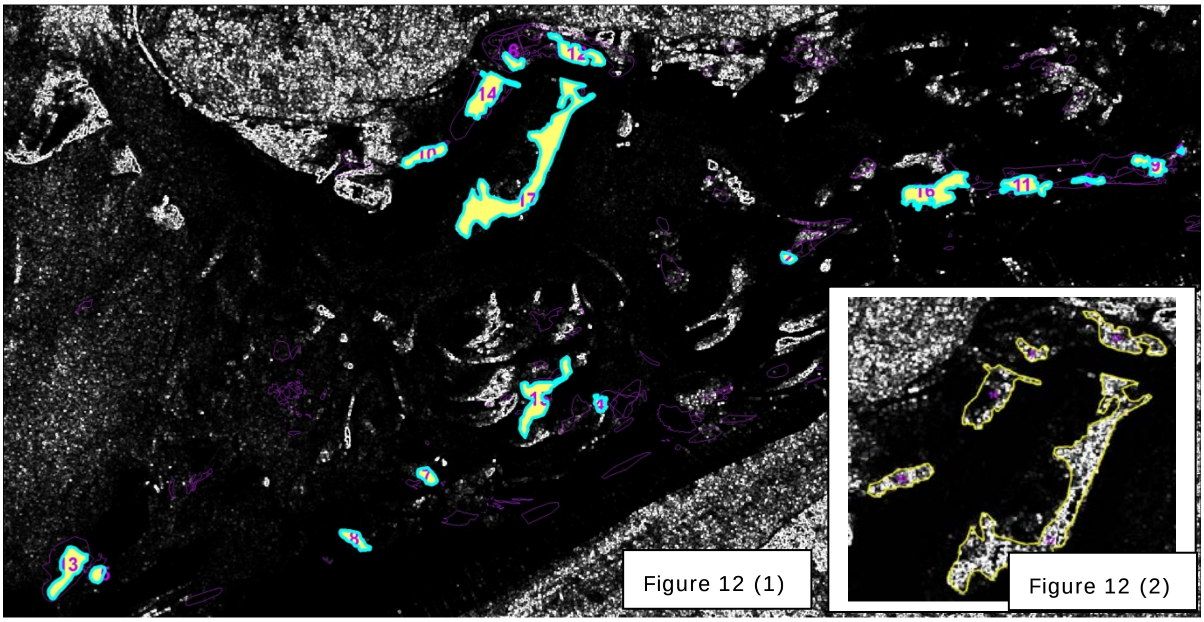

Figure 12-Digitized areas of mussel beds on ERS SAR image from 08 February 1995. The same image zoomed to a large mussel bed (right).

The image after the storm, acquired on 25 May 1995,represents the actual mussel bed coverage on the respective date of recording. A visual representation of change is presented in the image and highlights decrease (Figure 13).

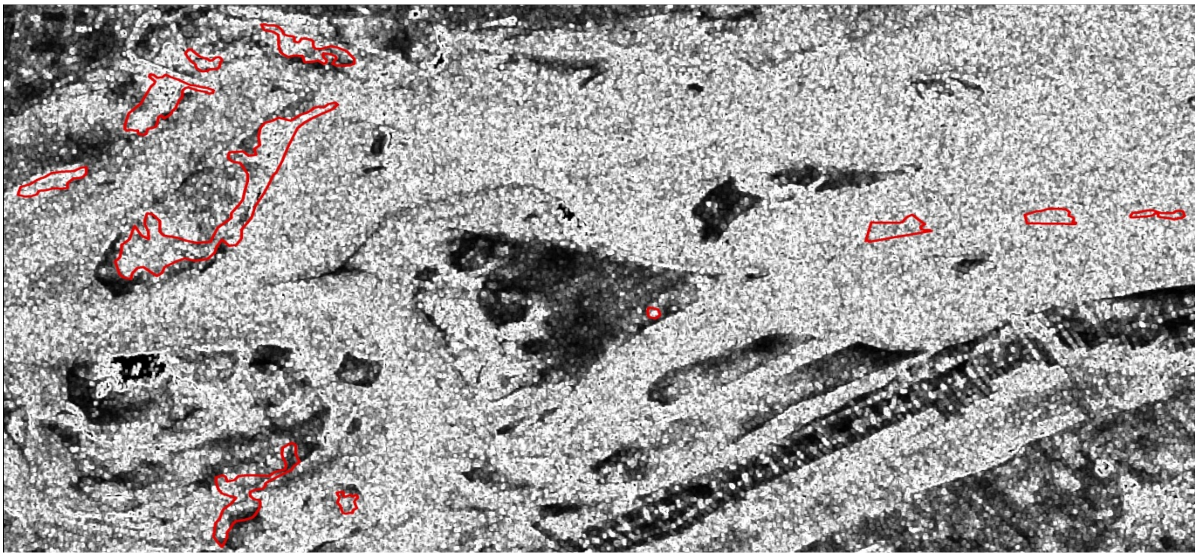

Figure 13-Digitized areas of mussel beds on ERS SAR image from 25 May 1995. The mussel and oyster beds is slightly zoomed in, compare with Figure 12.

The total area of the mussel beds on the image from 08 February 1995 was 382 ha (Table 7) and after the storm, on 25 May 1995, was 303 ha (Table 8).

Table 7-Mussel beds areas (ha), image from 08 February 1995

Marked mussel bed (number)	Area (ha)
1	1
2	5
3	5
4	6
6	7
9	14
10	19
11	23
12	26
14	38
15	44
16	47
17	147
Total	**382**

Table 8-Mussel beds areas (ha), image from 25 May 1995

Marked mussel bed (number)	Area (ha)
*	
2	2
3	5
4	6
6	7
*	
10	16
11	12
12	25
14	38
15	44
16	17
17	131
Total	**303**

3.1.2 Mussel and oyster beds on RADARSAT-2 images

The RADARSAT-2 image from 20 August 2012 presents an overview of the mussel and oyster beds. Due to time constraints, it was decided not to go into details,, but instead try to demonstrate the usefulness and applicability of RADARSAT-2 images for mussel and oyster bed monitoring.

The selected RADARSAT-2 image was processed using the Focal analysis tool, and the mean image was computed. The mean image was overlaid with field data on the location of mussel and oyster beds, to check whether the mussel and oyster beds are visible on the RADARSAT-2 image.

Overall, the visibility of the mussel and oyster beds was good, although a few mussel and oyster beds were not visible, probably due to a difference between data from the field survey and the low resolution of the RADARSAT-2 image (Figure 14). The visible mussel and oyster beds (yellow arrows) are presented in grey color, while invisible beds (brown arrows) are in dark color, similar to color of mud. Related with low resolution of the satellite image, it was not possible to detect small mussel beds, with size less than 25 meters. For this task comparison between different images and detailed survery data is required.

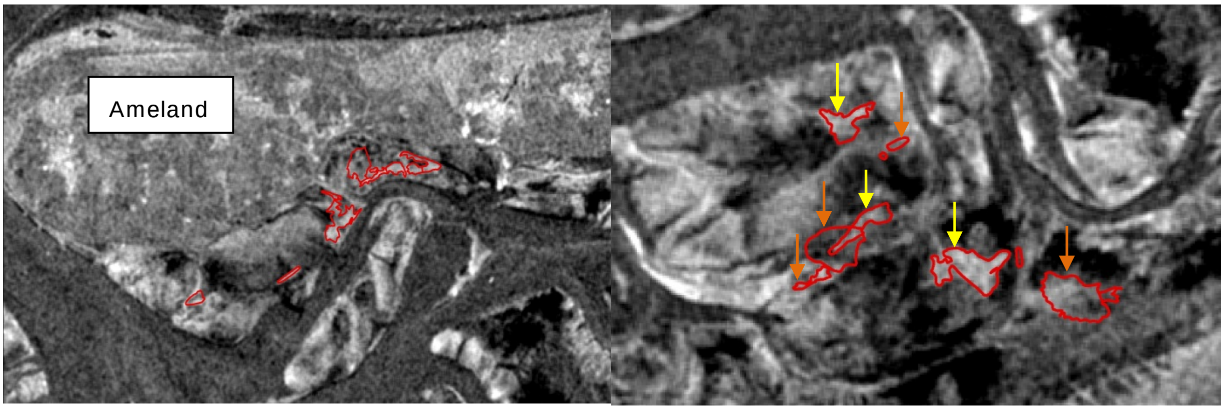

Figure 14-Mussel and oyster beds on the RADARSAT-2 mean image, date: 20 August 2012. Red polygons are surveyed mussel and oyster beds (which year?). Yellow arrows- visible mussel and oyster beds and brown arrows are beds which are not visible.

3.1.3 Mussel and oyster beds on FORMOSAT-2 images

Optical Remote sensing records the spectral characteristics of mussel and oyster beds, assisting in detecting their features. Visually, the intertidal mussel and oyster beds will appear in high resolution (from 2.5 meters and better) and medium resolution (from 10 meters and lower) images in a very distinct color (a very dark appearance compared to bare sediments), shape (stretched patterns along the tidal flats), size (irregular rounded) and shadow (originated from sediment deposits from mussels and oysters) (Davaasuren, Stapel *et.al*, 2012). The mussel bed classification method is described by (Bartholdy and Folving, 1986), (Brockmann and Stelzer, 2008), (Fey *et al.*, 2010) and (Hommersom *et al.*, 2010). In addition the Normalized Vegetation Index NDVI is used to detect macrophytes and the mussel and oyster beds covered by macrophytes (using fiels survey data).

The classification resulted in a shape file, which can be directly used in surveying and mapping and for further processing (Figure 15 and 16).

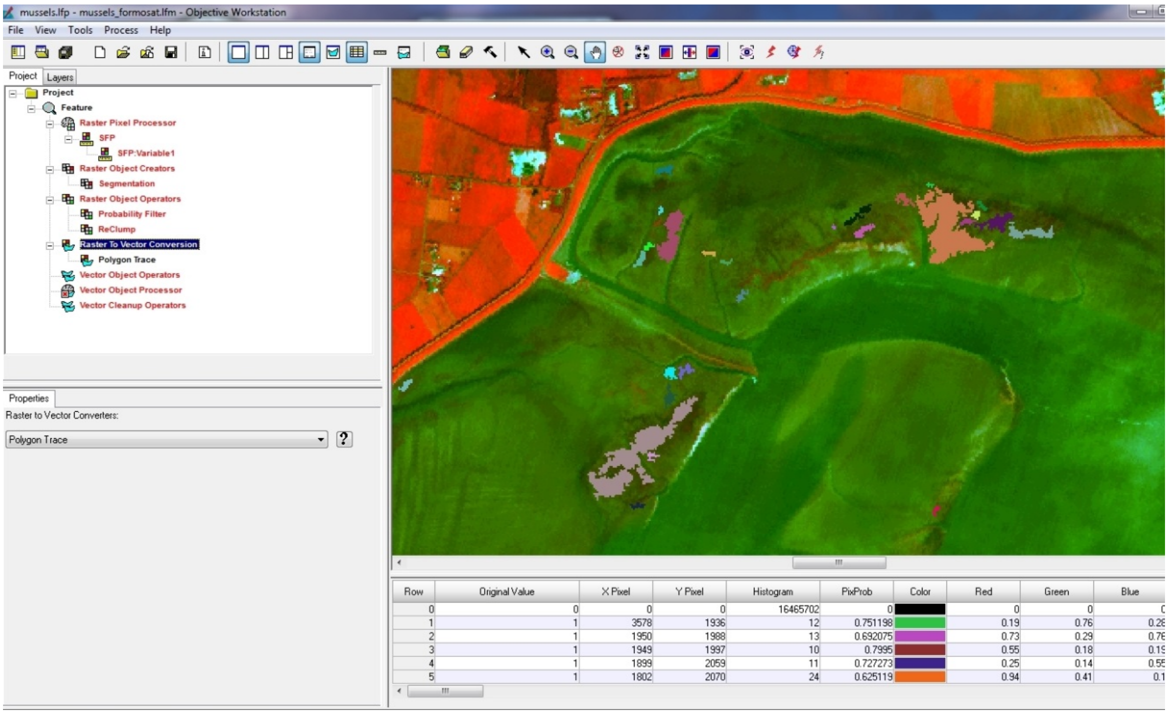

Figure 15-Imagine Objective classification tool, ERDAS IMAGINE 2011. Ameland. FORMOSAT-2 image, date: 08 August 2012. Different coloured fields in the green area of this picture represent areas of mussel and oyster beds identified by automatic classification.

Figure 16-Shape file of mussel and oyster beds (red polygons) classified using Imagine Objective tool on FORMOSAT-2 image, date of acquisition 08 August 2012.

3.1.4 Moisture content, texture and surface structure on radar images

Detecting moisture content, texture and surface structure is an important application of radar images. However, before analysing the textural information, it is necessary to remove the noise, contained in radar images generated from small bright objects. Such noise is called the speckle effect. The advanced Gamma frost filter has proven to be one of the best tools capable of removing such an effect and improving the visibility of the images (Figure 17).

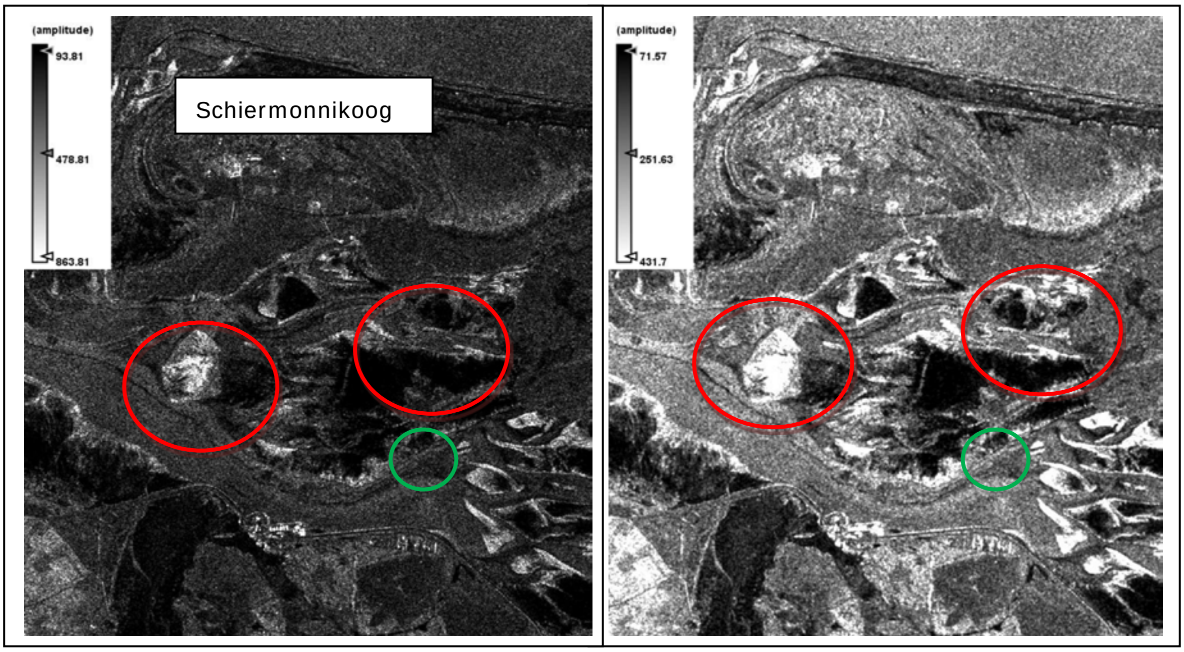

Figure 17- Image before (left) and after (right) applying the Gamma frost filter, together with contract manipulation. Red circles- the mussel beds. The muddy sediments circled in green in both images. Left and right image- ERS-1 SAR, date of acquisition 17 January 1997.

Figure 18 shows objects having different texture, in transition from light to dark grey (sandy sediments) and very light grey (mussel and oyster beds) on ERS images, after applying the Gamma frost filter.

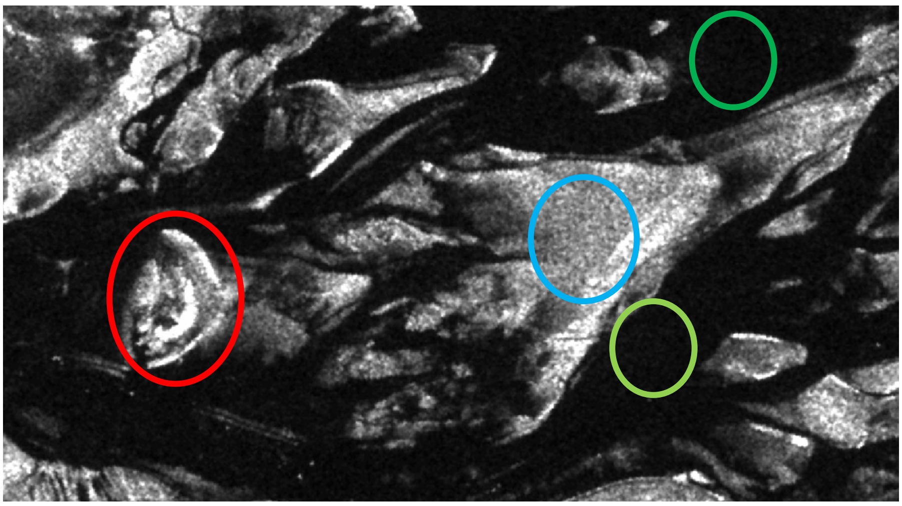

Figure 18- Red circle- mussel bed, blue circle- sediments, green circle- water.

It was decided to analyze the the texture of the mussel and oyster beds using the variance images from ERS intensity images computed from ERDAS IMAGINE Texture tool (Figure 19). Because of irregular surface structure, the mussel and oyster beds are clear on variance images, indicated in yellow and green color and were distinct compare with water (in blue).

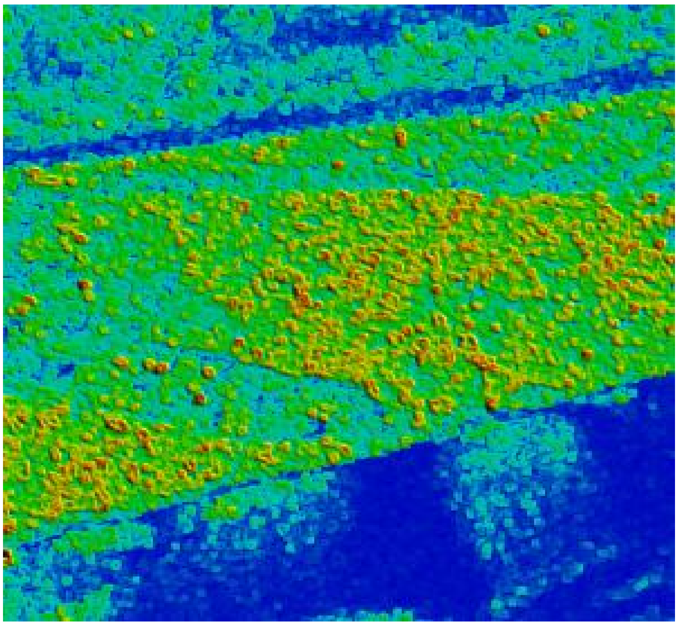

Figure 19- Intertidal flats, Ameland. Variance images. The mussel and oyster beds in yellow color, intertidal flats in green and water in blue.

The variance images were put into Moran's I statistical analysis, from which was revealed, that significant changes in texture of the mussel and oyster beds cannot be well distigwished, nor the changes in the structure of the ERS images taken before and after the storm are not present. For this we can conclude, that the storm did not have any significant effect on the texture of the mussel and oyster beds; changes mainly occurred as to the size of the mussel and oyster beds.

3.1.5 Temporal development of mussel and oyster bed elevation (vertical development)

The Single Look Complex ERS SAR images were used as input to the NEST program. The images were baseline-evaluated (Figure 20), showing the temporal difference between the images over 175 days.

Stack Overview and Optimal InSAR Master Selection

Input stack

File Name	Type	Acquisition	Track	Orbit
ERS2-SAR_IMS_1PXESA20010415_...	SAR_IMS_1P	15Apr2001	380	31296
ERS2-SAR_IMS_1PXESA20011007_...	SAR_IMS_1P	07Oct2001	380	33801

File Name	Mst/Slv	Acquisition	Track	Orbit	Bperp [m]	Btemp [days]	Model Coher...
ERS2-SAR_IMS_1PX...	Master	07Oct2001	380	33801	0.00	0.00	1.00
ERS2-SAR_IMS_1PX...	Slave	15Apr2001	380	31296	-234.87	175.00	0.01

Figure 20-Stack overview of ERS SAR images, acquired on 15 April 2001 and 07 October 2001.

To analyse the images, the precise orbit was first applied. The next step was to co-register the images and to choose the Master (main) and the Slave (secondary) image. The exact co-registration of the images is very important, as it will have an effect on interferometry and coherence generation. For this, sufficient number of Ground Control Points (GCP) is required and which is not always possible to take from areas of submerged tidal flats, due to unpredictability and differences during each tide on amount of sediments and size and location of submerged tidal flats. Related with that it was proposed to choose GCP points from surrounding land, in order to have approximation for co-registration of the tidal flats.

Unfortunately, because of limited time, generation of a Digital Elevation Model, which is required to access the vertical developments of mussel and oyster beds, was not implemented in this study, but will follow in the next report.

The Ground Control Points (GCP) between the co-registered Master and Slave images are displayed in Figure 21.

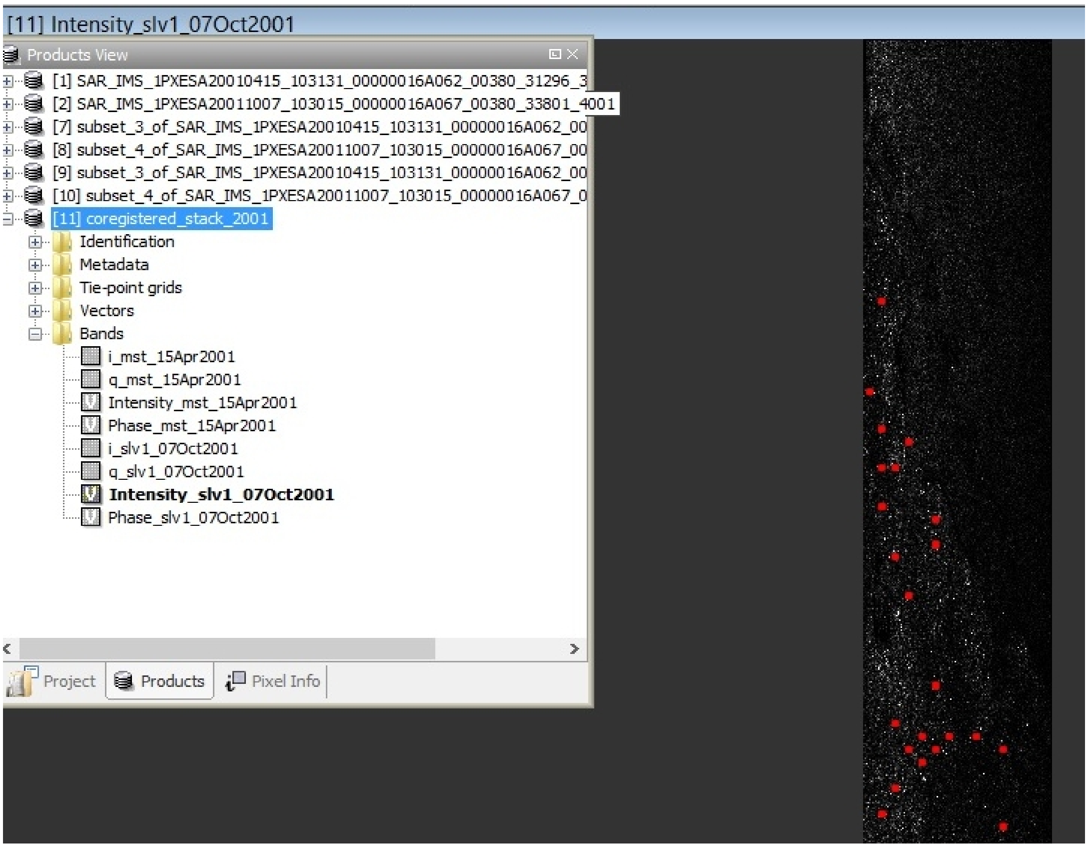

Figure 21-Ground Control Points (GCP) on the intensity Slave image (left), displayed in red.

The overlaid Master and Slave images displayed in Figure 22.

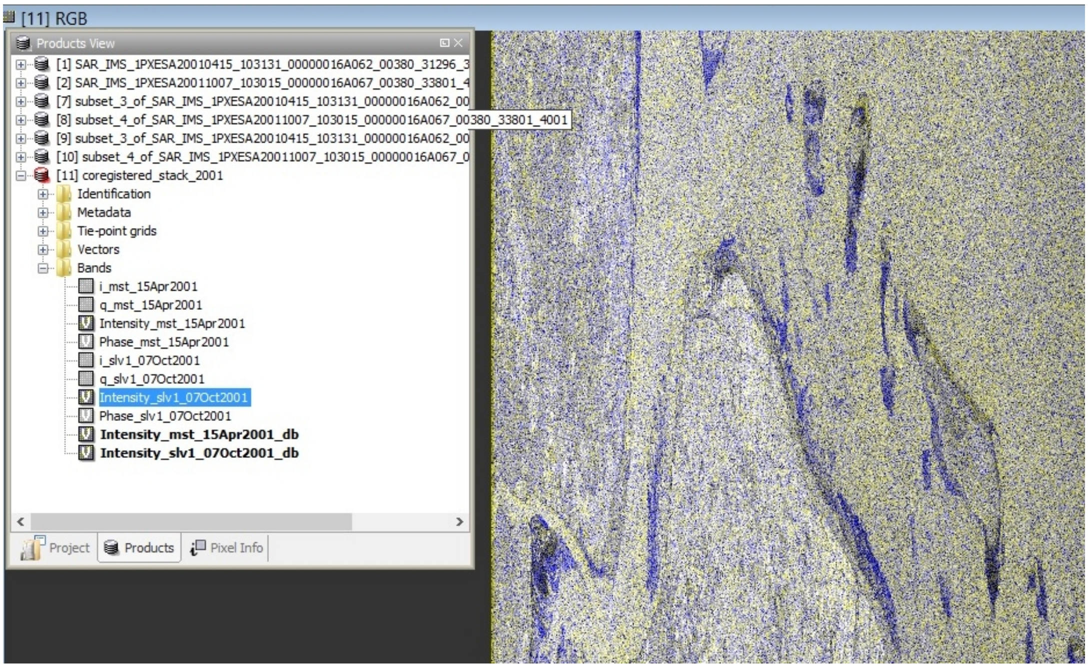

Figure 22-Master and Slave intensity images, presented in color. The tidal flats in yellow colors have very low intensity, meaning no change, the land areas (in dark) higher intensity, meaning there is some change, compare with tidal flats.

4. Discussion

4.1 The method

The radar camera records the amplitude and intensity of the signal, which can be presented in images of amplitude and intensity. The amplitude and intensity images can enhance classification, mentioned in (Engdahl and Hyyppa, 2003), (Del Frate *et al.*, 2008). The other use of amplitude and intensity images is data fusion with multi-spectral images to enhance the visibility of the features.

4.1.1 The specific of SAR radar system

Layover and Foreshortening

The SAR radar system is very different from optical multi-spectral systems. The strength of the signal depends on the distance and height of objects. Areas with many high objects and high mountain terrain have the effect of weakening and scattering of the signal. This is known as effect of Layover and Foreshortening (Figure 23).

Figure 23 describes the Layover and Foreshortening effect on ERS SAR radar images, by showing an example of the first mountain affected by the Layover effect, due to the high incidence (look) angle from the satellite antenna. The second and third mountains producing the Foreshortening effect are visually represented on the image as mountains with very short backsides. The fourth mountain combines all effects of Layover and Foreshortening, and is presented on the image with very long and stretched backsides.

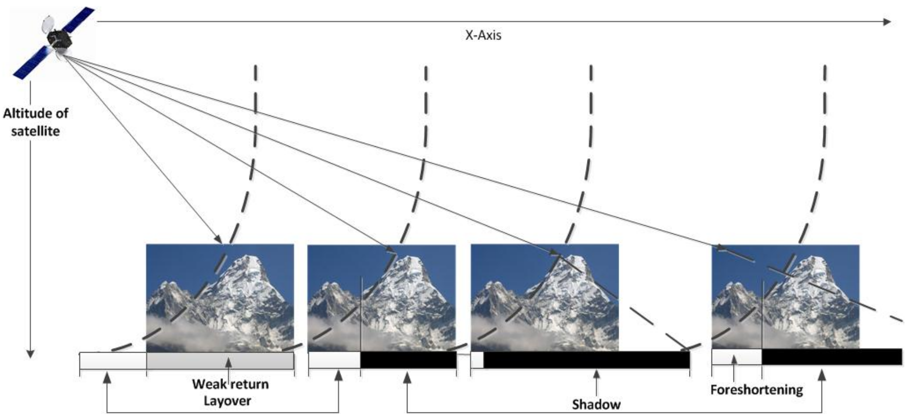

Figure 23- Effect of Layover and Foreshortening on the ERS-2 SAR radar image (picture by the author).

Signal scattering

Another effect from distortions of radar imaging is signal scattering, which can be specular (straight), or corner and diffusive (scattered in different directions). Such scattering happens because of irregularities of objects' structure. An example of differences in scattering is presented in Figure 24, where muddy sediments appear in black, because of homogeneity in the surface structure, and mussel and oyster beds from dark to light grey tone because of irregular and rough surface structure. That happens, because mussel and oyster beds scatter the radar signal in different directions, generating a chaotic collection of the signal by the camera and producing different grey intensity in the image.

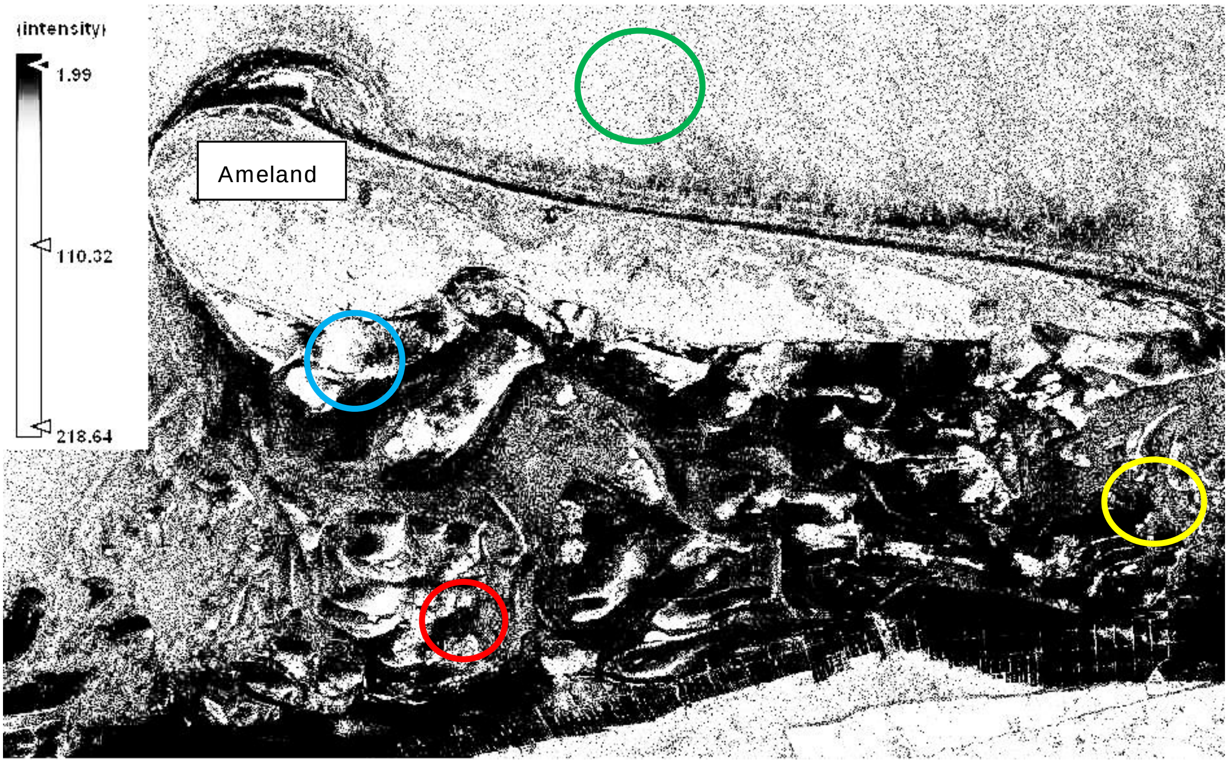

Figure 24-Differences in signal scattering presented on ERS-2 SAR image, Ameland, date 08 February 1995. Areas in red circle mussel and oyster beds; green circle- water; blue circle- sandy sediments, yellow circle- muddy sediments.

4.1.2 Advantage on common interface and tool

The classification tools for optical multi-spectral satellite data are quite advanced. Using the image segmentation and classification tools one is able to distinct algae and other green biomass, using the peculiarities of algae to strongly absorb the red and to reflect the near-infrared lights, which can be recorded by satellite.

The ground survey data plays an important role in initial detection of mussel and oyster beds and validation of the obtained results. The statistical Moran's I analysis delivers information on whether actual change has happened and the degree of covariance (the magnitude of the differences).

4.1.3 Python programming

Python is a programming language which runs on Windows, Linux/Unix, and Mac operating systems. It is open source software, even for commercial products. The recent developments in ERDAS IMAGINE and ArcGIS software have made it possible to connect programs by using a common python programming interface. The scheme of the automated tool for classification of mussel and oyster beds using a python interface, connecting ERDAS IMAGINE and ArcGIS, is presented in Figure 25.

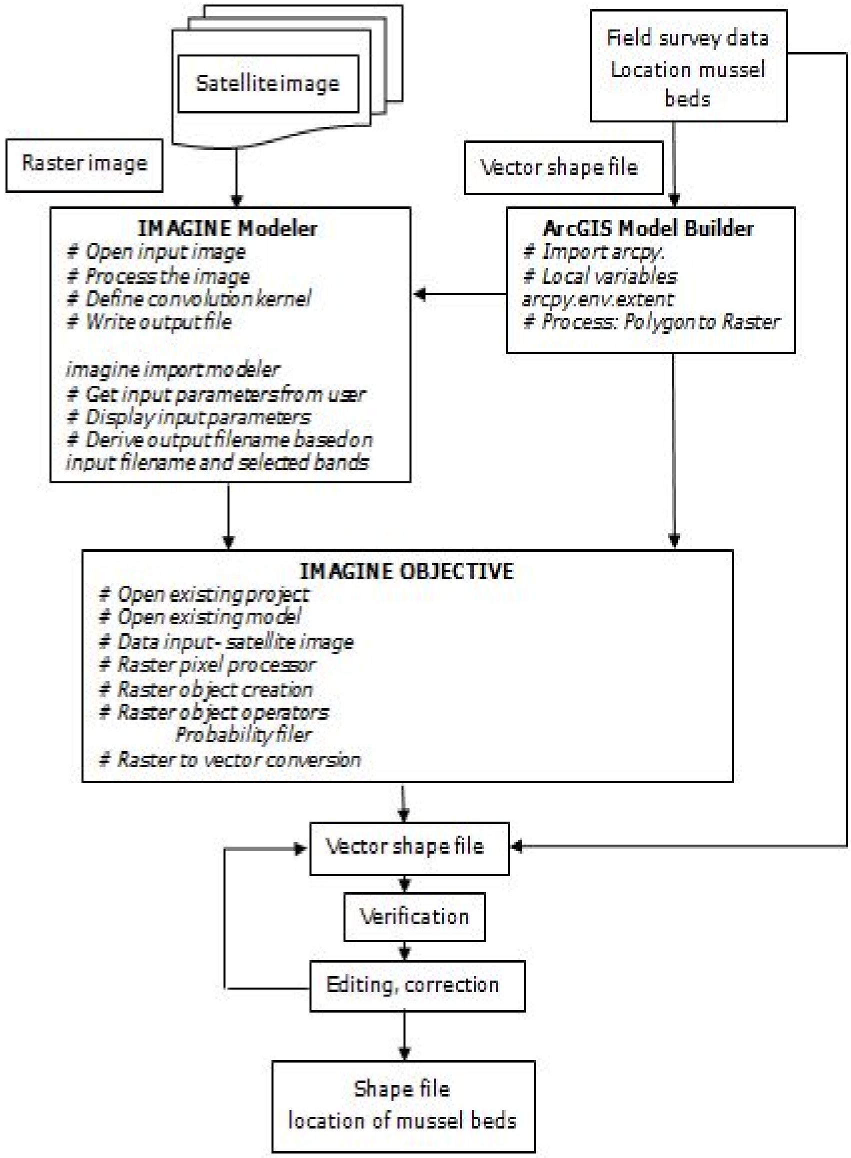

Figure 25-Schema of the automated tools for classification of mussel and oyster beds.

4.1.4 Temporal and spatial development of the location, size and elevation of mussel and oyster beds

Mussels and oysters, which are filter feeders, remove sediment from the water column and contribute faecal pallets back to the sediments, resulting in height development (accretion of intertidal mudflats) and changes in sediment composition, the extent of which depends on the abundance of feeding mussels and on the volume and residence time of the water overlying them (Vaughn et al, 2008). Mussels and oysters herewith modify the surrounding habitat, possibly contributing to reducing wave energy and stabilizing the intertidal areas in the Wadden Sea (Borsje *et al.*, 2011), (Folkard and Gascoigne, 2009) and (Van Leeuwen *et al.*, 2010).

An average mussel bed may contain 0.5 kg of so-called ash-free dry weight of the soft part (AFDW) per square meter (m^2), and with an average mass of let's say 0.5 g AFDW per individual, it constitutes roughly about 1000 mussels per square meter. Each mussel has the ability to filter about 20 litres of water per day and with an average silt content of 40 mg of silt per litre of water, the mussels will filter about 800 grams of silt per day (1000*20*40 = 800 g/d). In total, the amount of silt the mussel bed can contribute will be roughly about 0.5 mm per day, or a theoretical 180 cm per year. A substantial part of captured silt will erode during the storms and tides, but nevertheless, such rough calculation presents the role of mussel and oyster beds in sediment accumulation and stabilization of the tidal flats, and their contribution to vertical development (personal communication Bert Brinkman, Research scientist, Ecosystem department, IMARES).

Detecting the spatial and temporal development of mussel and oyster beds is important, as it will provide information about previous and presently on-going changes which might affect the stability and development of the mussel and oyster beds. In this case, satellite radar data can provide information about the texture, shape and surface structure of the mussel and oyster beds, combined with historical information dating back to 1990s, useful in long-term monitoring to a degree of precision of 12.5 meters. The recent advances of FORMOSAT-2 multi-spectral data down to 8 meters resolution provides information on their location and size, In this context the data fusion of radar and multi-spectral data produces an advanced image, inheriting the capability of radar and multi-spectral data, enhancing the visibility of the mussel and oyster beds, and the accuracy of their classification.

The main challenge to be solved in detecting the elevation of intertidal flats is that intertidal flats have few “hard” and stabile (i.e. no vertical variation) structures which can be used as reference points, but which are required to compute a good quality interferogram and Digital Elevation. The current study has been dedicated to fine-tuning methods for spatial detection and the identification of mussel and oyster beds using Remote sensing; and to evaluate possible tools for assessing their vertical development. With respect to vertical development, the research was successful in selecting pairs of ERS-2 radar satellite data suitable for data pre-processing, interferometric processing and processing of co-registration of the images over the intertidal flats (Ameland), for which a sufficient number of reference points were acquired.

The preliminary results on detecting the elevation of mussel and oyster beds presented in this study show promising perspectives for developing a remote sensing based approach to monitor vertical developments. Unfortunately, because of limited time, generation of a Digital Elevation Model, which is required to access the vertical developments of mussel and oyster beds, was not implemented in this study. It is suggested that further research continues with the current findings, by adding additional (land based) reference points and by using far more advanced image processing GAMMA software that specializes on interferometric processing.

4.1.5 Automated tools for classification of mussel and oyster beds

Using the Model Builder tool and programming all commands beforehand in one common interface has the distinct advantage that it can be used and run by anyone without prior knowledge of ArcGIS, ERDAS IMAGINE and programming tools. In this case, the model builder is responsible for writing the python script, specifying all commands, setting and selecting the classification parameters and producing a step by step manual, to be followed by people working with the inventory of the mussel and oyster beds. A similar tool is presented in the Co-EXIST project, on building suitability models for aquaculture, using the same principle.

4.1.6 False classification / problems encountered

False classification may easily occur when comparing satellite images acquired at different dates and different tidal phases, due to differences in tidal levels. To reduce such uncertainty it is recommended to validate the results from classification by using ground/survey data.

4.1.7 Evaluation and assessment of uncertainties

Shape represents the boundary of an object. When objects are crisp, the boundary is clear. When objects are fuzzy, detecting the boundary becomes problematic. In general, there are up to three levels of uncertainties (Molenaar, 2000) which may apply to classification of mussel beds:

- The existential uncertainty, whether we are certain that this object (the mussel bed) exists
- The geometric uncertainty, the precision of the boundary of the object (the mussel bed)
- The extensional uncertainty, whether the area covered by the object (the mussel bed) can be detected with very limited uncertainty.

All three levels of uncertainty will affect the area detectable on satellite images to a different extent, and such uncertainties can also apply during the field survey, since visibility of the mussel and oyster beds are dependent on the water level during each tide.

To reduce these uncertainties, it is recommended that both satellite mapping and field surveys are combined, and to check the quality (positional accuracy, corrections applied, etc.) of the satellite images used in the classification.

Figures 26 and 27 present an example on the difference of mussel bed coverage between February (before storm) and June (after storm) 1995. However, seasonal dynamic of the intertidal flats and tidal variations (Table 9) may affect the classification accuracy of satellite images. Tidal variations always have an effect on the visibility of the mussel and oyster beds on satellite images, which may be 'hidden' below the water surface on one image, and exposed (and thus 'visible' by satellite) on the other image. In that case, differences may not be attributed to be caused by the storm.

Table 9-Single ERS-2 images (ground resolution: 12.5 meters)

Image acquisition dates	Acquisition time (CET)	Tide level (in meters), Lauwersoog station, Netherlands
08 February 1995	21:38:39.28 (21 min before Low tide)	21:59 PM 0.62 meters Low Tide (NAP) 4:04 AM 2.45 meters High Tide (NAP)
02 June 1995	21:38:00.01 (1h 42 min after Low tide)	19:56 PM 0.22 meters Low Tide (NAP) 1995-06-03 2:02 AM 2.53 meters High Tide (NAP)

According to measurements from Lauwersoog station, the low tide water level difference between the two dates is about 0.40 m (Table 9). As can be seen from both images the exposed area of the intertidal flats is very different (Figure 26, 27).

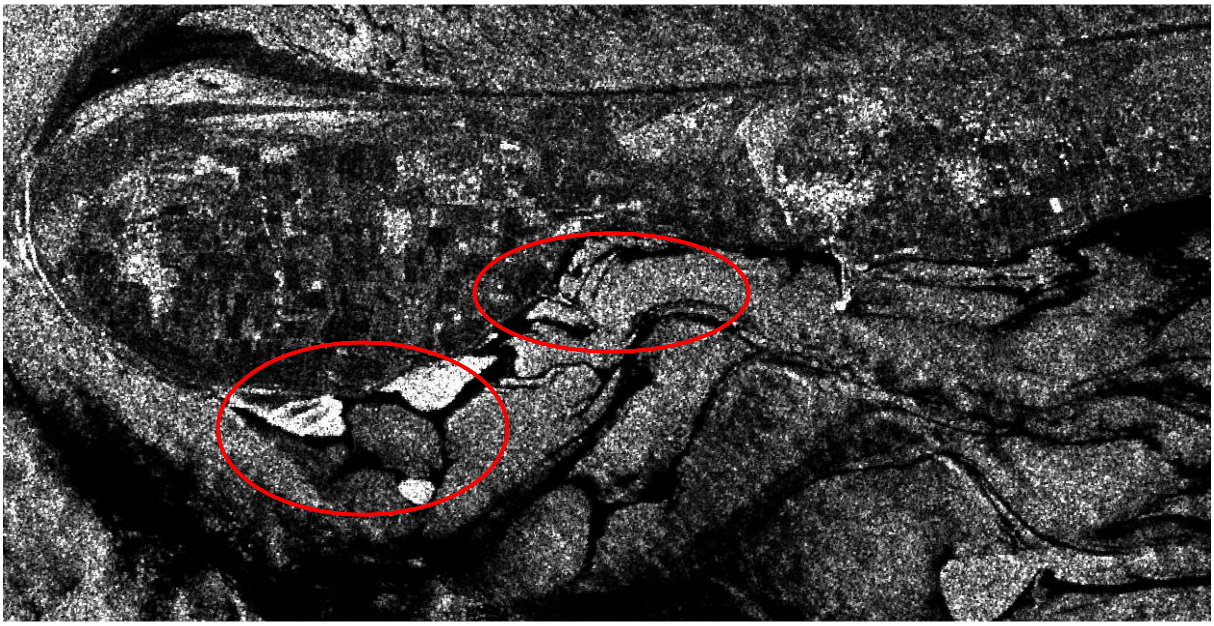

Figure 26-ERS SAR image from June 02, 1995. The red circles are tidal flat areas, with some inclusion of mussel and oyster beds, light grey on right circle.

Figure 27-ERS SAR image from February 08, 1995. The red circles are tidal flat areas, with some inclusion of mussel and oyster beds, light grey in the right circle.

In general, to be able to analyse the seasonal changes on mussel and oyster beds, images taken during September-October, February-April and July-August will be the most suitable for mutual comparison. In some exceptional cases, like after storms, additional images may be acquired to study the impact in detail.

4.2 Applicability in surveys

4.2.1 Assessment of the classification and the temporal and spatial development tool for mussel and oyster beds

The following steps are proposed in developing an automated mussel and oyster bed monitoring tool:

1. Spatial co-registration of Remote sensing images, to be able to compare multi-source images in different resolution at pixel level.

2. Image pre-processing.

The SAR images often show a noisy appearance caused by speckle. Pre-processing of the SAR images, applied to reduce and to remove the speckle effect, such as Gamma frost filter, is recommended. The atmospheric correction for multi-spectral images is important, as it enhances the visibility of the mussel and oyster beds, compared with surrounding sediments.

3. Selecting classification methods and tools.

The simple classification of ERS SAR data was conducted by using four four main characteristics of the radar system:

- Tone
- Shape
- Structure (of the object)
- Size.

The tone on radar images appear as average intensity of the signal. The light tone records a high intensity signal and dark areas are signal of low intensity. For our case the areas in light tone and therefore the high intensity of the signal refers to deep water, very dry sediments and mussel beds. The areas in dark tone and therefore low intensity indicate shallow water areas, smooth surfaces and sediments and mud with high water content.

The size of mussel and oyster beds can be computed by using information from multi-spectral FORMOSAT-2 images, and ERS SAR radar images.

The Imagine Objective classification tool proofed to be successful in the classification of multi-spectral satellite data, seen on the example of the FORMOSAT-2 image (Figure 19).

4. Multi-scale analysis.

It is necessary to consider difference in resolution when satellite images are taken from different sources. Using satellite data taken from different satellites, e.g. multi-spectral and radar, will always create a resolution bias. In our case we dealt with radar images in two spatial resolutions, ERS-2 in 12.5 meters and RADARSAT-2 in 25 meters, together with multi-spectral FORMOSAT-2 image in 8 meters resolution. In our study we used for valiadation of the results obtained from satellite data the survey data and therefore the image resampling was not used. However, if processing, e.g. classification of the satellite images taken from the different platforms (e.g. radar and multi-spectral) will be implemented before the ground survey, in this case for validation and for comparison of the final results, the adjusting and converting all images to one “common” resolution, considering which resolution is most suitable for the analysis must be made.

5. Change detection analysis.

A comparative analysis of independently produced classifications and simultaneous analysis of multi-temporal data should be performed to detect temporal changes. In this case, problems of dealing with uncertainty have to be addressed. Addressing the questions of data quality from different sensors, and data pre-processing and processing are important in checking the accuracy of the classification.

4.2.2 Implications for field monitoring and relevance for clients

The steps taken towards developing a tool for assessing spatial and temporal developments of mussel and oyster beds presented in this study show promising perspectives. It is proposed to further the tool development process based on the results obtained up to this point, and to extend the process to cover the entire trilateral area of the Wadden Sea.

For this purpose, a Common Interface Tool needs to be furthered and the method for analysing mussel and oyster bed elevation and vertical development needs further investigation. An easy way of selecting satellite images for different parts of the international Wadden Sea area that are cloud free (multi-spectral images) and taken during low tide is highly recommended, e.g. by automated scanning of meta-data.

The developed method has relevance for Wadden Sea management, Natura 2000 management, coastal zone management, Delta Programme Wadden Sea, Building with Nature, "Towards a Rich Wadden Sea" and WaLTER (Wadden Sea Long Term Ecological Research). Potential clients are local and national governments, mining industry, mussel industry and GOs. Remote sensing improves monitoring programs covering larger spatial scales at a higher temporal resolution, and at lower costs. It may prove usable as an early warning instrument for e.g. potential negative developments in relation to accelerated sea level rise.

5. Conclusion

The developed products and expertise will contribute to IMARES by serving as a first step in setting up new automated inventory systems which can be used to optimize the monitoring strategy for intertidal mussel and oyster beds and to obtain additional information on the elevation of these beds for monitoring the development of mussel and oyster beds (areal coverage, spatial distribution, elevation). Overall, it will expand the expertise of IMARES and WUR concerning new, innovative methods based on Remote sensing. The project aims at developing new markets and expanding the expertise of IMARES and WUR in new applications of satellite data and Remote sensing techniques. Some of the main target groups for technology transfer will be coastal municipalities, local administrations and coastal managers and mining companies, as monitoring of the processes in the Wadden Sea is important for coastal defence and infrastructure development along the coast, and for nature conservation. The results and methods can be used in countries with similar ecosystem settings of intertidal flats and mussel and oyster beds, for example including the UK, Denmark, and Germany. The technique and results may serve as a tool and method for the EcoShape Building with Nature consortium, the Delta Programme Wadden Sea and the NGO program “Rijke Waddenzee” as an alternative strategy in coastal defence solutions.

The proposed research is novel in that it combines satellite data from different platforms (i.e., multi spectral and radar) with detailed results from an on-going, long -term monitoring programme in which mussel and oyster beds are field surveyed and mapped throughout the Dutch Wadden Sea. The project will serve as the first step in developing an automated, modern tool producing continuous up-to-date and accurate information on spatial and elevation development of the mussel and oyster beds in the Wadden Sea and to assess the (qualitative and quantitative) contribution of mussel and oyster beds to vertical development of (intertidal) mudflats.

It is beneficial to use such advanced tools, because it will increase monitoring coverage, improves time efficiency, reduce the time spent on mapping and allows shifting focus from (quantitative) mapping activities to more qualitative monitoring of shellfish beds. Challenges in mapping the locations of mussel and oyster beds during field surveys may include the constraint of the number of locations that can be visited each year and areas that are difficult to access. However, satellite data provide regular full synoptic views over large areas.

Field surveys will continue to play an important role and it will remain an essential component in the proposed advanced monitoring system. The direct benefit of integrating remote sensing techniques will be a qualitative shift from solely operational mapping work, to the ability to perform detailed scientific analyses of the intertidal ecosystems of the Wadden Sea. It will help research institutes and policy makers internationally to advise on and to make evaluated knowledge based management decisions for the Wadden Sea and comparable ecosystems.

Quality Assurance

IMARES utilises an ISO 9001:2008 certified quality management system (certificate number: 124296-2012-AQ-NLD-RvA). This certificate is valid until 15 December 2015. The organisation has been certified since 27 February 2001. The certification was issued by DNV Certification B.V. Furthermore, the chemical laboratory of the Fish Division has NEN-EN-ISO/IEC 17025:2005 accreditation for test laboratories with number L097. This accreditation is valid until 1th of April 2017 and was first issued on 27 March 1997. Accreditation was granted by the Council for Accreditation.

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Justification

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The scientific quality of this report has been peer reviewed by the a colleague scientist and the head of the department of IMARES.

Approved: Karin Troost
Researcher

Signature:

Datum: October 28th 2013

Approved: Floris Groenendijk
Head department Maritime

Signature:

Date: October 28th 2013