Overview of satellite data for long-term monitoring in the Wadden Sea, WaLTER

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Summary

The Earth Remote Sensing observation started around 1980s, with the launches of Landsat, SPOT and ASTER satellites. In 1999, the ESA launched its first European Earth Resources satellite ERS-1 and ERS-2. The increasing use of satellite data, methods and tools actively started since then, involving both scientific and commercial users, which became dependent on the continuity of satellite missions.

Remote sensing nowadays is an almost indispensable tool in habitat mapping and monitoring. The numerous advantages of satellite data include global coverage combined with daily revisiting and relatively low cost, making it attractive to use in various infrastructural, agricultural and environmental monitoring programmes. The usability of satellite data specifically for monitoring certain parameters in the Wadden Sea is restricted by weather conditions and the tidal period. To use satellite data in Wadden Sea monitoring programmes, the existing advantages and disadvantages of the satellites' systems design, the range of wavelengths recorded and the resolution of the satellites' sensors need to be analysed in relation to the ecological specifics of the Wadden Sea habitats. The precision of satellite data, e.g. the ground resolution of the satellite sensor is an important factor restricting the potential usability of satellite data. Low resolution (from 200 meters and more) is in general not suitable for monitoring most Wadden Sea parameters that are of ecological interest. Data in medium resolution (starting from 30 meters) are found applicable for sediment classification, identification of locations and size of mussel and oyster beds and intertidal flats, the location of the coast line, gullies and channels. The usability of medium resolution data is limited for classification of vegetation on wetlands and salt marshes, because of high spectral mix and uncertainty in distinction of plant community types. Atmospheric correction of multi-spectral images is important, as it improves visibility of ground features that is normally reduced by smog, fog and presence of water particles in the atmosphere.

Classification algorithms for a highly dynamic and heterogeneous area as the Wadden Sea are very habitat specific. The spectral properties of the objects in the Wadden Sea are strongly dependent on water content, submergence duration of the tidal flats and their heights relative to mean sea level, and the area extent of the objects and surface structure. The specifications of parameters, objects or processes to be monitored determine to a large extend the choice of resolution of the satellite data, pre-processing and processing algorithms, the classification methods needed for monitoring, and the required satellite sensor. There are three important factors that need to be taken into account when trying to classify Wadden Sea habitats:1) the relationship between sediment water content and reflectance, 2) the correlation between sediment composition (grain size) and reflectance and 3) the distinct spectral reflectance of mussel and oyster beds (or other surface features) compared with surrounding sediments.

The classification methods which are suitable specifically in the Wadden Sea are spectral unmixing, supervised classification and change detection using multi-temporal images.

A sustainable data provision is very important in ensuring the functioning of a monitoring system into the future. In this respect the main data provider for the Wadden Sea, the European Space Agency (ESA), has a policy to provide data from ESA and Third party missions free of charge to Europe's scientific and commercial communities and to continue consistent data provision in the future, e.g. with the launching of the Sentinel satellites. As of 2012, the Netherlands Space Office provides medium resolution satellite data to the Netherlands scientific and commercial communities free of charge (FORMOSAT-2 (2 and 8 meters), DEIMOS-1, 2 UK-DMC-2 (22 meters), Radarsat-2 (25 meters) and radar Radarsat-2 (25 meters)). The data is divided in two main groups: the free dataset and restrained dataset. The only difference between these datasets is the requirement of a scientific proposal for restrained data, allowing ESA to plan the data acquisition and allow time to process the data from historical archives.

The activities of European Space Imaging are aimed to provide very high resolution satellite data to European users. The activities includes near real-time data tasking and rapid delivery (within 1 to 3 hours) of satellite data for European waters or under Emergency delivery conditions (24 hours) for the rest of the world. The latest developments at ESA concern provision of Third party missions and historical data from some commercial missions free of charge to European user's community. The latest example is

an ESA agreement with RapidEye high resolution satellite company to provide historical data of RapidEye starting from 2009, on so-called demand basis.

The sustainability of long term monitoring methods and tools will be not affected by changes in the satellite missions, as current policy of ESA and other satellite companies is to ensure the continuity of spatial resolution, revisiting frequency and range of the wavelengths in new missions of radar and multi-spectral satellites. They also ensure the interoperability between historical, present day and future missions.

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1. Introduction

1.1 Opportunities for Remote Sensing

Until now many people have used satellite data for specific investigations, however often from a "sectoral" approach. Often detailed ground truth was missing or specific knowledge on Remote sensing was not available to field workers. Now data become more readily available at low cost and computers are cheap and fast enough to deal with large data sets and new promising applications appear. Much can be expected from using data from very different platforms (multi/hyper-spectral and radar) in combination with good ground truth. When developed in a specific well studied area it is expected that the methodology can be extrapolated to a larger spatial scale and to shorter temporal scales thereby also allowing studying processes instead of being "only" descriptive.

1.2 WaLTER program

One of the aims of the WaLTER project (Wadden Sea Long-Term Ecosystem Research) is to define an integrated monitoring plan for environmental and managerial issues that are relevant to the Wadden Sea area, in relation to issues such as sea-level rise, fisheries, recreation and industrial activities. The monitoring network should provide an effective basis for decision-making, and stimulate valid data interpretation. The participants of the WaLTER project include a number of institutes and organisations that carry out long-term measurements and research in the Wadden Sea area. The project is financed by the Wadden Fund with supporting contributions from the Provinces of Noord-Holland and Fryslân.

1.3 Remote sensing

Remote Sensing in the Wadden Sea

Remote sensing has been used as a monitoring tool in the Wadden Sea since about 30 years. One of the first attempts was to classify the sediments by grain size and composition in the Wadden Sea in the 1980s, using Landsat TM and MSS-4 satellite data, in a resolution of 30 and 60 meters (Bartholdy and Folving, (1986)). The analysis combined satellite data and spectrometry measurements to classify different sediment types, validated with ground measurements on intertidal flat sediment composition.

Back in the 1980s, the sources for satellite data were quite limited. All data were commercial, and pre-processing required substantial funds and knowledge on data processing methods and tools. Historical data covering the Wadden Sea go back to the 1980s and are available from U.S.A National Aeronautics and Space Administration (NASA) and the U.S.A Geological Survey (Landsat), with latest data provided by the French Space Corporation (SPOT satellite). The historical Landsat and SPOT missions continued with missions till the present day.

New advances in satellite design initiated by the Japan Space Agency (NASDA) in 1999 provided multi-spectral data from the ASTER satellite, in resolution of 15 meters. This satellite imaged the entire globe, including the Wadden Sea. Data for a specific area of interest can be acquired through a satellite tasking process.

Starting in 2000, the European Space Agency initiated radar missions with the launching of the ERS-1 and ERS-2 satellites, providing data a resolution of 12.5 meters.

A new era in commercial high resolution imaging, the IKONOS, Quickbird and Worldview-2 missions provide panchromatic band data in a resolution of a few centimetres, and up to one meter in multi-spectral bands.

1.4 The objective

The objective of this report is to provide an overview of historical, present and future satellite data, applicable for long-term monitoring in the Wadden Sea. The potential use and limitations of satellite data is discussed and short descriptions of each mission are presented. The aim of this study is to know whether Remote sensing and changes in satellite missions could potentially be used for or affect the sustainability of current long term monitoring methods and tools.

The general objective

The general objective focusses in particular on sediment classification, identification of locations of mussel and oyster beds, intertidal areas, coast line, salt marshes, gullies and channels, and the detection of temporal and spatial changes thereof.

To meet this objective, an overview of historical and present satellite data and methods used for Wadden Sea monitoring is provided. The continuity of historical and present-day missions is discussed in relation to future missions. Factors restricting satellite data availability such as weather conditions (clouds) and tide, limiting the usability of Remote sensing in monitoring programmes, are discussed in Section 3.1.

The specific objective

The specific objective of the study is to define the usability of Remote sensing and the availability of satellite data and tools for long-term monitoring of the parameters in the Wadden Sea as specified in the 5 parameter groups of the WaLTER project (Figure 1).

Figure 1 presents the available data sources specified in the WaLTER project, covering the trilateral area of the Wadden Sea (the Netherlands (NL), Germany (D) and Denmark (DK)). A more detailed description of the data sources can be obtained from the inventory project for the Program "Rijke Waddenzee" Kraft et al (2011) and Folmer (2012). The need for better data inventories and more detailed description of existing methods for research in the Wadden Sea is presented in report by Folmer (2012).

Parameter Group Parameter	Demand	Quality	Effort	Availability			Spatial coverage			Sources		
				NL	D	DK	NL	D	DK	NL	D	DK
General												
bathymetry	H		L	H	M	M	A	A	A	RWS	*BSH*	*DMSA*
hydrology[k]	M		M	H	M	M	A,P	A	A	RWS[Lit]	COASTDAT	COASTDAT
sea water level	H	H	L	H	H	H	P	P	A	LMW	*BSH*[f]	TMAP
sediment[l]	H		M	H	M		A,P	A		RWS	*BSH*	
weather, climate	H	H	L	H	H	H	P,A	A	A	KNMI, Cesar	*DWD*	DMI
land cover	M	H	L	H	H	H	A	A	A	CLC	CLC	CLC
Physical												
temperature	H	H	L	M	H	H	P	P,A	P,A	RWS	BLMP[d], TMAP[e]	MADS
salinity	H	H	L	M	H	H	P	P,A	P,A	RWS	BLMP[d], TMAP[e]	MADS
currents	H	M	L	M	H	H	A,P	A	A	HMCN, COASTDAT	COASTDAT	COASTDAT
waves	H	M	L	M	H	H	A,P	A	A	HMCN, COASTDAT	RA[g],COASTDAT	COASTDAT
Chemical												
chlorophyll	H	L	M	H	L	H	P		P	RWS		MADS
nutrients	H	M	H	H	M	H	P	P	P	RWS, TMAP	BLMP, TMAP	MADS, TMAP
turbidity	H		L	M	H		P	P		RWS, TMAP	BLMP, TMAP	[c]
organic matter	H	M	H	M		H	P			RWS, TMAP	[c]	[c]
pH	H		L	H	H		P	P		RWS, TMAP	BLMP, TMAP	[c]
oxygen	H	L	L	H	H	H	P	P	P	RWS, TMAP	BLMP, TMAP	MADS
toxins[b]	L	M	L		H	H	P	P	P	RWS, TMAP	BLMP, TMAP	TMAP, MADS
Biological[o]												
dolphins	H		M	H	H	H	P	P	P	NIOZ, IM, TMAP	TMAP	TMAP, MADS
seals	H		L	H	H	H	P	P	P	TMAP	TMAP	TMAP
birds[p]	H			M	H	H	P	P	P	SOVON, RWS, TMAP[e]	TMAP	TMAP
fish	H		L	H	H	L	P	P		NIOZ, IM, TMAP[e]	vTI, TMAP	
macrophytes	M		L	H	H	H				TMAP[e]	TMAP	TMAP
macrozoobenthos	H		M	H		M	P,A	P	P	RWS, IM, NIOZ	TMAP	MADS
phytoplankton	H		M	H	M	H	P	P	P	RWS	*BLMP*	MADS[a]
microphytobenthos	H			L			P			ZKO[q]		
zooplankton	H			L			P	P		ZKO	AWI-sylt	
neobiota	H		L	H	H	H	P	P	P	TMAP	TMAP	TMAP
Habitat[h]												
tidal area[j]	H	H	L	H	H	H	A	A	A	TMAP	TMAP	TMAP
salt marshes	H	H	L	H	H	H	A	A	A	TMAP	TMAP	TMAP
dunes	M	H	L	H	H	H	A	A	A	TMAP	TMAP	TMAP
blue mussel beds	H	H	L	H	H	H	A	A	A	TMAP	TMAP	TMAP
seagrass beds	H	H	L	H	H	H	A	A	A	TMAP	TMAP	TMAP
Human use												
fishing	H	L	M	H	M	M					scattered	scattered[n]
dredging	H		H	M								[n]
dumping	H		M	L								[n]
mining (shells and sand)	M		H	H								[n]

[a] in total 144 stations
[b] water, sediment, bird eggs, flounder, bleu mussel
[d] probably available according to obtained parameter list; not covered TBs 8,9,15,16,17,27
[g] regional authorities responsible, data scattered and hard to obtain
[h] adopted from QSR 2004 and 2009
[j] intertidal, sublittoral; including rivers and deltas
[k] including emersion time, tidal amplitude, tidal prism, residence time
[l] including sediment compostition, silt concentrations, organic material
[o] numbers and densities
[p] high tide roost counts

A: Real data
P: Point measurements

H= high
M= medium
L= low

[Lit] Literature
[c] probably add-on at all contaminants stations
[e] TMAP: no information for SH/HH (TB 30-39), Data units off-line
[f] 5 stations in the German Bight only
[n] use restricted by law
[q] only since recently one location in Western Dutch Wadden Sea

Figure 1-The parameters specified in the Rijke Waddenzee project (Reference: Kraft et. al (2011).

In relation to the main objective and goal of the WaLTER project, historical and present-day missions and future missions are relevant for monitoring five groups of specific parameters from Figure 1. These groups are:

Group 1- General parameters
- Bathymetry
- Sediments
- Land cover

Group 2- Physical parameters
- Temperature
- Salinity

Group 3- Chemical parameters
- Chlorophyll
- Turbidity and organic matter

Group 4- Biological parameters
- Macrozoobenthos
- Phytoplankton
- Macrophytes
- Microphytobenthos

Group 5- Habitat parameters
- Tidal area
- Salt marshes
- Dunes
- Blue mussel beds
- Sea grass beds.

To reach this specific objective, the following tasks are implemented:
- Description of satellite systems, precision of satellite data and factors restricting satellite data usability (Section 2).
- Review of scientific and other information sources on satellite missions and specifications of satellite data which can be used to detect the parameters specified in WaLTER's General, Physical, Chemical, Biological and Habitat groups (Sections 3 and 4).
- Analysis of satellite data pre-processing and processing and classification methods applicable for long term monitoring of sediment characteristics, identification and location of mussel and oyster beds, gullies and channels, and detecting temporal and spatial changes thereof, and land cover changes of salt marshes (Section 5 and 6).
- Analysis of opportunities and limitations of satellite data for long-term monitoring in the Wadden Sea, by comparison of historical, present and future missions (Section 7 and 8).

A description of satellite data providers is listed in Chapter 6 and includes the European Space Agency (ESA), the Netherlands Space Office (NSO), the National Aeronautics and Space Administration (NASA) and third party missions.

2. Description of satellite systems, precision of satellite data and factors restricting satellite data usability

The Remote sensing technology, data and tools become increasingly important in habitat mapping. The main advantage of satellite data is global coverage, frequent- daily or within 3 days revisit of the same area (depending on satellite) and relatively low cost, with archived data at no cost (from some providers), making it attractive to use in monitoring.

Satellites are imaging the earth on a daily basis and depending on the satellite orbit, the satellites can revisit the same area on a daily basis, the sun-synchronized satellites, revisiting the same area at the same local mean solar time and or within a short period of time (less than 3 days), the geostationary (high altitude) satellites.

This section presents information about specifications of satellite data that is most relevant for monitoring of the Wadden Sea, in groups of multi-spectral and radar satellites.

2.1 Satellite systems

A satellite system can be active (sending, receiving and recording signals) and passive (recording the reflected sunlight from the earth). Each system has its own advantages and disadvantages, which are related to system design, range of wavelengths and resolution of the camera.

2.1.1 Active systems

The advantage of active (radar) systems is the ability of radar signal to penetrate the clouds and rain and image the earth during the night. The imaging is made in two modes- vertical (VV) and horizontal (HH). There are two passes - ascending (South to North) and descending (North to South). Radar systems characterised by the signal frequency, expressed in Gigahertz (GHz). The resolution of the ERS radar system is 12.5 meters and the resolution of the RADARSAT-2 system ranges from 3 to 100 meters (Table 1).

Table 1-The radar missions

Satellite mode	Satellite	Country of origin	Ground resolution (meters)
C-band (4 GHz to 8 GHz)*	ERS SAR-1,2	ESA	12.5
	ENVISAT ASAR	ESA	30
	RADARSAT-1,2	Canada	from 3 to 100
X-band (8GHz to 12GHz)	Cosmo-SkyMed	Italy	from 1 to 30
	TerraSAR-X	Germany	from 1 to 16
	TanDEM-X	Germany	250-500
	SeoSAR	Spain	from 1 to 18

Radar images cannot be viewed directly after the acquisition and require special pre-processing of the recorded collection of pulses. After pre-processing, the radar images can be viewed in black and white (panchromatic) images. Combining images recorded during descending and ascending passes can be used for computing terrain height.

2.1.2 Passive systems

The images from multi-spectral passive systems can be viewed directly after the acquisition. The pre-processing in this case can be e.g. to remove the effects from atmosphere and other image enhancing techniques and to merge (fuse) with other data.
Cameras of multi-spectral satellites record the reflected sunlight using sensors tuned in different wavelengths. The spectrum of recorded wavelengths may range from visible Red, Blue, Green and Yellow, and expands to variations of infra-red, and thermal and microwave bands.

Table 2 present examples of hyper-spectral and multi-spectral missions, which are a modification of multi-spectral missions. The hyper-spectral bands are multi-spectral bands divided over short intervals. The advantage of a hyper-spectral mission is the ability to focus on one particular wavelength. However, some parts of features may not be visible in one wavelength, especially sediment features, and may extend over a broader wavelength range. Another disadvantage of hyper-spectral missions is the extremely large number of bands, starting from 20 to up to 200, which will require additional time for pre-processing and image classification. The hyper-spectral data covering the Wadden Sea is from MODIS and ENVISAT MERIS satellites. Some products from MODIS TERRA satellite include Chlorophyll-a, Colored Dissolved Organic Matter, Particulate Inorganic Carbon, Particulate Organic Carbon and Sea surface temperature. However, because of its low resolution, this mission is not discussed in this report.

Table 2-The hyper-spectral and multi-spectral missions

Satellite mode	Satellite	Country of origin	Ground resolution (meters)
Hyper-spectral	TERRA MODIS	U.S.A NASA	200
	AQUA MODIS		9000
Multi-spectral	Landsat	U.S.A NASA	30
	DEIMOS	U.K DEIMOS Imaging	22
	ASTER	Japan NASDA	15
	Worldview-2	U.S.A. Digital Globe	2.5

To show the difference between radar and multi-spectral images, Figure 2 presents the area of Ameland, showing the intertidal flats on radar image (left) and intertidal flats on DEIMOS multi-spectral image (right).

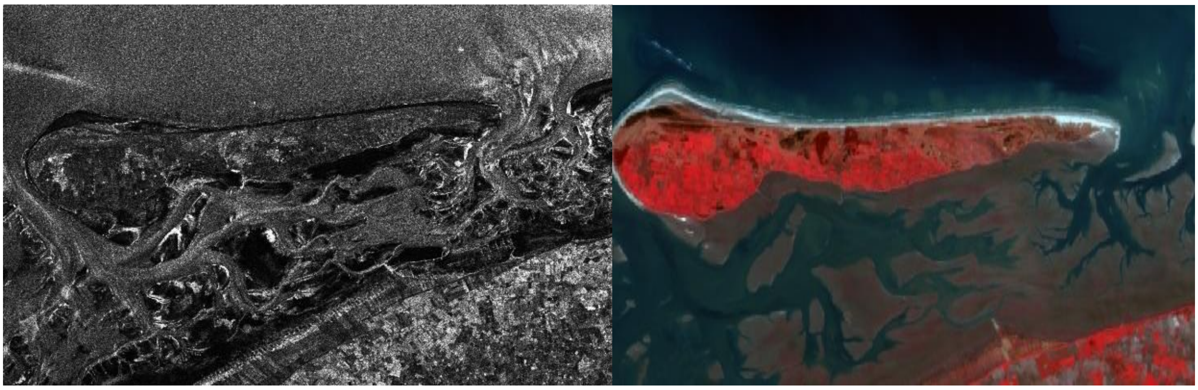

Figure 2-Radar ERS SAR image, date 20 August 2010 (left), multi-spectral DEIMOS image, date April 14, 2010 (right). The radar image has one band (intensity image) whereas the multi-spectral image is presented in a combination of 3 bands (near-infrared, red and green).

2.2 Precision of satellite data

The precision of satellite data is expressed in metres, and it is related to the resolution of the satellite sensor. The definition of sensor resolution starts from low to medium and extends to high and very high. According to the definition of satellite sensors made by the European Space Agency (ESA), the low resolution starts from 200 meters to 10 km and more; medium from 30 to 200 meters; and high from 30 meters and better. The high resolution is further subdivided into high (in meters) and very high (in centimetres).
The usability of low and medium resolution data is very limited for Wadden Sea monitoring, because of the large pixel size and therefore reduced distinctiveness in location and size of e.g. mussel and oyster beds, especially if beds are in size less than 200 meters.

From medium resolution data, the Landsat data in 30 and 60 meters have been used for sediment classification in the Wadden Sea and to detect location and size of mussel beds from cloud free and low tide images. The upper limit in pixel size for the medium resolution dataset is stated in study by Doerffer and Murphy (1989) mentioning the uncertainties in sediments classification by surface type, due to high variations present in small areas (smaller than one Landsat pixel). This is in contrast to a study by Herlyn (2005) who concluded that a resolution of 100 metres on the ground is suitable for analysis of location and area of mussel beds (tested using aerial photography).

Research by Van der Wal et al (2005) to characterise the surface of the intertidal flats using high resolution 12.5 meters ERS SAR data has shown good results. In general, their literature review revealed the applicability of medium and high resolution satellite data in detecting mussel and oyster beds and classification of sediments, and satellite data in low resolution starting from 100 meters and more revealed the applicability for regional studies, e.g. the estimation of intertidal benthic algal biomass using Aqua MODIS 250 meters resolution in the Westerschelde and the Ems-Dollard estuaries, (Van der Wal et al (2010 a)) and estuarine mud dynamics by MERIS in 250 meters resolution (Van der Wal et al (2010b)).

Consequently, the choice between high and low resolution will depend upon the objects/characteristics to be detected and to classify, related to their spectral properties. In general, Van der Wall et al (2010 a, b) concluded that synchronous data from field survey and satellite data would be an optimal choice.

2.3 Factors restricting satellite data usability- weather condition and tide

The area of the Wadden Sea is imaged on daily basis and some satellites like Quickbird in less than 3 days. However, usability of satellite data for monitoring specific parameters in the Wadden Sea is restricted by weather and tide conditions.

Multi-spectral earth surface monitoring from satellite platforms requires a daytime clear (cloudless) sky over the area of interest at the moment the satellite passes. According to statistical information from the Royal Netherlands Meteorological Institute (KNMI) the incidences in the Netherlands of rain, sleet, snow or hail in amounts greater than 0.1 mm per day on average is about 18 days per month, or 217 days annually. Precipitation coincides with cloud cover for at least part of the day. According to weather information (Publication 140, 2007), the maximum number of days with clear sky and minimum clouds along the coast of the North Sea and the Netherlands is mainly during spring, in May and June

Monitoring of intertidal areas, such as large parts of the Wadden Sea, from satellite platforms requires that the areas of interest are exposed at the moment the satellite passes. Exposure of intertidal areas depends on the phases of the lunar and tidal cycles and wind speed and wind direction causing additional water level increase or decrease. This has great impact on the visibility of mudflats and structures such as mussel beds. The tidal wave also propagates along the coastline, which forms another challenge. Depending on swath of the recorded satellite image, at some parts of the image it is low tide, while at other parts the tide is already coming in (Figure 3).

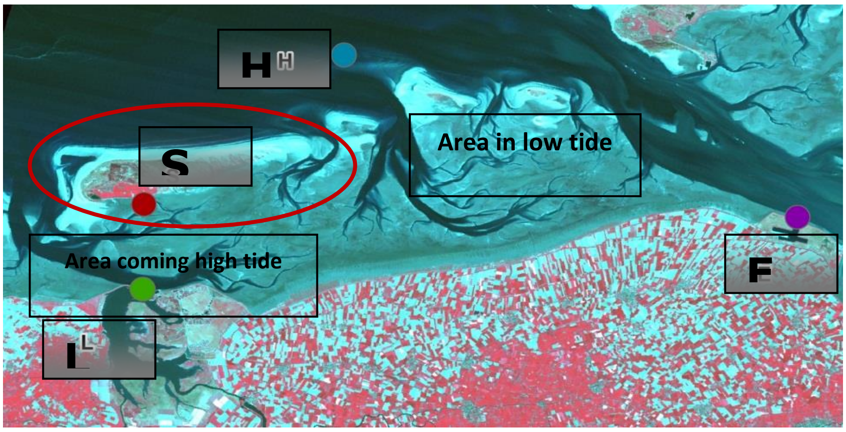

Figure 3-Landsat -5 Thematic Mapper image showing the tidal difference. Tide stations- Huibertgat (H), Lauwersoog (L), Schiermonnikoog (S) and Eemshaven (E).

The constructed harmonic of the tidal waves (Figure 4) presents tidal variations and differences in water level between the stations of Huibertgat (blue line), Lauwersoog (green line), Eemshaven (purple line) and Schiermonnikoog (red line). At the moment a satellite image is recorded it may be low tide at Eemshaven, while at e.g. Huibertgat the tidal phase is already half way between low and high tide.

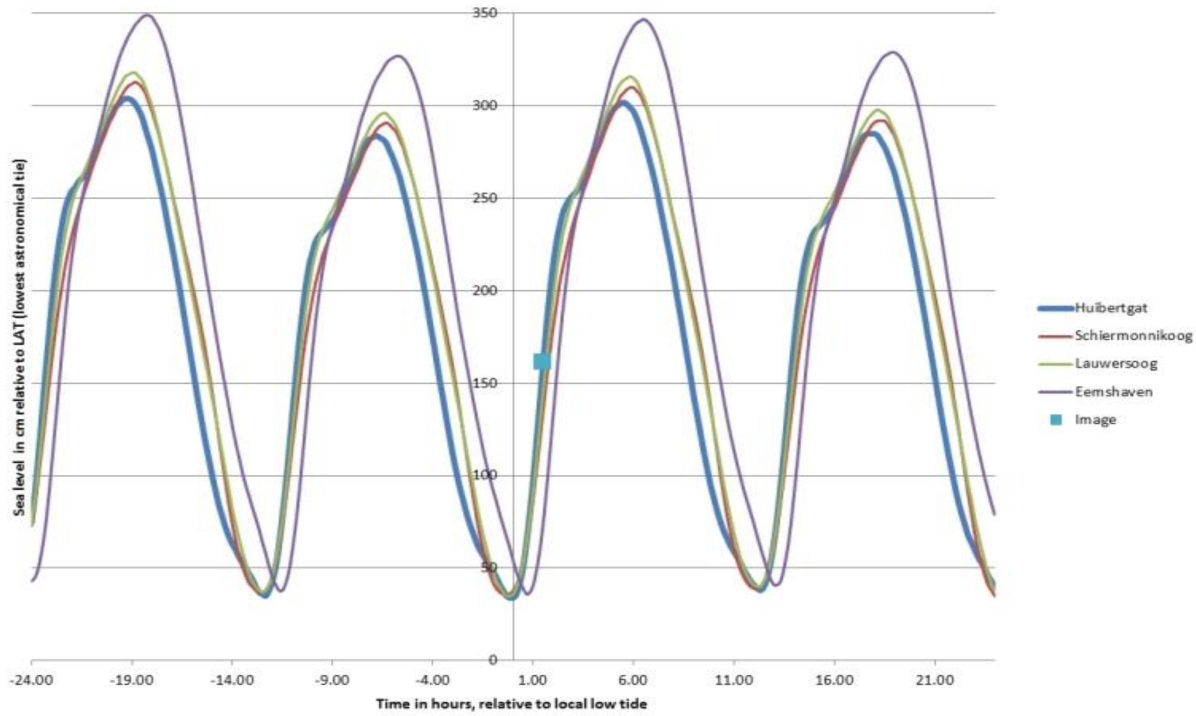

Figure 4-Tidal movements over the stations of Huibertgat (H), Schiermonnikoog (S), Eemshaven (E). Reference: Davaasuren, Stapel et al (2012).

So even from an image that is free from clouds at low tide only part of the image may be usable for classification. Multiple (archived) images are needed to cover the whole Wadden Sea during low tide.

A higher number of *radar* images are usable for classification and monitoring, because radar acquisitions are independent from weather conditions and daytime.

3. Satellite missions

3.1 Historical missions

The data from historical missions of Landsat, ASTER and ERS-1 and ERS-2 have been used for classification of sediments, identification of mussel and oyster bed locations, intertidal areas, coast line, salt marshes, and gullies and channels, and detection of temporal and spatial changes thereof.

The advantage of historical missions is time coverage, dating back to the 1980s. The archives can be used to look back in time to find answers for contemporary issues. The historical data from Landsat, ASTER, ERS and some other missions are available at no cost from online archives from the National Aeronautics and Space Administration (NASA) and the European Space Agency (ESA).

The agencies also provide support in obtaining the historical and current satellite data from third party missions, including the Japan Aerospace Exploration Agency (JAXA), the Japanese Space Agency (NASDA), the French Space Corporation (SPOT) and other missions from European and non-European countries that have an agreement with ESA.

3.1.1 National Aeronautics and Space Administration (NASA), Landsat program

The regular provision of satellite data from the Landsat program started with Landsat-3 in 1980s, although the first satellite was launched in 1972. Landsat-3 started imaging of the entire globe, in in multi-spectral, thermal and panchromatic bands, with revisit of the same area every 18 days, meaning that Landsat-3 images are available for the same area every 18 days (Figure 5- Landsat missions).

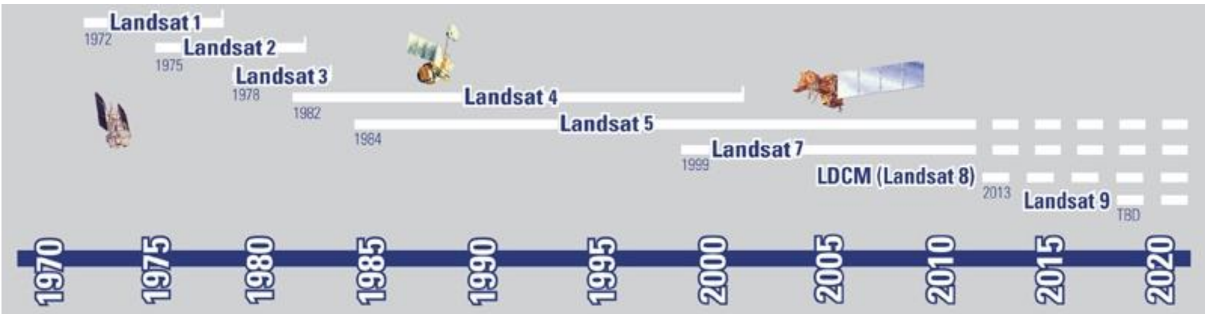

Figure 5- Landsat missions (U.S. Geological Survey, 2013).

The success of the Landsat missions and expanding user's communities triggered the modification of the Landsat sensor design. The Thematic Mapper™ sensor was modified to Enhanced Thematic Mapper Plus (ETM+) and improvement in resolution of thermal bands from 120 to 60 meters, providing thermal information in high and low gains (Table 4).

Table 3- Overview of the Landsat historical missions (Davaasuren, Stapel et al 2012)

Satellite	**Landsat 1-3 (RGB, MSS)**	**Landsat 4, 5 (TM, MSS)**	**Landsat 7 ETM+**
Period of operation	1972 - 1983	TM: 1982 -2012 MSS: 1982 - 1995	1999 -2012
Resolution scene	57 x 79 m (multi-spectral) 170 x 185 km	30 m (multi-spectral) 120 m (thermal) 170 x 185 km	30 m (multi-spectral) 15 m (panchromatic) 60 m (thermal) 170 x 185 km
Revisiting frequency	18 days, the same area	16 days, the same area	16 days, the same area
Purchasing details	ESA: until 2010 free of charge for the scientific community. 2010 and 2011 available upon request		
Wave bands (spectrum)	RGB (Red, Green, Blue) sensor 1: 475-575 nm- B 2: 580-680 nm- G 3: 690-830 nm- R Multi-spectral Scanner (MSS) sensor 4: 0.5-0.6 µm 5: 0.6-0.7 µm 6: 0.7-0.8 µm 7: 0.9-1.1 µm 8: 10.4 – 12.6 µm (L3)	Multi-spectral Scanner (MSS) sensor 4: 0.5-0.6 µm 5: 0.6-0.7 µm 6: 0.7-0.8 µm 7: 0.9-1.1 µm Thematic Mapper (TM) sensor 1: 0.45-0.52 µm 2: 0.52-0.60 µm 3: 0.63-0.69 µm 4: 0.76-0.90 µm 5: 1.55-1.75 µm 6: 10.40-12.50 µm 7: 2.08-2.35 µm	Enhanced Thematic Mapper Plus (ETM+) sensor 1: 0.45-0.52 µm 2: 0.52-0.60 µm 3: 0.63-0.69 µm 4: 0.76-0.90 µm 5: 1.55-1.75 µm 6: 10.40-12.50 µm 7: 2.08-2.35 µm 8: 0.52-0.90 µm

3.1.2 Japanese Space Agency (NASDA), ASTER

The Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) is a high resolution multi-spectral satellite designed by the Japanese Space Agency (NASDA), providing images in 15 meters resolution (Table 5) in 3 different processing levels. Level 1A is unprocessed raw data and Level 1B is pre-processed data calibrated for atmospheric effects and registered to the coordinate system. Level 2 is acquired in several modes- in Visible Near-infrared (VNIR), in 15 meters, Shortwave Infrared (SWIR) in 30 meters and thermal infra-red (TIR) in 90 meters. Level 3 data are used in the computation of a Digital Elevation Model (DEM), in 15 meters resolution, delivered to users in 30, 60 and 90 meters resolution.

Table 4-Overview of ASTER historical mission

Satellite	ASTER (NASA + NASDA)
Period of operation	1999 – to present
Resolution (and coverage)	15 m (multi-spectral) (60 x 60 km)
Revisiting frequency	16 days
Wave bands (spectrum)	Blue 1 (0.45 -0.52 μm) Red 3 (0.63-0.69 μm) Near infrared 4 (0.76 - 0.90 μm) Shortwave infrared 5 (1.55-1.73 μm) Thermal infrared 6 (10.4-12.5 μm)

3.1.3 French Space Corporation, SPOT program

The French Space Corporation together with Landsat started its initiative on providing daily, for the same area medium resolution satellite data with the launching of the SPOT series satellites. Similar to Landsat, the SPOT satellite has a combination of multi-spectral and high resolution panchromatic bands (Table 6). The historical data is available at no cost from the ESA data archive.

Table 5-Table Overview of SPOT satellite mission

Satellite	SPOT-1,2,3,4,5
Period of operation	1986-2013.
Resolution (and coverage)	2.5-5.0 m (panchromatic) 10 m (multi-spectral) 20 m (shortwave infrared) (60 x 60 km)
Revisiting frequency	Daily, the same area
Wave bands (spectrum)	Green 1 (0.50- 0.71 μm) Red 2 (0.61-0.68 μm) Near infrared 3 (0.78 - 0.89 μm) Short wave infrared (1.58 – 1.75 μm) Panchromatic (0.48 -0.71 μm)

3.1.4 European Space Agency (ESA), ERS-1, 2 mission

The ERS-1 satellite was launched by the European Space Agency in 1991, followed by ERS-2 satellite in 1995. The ERS-1 and ERS-2 satellites completed their missions in 2002. The data is available at no cost for European users and research communities (Table 7). The resolution of ERS images is 12.5 meters. The ERS satellite provided images of intensity and amplitude and images in Single Look Complex (SLC) format. The images can be used in visual interpretations, image fusion with low resolution multi-spectral images and SLC images in interferometric processing, to compute the Digital Elevation Model (DEM).

Table 6-Overview of ERS-1, 2 satellite missions

Satellite	ERS-1 and ERS-2
Period of operation	1991– 2011
Resolution (and coverage)	12.5 m (intensity, amplitude) (5 x 5 km)
Revisiting frequency	Revisit depends from the area, starting from 3, 35 and up to 168 days. European area revisit time is from 3 to 35 days
Wave bands (spectrum)	Frequency- 5.3 GHz Single Look complex images, intensity, amplitude

3.2 Present-day missions

3.2.1 Low resolution satellites

MODIS TERRA, MODIS AQUA and SMOS

The low resolution satellites of MODIS TERRA, MODIS AQUA, and SMOS provide data on ocean color-chlorophyll-a, Colored dissolved organic matter CDOM, Sea Surface Salinity and soil moisture. Because of the large pixel size of more than 100 metres, the low resolution satellites are less suitable for monitoring in the Wadden Sea. However, low resolution data can be used in modelling, as additional information source. The chlorophyll is derived from MODIS data using the explicit fact that chlorophyll fluorescence is specific to chlorophyll concentration (Abbott et al 1998; Chamberlin et al 1990). The Sea Surface Salinity SSS is expressed in practical salinity units (Liliams, 1962).

The specifications of low resolution MODIS TERRA, MODIS AQUA and SMOS satellites are presented in Table 8.

Table 7- Low resolution satellites

Satellite	MODIS TERRA	MODIS AQUA	SMOS
Period of operation	1999 - 2013	2002 - 2013	2009- 2015 (expected service time)
Resolution (and coverage)	1000 m (hyper-spectral) (2330 x 2330 km)	1000 m (hyper-spectral) (2330 x 2330 km)	2000 m (microwave) (10 x 10 km)
Revisiting frequency	Daily	Daily	2.5 to 3 days
Wave bands (spectrum)	36 bands Bands 8-16 ocean color, chlorophyll, Colored dissolved organic matter, 405- 877 nm	36 bands Bands 8-16 ocean color, chlorophyll, Colored dissolved organic matter, 405- 877 nm	L-band 1400-1427 MHz

3.2.2 *Medium resolution satellites*

FORMOSAT-2

The FORMOSAT-2 satellite was launched by the Taiwanese Space Agency. For users in the Netherlands, the data became available as of 2011 from the Netherlands Space Office at no cost for research and business companies. The images are provided in DIM format, as geo-referenced product in UTM projection. Data is available in a DIM format, which needs conversion to regular (GeoTIFF, TIFF, etc.) image format. The images of the Netherlands including the Wadden Sea are available on a daily basis. The data is available in 1A level (basic processing), 2A (geo-referenced, basic corrections applied) and Ortho (stereo images) (Astrum Geoservices, 2013).

The specification of the FORMOSAT-2 mission is given in Table 9.

Table 8- Overview of FORMOSAT-2 satellite mission

Satellite	FORMOSAT-2
Period of operation	2004-2013.
Resolution (and coverage)	8 m (multi-spectral) 2 m (panchromatic) (24 x 24 km)
Revisiting frequency	Daily. Images for the Netherlands available since 2011
Wave bands (spectrum)	Blue 1 (0.45 -0.52 µm) Green 2 (0.52- 0.60 µm) Red 3 (0.63-0.69 µm) Near infrared 4 (0.76 - 0.90 µm) Panchromatic (0.45 -0.90 µm)

DEIMOS-2 (UK DMC-2)

Medium resolution data (in resolution from 30 meters up to 200 meters) is currently provided by multi-spectral and radar missions. The Netherlands Space Office provides free access to medium resolution satellite data, including DEIMOS-2 (UK DMC-2) provided by the British National Space Centre.

The specification of DEIMOS-2 (UK DMC-2) is presented in Table 10.

Table 9-Overview of UK DMC-2 satellite mission

Satellite	UK DMC-2
Period of operation	2009- expected service time for at least 3 years
Resolution (and coverage)	22 m (multi-spectral) (24 x 24 km)
Revisiting frequency	Daily. Images for the Netherlands available since 2011
Wave bands (spectrum)	Blue 1 (0.52 -0.61 µm) Red 3 (0.63-0.69 µm) Near infrared 4 (0.77 - 0.90 µm) Panchromatic (0.45 -0.90 µm)

Landsat-8 (LDCM)
The U.S. Geological survey and the U.S.A government decided to continue the successful Landsat series and launched the Landsat-8 (LDCM) satellite (Figure 6) in February 2013. The Landsat-8 inherited all advantages from previous missions, and started to provide data from June 2013 in 30 meters multi-spectral, 15 meters panchromatic and 100 meters thermal infrared band resolutions.

Figure 6-Landsat 8 (LDCM) satellite. (Source: U.S. Geological survey, 2013)

The specifications of Landsat-8 satellite data are presented in Table 11.

Table 10-Landsat 8 (LDCM) mission

Satellite	Landsat-8
Period of operation	2014- expected service time minimum 5 years
Resolution (and coverage)	30 m (multi-spectral) 15 m (panchromatic) 100 m (thermal) (170 km x 185 km)
Revisiting frequency	Daily
Wave bands (spectrum)	Band 1 Visible (0.43 - 0.45 µm) 30 m Band 2 Visible (0.450 - 0.51 µm) 30 m Band 3 Visible (0.53 - 0.59 µm) 30 m Band 4 Near-infrared (0.64 - 0.67 µm) 30 m Band 5 Near-infrared (0.85 - 0.88 µm) 30 m Band 6 Short wave-length infrared (SWIR) 1 (1.57 - 1.65 µm) 30 m Band 7 Short wave-length infrared (SWIR) 2 (2.11 - 2.29 µm) 30 m Band 8 Panchromatic (PAN) (0.50 - 0.68 µm) 15 m Band 9 Cirrus (1.36 - 1.38 µm) 30 m Thermal Infrared Sensor (TIRS): Band 10 TIRS 1 (10.6 - 11.19 µm) 100 m Band 11 TIRS 2 (11.5 - 12.51 µm) 100 m

SPOT-6 and 7
The French satellite corporation continued the SPOT series and launched 2 SPOT satellites in 2012. The satellites have the capability to produce stereo images (Table 12). Recent data is commercially available and historical data (since 1986) can be ordered from ESA and are provided at no cost.

Table 11-SPOT-6 and SPOT-7 mission

Satellite	SPOT-6 and 7
Period of operation	SPOT 6: 2012-2022 SPOT 7: 2014-2024
Resolution (and coverage)	35 m (multi-spectral) 10 m (panchromatic) (60 x 60 km)
Revisiting frequency	Daily
Wave bands (spectrum)	Blue 1 (0.45-0.52 µm) Green 2 (0.53-0.59 µm) Red 3 (0.62-0.69 µm) Near Infrared 4 (0.76-0.89 µm) Panchromatic (0.45-0.74 µm)

PROBA-1 CHRIS

PROBA is a Compact High Resolution Imaging Spectrometer (CHRIS) instrument. The satellite was launched in 2001, providing the following options on imaging:

- Full mode
- Water imaging mode
- Land imaging mode 3
- Land imaging mode 5
- Chlorophyll-a imaging mode.

Table 13 presents specifications for the PROBA CHRIS mission.

Table 12-PROBA CHRIS mission

Satellite	PROBA CHRIS (Hyper-spectral Imagery)
Period of operation	2001-still operational
Resolution (and coverage)	17 m (hyper-spectral) (13 x 13 km)
Revisiting frequency	Approximately 7 days
Wave bands (spectrum)	19 bands, 415-1050 nm

3.2.3 High and very high resolution satellites

The latest developments in satellite technology opened a new era in high resolution imaging. The high and very high resolution satellites are commercial. The high resolution satellites RapidEye, Worldview, Quickbird, IKONOS and Pléiades (Table 14, Table 15) are able to do multi-spectral and panchromatic bands imaging in a resolution of a few centimetres, highly suitable for sediment mapping, identification of mussel and oyster beds, classification of vegetation on salt marshes, gullies and channels. The data is suitable for detection of details- e.g. erosion along the coast line.

Table 13 -High resolution satellites

Satellite	RapidEye	Worldview-2	Quickbird
Period of operation	2008-2019 (expected service time)	2009-2019 (expected service time)	2001-still operational
Resolution (and coverage)	6.5 m (multi-spectral) (77 km x 77 km)	2.07 m (multi-spectral) 0.60 m (panchromatic) Single images: 138 x 112 km (8 strips) Stereo imaging: 63 x 112 km (4 pairs)	2.5 m (multi-spectral) 0.60 m (panchromatic) (16.5 x 16.5 km)
Revisiting frequency	Daily, the same area	Daily, the same area	Daily, the same area
Wave bands (spectrum)	Blue 1 (0.44 -0.51 μm) Red 2 (0.52-0.59 μm) Red Edge 3 (0.69-0.73 μm) Near infrared 4 (0.76 - 0.85 μm)	Coastal Blue 1 (0.40-0.45 μm) Blue 2 (0.52 -0.51 μm) Red Edge 3 (0.705-0.745 μm) Green 4 (0.51-0.58 μm) Near infrared (1) 5 (0.77 - 0.85 μm) Yellow 6 (0.58 - 0.62 μm Near infrared (2) 7 (0.86 – 1.040 μm) Panchromatic (0.45 -0.80 μm)	Blue 1 (0.45 -0.52 μm) Red 2 (0.52-0.60 μm) Red Edge 3 (0.63-0.69 μm) Near infrared 4 (0.76 - 0.90 μm) Panchromatic (0.45 -0.90 μm)

Pléiades is a constellation of two satellites providing multi-spectral data in 4 bands in a resolution of 2 metres, high resolution panchromatic band data in 50 cm and color photography in 50 cm (Table 15). The data is available over the European territory, including other continents and poles and can be ordered from ESA and the French Space Corporation. Recently ESA made an agreement for open access of archived data from the RapidEye satellite for European users.

Table 14-High resolution satellites

Satellite	IKONOS-2	Pléiades-1A, Pléiades- 1B	GeoEye1
Period of operation	1999 (over 7 years), still operational	2012- 2017 expected service time 5 years	2008- 2018 expected service time
Resolution (and coverage)	3.2 m (multi-spectral), 0.83 m (panchromatic) (13.8 x 13.8 km)	50-cm black and white 50-cm color 2 m (multi-spectral) (20 km)	0.41 m (panchromatic) 1.65 m (multi-spectral) (15.2 x 15.2 km)
Revisiting frequency	14 days maximum, the same area	Daily, the same area	Less than 3 days, the same area
Wave bands (spectrum)	Blue 1 (0.45 -0.52 μm) Green 2 (0.52-0.60 μm) Red 3 (0.62-0.69 μm) Near infrared 4 (0.76 - 0.90 μm)	Blue 1 (0.43 -0.55 μm) Green 2 (0.49-0.61 μm) Red 3 (0.60-0.72 μm) Near infrared 4 (0.75 - 0.95 μm) Panchromatic (0.48 -0.83 μm)	Blue 1 (0.45 -0.51 μm) Green 2 (0.51-0.58 μm) Red 3 (0.65-0.69 μm) Near infrared 4 (0.78 - 0.92 μm) Panchromatic (0.45 -0.80 μm)

3.3 Future missions

3.3.1 Sentinel

The new missions of Sentinel satellites will become operational as of 2014. The selected Sentinels missions applicable for monitoring in the Wadden Sea are:

1. Sentinel-1 (resolution from 5 to 20 meters). The Sentinel-1 is a radar satellite and it is a continuation of the Synthetic Aperture Radar (SAR) missions of ERS-1, ERS-2, RADARSAT-1 and RADARSAT-2. The satellite will be launched in 2013, with expected data delivery in 2014. A following mission is planned a few years later (to be defined).
2. Sentinel-2 (resolution 10, 20 and 60 meters). The Sentinel-2 will carry visible, near infrared and shortwave infrared sensors, and it is a continuation of the SPOT- and Landsat-type data. The satellite will be launched in 2014.
3. Sentinel-3 will carry 3 different instruments. A Sea and Land Surface Temperature Radiometer (SLSTR), with resolution of 500 m and 1 km in the thermal infrared channels; an Ocean and Land Colour Instrument (OLCI), with resolution of 300 meters; a dual-frequency (Ku and C band) advanced Synthetic Aperture Radar Altimeter (SRAL), with resolution in 300 meters. The launch is expected in 2014.

The access to data from Sentinel missions will be provided by ESA. The short description of Sentinel missions is presented in Table 16.

Table 15-Sentinel missions

Satellite	Sentinel-1	Sentinel-2	Sentinel-3
Period of operation	2013	2014	2014
Resolution (and coverage)	5-20 m (250 km)	10, 20, 60 m (290 km)	300,500-1000 m (1 km)
Revisiting frequency	Europe, Canada (the same area) and main shipping routes in 1–3 days;	Daily, the same area	Daily, the same area
Wave bands (spectrum)	C-band SAR data	Visible, NIR, SWIR*	Ku and C-band
Missions that will be taken over	ERS-1, ERS-2, ENVISAT and RADARSAT	SPOT-6,7 Landsat	MERIS

**Visible- includes Red, Green, Blue, Yellow wavelengths*
NIR- near-infrared
SWIR- shortwave infrared.

Sentinel-4 and 5 are low resolution missions, with pixel size in 8 km, which is not suitable for monitoring in the Wadden Sea. Table 17 presents example of continuity of DEIMOS-3 (UK-DMC) and Worldview-3 satellite missions.

Table 16-UK-DMC and Worldview-3 missions

Satellite	UK-DMC 3A UK-DMC 3B UK-DMC 3C	Worldview-3
Period of operation	2014- 2021 (expected duration of contract)	2014-2025 (expected service time)
Resolution (and coverage)	1m (panchromatic), 4m (multi-spectral, 3 bands) (23 x 23 km)	0.31m (panchromatic) 1.24 m (multi-spectral) 3.7 m (shortwave infrared) (Mono: 66.5 km x 112 km (5 strips) Stereo: 26.6 km x 112 km (2 pairs)
Revisiting frequency	Daily, the same area	Less than one day, the same area
Wave bands (spectrum)	Green 1 (0.5-0.6 µm) Red 2 (0.6-0.7 µm) Near infrared 3 (0.7-0.8 µm)	8 Multi-spectral: Coastal (0.40 – 0.45 µm) Red (0.63 – 0.69 µm) Blue (0.45 – 0.51 µm) Red Edge (0.70 – 0.74 µm) Green (0.51 – 0.58 µm) Near-IR1 (0.77 – 0.89 µm) Yellow (0.58 – 0.62 µm) Near-IR2 (0.86 – 1.04 µm) 8 shortwave infrared (SWIR): SWIR-1: 1.195 – 1.225 µm SWIR-5: 2.145 – 2.185 µm SWIR-2: 1.550 – 1.590 µm SWIR-6: 2.185 – 2.225 µm SWIR-3: 1.640 – 1.680 µm SWIR-7: 2.235 – 2.285 µm SWIR-4: 1.710 – 1.750 µm SWIR-8: 2.295 – 2.365 µm 12 CAVIS Bands (specially corrected): Desert Clouds: 0.405 – 0.420 µm Water-3: 0.930 – 0.965 µm Aerosol-1: 0.459 – 0.509 µm NDVI-SWIR: 0.1220 – 0.1252 µm Green: 0.525 – 0.585 µm Cirrus: 0.1350 – 0.1410 µm Aerosol-2: 0.620 – 0.670 µm Snow: 1.620 – 1.680 µm Water-1: 0.845 – 0.885 µm Aerosol-3: 2.105 – 2.245 µm Water-2: 0.897 – 0.927 µm Aerosol-3: 2.105 – 2.245 µm
Missions that will be taken over	UK-DMC-1 UK-DMC-2	Worldview-2

TerraSAR-X and TanDEM-X

The new mission of TerraSAR-X and TanDEM-X satellites that are operated by the German Aerospace Agency will produce a new Digital Elevation Model (DEM) starting from 2014, in resolution of 12 meters, replacing the global 30 meter resolution Shuttle Radar Topography Mission (STRM) from NASA. The new product is called WorldDEM, delivering 3 dimensional product with vertical accuracy in 10 meters. The WorldDEM will be commercially available from Astrium GEO-Information Services, Infoterra GmbH, Germany. Figure 7 shows a comparison of existing DEMs: SRTM in 90 meters, SRTM in 30 meters and new TanDEM-X in 12 meters.

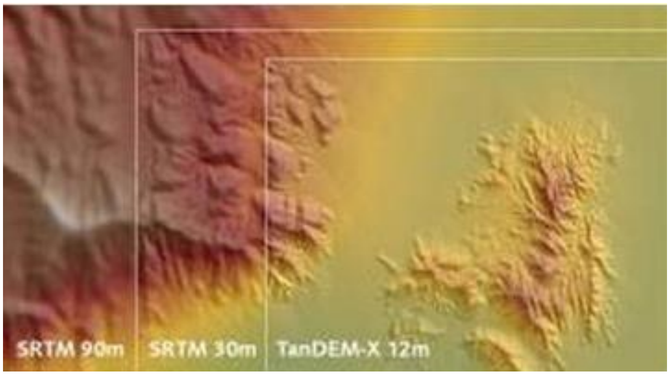

Figure 7-Comparison of global DEMs. SRTM in 90 meters, SRTM in 30 meters and TanDEM-X in 12 meters. (Source: Astrium GEO-Information Services, 2013. http://www.astrium-geo.com/worlddem)

4. Data processing methods

4.1 Satellite data pre-processing

4.1.1 Atmospheric correction

Atmospheric correction is an important process, as it improves the visibility of ground features and therefore the classification accuracy. The reason to do the atmospheric correction is contamination of the atmosphere by smog and fog and presence of water particles and other aerosols. In general, the correction follows two steps:

1. Estimation of sunlight considering no effects from atmosphere: the Top-of-Atmosphere-Reflectance.
2. Calibration of image values according to Top-of-Atmosphere-Reflectance, accounting for the position of the sun (sun zenith angle, Earth to Sun distance and position of Earth to the Sun during image acquisition) and the Top-of-Atmosphere-Radiance.

The algorithms for atmospheric correction are specific for each satellite depending on satellite design, orbiting height and speed. The description of atmospheric correction algorithms can be found in technical documentation available for each mission and can be requested from data providers. Figure 8 presents a comparison of an uncorrected and corrected image of the island of Schiermonnikoog.

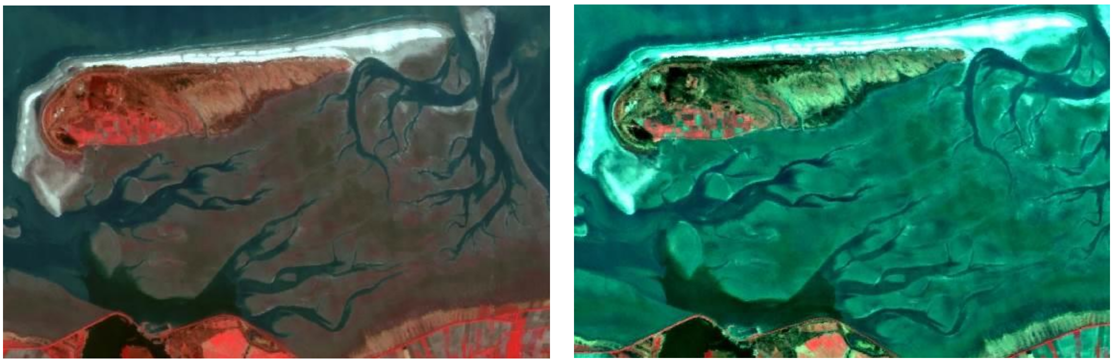

Figure 8-Uncorrected (left) and atmospheric corrected image (right). The corrected image is enhanced in green band. Image- DEIMOS-2, date of acquisition March 15, 2012.

4.1.2 Image co-registration

In case more than one image is used in classification, pixel colocation is very important for which image co-registration tools are available. The satellite companies provide data projected in the Universe Transverse Mercator (UTM) format.

4.1.3 Projections used for the Wadden Sea

The data from the Wadden Sea area can be obtained in two different projections.

The UTM projection with World Geodetic Ellipsoid (WGS 1984), zone number 41 and 42 (depending on location in the Wadden Sea) is currently used by satellite data providers. The companies from the Netherlands are using Dutch RD new projection, together with UTM and other international systems. The international code for Dutch RD new coordinate system is EPSG 28992.

The EPSG stands for international code for Geodetic Parameter Dataset, the Coordinate Reference Systems and Coordinate Transformations. The parameters of the Dutch grid RD are identical to parameters of international Double Stereographic projection.

4.1.4 Image co-registration

Co-registration is a process to match the location of each pixel. The image co-registration requires a sufficient number of Ground Control Points (GPS). The satellite data providers deliver data as geometrically corrected (for positional accuracy) product. However, this is not always the case and sometimes satellite data needs to be checked and corrected, for instance FORMOSAT-2 data.

From historical missions all Landsat data are projected to the Universal Transverse Mercator (UTM) system. However, some very old Landsat images dating back to 1980s sometimes needs re- projection. The data provided by ESA, NASA and third party missions are projected in UTM system.

4.1.5 The spectral analysis

The aim of the spectral analysis is to analyse the following:

1. Spectral reflectance (spectral signature) of the objects,
2. Object- location and size, spatial pattern using indexing (soil and vegetation),
3. Data from different sources. To make such analysis, the method of data fusion is used.

4.1.6 Analysis of spectral reflectance (spectral signatures) of the objects

The Wadden Sea area is different compared to other places in the Netherlands, because of its spectral properties. The reflectance of the objects in the Wadden Sea is strongly dependents on surface structure, however, difference on water content and tidal exposure can be different for sand, mud and mudflats. Figure 9 presents a schematic overview of the substances and processes in the Wadden Sea, which may all play a role in the resolution of the satellite data and pre- and processing algorithms and classification methods needed for monitoring a specific parameter or process.

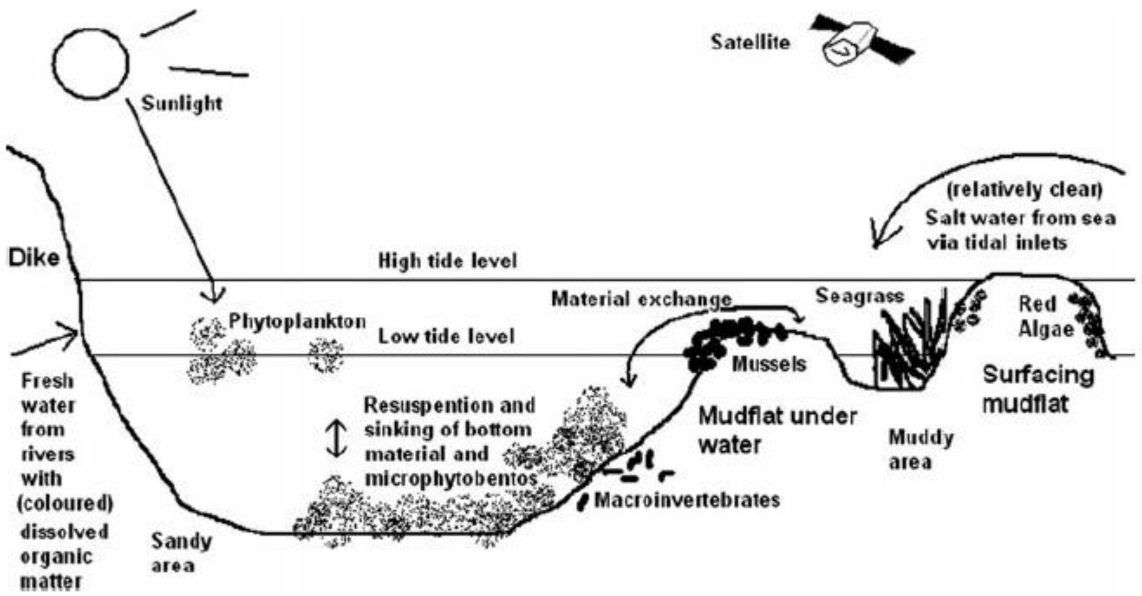

Figure 9- Schematic overview of substances and occurrence of processes in the Wadden Sea. (Reference: Hommersom et al (2010) (Figure 3, page 88)).

In general, there are three factors, which need to be taken into account:

1. The relationship between water content and reflectance.

Rainey et al., (2000) mentioned the case of low reflectance and therefore low distinction between completely saturated sediments (wet and very wet sediments) and mud on satellite images. On the other hand, good distinction between completely dry sediments and complete dry mud is observed. The grain size of sediments was not a major factor obscuring the classification of saturated sediments.

The Principal Component Analysis (PCA) on Landsat-5 data (medium resolution) in a study by Rainey et al (2000) clearly showed very distinct differences in spectral signature of dry mud and dry sand sediment (Figure 10). Figure 10 presents along y-axis reflectance values (in Digital Numbers (DN)), and along the x-axis the satellite bands, starting from IRIS Mk IV spectroradiometer. The spectroradiometer bands are calibrated with Airborne Thematic Mapper (ATM) sensor.

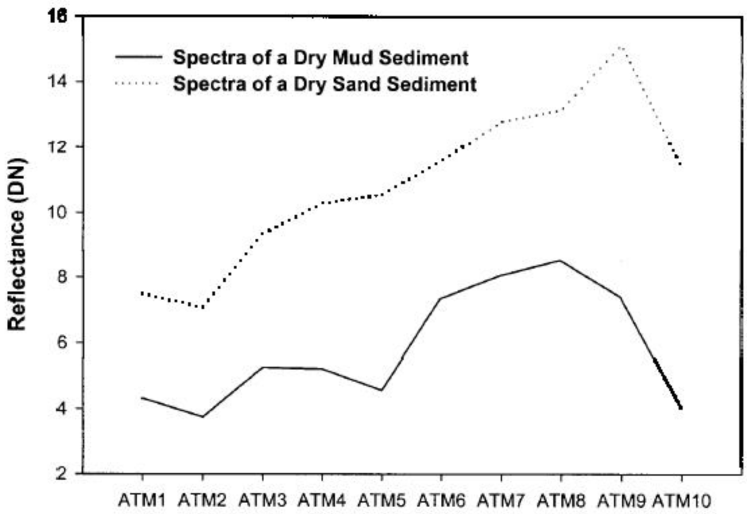

Figure 10-Difference in spectral signatures (spectra) between dry mud and dry sand sediment. Reference: Rainey et al 2000 (Figure 4, page 11).

2. The correlation between sediment composition and reflectance.

Different grain size sediments reflect differently, as is mentioned in studies by Bartholdy and Folving (1986); Gade et al (2008) and Van der Wal et al (2005). Bartholdy and Folving (1986) concluded that fine-grained sediments can be classified on Landsat data in two large groups:

- Very fine-grained sediments containing more than 70% silt and clay
- An intermediate group containing between 30-70% silt and clay.

The further division into group containing less than 30% silt and clay was not made, because of limitation on low resolution of Landsat data (30 meters pixels), which did not allow to go into more details (Figure 11).

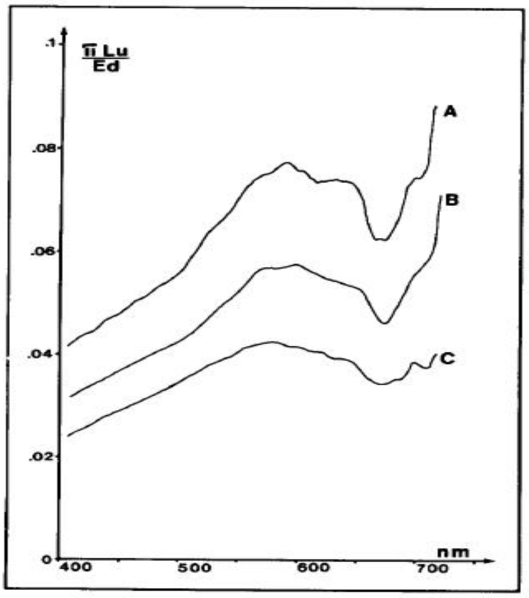

Figure 11-Reflectance of very dry sand (A), wet sand (B) and fine-grained mud (C) on Landsat image, resolution 30 meters. Reference: Bartholdy and Folving, 1986 (Figure 6, page 341).

A study by Dube (2012) mentioning the analysis of spectral signatures for two sediment classes, has shown promising results in detecting sandy sediments and clay, covered by brown algae (Dube erroneously called brown algae) (Figure 12).

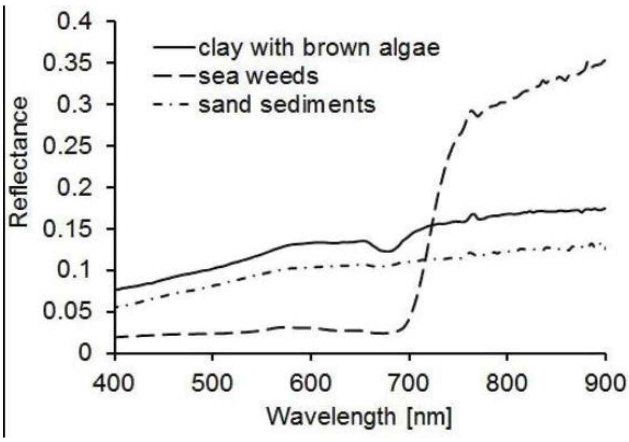

Figure 12-Spectral signatures of different sediment types in intertidal flats, Wadden Sea. Reference: Dube, 2012 (Figure 4-1, page 15).

3. The distinct spectral reflectance of ground features.

Mussel and oyster beds are quite distinct compared to their surrounding sediments, because of their surface structure, color and tone.

A comparison between coastal land, main land of the island (Ameland), salt marshes and mussel and oyster beds on Worldview-2 image, band 2- Green and band 3 – Red using statistical analysis of variance (ANOVA test), is presented in Figure 13 and Figure 14.

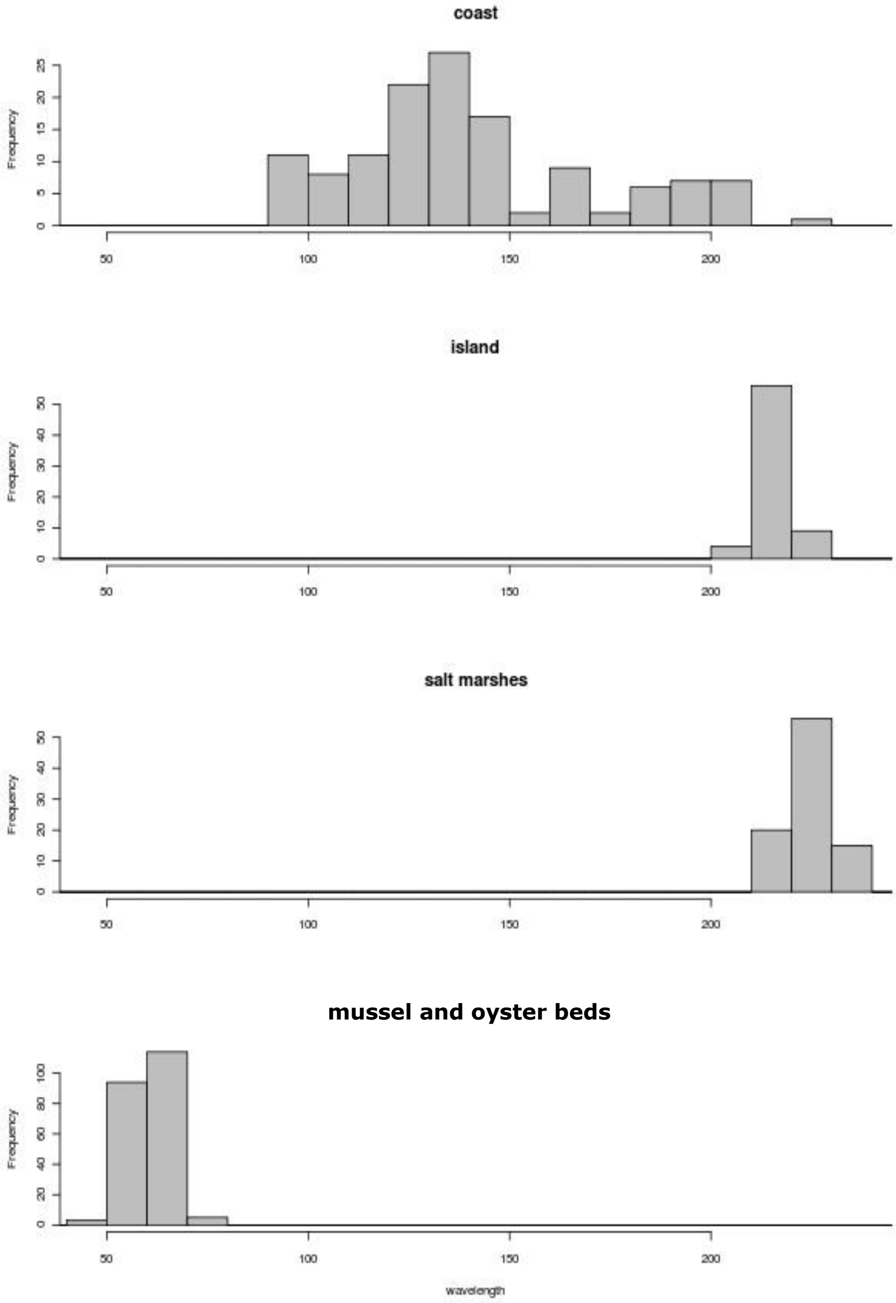

Figure 13- Spectral difference between coast (coastal land); island (main land of Ameland), salt marshes and mussel and oyster beds, band 2- Green on Worldview-2 image, resolution 2.5 meters. Date of acquisition- July 21, 2006.

The ANOVA statistical test analysed variances among different locations and showed dictinct differences in reflection of mussel and oyster beds compared to coastal land and salt marshes. In band 2, which is for Green light, the peak reflectance of healthy vegetation can be seen in wide distribution of image values along the coastal land (Figure 14) and clear dictincion in areas with no vegetation (mussel and oyster beds) and coast and salt marshes in band 3 (Figure 14).

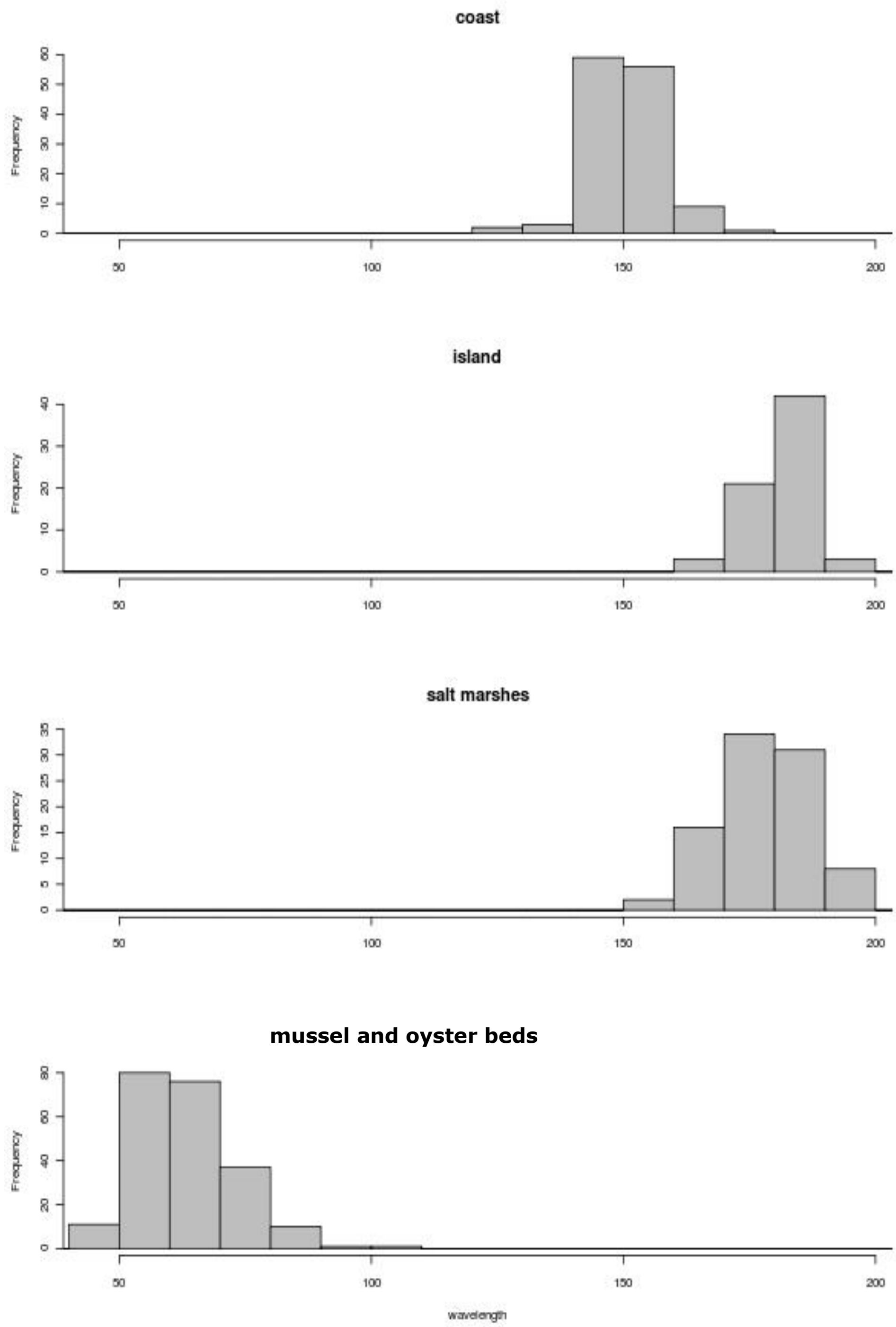

Figure 14-Spectral difference between coast (coastal land); island (main land of Ameland), salt marshes and mussel and oyster beds, band 3- Red on Worldview-2 image, resolution 2.5 meters. Date of acquisition- July 21, 2006.

4.1.7 Indexing (soil and vegetation) in object detection

Indexing is used in object detection and classification. Soil indexing is used e.g. to detect the moisture content (on medium and high resolution images) and soil type (by sediments composition).

An example showing the difference in soil moisture is presented in Figure 15, on Landsat-5 image, in resolution of 30 meters. The satellite image shows high moisture areas in black tones, dry areas on main land in white, with white area at Schiermonnikoog as a polder with grass and areas in different moisture in grey tone.

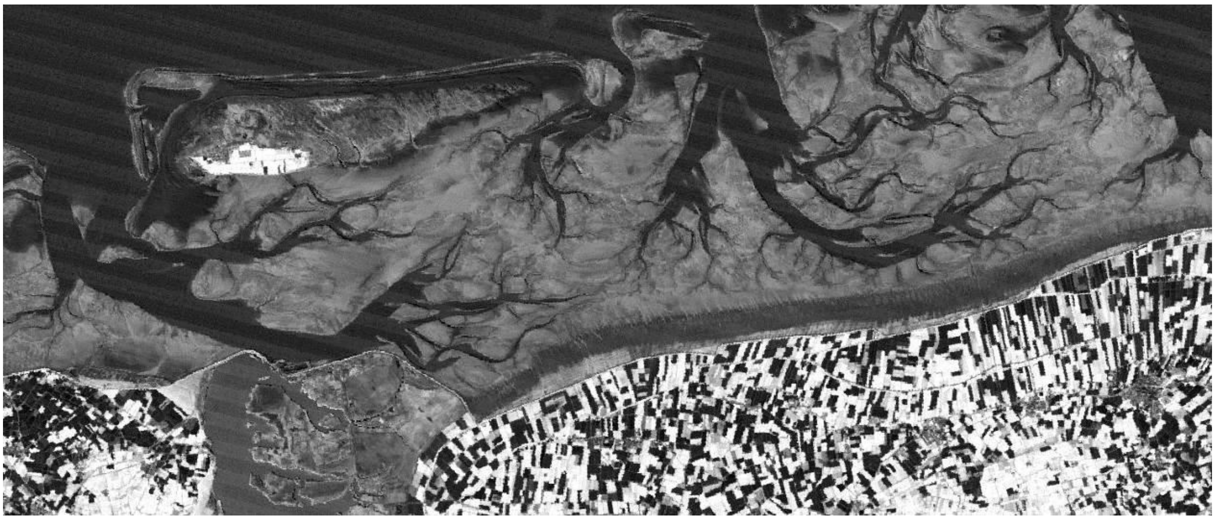

Figure 15-Soil moisure index. Image Landsat-5, date of acquisition 25 November, 1995.

For soil indexing the combination of Red and Near-infrared bands is used. The studies by Richardson and Everitt (1992) and Lyon et al (1998) concluded that in dry areas the "soil brightness" must be corrected, especially if it is not covered by vegetation. Comparing different resolutions, the high resolution image, for example of Worldview-2 is better in presenting more details (Figure 16).

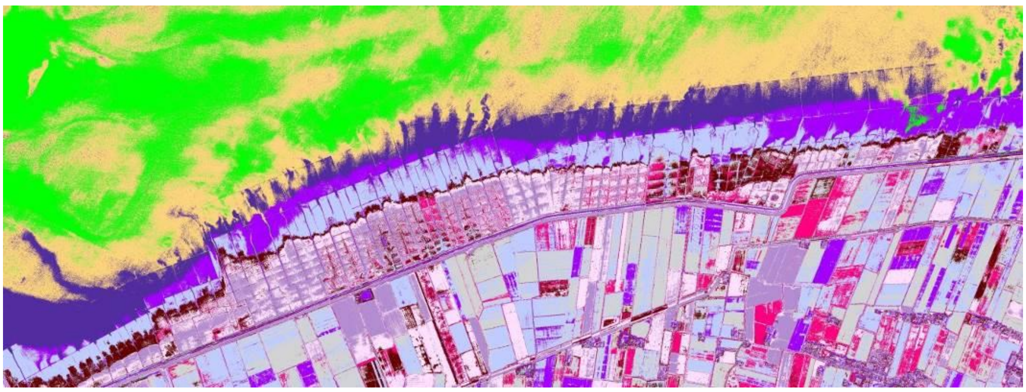

Figure 16-Soil indexing, north-east of Groningen, De Marne. Soil with high moisture content in violet color, dry soil areas in red and pink. Deep water areas in green, shallow water in yellow. Worldview-2 image acquired on September 26, 2011.

The vegetation index is used in estimating the amount of vegetation, and will show areas in high, medium and low cover of vegetation. The chlorophyll contained in healthy, green vegetation strongly reflects in Red and Near-infrared light, and lower reflectance will be when overall biomass and or vegetation density is low and or when vegetation (plant communities) are degraded (not healthy).

Figure 17 is showing areas on Landsat-5 image without vegetation in red color, wet areas on land and water (sea, gullies and channels) in green and vegetation on salt marshes in blue and greenish color.

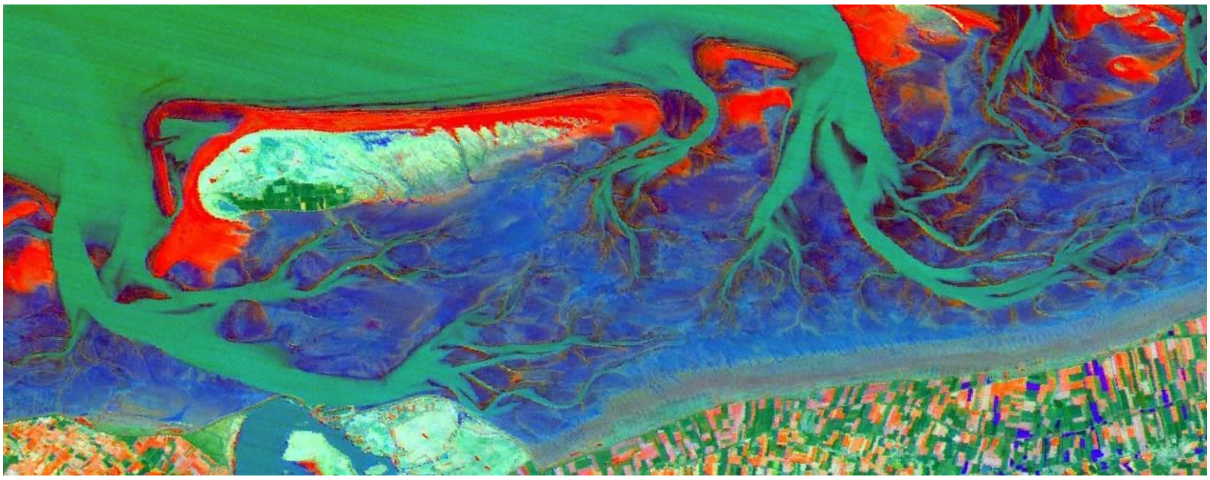

Figure 17-Vegetation indexing on Landsat-5 data using Near-infrared and red bands. Image date 25 November 1995.

4.1.8 Mapping wetland and salt marsh vegetation

Compared with terrestrial vegetation, vegetation on wetlands and salt marshes is not easily detectable on satellite images. Mapping by vegetation community types on satellite images is limited, because spectral signatures of wetland and salt marsh vegetation are mixed with spectral signatures from underlying soil and there is no clear demarcation between vegetation community types. Some other factors like the effect of evaporating moisture from wetlands and salt marshes further increase the spectral mix of the objects (Adam and Mutanga, (2009); Zomer et al (2008); Schmidt and Skidmore, (2003); Guyot (1990), Malthus and George, (1997); Lin and Liquan, (2006).

The hyper-spectral sensor is considered as the best instrument for monitoring wetlands and salt marsh vegetation (Adam et al (2010)). The hyper-spectral sensor will record spectral signatures within short wavelengths intervals, which will allow better differentiation of the different plant species under different environmental conditions (e.g. content of moisture, wetness of underlying soil, density of the plants, etc.). However, in areas such as the Wadden Sea this option may be limited as for the occurrence of many vegetated areas smaller than 30 meters in size, which cannot be detected from a satellite platform because of the limited resolution (larger than 30 meters) of the hyper-spectral sensor.

4.1.9 Data fusion

To combine data from different sources, the method of data fusion is used. Ideally, the images must cover the same area and repeated over time. However, for the Wadden Sea, the tidal conditions are different each day and therefore obtaining images in the exact same water level is very difficult, if not impossible. The data fusion used in studies by Brockmann, Stelzer (2008), Van der Wal et al (2010)a, Van der Wal et al (2010)b to enhance and to increase the resolution of multi-spectral Landsat data (30 meters) by fusing with ERS-2 radar data. The advantage is on fusing high resolution ERS-2 data (12.5 meters), assisting in enhancing the details not visible on Landsat images.

5. Classification methods

The specific non-correlated pattern of temporal and high spatial variability on each image makes the classification process in the Wadden Sea complex. Related to differences in tide, every image must be treated separately and results from classifications must be validated with data from field surveys.

Choosing the classification methods for the Wadden Sea, the most applicable will be the method of:
- Spectral unmixing
- Supervised classification
- Object oriented classification
- Change detection.

Each method contains advantages and disadvantages and related to that, the choice of resolution and methods will be in every case different.

Spectral unmixing

Spectral unmixing is a process for detecting and separating the spectral signatures of different objects and use the result as input for classification. The unmixing can be limited in the Wadden Sea, because of patterns of high temporal and spatial variability, and tidal asymmetries (Davaasuren, Stapel et al (2012). The effect from high spatial variability will be on difficulties in detecting distinct spectral signatures for different sediment types, because it will produce large number of spectral signatures, which are not always easy to separate.

The method of spectral unmixing is used e.g. in classification of sediments into groups of mudflats, muddy or mixed sediment flats, wet or moist sand banks, dry sand banks and almost pure sand using Landsat-5 data (Brockmann and Stelzer, (2008)). The advantage of the method is the possibility to "reuse" derived spectral signatures from one image to another, but it still needs comparison with field data.

Supervised classification

The supervised classification is a method using the known (field evidence) spatial locations of e.g. mussel and oyster beds and sediments (by type) to derive the spectral signatures of the objects, which can be extrapolated to the rest of the image. The advantage of this method is good accuracy, but it is required to have beforehand ground data.

Change detection

Comparing images acquired in different periods will produce images showing temporal change of a particular location, e.g. a change in mussel and oyster bed cover, salt marsh extent or vegetation change, or changes in the position of gullies and channels. For the Wadden Sea it is important to compare images with the same tidal level and sediment water content.

6. Satellite data sources

European Space Agency (ESA)

The ESA provide medium and low resolution satellite data at no cost for European scientific users. The data can be requested from the ESA Earthnet website (Figure 18).

Figure 18-ESA Earthnet website

European Space Imaging (EUSI)

The European Space Imaging founded in 2002, as provider for very high resolution data provided by the IKONOS, Quickbird, Worldview-1,2, GeoEye-1 and Imagesat International's EROS-B satellites. The company is located in Munich, Germany and has an agreement with Digital Globe company (U.S.A), providing data to European customers. The very high resolution data can be ordered from the Digital Globe company archive and specific areas of interest can be imaged upon request. The latest developments in activities of the European Space Imaging is to task the satellites and receive imagery and derived products in near real-time (1 or 3 hours) within European waters or under Emergency delivery conditions (24 hours) for the rest of the world (European Space Imaging, (2013)).

Netherlands Space Office (NSO)

From 2012 the Netherlands Space Office NSO started an initiative to provide access to satellite data in low and medium resolution. The goal of this initiative is to establish a satellite data user community in the Netherlands, and extend this community to future Sentinel missions.

Third Party missions- National Aeronautics and Space Administration (NASA)

The NASA has a long time effort in providing data covering the entire globe. NASA and ESA have an agreement on data exchange and Third Party missions, e.g. data from NASA satellites are available for European users. The purpose of such agreement is to ensure the continuity of data provision and the promotion of scientific and commercial user communities.

7. Potential for long-term monitoring

The usability of satellite data for long-term monitoring will be affected by the following factors:

7.1 Availability of historical and present satellite data, and whether satellite data is available in establishing the monitoring system, and to be used in change analysis.

The monitoring system based on satellite data can provide valuable information over specific areas, together with insight into temporal change. A review of historical and present missions demonstrates the availability of medium resolution historical and present satellite data, continuously covering the area of the Wadden Sea by Landsat, ASTER and ERS-1, 2 satellites starting from 1980s to the present day. The recent missions in high and very high resolution can provide a very valuable extension to historical and present missions, extending the spatial coverage, increasing the revisiting frequency and enlarging the wavelengths range. With improvements made to the sensor systems, and additions of new bands in high and very high resolution, new satellites enhance the existing datasets, fostering developments of more accurate and higher resolution monitoring and enlarging the number of the parameters and parameter details that can be detected by Remote sensing.

To establish an operational monitoring system the availability of models, methods, algorithms and tools is important for e.g. sediment classification, identification of locations of mussel and oyster beds, intertidal areas, coast line, salt marshes, and gullies and channels, and the detection of temporal and spatial changes.

7.2 The continuity of the satellite missions, because this could potentially affect the sustainability of long term monitoring methods and tools, which are already in place.

The typical length of the satellite missions is from 3 to 5 years, and this is related to expected service time of the satellite. The continuity of the satellite missions are explained in Table 18, showing the continuity of the satellite missions, in terms of spatial resolution, revisiting frequency and range of the wavelengths.

Table 17-Continuity of the satellite missions

Future satellites	Sentinel-1	Sentinel-2
Period of operation	2013	2014
Resolution (and coverage)	5-20 m (250 x 250 km)	10, 20, 60 m (290 x 290 km)
Revisiting frequency	Europe, Canada and main shipping routes in 1–3 days;	
Wave bands (spectrum)	C-band SAR data	
Missions that will be taken over	ERS-1, ERS-2, ENVISAT and RADARSAT	SPOT, Landsat

The sustainability of long term monitoring methods and tools will not be affected by changes in the satellite missions. The main policy of the European Space Agency ESA as indicated in policy documents, in addition to new technological developments, is to follow-up the spatial resolution, revisiting frequency and the range of wavelengths from earlier missions into new missions of radar and multi-spectral satellites.

7.2.1 The interoperability of bands (wavelengths) among satellite missions.

The interoperability between satellite missions plays an important role, as it enhances the usability of historical satellite data by extending to recent satellite missions. Such datasets can be used in long-term monitoring, and already existing algorithms can be used.

The interoperability of the satellite bands between different missions is demonstrated by the continuity of the satellite missions, taking the example of DEIMOS-2 (UK DMC-2) and Landsat- 5 ETM+ sensor mission ESA (Earthnet, 2013). The match between the DEIMOS-2 (UK DMC-2) and Landsat- 5 ETM+ bands is presented in Table 19.

Table 18-Interoperability of UK DMC-2 and Landsat-5 ETM+ bands

Spectral bands UK DMC-2	Description UK DMC-2 bands	Corresponding bands of Landsat-5 ETM+	Description of Landsat-5 ETM+ bands
NIR*	0.77 – 0.90 µm	4 NIR	0.75-0.90 µm
Red	0.63 – 0.69 µm	3 Red	0.63-0.69 µm
Green	0.52 – 0.60 µm	2 Green	0.52-0.60 µm

**NIR- Near-infrared band*

8. Opportunities

ESA is looking beyond individual missions to improve the use of Remote sensing in long-term monitoring programmes. ESA initiated campaigns collecting data from Third party missions, airplane, balloons and ground measurements, and uses this to calibrate satellite data and improve classification accuracy. The ESA's Directorate of Earth Observation cooperates with research programmes, including the 6th and 7th EU Framework Programmes and promotes use of Remote sensing including the Data User Element and Earth Observation Market Development programme. These activities assist in forming new user groups of scientific and business communities and demonstrate novel uses of Earth observation. The ESA collaboration will continue in Framework Programme 8 of the European Commission, and will draw more attention to emerging global issues, such as climate change and ocean changes. ESA already initiated a first step in launching the microwave SMOS satellite measuring the surface ocean salinity and soil moisture on a global scale.

The opportunities of using Remote Sensing for a number of parameters relevant to WaLTER in each of the five groups mentioned before are presented in the Tables below (Table 20-24). The opportunities are presented for Group 1- General parameters, Group 2- Physical parameters, Group 3- Chemical parameters, Group 4- Biological parameters and Group 5- Habitat parameters.

Table 19-General parameters

Group 1- General parameters		
Description of method	Resolution of satellite data, missions	Opportunities, Limitations
Bathymetry		
Bathymetry 1. Feasibility phase, using medium resolution satellite data in resolution of 30 meters to generate preliminary depth profile. 2. Detailed mapping phase. Generating the detailed bathymetric information in a fine grid in resolution of 2 to 10 meters, detected water depth in maximum up to 25 meters.	Medium and high resolution – -Historical and present missions: Landsat (30 meters multi-spectral). Worldview-2 (2 meters multi-spectral), RapidEye (6.5 meters multi-spectral). -Future missions: Worldview-3 (2 meters multi-spectral). Sentinel-2 (from 2014), in 10, 20 meters multi-spectral.	Opportunities: Depth profile in resolution of 30 meters using medium resolution data; bathymetry information in maximum depth up to 25 meters, using the coastal blue band (400-450 nanometres spectral range). Limitations: -Availability of cloud-free images. -Method is applicable only for clear and shallow depth waters and not applicable for turbid waters, including turbid waters of the Wadden Sea.
Sediments		
Sediments classification by: -sediment composition (content of mud and sand), Sediments classification (2 groups) using Landsat MSS (60 m), as of 1986: -Very fine-grained sediments containing more than 70% silt and clay -Intermediate group containing between 30-70% silt and clay (Bartholdy and Folving, 1986). Sediments classification (5	Medium resolution -Historical and present missions: Landsat (30 meters multi-spectral), ASTER (15 meters multi-spectral). -Future missions: Sentinel-2 (from 2014), in 20, 60 meters resolution. High resolution images can be used in generating detailed overview over selected areas.	Opportunities: -Classifying sediment by composition, location and size of the area - Opportunities in detecting sediment grain size using high resolution data. -Continues and extended coverage of the Wadden Sea by medium resolution multi-spectral data, starting 1990s. -Availability of algorithms on detecting sediments concentrations, location and size

Group 1- General parameters		
Description of method	Resolution of satellite data, missions	Opportunities, Limitations
Bathymetry		
groups) applying spectral unmixing method using Landsat TM (30 m) as of 2008: - mudflat, muddy or mixed flat, wet or moist sand flat, dry sand flat and pure sand The distinction between sandy sediments and clay, covered by brown algae using Landsat TM data (30 m) as of 2012. -location and size (area) of mudflats -areas covered with vegetation (fugus, algae, other green biomass). -Water content		and areas covered by vegetation. <u>Limitations:</u> -Availability of cloud-free images and low tide. -Sediments can be classified only on exposed intertidal flats, -Algorithms and methods must be suited for local conditions of the Wadden Sea. -Detection of sediments by grain size is not possible on low and medium resolution data. -Results must be verified with ground data. -Relatively high cost of high resolution data. -Verification with ground measurements is required
Land cover		
<u>Land cover</u> by: -detailed land cover/vegetation (by plant community) product. -general land cover (green biomass) product.	<u>Low resolution</u> MODIS TERRA (300, 500 m) <u>Medium and high resolution</u> – -Historical and present missions: -Landsat (30 meters multi-spectral). -Worldview-2 (2 meters multi-spectral), RapidEye (6.5 meters multi-spectral). -Future missions: Worldview-3 (2 meters multi-spectral). Sentinel-2 (from 2014), in 10, 20 meters multi-spectral.	<u>Opportunities:</u> -Global coverage -Classification of wetland and salt marsh vegetation by location and size of the area -Availability of classification algorithms -Opportunity to monitor spatial and temporal change <u>Limitations:</u> -Land cover made from low resolution hyper-spectral data (300 meters and lower) is not suitable for the Wadden Sea. -Availability of cloud-free images -Limitations of multi-spectral data in distinction of plant communities -High cost of high resolution multi-spectral data -Verification with ground measurements is required

Table 20-Physical parameters

Group 2- Physical parameters		
Temperature		
Description of method	Resolution of satellite data, missions	Opportunities, Limitations
Estimated sea surface temperature, as difference of sea surface temperature measured in different wavelengths.	Low resolution -Present-day missions: MODIS TERRA and MODIS AQUA satellites in 500 meters	Opportunities -Mapping sea surface temperature from the satellite -Opportunities to monitor changes in the sea surface temperature on daily, monthly and annual basis Limitations - Availability of cloud-free images -Low resolution, not suitable for the Wadden Sea -Algorithm is limited to hyper-spectral MODIS missions
Salinity		
The sea surface salinity is estimated using the inverse models taking as main input the sea surface brightness and temperature measured in radar L-band (low frequency from 1 to 2 GHz). The data is available every 3 days, globally.	Low resolution -Present-day missions: SMOS, in 50 by 50 km pixel size.	Opportunities -Mapping changes in the sea surface salinity every 3 days -Opportunities for global overview Limitations -Low resolution not suitable for the Wadden Sea, with limitations in data coverage (no data along the coast) -Algorithm is limited to microwave SMOS mission

Table 21-Chemical parameters

Group 3- Chemical parameters		
Chlorophyll-a		
Description of method	Resolution of satellite data, missions	Opportunities, Limitations
The chlorophyll-a concentrations are estimated as difference in water reflectance containing different concentrations of chlorophyll in different wavelengths	Low resolution -Historical and present-day missions: ENVISAT in 260 meters by 300 meters pixel size , SeaWiFS (1.1 km) MODIS TERRA and MODIS AQUA satellites in 500 meters	Opportunities -Regional mapping of chlorophyll-a concentrations -Opportunity to compare ground measurements with satellite data -Availability of historical data set going back to 1980s Limitations -Availability of cloud-free images -Low resolution of the dataset---Algorithm is limited to hyper-spectral MODIS missions -Verification with ground measurements is required
Turbidity and organic matter		
The turbidity of the water is estimated as difference in water reflectance, between clear water and water containing the organic and dissolved matter	Low resolution -Historical and present-day missions: ENVISAT in 260 meters by 300 meters pixel size , SeaWiFS (1.1 km) MODIS TERRA and MODIS AQUA satellites in 500 meters	Opportunities -Regional mapping of water turbidity and organic matter --Availability of historical data set going back to 1980s Limitations -Availability of cloud-free images -Low resolution of the dataset- -Algorithm is limited to hyper-spectral historical and present-day missions -Verification with ground measurements is required

Table 22-Habitat parameters

Group 5- Habitat parameters		
Tidal area		
Description of method	Resolution of satellite data, missions	Opportunities, Limitations
The tidal areas are mapped in terms of location, size and composition (sediment concentration). The tidal areas can be only mapped on submerged flats	Medium resolution -Historical and present-day missions: Landsat (30 meters multi-spectral), ASTER (15 meters). -Future missions: Sentinel-2 (from 2014), in 20, 60 meters resolution. High resolution All present-day and future missions	Opportunities -Regional mapping of the tidal flats -Change detection using multi-temporal images -Opportunity to couple with other data Limitations -Availability of cloud-free images -Algorithm must be suited specifically for the Wadden Sea -Verification with ground measurements is required -Large uncertainties in comparing different classification methods
Salt marshes, dunes		
The mapping of salt marshes and dunes is by vegetation (land cover type) and soil (sediment) type, using Natura 2000 classification schema	Medium resolution -Historical and present-day missions: Landsat (30 meters multi-spectral), ASTER (15 meters). -Future missions: Sentinel-2 (from 2014), in 20, 60 meters resolution. High resolution All present-day and future missions	Opportunities -Regional mapping of the salt marshes and dunes is by vegetation (land cover type) and soil (sediment) type, -Change detection using multi-temporal images -Opportunity to couple with other data Limitations -Availability of cloud-free images -Algorithm must be suited specifically for the Wadden Sea -Verification with ground measurements is required -Large uncertainties in comparing different classification methods
Blue mussel beds		
The mapping of the blue mussel beds are by location and size, on submerged tidal flats	Medium resolution -Historical and present-day missions: Landsat (30 meters multi-spectral), ASTER (15 meters). -Future missions: Sentinel-2 (from 2014), in 20, 60 meters resolution. High resolution All present-day and future missions	Opportunities -Regional mapping of the location of the mussel beds -Change detection in location (disappearance and appearance) using multi-temporal images -Opportunity to be used as additional data to ground survey Limitations -Availability of cloud-free images for multi-spectral data -Algorithm must be suited

Group 5- Habitat parameters		
Tidal area		
Description of method	Resolution of satellite data, missions	Opportunities, Limitations
		specifically for the Wadden Sea -Mapping of the mussel beds only on emerged tidal flats -Mapping on medium resolution satellite data is limited to large mussel beds -Visibility of the mussel beds depends on water level, amount of sediments and green biomass (algae, fugus) covering the mussel beds -Verification with ground measurements is required -Large uncertainties in comparing different classification methods
Sea grass beds		
Mapping location of the sea grass beds based on difference in water reflectance in areas with sea grass and without	Medium resolution -Historical and present-day missions: Landsat (30 meters multi-spectral), ASTER (15 meters). -Future missions: Sentinel-2 (from 2014), in 20, 60 meters resolution. High resolution All present-day and future missions	Opportunities -Regional mapping of the location of the sea grass beds -Change detection in location (disappearance and appearance) using multi-temporal images -Opportunity to be used as additional data Limitations -Availability of cloud-free images -Mapping is limited to shallow and clear waters -Mapping using medium resolution data can provide only regional overview -High cost of the satellite data -Best results only with combination of the coastal band from present-day and future missions

9. Discussion

Long-term monitoring in the Wadden Sea is possible because of availability of historical medium resolution satellite data, historical and on-going ground measurement programmes, and interoperable current and future satellite missions.

The development of Remote sensing techniques, providing end-users with interpretable good quality data, is very resource intensive and starts with satellite design, launching procedure, operation and maintenance. In order to continue using the (expensive) developed algorithms and methods, mission continuity and interoperability of the historical, recent and future missions are required. Some minor adjustments may be developed, for instance adjusting the new bands of Worldview-2 data in blue, red edge and infra-red. The policy of the satellite data providers therefore is to ensure the interoperability of the satellite data, and to provide data which are similar in spectral information, and spatial and temporal coverage.

Medium resolution programs like Landsat, SPOT and radar satellites (RADARSAT) are sponsored and became a part of national policies on science and technology. The recent boom of high and very high resolution commercial multi-spectral satellites is a continuation of previous (medium resolution) missions and aims to enhance the ground resolution and spectral information of the medium resolution data, and to provide new information from additional wavebands and/or new tools. The new Landsat-8 mission already supplies information in two additional Short wave-length infrared (SWIR) bands in 30 meters resolution, adding extra information to previous Landsat missions.

The latest example of continuation of satellite missions and data interoperability is the DEISMOS -2 (UK DMC-2) continuing the Landsat-5 ETM sensor mission, which allows the use of historical data and merger with present datasets. The Sentinel satellites will continue the ERS-1, ERS-2 and ENVISAT satellite missions and the Third party RADARSAT mission of the Canadian Space Agency, the French SPOT and the USA Landsat missions.

The heterogeneity of the Wadden Sea and its high dynamic processes characterise the set-up of a Remote Sensing based monitoring programme. Integral and combined use of multiple satellite platforms, algorithms and classification methods and tools and ground information is required. The choice of using Remote Sensing always depends on data cost and temporal and spatial coverage in comparison to field measurements. In this respect, the historical and current medium resolution data can be used as baseline information in establishing such long-term monitoring systems. The high and very high resolution data may serve as additional information, and will allow zooming in on specific areas of interest. An overview of regional (large scale) processes and trends can be complemented using global data in low resolution.

10. Conclusion

The long-term monitoring in the Wadden Sea looks promising and ESA efforts to ensure continuity of satellite missions provides stability and continuity in data provision and extended support for the data users in the coming decades.

Remote sensing provides numerous advantages for spatial and temporal monitoring of the Wadden Sea, potentially covering the complete Wadden Sea basin. The overview of historical and recent satellite data presents continuous coverage for the Wadden Sea starting in the 1980s with Landsat data and classification of the sediments. The application expanded and today, new high resolution data is used to retrieve details on e.g. mussel beds. The historical and current missions will be continued in the future, by Landsat-8, Sentinel-1, 2, Worldview-3, SPOT-6, 7 and DEIMOS-2 satellites, and potentially other yet to determine missions, depending on users' demand.

Repeated daily coverage, including high and very high resolution data, currently ensures data provision on a regular basis, which is important, considering the limitation imposed by weather conditions for multi-spectral data and tidal limitation for both multi-spectral and radar datasets. Data acquisition during low tide will be the most important requirement for Remote Sensing based Wadden Sea monitoring. The method of data fusion may provide a solution for enhancing multi-spectral data and providing additional coverage when multi-spectral data are not available because of cloud cover.

Continuity of spectral information from new satellites guarantees interoperability of historical, current and future satellite missions, demonstrated for example by the current DEIMOS-2 and the historical Landsat-5 satellites.

Recent developments dramatically increased resolution from meters to centimetres, allowing for the development of new algorithms for monitoring parameters and features that were previously not possible.

Considering all limitations and challenges, expanding the use of Remote sensing data and tools in Wadden Sea monitoring programmes is advisable: it is cost-effective, promising to answer some current issues related to temporal and spatial changes in Wadden Sea features (e.g. mussel and oyster beds) and may lead to the development of new applications for monitoring parameters that are not yet considered possible.

11. Quality Assurance

MARES 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 27 March 2013 and was first issued on 27 March 1997. Accreditation was granted by the Council for Accreditation.

Glossary of Technical Terms

- **Remote sensing**- is defined as data collection about an object from a distance. Humans and many other types of animals accomplish this task with aid of eyes or by the sense of smell or hearing. Geographers use the technique of Remote sensing to monitor or measure phenomena found in the Earth's lithosphere, biosphere, hydrosphere, and atmosphere. Remote sensing of the environment by geographers is usually done with the help of mechanical devices known as remote sensors. These gadgets have a greatly improved ability to receive and record information about an object without any physical contact. Often, these sensors are positioned away from the object of interest, features (see Features) by using helicopters, planes, and satellites. Most sensing devices record information about an object by measuring an object's transmission of electromagnetic energy from reflecting and radiating surfaces. Features- features can be objects of nature- forest, land, water, etc. and artificial, man-made- e.g., urban structures, artificial mountains, structures in the sea, ships, platforms, etc. Objects of the nature and man-made objects can be detected from the space and recorded on satellite images, based on reflectance or spectral signature (see Reflectance).
- **Features**- features can be objects of nature- forest, land, water, etc. and artificial, man-made- e.g., urban structures, artificial mountains, structures in the sea, ships, platforms, etc. Objects of the nature and man-made objects can be detected from the space and recorded on satellite images, based on reflectance or spectral signature (see Reflectance).
- **Reflectance** (spectral signature) - when sunlight hits any surface on earth, the sunlight can be absorbed (for example by water), transmitted back (dry soil), reflected in full extent (house roof, ice and snow cover) or partially- forest, land, etc. The strength of the transmission, absorption and reflection is depending from the texture and type of the surface. The satellite sensors record the transmitted and reflected signals. Reflectance value (Spectral signature) is a number, presented in bits and stored as numerical values in the image.
- **Texture** (of the feature) - the real objects often do not exhibit regions of uniform intensities. For example, the image of a wooden surface is not uniform but contains variations of intensities which form certain repeated patterns called visual texture. The patterns can be the result of the physical surface properties such as roughness or oriented strands which often have a tactile quality, or they could be the result of reflectance differences such as the colour on a surface. In Remote sensing the texture of the surface is used in image classification.
- **Image**- image is representation of captured signal or sunlight. The features are shown in colours if image is in colours (see Colours) or in black and white (see Panchromatic image). The image can be analogue- printed, or digital- stored in the computer. In Remote sensing, image has two dimensional functions- X and Y coordinates, and size of the image consists from Row and Columns (Height and Width). Such image is called a raster image.
- **Raster** (image) – raster (image) consists from the squares (grid). Each cell of the grid (see Grid) is represented by a pixel (see Pixel), also known as a grid cell.
- **Grid-** square in the image, representing the smallest element of the image. In Remote sensing, the grid is called Pixel (see Pixel).
- **Colors**- the colors are continuous range, starting from Black to Red, Magenta, Yellow, Green, Blue, Violet to White. The colours used in images represented in mixtures. Each feature can be identified by distinct colour.
- **Panchromatic image**- it is black and white image and image values (see Image) are represented in range from black (zero value) to the white. The image values from black to white are represented in shades of grey.
- **Multi-spectral image**- it is image containing several bands (see Bands) and it shows features in different colours, depending from bands combination.
- **Wavelengths**- are the distances between repeating units of a propagating wave of a given frequency. The light, microwaves, x-rays, and TV and radio transmissions are all kinds of electromagnetic waves. They are all the same kind of wavy disturbance that repeats itself over a distance called the wavelength.

- **Electromagnetic spectrum**- it is physical definition of wavelengths, expressed in nanometres (see Nanometres). The spectrum used in Remote sensing starts from infrared region (near, middle and far infrared), visible region (Red, Green, Blue) and thermal.
- **Nanometres**- a nanometre is 0.000000001 meters, equal to 10^{-13} meters.
- **Infrared** region of wavelengths- starts from 0,7 to 5,0 nanometres.
- **Optical range**- often referred as visible region (Red, Green and Blue light). The Blue region starts from 0,4 to 0,5; Green region from 0,5 to 0,6 and Red from 0,6 to 0,7 nanometres.
- **Satellite sensor**- is a camera mounted on satellite, which records reflected and transmitted reflectance of features in selected wavelengths. Every satellite has distinct range of electromagnetic spectrum to record.
- **Image Processing**- is a process which extracts information about features based on their reflectance, transmission and absorption property of the sunlight.
- **Resolution** of the satellite image- is a broad term commonly used to describe the number of pixels you can display on computer, or area on the ground (in meters, centimetres, etc.), often called a pixel (see Pixel) represented in an image. The resolution is fixed for each satellite. For instance the resolution of the Landsat satellite is 30 meters.
- **Pixel**- it is area on the ground which represents is a single point on a raster image, or the smallest addressable screen element on a display device; it is the smallest unit of picture that can be represented or controlled. In satellite image the pixel is related with sensor resolution.
- **Spectral resolution**- the specific wavelength intervals that a sensor can record and it is fixed for each satellite. For example for the WordView-2 satellite, the spectral resolution is starts from Blue wavelength (see Wavelengths) and includes another blue wavelength, green, yellow, 2 red and 2 infrared wavelengths of the spectrum. Often these wavelengths are called bands of the image (see Bands).
- **Bands** (of image)- bands are recorded range of Electromagnetic spectrum by satellite sensor of reflectance's of the features. The range of the bands is expressed in nanometres and each satellite sensor has predefined range.
- **PCA- Principal Component Analysis**. The technique based to compress information, especially when image contain several bands. The so-called principal components are indicating where the most of the information is and in which bands.

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