Measuring water quality in coastal regions using remote sensing

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Abstract

CoastSat is a mission designed to produce improved measurements to assess the water quality of coastal regions, rivers and lakes. The primary goal is to give access to advanced data products on turbidity, chlorophyll-a and coloured dissolved organic matter (CDOM), with good temporal and spatial resolution, providing also Sea Surface Temperature (SST) data for contextual usage. *CoastSat* will allow for an extensive evaluation of the state of coastal waters, since these observables comprise invaluable inputs for a wide range of applications including data assimilation for hydrological models. *CoastSat* is a space mission consisting of two identical satellites, both equipped with a multispectral imager in order to observe the Earth in the range from 350 to 880 nm and a thermal imager. The mission will provide data with a spatial accuracy up to 20x20m^2 and a revisit time of 3 days to account for the dynamics of turbulent mixing and algae growth.

Scientific background

Water covers 71% of the Earth's surface and 96.5% it is located in the oceans. According to the United Nations Environment Programme (2016) half the world's population lives within 60 km of the coast. Furthermore, coastal regions are important areas of biological productivity and support 90% of the world's fish catches (Pauly et al. 2002). Thus, coastal areas have a significant importance for humanity both as a habitat and also for economical reasons. However, these coastal areas are endangered since they are exposed to a variety of different kinds of pollution causing a serious deterioration of the water quality. For example, diffuse pollution, mainly caused by agriculture, significantly affects 90% of river basin districts, 50% of surface water bodies and 33% of groundwater bodies across the EU (European Commission 2015).

Pollution from agriculture, aquaculture, wastewater and urban runoff causes the eutrophication of coastal waters (Bricker et al. 2008, Hadley et al. 2015). Eutrophication describes the process by which a body of water, that is enriched with nutrients (e.g. nitrate), stimulates the growth of aquatic plant life. It is one of the greatest threats to coastal ecosystem health as it can result in an increasing abundance of harmful algal blooms, depleted oxygen content, decimated shell and finfish abundance, as well as the decline of coral reefs (Bricker et al. 2008, D'Angelo & Wiedenmann 2014).

Science Objectives

In order to assess the water quality of coastal regions, rivers and lakes we identified the following science objectives:

1. To improve retrieval of water quality indicators from spectral radiance measurements
2. To develop a better process-understanding of turbulent mixing in coastal regions
3. To analyse the nutrient transport (i.e. nitrate) from land into rivers, lakes and coastal waters
4. To build prototype monitoring systems for coastal waters, rivers and lakes (i.e. algae blooms)

Observables

Water quality is influenced by the amount of suspended sediments, algae, chemicals, thermal releases, aquatic vascular plants, pathogens, and oils in the water. Monitoring these factors and hence assessing the quality of surface water is critical for managing and improving the quality of aquatic ecosystems. *In-situ* measurements and the collection of water samples are used to measure these, but they neither give the spatial nor the temporal information needed. Compared to *in-situ* data, satellite sensors provide a global coverage, high temporal resolution and help to investigate the water pollution in remote areas. Satellite sensors can be used to observe turbidity, as a measure of the amount of suspended sediments in the water, chlorophyll-a (chl-a), coloured dissolved organic matter (CDOM) and sea surface temperature (SST), as these variables affect the spectral and thermal properties of surface waters (Dierrsen 2010).

Chl-a is one of the key biochemical components in the molecular apparatus, which is responsible for photosynthesis, the process in which energy is used to produce oxygen. Chl-a is present in algae and phytoplankton and thus chl-a concentrations serve as an indicator of the abundance and distribution of algae and phytoplankton in the water. An understanding of the distribution of these organisms enables conclusions about a water body's health, composition and quality (YSI, 2016). High levels of nutrient in the water column, coming from anthropogenic pollution, such as fertiliser runoff, accelerate algal growth. Under good conditions the algal growth rate results in a doubling of the total algae count every 3-4 days (Asterio-Sánchez et al. 2002). Observing chl-a with a revisit time of 3-4 days enables the assessment of algae growth in water bodies.

CDOM refers to the organic matter dissolved in water. It absorbs strongly near the 400 nm end of the spectrum and thus takes up most of the energy in the blue wavelength. In combination with the strong absorption of red light by water itself, the water appears to be green or yellow to brownish in colour depending on the amount of CDOM present (Nieke et al. 1997). Nutrient enrichment or point source pollution from pulp and paper mills or wetland drainages increases CDOM levels in freshwater and estuarine systems (Blough & Green 1995). CDOM further affects the biological activity in aquatic systems as it diminishes the amount of light, which penetrates through the water and so impedes phytoplankton growth (SCCF RECON 2015). CDOM and chl-a both absorb light in the same spectral range so it also interferes with the use of satellite spectrometers to remotely estimate phytoplankton population distribution from chl-a.

Turbidity is the measure of relative clarity of a liquid. Physically it describes how much light is scattered by material in the water when light hits it, resulting in an optical characteristic. A high intensity of scattered light means a high turbidity. Clay, silt, organic matter, algae and plankton are factors which increase turbidity by turning the water cloudy or opaque. Turbidity affects the amount of light penetrating into the water, thus reducing the biological productivity (USGS, 2016).

Satellite measurements of SST in combination with chl-*a* can be used to estimate nitrate using algorithms, which are based on empirical data (Goes et. al. 1999). The degradation of surface water quality, through eutrophication, is strongly associated with nitrate leakage due to anthropogenic activities (Keeney et al. 1986). Thus, a combined measurement campaign of SST and chl-*a* is required to analyse the transport of nitrate from land into rivers, lakes and coastal waters. The measurement range for turbidity is 0.001 to 0.1 (5% accuracy), 0.001 to 150 mg/m² for Chl-a (10-70% accuracy), 0.01 to 2 1/m for CDOM (10 to 70% accuracy) and finally 0.1 K of accuracy is required for temperature.

Science Requirements

Current satellite sensors, which can be used to derive water quality (i.e. MODIS, SeaWiFS & OLCI), are primarily designed for observing the open ocean, but fail on delivering accurate data for observing coastal and inland waters (Mouw et al. 2015). Therefore, a satellite sensor with an adequate spectral, spatial and temporal resolution is required in order to capture small scale processes in these highly dynamic areas and also to minimise the effects of mixed pixels along the coastline.

A spectral range from 350 – 880 nm is required in order to fully distinguish between CDOM and chl-a (Figure 1, NASA 2012). Current sensors, such as MODIS or OLCI, cover the upper part of this spectrum, but not the lower part. While, different chl-*a* concentrations can be derived from the spectral bands around 430 and 680 nm, high-resolution spectral information between 430 and 500 nm are further needed to differentiate between different types of phytoplankton, such as diatoms and cyanobacteria (Dierrsen 2010). To a large extent OLCI provides the required spectral bands at a comparably wide bandwidth. However, OLCI does not provide the required spatial resolution, which is addressed in the next paragraph.

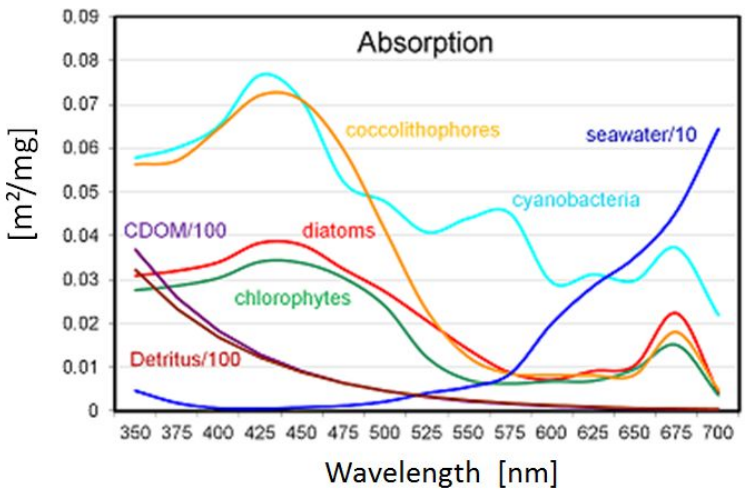


Figure 1. Spectral absorption of CDOM, chlorphyll-a and various other types of phytoplankton.

Compared to other satellite missions that are currently used to observe ocean colour (i.e. MODIS, OLCI), a higher spatial resolution is required for coastal areas in order to analyse processes such as turbulent mixing and algae blooms. A resolution of less than 500 m is required to resolve dispersion of optically active components in river plume regions (Mouw et al. 2015). For well mixed conditions, Bissett et al. (2004) showed that an optimal resolution of 100 m for nearshore waters (within 200 m of shore) and greater than 1 km for offshore waters is needed (10 m from shore). However, to observe turbulent mixing processes in river deltas, that take place on a spatial scale depending on the width of the contributing river, a spatial resolution of up to 50 m is needed. When phytoplankton which is capable of regulating its buoyancy, such as some cyanobacteria, is present, a 30 m spatial resolution was found to significantly underestimate chl-a concentration due to the horizontal and vertical structure of the bloom (Kutser 2004). Thus, a spatial resolution higher than 30 m is required to provide accurate estimates of phytoplankton blooms. This resolution is further important for coastal regions, as it helps to differentiate between land and water and so minimises the effect of mixed pixels.

Satellite sensors with a higher temporal resolution together with additional spectral channels will help to improve and the develop models for detecting and monitoring phytoplankton blooms in coastal areas (Blondeau-Patissier et al. 2014). The coastal regions are very dynamic areas, where the observables show significant changes over a short period of time. Changes in turbidity occur on the timescale of weeks, while changes in chl-a happen in the order of days (Elsdon & Connell 2009). In the case of chl-a the fast rate of change is the result of the exponential growth of algae (in terms of cells/ml) (Mirón et al. 2002), which currently makes a detailed study of algae growth by satellites impossible.

The required lifetime of the mission shall be three years with a possible extension for two additional years. The lifetime was chosen to obtain measurements that can capture intra- and inter-annual variation in the observables. Intra-annual observations enable the study of seasonal changes in the coastal regions, which is crucial to understand how variations in river discharge, precipitation and SST affect the water quality (Giorgi et al. 2004). Inter-annual measurements improve the understanding of long-term changes in water quality at coastal regions. Annual changes in the observables help to define which regions are and gradually become more vulnerable to algae blooms and low water quality. An extension of our mission by two more years will increase the probability of observing extreme events, such as anomalously large algae blooms and/or changes in water quality during El Niño and La Niña events. Studying these events will help to understand the possible combined effect of physical phenomena and anthropogenic activities on the abundance and distribution of algae in certain regions.

Instruments

CoastSat hosts two payloads for the measurement of water quality indicators: a multispectral imager for CDOM, chl-a and turbidity, and an infra-red imager for SST.

Multi-Spectral Ocean Imager (MSOI)

The MSOI is based on the Sentinel-2 MSI instrument with a Three-Mirror Anastigmat telescope with a pupil diameter equivalent to 150 mm, 12 spectral bands and 12 sensors. To adapt the instrument for the *CoastSat* mission, the instrument shall be scaled to 15 spectral bands, 350 km swath and 20 m ground resolution at the corresponding altitude. To cover the whole swath, the focal-plane-assembly shall feature 18 sensors. At the swath edges, the ground resolution would be 26 m instead of 20 m. The uniformity of the ground resolution throughout the swath shall be improved by implementing a correction lens. The instrument shall be 2.2 x 0.93 x 0.62 m, 377 kg, with a power consumption of up to 399 W. Spectral filtering shall be performed with assemblies of narrow bandpass filter strips (imec) on top of each sensor. In the design, 18 CCD sensors (e2v CCD 42-10) with 2048 x 512 pixel format are used with a 12-bit analogue to digital converter. Sensor height (512 pixels) is divided into 15 spectral bands. The current signal to noise ratio (SNR) estimates have been calculated with the assumption that each spectral band has 34 pixels, 13.5 x 13.5 μm each. This translates to an effective pixel size of 78 μm. Based on the footprint velocity of around 6.95 km/s at 500 km, the maximum exposure time would be 2.87 ms. Whereas the SNR values have been calculated with a margin of 40%, it has been assumed that the e2v enhanced broadband coating has been applied to the sensor surface. The coating improves the quantum efficiency of the sensor by up to 30%. Table 1 lists the spectral bands with bandwidth, signal to noise ratio and reference level.

With a mechanical shutter, the instrument is protected from direct exposure to sunlight during the tumbling and commissioning phases of the mission. Stray light is reduced with a baffle. The focal plane array is cooled to 233 K with a passive cooling system, to reduce thermal noise. During imaging, the system tolerates a temperature drift of 10 K at 233 K, which causes at most an 0.5 electron per pixel per second increase in the dark current.

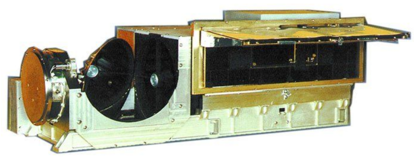
Table 1: Spectral bands of the *CoastSat* MSOI instrument.

Band Nr.	Central wavelength [nm]	Bandwidth [nm]	Application	SNR	Reference level [W/str]
1	360	20	CDOM	573	472.58
2	410	3	CDOM	400	771.23
3	412	3	CDOM, Turbidity	316	482.09
4	443	3	Chlorophyll, CDOM, Turbidity	504	1077.12
5	488	20	Turbidity	2192	1961.53
6	540	20	Turbidity	2406	2130.13
7	645	3	Chlorophyll	721	1465.61
8	667	3	CDOM, Turbidity	735	1466.28
9	670	3	Chlorophyll	738	1451.24
10	676	3	Chlorophyll, Turbidity	738	1451.24
11	748	20	Turbidity	2214	1473.93
12	764	4	Reference	653	814.84
13	767	3	Reference	490	814.84
14	868	20	Turbidity	1933	1600.44
15	940	20	Reference	631	857.86

Each CCD shall be complemented with a control unit, pre-amplifier, analog to digital converter, and a digital data processing unit that accounts for the overlap between the sensors. The data rate from MSOI to the on-board data handling system will be 880 Mbps. Assuming a worst-case coastline of 5000 km, the instrument would produce about 77 GB of data per orbit. Orbital data rate can be reduced by switching between scanning configurations with different ground resolution in different parts of the swath. Optionally, spectral acquisition could be limited to specific bands in different regions of interest.

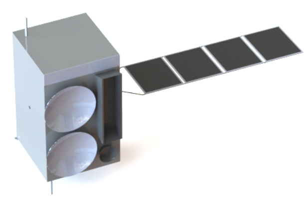
Thermal Imager

To provide data for the complementary observable SST, a low-risk instrument with prior flight heritage has been selected. The Advanced Very High Resolution Radiometer AVHRR/3 by National Oceanic and Atmospheric Administration has been chosen in order to obtain SST measurements at accuracy of 0.1 K, improved with respect to the existing satellite-based SST data (e.g. MODIS). This would make the data provided by *CoastSat* able to improve the models which describe the distribution of nitrate in coastal ocean water. The six spectral channels of the AVHRR/3 lie at the central wavelength of 630, 862, 1670, 3740, 11000 and 12000 nm, and have bandwidths of 100, 275, 60, 380, 1000, 1000 nm respectively. The footprint is of 1.1 km at nadir. The data rate is of 1.9 Mbps and 114 MB per scan. The AVHRR/3 weighs ca. 33 kg and has a total volume of 0.085 m^3.



Design Procedure

In order to arrive at an estimate of the spacecraft subsystems, an empirical approach is used. Starting from the payload requirements, the mass and power breakdown



structure is derived from heritage mission mass and power fractions (Wertz & Larson 2003).

Space Segment & Orbit

As the scientific payload is comparable in size and requirements to the MSI instrument flown in Sentinel-2, the Airbus Astrobus L satellite bus is taken as a baseline. The satellite bus must have sufficient volume to accommodate the sensor array of the multispectral camera. In turn, the instruments dimensions must be adequate to accommodate the size of the focal plane assembly, which is driven by swath width, ground resolution and SNR. To fulfill the revisit time requirements (Figure 2) and match the SNR and altitude requirements, two space segments will be placed into a 511 km sun synchronous orbit at a retrograde 97° inclination. Such an orbit ensures that the descending path is always facing the sun with reliable lighting conditions throughout the year.

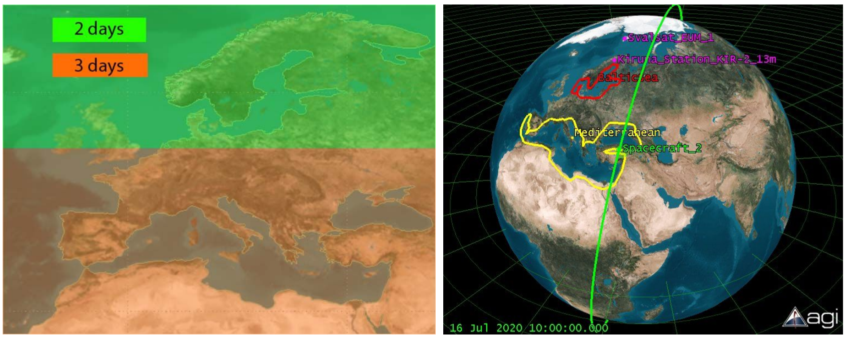


Figure 2: Revisit time for different latitudes (left). Orbit with the coastal areas marked.

Power Budget & EPS

During operation, the PPU provides both scientific payloads with 600 W of power, which is 48.4% of the total power budget. The power consumption of two X-band transmitters is 11%, and S-band communication module for Telemetry and Telecommand makes up an additional 11% of the total power budget. In order to protect the subsystems and especially the instrument from temperature fluctuations which could compromise operation, a thermal management system will distribute the heat at the cost of 9.7% of the total power budget. The operation of the Attitude Determination and Control System (ADCS) will use 9.2% of the total system power, while PPU losses contribute additional 8.3% to the overall power consumption. The overall power demand adds up to 1473 W and hence 7 m^2 of GaAs solar panels will be used.

Thermal Subsystem

The scientific payload needs to be kept between - 50° and - 30°, which can be reached by passive radiative cooling towards deep space. Passive radiators will be sufficient to emit surplus energy dissipated by different S/C components. In the conceptual design phase, the thermal analysis can assume a spherical model and evaluate the steady state solutions within the environment encountered during the operational scenario. With these considerations, in the hot case scenario within sunlight the incoming heat sources are in descending order: Heat from the Sun (8550 W), Earth Albedo (2190 W), IR from Earth (1706 W) and the dissipated power from the instruments (1473 W).

Attitude Control & Propulsion system

While the spacecraft is in orbit it will be subjected to a number of environmental perturbations such as atmospheric drag or solar wind which affect the position and attitude. The delta-v budget to mitigate those influences is shown in Table 2 (TU Delft, 2016). The pointing accuracy of 0.001 deg arising from the the ground resolution of 20 m and the altitude of 511 km will be achieved by combining an ASTRIX 200 high precision gyro with MTR-5 momentum wheels, 2 Rigel L star trackers, a 3 axis magnetometer, three magnetotorquers and 8 hydrazine thrusters with a pressure fed blowdown system and a 1N thrust.

Mass Budget

The payload, consisting of the multispectral camera and the infrared camera weighs 400 kg. By comparing the payload with heritage weight fraction of comparable systems, the mass breakdown structure can be estimated. The structure will have approximately 348 kg, the PPU 132, and the ADCS system 77 kg. Together with the other subsystems, the dry mass of the entire spacecraft will add up to 1453 kg. From the delta-v requirements (Table 2) and the dry mass the amount of propellant can be calculated to be 73 kg.

Table 2: Delta-V budget.

Maneuver	Delta-v / year [m / s]	Delta-v / lifetime (5 years) [m / s]
Altitude maintenance	5	25
Momentum wheels unloading	3	15
Attitude control	10	50
Phasing	8.5	8.5
Overall	26,5	98,5

Data collection, handling and Down-link

Each space segment has an accumulated contact time to the ground stations Svalbard and Kiruna of 11269 seconds per day at optimal weather conditions. Taking the bandwidth limits of the two stations into account (300 and 100 Mbit/s) a maximum daily download of 2.3 Tbit can be achieved. To bridge the gap between available download period, and taking into account one possible failed downlink, two AIRBUS solid state recorder with a capacity of 3 Tbit/s each are used. Sentinel-2 uses the EDRS (European Data Relay System) to increase data downlink, which can also be considered for the proposed mission.

Launch Vehicle

The total weight of the spacecraft is 1453 kg which exceeds the capabilities of a Delta rocket but is well within the capabilities of one Soyuz rocket per space segment.

Development Costs

The proposed cost of the mission can be divided into five main contributors: launch (Soyuz), space segment, payload, science operations. The proposed double spacecraft mission has on overall budget of 723 M € of which launch makes up 150 M € (21%), the space segment is 180 M € (25%), the payload is 313 M € (43%) and finally the science operation is 80 M € (11%) of the total cost. In case of the descoping option (single spacecraft) the expected budget is the following: launch 75 M € (18%), space segment 90 M € (21%), payload 185 M € (44%) and science operation 70 M € (17%) (Wertz & Larson 2003).

Timeline

The mission lifetime is divided into 5 phases. The conceptual design - Phase 0 (2017-2019) which will be followed by the feasibility and preliminary design - Phase A, B1 (2019-2022), detailed design, test and integration - Phase B2, C, D (2022-2030), operation - Phase E (2030 - 2035) and space segment de-orbiting - Phase F (2036 - 2050) at the end of operation (Table 2).

Operational Modes

The large amount of data, which will be produced by *CoastSat* due to the high spatial and temporal resolution, requires selective acquisition and on-board processing of the data. Therefore, only the coastal areas of interest are mapped, which means no data is collected further than 200 nautical miles (~370 km) off the coast. Between 10 times typical river width and 200 nautical miles away from the coast on-board averaging is used to collect data at a spatial resolution of 500x500 m^2. From the 10 times typical river width until 100 m off the coast we will collect data at a 50x50 m^2 spatial resolution again using on-board averaging. Finally, the actual resolution of our sensor (20x20 m^2) will only be used to cover the areas from 100 m off-coast till 10 km in land. There will further be an additional mode, which can be scheduled according to request in order to observe specific regions of interest with a given spatial resolution in given spectral bands. This will enable the observation of specific inland lakes and rivers at a high spatial and temporal resolution, as well as the monitoring of extreme events, such as volcano eruptions, forest fires, floods and hurricanes.

Ground Segment

Existing ESA infrastructure will be used to operate the ground segment. The Flight Operations Segment (FOS), responsible for command, telemetry and tracking of the satellite, will be located at ESOC in Darmstadt (Germany). Telemetry and tele-communication will be performed through S-band communication with the FOS. The Payload Data Ground Segment (PDGS), located at DLR (German Aerospace Center) in Oberpfaffenhofen, will be responsible for scientific data acquisition, processing and archiving of the data products. PDGS will receive the data via X-band downlink and will be responsible for calibration of the operating instruments and validation of the data products. Once the Level 3 products are derived, the PDGS will further distribute these to the user segment.

Risk analysis

As with any space missions there are risk in form of launch failure, loss of space segment, a delay in instrument development and the fact that the orbit and ADCS might not fulfill the requirements of the mission. Launch failure is improbable, as the launcher is a well tested system. But it would have a major impact on the mission if either the launch is delayed or the satellite is lost. Both the loss of a space segment as well as the delivery of the satellite to an incorrect orbit are remote possibilities that would have a significant impact on revisit time and the usability of the data. The consequences of delays in instrument development are moderate and will result in an increase in mission costs. In the case that ADCS fails to meet the requirements the severity is moderate as the usability of the data would decrease.

Data Distribution and Outreach Activities

Data products will be distributed following Committee on Earth Observation Satellites standards to fulfill the needs of different users. The Level 1 Product is Top-Of-Atmosphere radiance [W/m^2 sr] in sensor geometry as well as cartographic geometry. As Level 2 Products atmospherically corrected Bottom-Of-Atmosphere reflectance in cartographic geometry [W/m^2 sr] as well as SST [°C] are provided. Level 3 products will contain chl-a [mg/m^3] and CDOM [mg/m^3] and a prototype nitrate product [mg/m^3], that will be limited to regions, where *in-situ* data for calibration purposes is available. Whereas Level 2 products are suited for people working on data assimilation and the improvement of radiative transfer models, the target group of Level 3 products are local authorities or scientists, such as ecologists or marine biologists. Calibration and validation data will be provided by a dedicated network of partner institutions, which provide data derived from measurement campaigns or Argos floats. To guarantee consistent calibration and validation data, measurement protocols and standards will be distributed to all participating partners. Schools and Universities can participate in the calibration and validation activities by providing additional *in-situ* measurements. This can be combined with additional ways of attracting students to science by organising Science Camps, field visits and measurement campaigns for children. Water quality measurement kits can be given to partner schools or universities, hereby introducing children to the issue of water pollution. Outreach activities to the science community encompass an online forum to support the scientific use of the data and knowledge exchange, as well as the user symposium "COAST", to exchange state-of-art research every 2 years. To reach a broader target group, social media channels such as Facebook, Twitter and Instagram will be used to share information about the status of the mission during development, launch and operation, as well as to distribute interesting scientific results and images from the *CoastSat* mission.

Model and Data Assimilation

The assimilation of ocean colour data in biogeochemistry operational forecast models have shown a general good improvement of the forecasts (Teruzzi et al, 2014). A higher spatial and temporal resolution will increase the amount of assimilated data, and will further improve the forecasts. Combined with existing missions, *CoastSat* will provide a better spatial (350 km of swath width) and temporal (three days) coverage, which is also important for model validation and will contribute to the improvement of the physical processes inside the model.

Conclusion

CoastSat is a mission proposal hosting two instruments: a MSOI and a thermal imager. Particularly the MSOI offers a fine spectral resolution on specific bands, which is the key to effectively detect, discriminate and identify the agent involved in the water pollution (Chl-a, CDOM, turbidity). The thermal imager instrument will measure SST. Combined with chl-a concentration, empirical relationships can be used to retrieve Nitrate concentrations. In order to achieve a revisit time of 3 days, two *CoastSat* satellites will be launched with an inclination of 97°. The spatial resolution will be a function of the distance to the coastal areas. The high temporal and spatial resolution proposed by *CoastSat* will enhance the knowledge in coastal areas and improve the oceanic and biochemical model forecasts. Besides scientists, who will be provided with new observation capabilities, these measurements will support decision making to preserve and protect coastal areas. Thus, *CoastSat* is expected to have a strong socio-economic impact on human societies.

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