HIGHROC Project Final Report

Version 1.0

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2. Université Pierre et Marie Curie – Paris 6, (UPMC), Laboratoire Océanographique de Villefranche (LOV)

3. Norsk Instituut for Vannforskning (NIVA)

4. Brockmann Consult GMBH (BC)

5. Vlaamse Instelling voor Technologish Onderzoek NV (VITO)

6. Centre for Environment Fisheries and Aquaculture Science (CEFAS)

7. University of Hull (UHULL)

Satellite data was received from European Space Agency (Sentinel-2 and Sentinel-3), EUMETSAT (Sentinel-3 and MSG/SEVIRI), NASA (MODIS), NOAA (VIIRS), Royal Belgian Meteorological Institute (MSG/SEVIRI) and USGS (Landast-8).

Many other organisations and individuals contributed to specific substudies and are acknowledged in the corresponding publications.

Executive Summary

This final report of the HIGHROC project summarises the main scientific results and the dissemination activities and outlines the potential impacts of the project on the public and on the scientific community.

The HIGHROC (“HIGH spatial and temporal Resolution Ocean Colour”) project had the objective to carry out the R&D necessary for the new generation of coastal water products and services from ocean colour space-borne data, giving an order of magnitude improvement in both spatial and temporal resolution and thereby opening up new applications and strengthening existing ones. The HIGHROC project designed, validated and had evaluated by users this new generation of coastal water products and services from satellite missions with optical sensors. Products at high temporal resolution (15 minutes from SEVIRI) and high spatial resolution (10m from Sentinel-2 and Landsat-8) are original additions to existing medium resolution products.

The HIGHROC project developed new algorithms dedicated to coastal waters for high spatial/temporal resolution sensors. Those algorithms were validated with in situ measurements achieved during the project and final algorithms were integrated in processor chains in order to process historic and current (near real time) satellite image databases. During one year, HIGHROC satellite products were provided by partners to key users. This one-year user service trial allowed to assess the potential impact of HIGHROC products and services to the marine user community. Key users included marine policy makers, marine environmental agencies and the marine/maritime industrial sector.

HIGHROC activities, products and results were also extensively presented to the wider potential user community via dedicated workshops, presentation during targeted meetings, website and brochures. HIGHROC scientific results were presented to the scientific community via publications (11 peer-review publications during the project period), presentations in international conferences and via the organisation by the HIGHROC Science Conference. This conference gathered experts from the international scientific community to discuss the state of the art on coastal ocean colour remote sensing. Finally, HIGHROC activities were also presented to external organisations and space agencies.

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1 Introduction

1.1 Project context and objectives

The HIGHROC ("HIGH spatial and temporal Resolution Ocean Colour") project had the objective to carry out the R&D necessary for the next generation of coastal water products and services from ocean colour space-borne data, giving an order of magnitude improvement in both spatial and temporal resolution and thereby opening up new applications and strengthening existing ones. This responds to SPA.2013 topic 1.1-06 "stimulating development of downstream services and service evolution". HIGHROC was expected to design, validate and have evaluated by users the next generation of coastal water products and services from satellite missions with optical sensors. In particular, products at high temporal resolution (15 minutes from SEVIRI) and high spatial resolution (10 minutes from Sentinel-2 and Landsat-8) will be the original additions to pre-existing medium resolution products.

In the previous GMES/Copernicus downstream services MARCOAST project, the potential areas and markets of application of coastal water quality products and services have been well-established and prepared. The monitoring requirements arising from the EU Water Framework Directive (WFD) and the Marine Strategy Framework Directive (MSFD) have been clear drivers for end-user requirements and hence service definition. As examples these directives contain mandatory requirements for monitoring of eutrophication, including Chlorophyll a, and turbidity, both parameters which will be improved and provided by HIGHROC.

Pre-existing ocean colour-based products and services, e.g. Copernicus services for marine end-users for WFD reporting, routinely use data from ocean colour remote sensors such as MERIS and MODIS, now followed by OLCI and VIIRS. Despite these existing services successfully providing data to end-users, the MERIS, MODIS, OLCI and VIIRS sensors have critical limitations of spatial and temporal resolution (typically 300m, 1/day) with respect to user requirements.

The HIGHROC objective was to perform innovative R&D to add to the existing service portfolio new coastal water products from Sentinel-2 (S2) and Landsat-8 (L8) at high spatial resolution and SEVIRI at high temporal resolution giving an order of magnitude improvement in respectively spatial (down to 10m) and temporal (down to 15 minutes) resolution (Figure 1 and Figure 2). The resulting merger of Sentinel-3/OLCI (plus MODIS and/or VIIRS) with the new HIGHROC Sentinel-2/Landsat-8 and SEVIRI products will dramatically improve information content for nearshore waters, e.g. 10m instead of 300m resolution within first nautical mile of coast for WFD, and improve data availability in periods of scattered or fast-moving clouds, e.g. 30-50 images per day instead of one. The advantages proposed by HIGHROC over the existing products are thus very clear.

In addition to these dramatic improvements for established services, the new HIGHROC products open up entirely new application areas including support for dredging, windfarm construction and operation and aquaculture, that were previously inaccessible because of the limited 300m spatial resolution of MERIS/OLCI.

To create valuable coastal ocean colour based products and services, HIGHROC activities included (1) discussions and close interactions with end-users and potential user groups to define the user needs and service requirements and (2) the implementation of a one year service trial with evaluation by the users of the new products and services. These service trials required the definition and validation of specific algorithms as well as the implementation of automated processing chains for each type of satellite data used.

A number of users were selected to evaluate the HIGHROC products and services during this one-year User Service Trial period. These users include member state officials responsible for reporting of water quality under the EU Water Framework and Marine Strategy Framework Directives; dredging consultants; government officials responsible for assessing environmental impact of offshore constructions (offshore windmills, ports, etc.) and private consultancies responsible for compiling such assessment reports; and a representative of aquaculture activities.

Theoretical work consisted of developing atmospheric correction and level 2 product algorithms (i.e. atmospheric correction) for the S2/L8 and SEVIRI sensors and Level 3 algorithms (e.g. for suspended particulate matter or chlorophyll-a concentration) for multitemporal and synergistic exploitation of the new products with existing products such as those from OLCI and VIIRS. Image processing chains provided full mission historical and near real time products for local areas including the dedicated test sites. In situ measurements were acquired for dedicated test sites and used to validate the new S2/L8 and SEVIRI products. Exploitation of the products was supported by interaction with user partners and potential user groups with particular focus on the opportunities offered by the new HIGHROC products both for entirely new application areas, e.g. assessing the environmental impact of human activities such as offshore constructions or dredging operations, and for significantly improved spatial and temporal resolution for existing applications, e.g. WFD monitoring and reporting. Post-HIGHROC commercialisation of the products and services is being prepared in the H2020/DCS4COP project, which fully includes the HIGHROC Consortium and one new private company partner.

After success in the User Service Trials the HIGHROC products and services can be upscaled (post-HIGHROC) to similar applications in all EU countries, where similar monitoring requirements apply (WFD and MSFD). The potential for exploitation outside Europe is also high, although different implementations of higher level products (e.g. multitemporal composites) will be required under different national legislations, e.g. Australia, US, Canada, etc. The exploitation of HIGHROC products and services for other non-EU countries without existing monitoring of coastal waters is also technically simple, although end-user requirements may be less clear or less motivated by mandatory legislation.

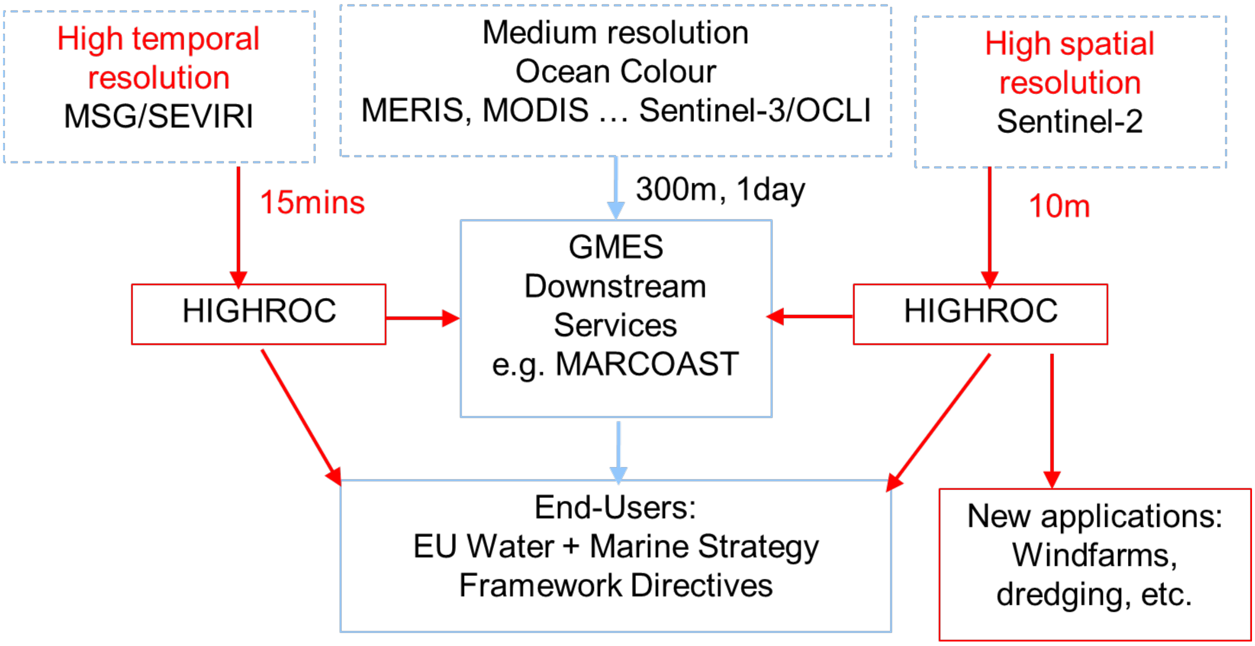


Figure 1. Schematic representation of the HIGHROC contribution to the generation and distribution of satellite products derived from ocean colour for coastal regions.

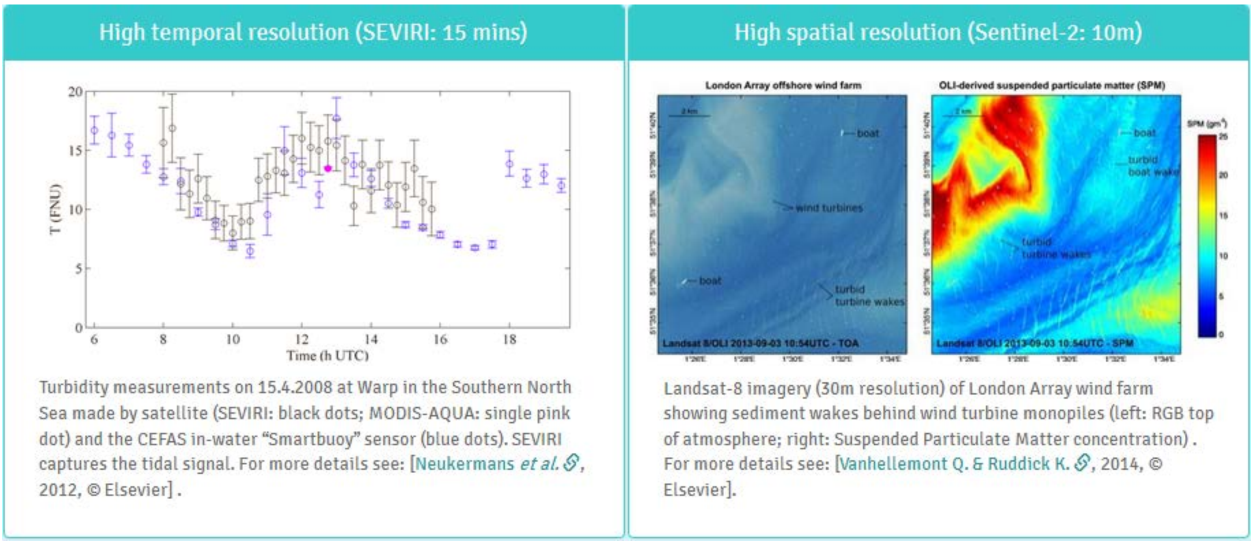


Figure 2. Precursor activities (pre-2014) demonstrated the potential value of (left) high frequency observations from the geostationary SEVIRI and (right) high spatial resolution observations from Landsat-8. See www.highroc.eu.

1.2 Document structure

The main science and technology results can be structured by the corresponding RTD work packages (WP): WP4 (algorithm development), WP5 (in situ measurement), WP6 (image processing) and WP7 7 (product validation). This structure is adopted in the following subsections.

2 Scientific Results

2.1 WP4: Algorithm Development

Objectives

The objectives of WP4: Algorithm Development were:

- To develop the algorithms required for the generation of coastal water products from a) Sentinel-2 and Landsat-8 (S2plus) and b) Geostationary sensors (GEO)
- To select and define the algorithms to be used within HIGHROC for the generation of coastal water products from the other medium resolution ocean colour sensors: S3/OLCI, MODIS, and VIIRS (S3plus hereafter).
- To develop algorithms for multi-sensors and multi-temporal (daily, monthly, seasonal and annual) products.
- To develop efficient pixel identification algorithms, particularly for cloud and cloud shadow masking.

Results: Algorithms for atmospheric correction (AC)

Atmospheric correction algorithms have been designed and tested for each type of sensors (S2plus, GEO and S3plus). HIGHROC algorithms were designed to be accurate in coastal waters, including turbid waters.

1. **S2 and L8**

A SWIR based atmospheric correction was developed for Landsat-8 and Sentinel-2 and publicly released in the ACOLITE processor. The use of SWIR bands is preferred in extremely turbid or productive waters where the assumption of a fixed red/NIR water reflectance is no longer valid. The SWIR based aerosol correction was especially useful in the Belgian coastal zone and French river plumes and estuaries. A band filtering technique was developed to reduce noise propagation from the low SNR SWIR bands into the VNIR bands.

The atmospheric correction module ICOR (previously called "OPERA") has also been developed. iCOR can be used to correct both land and water (inland and coastal) scenes and includes the adjacency correction SIMEC (SIMilarity Environment Correction). SIMEC can be used as well as a pre-processor for any type of atmospheric correction including ACOLITE). ICOR consists of 4 modules: land/water masking, land based AOT retrieval, adjacency correction and atmospheric correction. The atmospheric correction parameters are derived from pre-calculated MODTRAN-5 Look-Up-Tables (LUTs) in function of among others sun and view geometry, aerosol optical depth, ozone, water vapour and elevation. The aerosol optical thickness (AOT) is derived above land through a TOA radiance inversion of selected end-members in the scene following the approach described in Guanter et al. (2007). Over water the AOT is retrieved through spatial extension of the derived values of neighbouring land pixels assuming local spatial invariability of the aerosol.

ICOR has been made operational for Landsat-8 and Sentinel-2. An example of a Sentinel-2 product using ICOR for atmospheric correction is given in Figure 3.

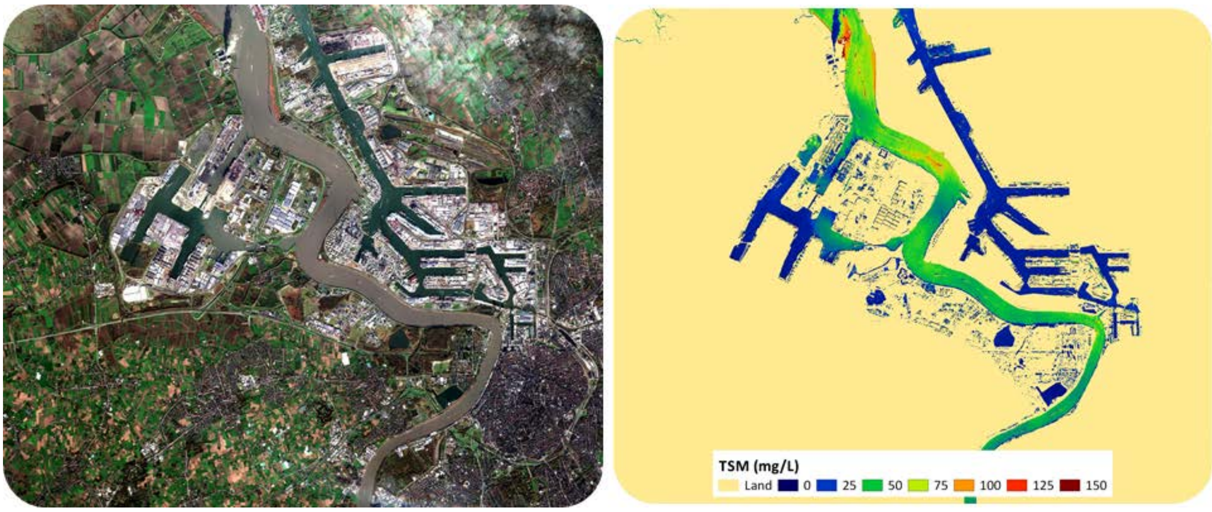


Figure 3. Sentinel-2 image of the Scheldt river (Port of Antwerp, Belgium) processed with OPERA. (left) the RGB image (right) total suspended sediment map using the formula of [Nechad et al., 2015].

2. **GEO (SEVIRI)**

The theoretical basis for atmospheric correction of GEO (SEVIRI) data was summarised based largely on the approach previously implemented by [Neukermans et al, 2009, 2012]. Rayleigh correction is based on a look up table generated by 6SV. Absorbing gas corrections are implemented via atmospheric transmittances using auxiliary data for gas concentrations where available. Aerosol correction is based on deriving aerosol type from clear waters and extrapolating in space, assuming uniform aerosol type over turbid waters. A SWIR based atmospheric correction was implemented which avoids the need for assumptions on the water leaving reflectances. This is particularly useful for regions outside the HIGHROC study areas such as the Amazon river plume and the West African coast.

3. **S3plus (MODIS, VIIRS and OLCI)**

HIGHROC considers “S3plus” to represent S3/OLCI plus one or more of the other medium resolution ocean colour sensors ENVISAT/MERIS, MODIS/TERRA, MODIS/AQUA and/or VIIRS. In general, mature atmospheric correction algorithms for the S3plus sensor family already exist and the corresponding L2R atmospherically-corrected products were used directly by HIGHROC. In cases where the standard products were considered suboptimal, HIGHROC implemented its own algorithms as extensions of existing processors, e.g. namely ODESA for MERIS and/or OLCI and SeaDAS for TERRA, AQUA, VIIRS, MERIS and/or OLCI.

Whereas mature atmospheric correction algorithms existed for the S3plus sensors, mature adjacency corrections were not yet in place. Therefore, the SIMEC adjacency correction was tested extensively for MERIS (and OLCI) for several coastal and inland waters in Europe. In addition, an evaluation of suitable bands was performed for MODIS and VIIRS.

Results: Algorithms for pixel identification

Different algorithms for pixel identification were evaluated and further developed for Landsat-8 and Sentinel-2. The FMASK algorithm was found to be insufficient for water applications, and the AFAR algorithm was developed for cloud and shadow masking. The IDEPIX toolbox was developed for automatically identifying pixel characteristics, and was implemented in the operational processing screen as it was more generic than the AFAR approach, which relied on the L8/OLI thermal bands not present on Sentinel-2.

Results: Algorithms for coastal water products

Specific algorithms have been developed to retrieve in water characteristics from water reflectance. A default algorithm was defined for each parameter as well as regional algorithms for certain parameters and regions.

The following table summarises the water parameters for which algorithms have been developed in the HIGHROC project and their availability by sensor. All parameters are not available for each sensor (e.g. chlorophyll-a not available for Landsat8 nor for GEO) because the required specific spectral bands are not available. All the algorithms have been developed to be valid in coastal waters which are more complex than open ocean waters because of the presence of suspended sediments and colour dissolved organic matter. A regional band switching turbidity algorithm for the entire Gironde estuary was developed, switching from the green band in the clear offshore waters, the red band in the moderately turbid waters, and the NIR band in the most turbid upstream part of the estuary. The retrieval of chlorophyll concentration from Sentinel-2 was demonstrated for the Belgian coastal zone and the Bourgneuf Bay.

Parameter (units)	Symbol	S2PLUS (S2/L8)	GEO	S3PLUS
Suspended Particulate Matter (g m-3)	SPM			
Turbidity (FNU)	TUR			
Particulate backscatter at 555nm (m-1)	bbp555			
Chlorophyll a (mg m-3)	CHL			
Algal pigment absorption coefficient at 443nm (m-1)	apig443			
Diffuse attenuation coefficient spectrum (m-1)	Kd			
Diffuse attenuation coefficient of PAR (m-1)	KdPAR			
Euphotic depth (m)	Ze			
CDOM absorption coefficient at 443nm (m-1)	aCDOM443			
Secchi Depth (m)	SD			
RGB Image (Rayleigh corrected)	RGB			

	HIGHROC has developed algorithm
	Not developed by HIGHROC
	Not applicable

Table 2-1. Overview of parameters made available by HIGHROC for each satellite data steam.

Results: Algorithms for multi-sensors and multi-temporal products

Multisensor (MS), multitemporal (MT) and time-series (TS) products were foreseen in the HIGHROC project. Specific algorithms were designed for each product.

1. **MT Products:**

MT products are 2 dimensional single-sensor image composites. The creation of MT products is rather straightforward: combine all data from a single product and derive certain statistics (e.g. mean, percentiles, standard deviation). L2 products need to be co-registered to a common grid before aggregation.

Each partner generated MT products for their users using tools provided by HIGHROC partners with a configuration specific to the user needs. One exception is the GEO stream, where both the unfiltered and filtered (5-points running average) datasets were provided as a standard product.

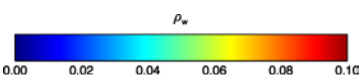
2. **MS Products:**

The merging of MODIS Aqua and SEVIRI data was demonstrated by [Vanhellemont et al., 2014], and a similar approach was used in HIGHROC. This method uses the assumption that any change observed by the high-temporal/low-spatial resolution GEO sensor is due to vertical resuspension of sediments, and that the spatial features observed by the high-spatial/low-temporal resolution GEO sensor are stable in time. An example product from the southern North Sea is replicated here in Figure 4.

It was not feasible to merge of S2plus and GEO products due to the large resolution differences and the dynamic temporal (tidal) changes including horizontal advection processes. This is a scientific obstacle, not an implementational difficulty – the merged products just do not correspond to reality because parameters are interpolated over time scales containing too much mixed, i.e. unseparable, spatio-temporal variability.

3. **TS Products:**

Time-series were evaluated for algorithm performance and anomalies were examined. No standard time-series products were provided by the HIGHROC project, but partners provided support for time-series analysis.



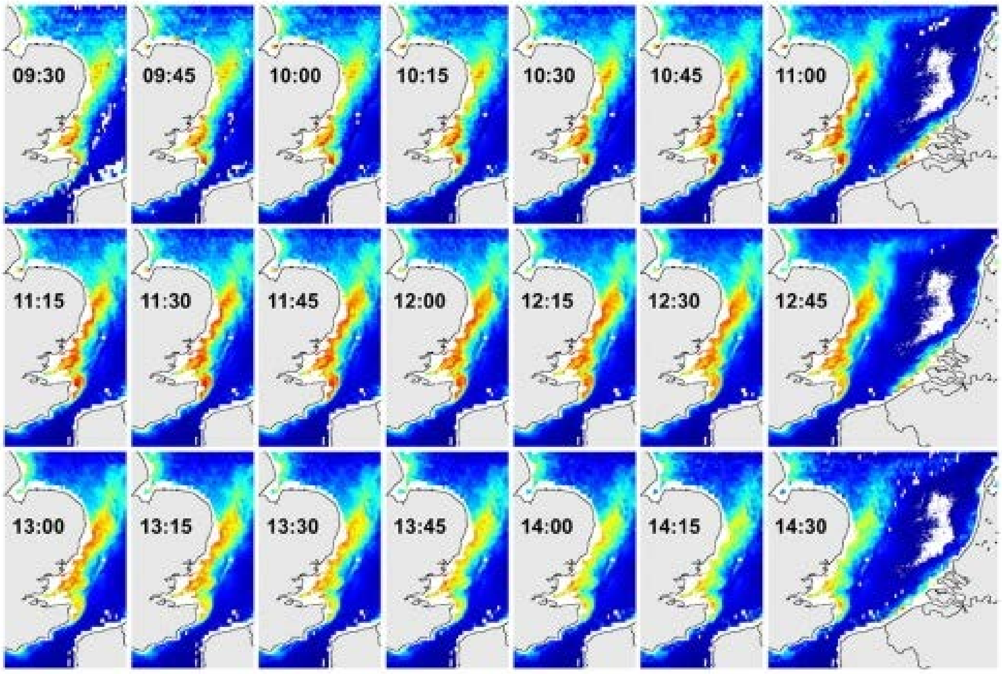


Figure 4 MODIS-Aqua / SEVIRI synergy ρw products for 2008-02-11, replicated from [Vanhellemont et al., 2014].

2.2 WP5: In situ measurements

Protocols and intercomparison studies

The objectives of WP5 were to compare the different *instruments, calibrations,* and *protocols* used by the partners for the in-situ measurements in order to identify the critical issues and define standard in situ measurements methods and quality controls to get a coherent and uniform dataset to validate HIGHROC satellite products. A HIGHROC protocol deliverable was produced as well as datasets for parameters listed in table section 1.3.1.

Intercalibration exercises

To define protocols and intercompare instruments, several dedicated cruises and experiments were organized within the HIGHROC project.

(1) Some partners were represented at a field campaign held on board the RV Belgica in April 2014 (Figure 5). The purpose was to intercompare the measurement protocols and to acquire in situ measurements for marine remote sensing reflectance and the corresponding laboratory measurements of optically active compounds. One lesson-learned was that doing proper radiometric intercomparison for a moving ship in waters with strong tides is challenging and can easily cause errors.

Figure 5. Photos of intercomparison of RAMSES on RV Belgica April 2014

(2) An intercomparison field campaign was organized by JRC at Venice Tower AquaAlta in the period June 23-27, 2014. The aim was to intercalibrate Trios Systems and different optical instruments and profilers. Among HIGHROC partners, both RBINS and NIVA were represented with their Trios RAMSES systems.

(3) Based on the experience from the Belgica cruise the next intercomparison workshop was performed at NIVA Research Station in Oslo in March 2015. This workshop included also sensors for Inerent Optical Properties. During this workshop, radiometry calibration and intercomparison were performed (Figure 6). Turbidity sensors were compared for different types of waters (river water, high Chl-a water, and sea water added kaolin or formazin), in parallel with filtrations for suspended particulate matter (SPM). SPM filtration protocols as well as Chl-a analysis were also compared for the cruise on the RV Belgica.

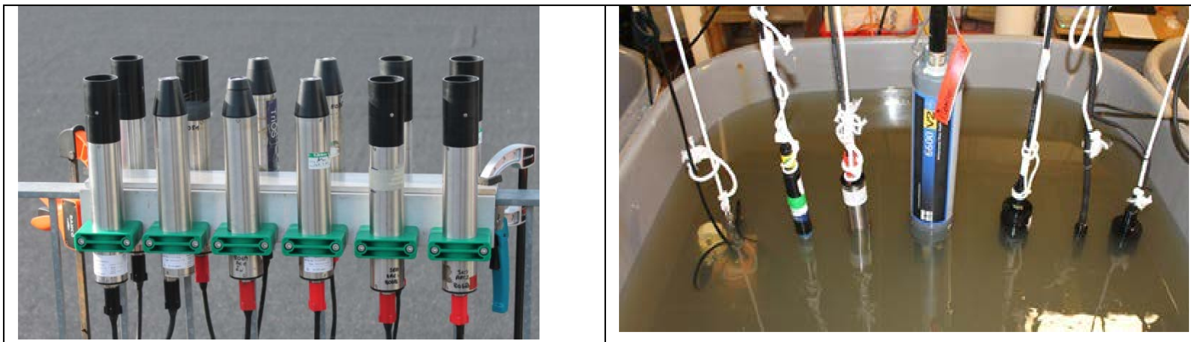


Figure 6 Photos from the radiometric and in water sensor intercomparison

The exercise showed that measurements made of turbidity using a hand-held turbidimeter was easy to perform and the results were reliable and comparable between the partners. Significant differences between turbidity sensors were identified under the different water types when compared to the ISO turbidity standard using the handheld turbidimeters. Overall, the workshops have led to a good practices guide, describing the measurements methodology and the recommended quality controls.

(4) An intercomparison exercise was organized by University of Stockholm as part of the Nordic Network collaboration. It took place at field station in Askø 10-14 May 2016. The aim was to intercalibrate radiometers in case 2 water with high CDOM absorption. Among HIGHROC partners NIVA and RBINS were taking part in the Trios RAMSES Systems measurements onboard R/V Oceania. All Trios systems had been calibrated at Tartu Observatory shortly prior to the experiment.

Additional reference measurements and sensor controls were carried out at the laboratory facility in Askø.

In situ measurements for HIGHROC datasets

(1) UPMC partner has acquired data in the Rhone river and Gironde estuary (one cruise with RBINS participation). New buoys and upgrades of sensor were made and a large dataset of validation data has been produced and used in the other validation workpackages. Figure 7 shows the test area in the Bay of Biscay and the stations visited.

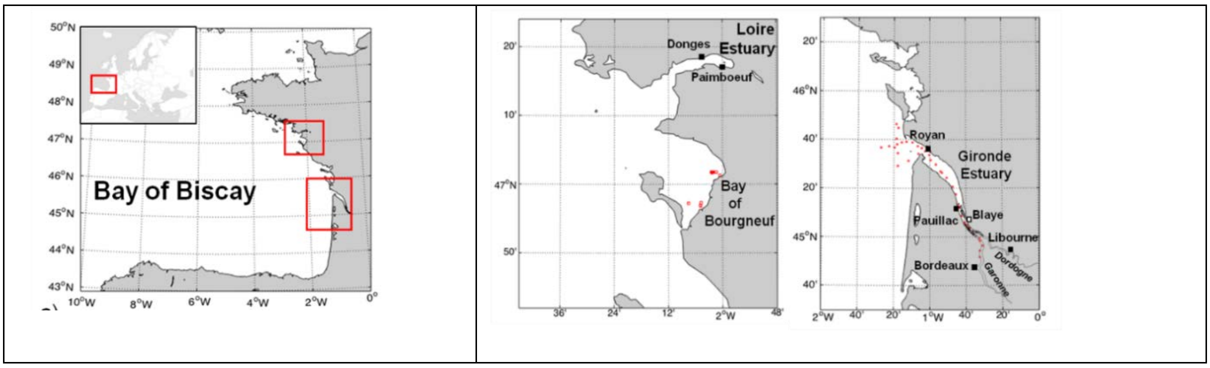


Figure 7. Map of the test areas of Bay of Biscay

(2) RBINS has maintained two AERONET-OC stations in Belgian waters (Zeebrugge MOW-1 and Thornton/Cpower) and University of HULL has installation an AERONET-OC station at the Blyth wind site – see Figure 8. These data are acquired autonomously by a CIMEL-SeaPrism system and transmitted on a daily basis to the centre managed by NASA for near real time processing. An upgrade was made of one AERONET-OC stations and the 3 stations have been successfully operated and produced important validation data. AERONET-OC systems provided a very good dataset of water leaving radiance to validate atmospheric correction algorithm.

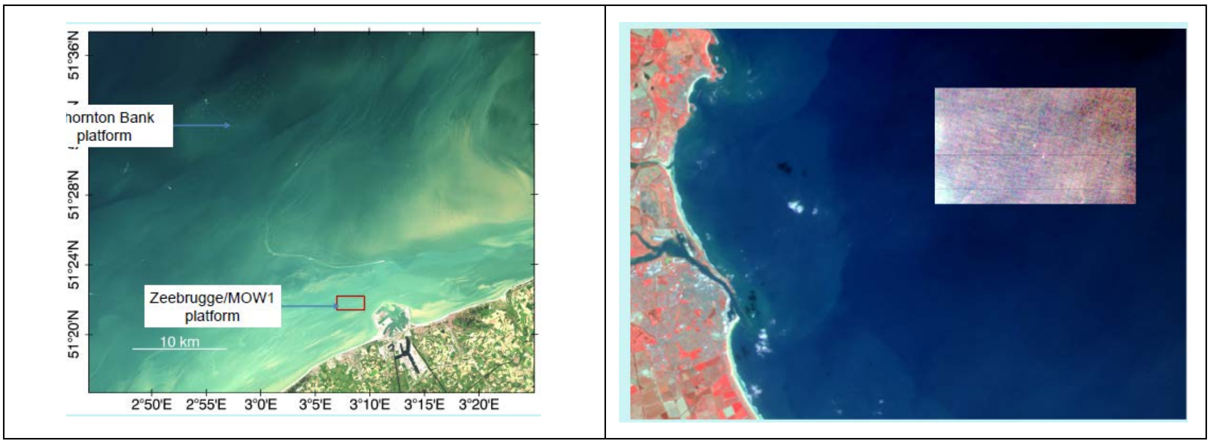


Figure 8. Images of the AERONET-OC stations in (left) Belgian waters and (right) Blyth, UK waters.

(3) CEFAS has maintained three North Sea SmartBuoy moorings system throughout 2014-2016 equipped with turbidity sensor and PAR sensor for calculating Kd. CEFAS surface buoys are smartbuoys deployed for 3 months at a time and serviced in February, May, August and November. The turbidity sensors are used with wipers to reduce interference from biofouling. Measurements are performed by mean burst of 5 or 10 minutes every 15 or 30 minutes. The three North Sea sites are shown in Figure 9 together with the Liverpool Bay site in the Irish Sea.

Figure 9. Map of the Smartbuoy sites in the North Sea (3) and Irish Sea (1).

(4) NIVA has operated Ferrybox-lines along the Norwegian coast throughout 2014-2017 producing validation data of both water reflectance and Chl-a, Turbidity data and CDOM. NIVA's Ferrybox system is mounted on the Coastal Express sailing along the Norwegian cost between Bergen and Kirkenes and a Ferry between Oslo and Kiel in Germany. A water sampler was activated in selected areas to provide additional data for matchups at fixed stations. The vessel is also equipped with hyperspectral Trios RAMSES Systems for determining water reflectance.

CEFAS has used FerryBox onboard the research vessels in 2014-2016 in addition to sampling on clear sky occasions during research cruises in the North Sea – see Figure 10. Several in situ campaigns has also been performed with RV Belgica in the North Sea in 2014-2015, when also other WP5 partners participated, and in 2017.

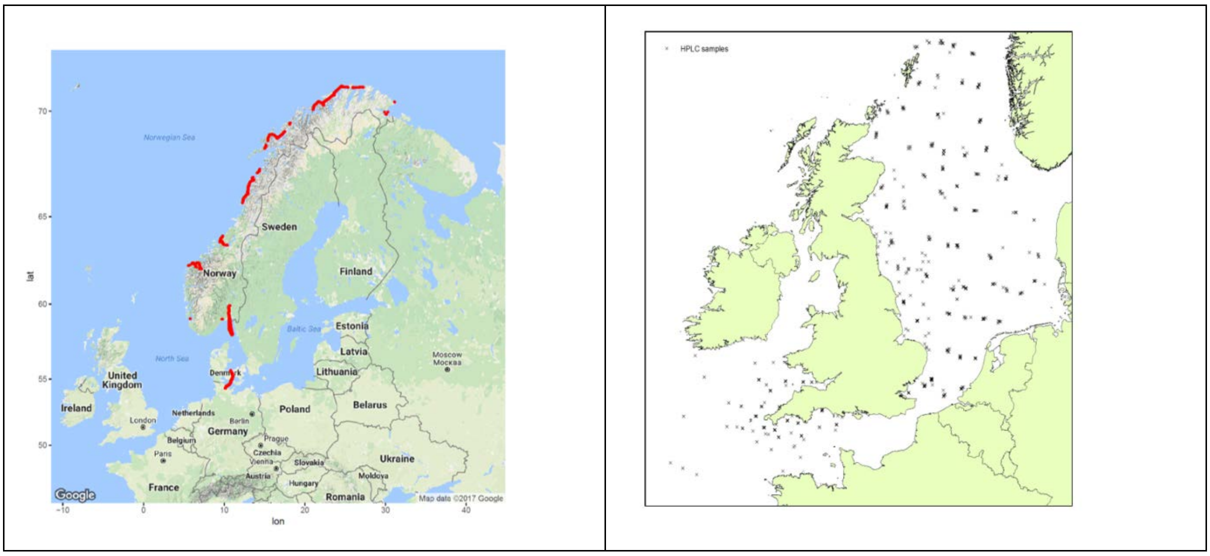


Figure 10. The map of the Ferrybox validation areas (daytime) and the station for discrete samples in the North Sea and Celtic Sea.

Description of HIGHROC datasets

All partners collected in situ data up to summer 2017 and compiled them in the final dataset. All the data were formatted within the standard defined by the consortium.

Provider	Platform	Parameters	Site
CEFAS	Surface Buoy	CHL, Kd, SPM, TUR	Dowsing
CEFAS	Surface Buoy	CHL, Kd, SPM, TUR	West Gabbard
CEFAS	Surface Buoys	CHL, Kd, SPM, TUR	West Gabbard 2
CEFAS	Surface Buoys	CHL, Kd, SPM, TUR	Liverpool Bay
CEFAS	Surface Buoys	CHL, Kd, SPM, TUR	Warp
CEFAS	Stations	CHL, Kd, SPM	North Sea and Celtic Seas
LOV	Stations	Ed, Ld, Lu, TUR, SPM	Gironde
LOV	Stations	Ed, Ld, Lu, TUR, SPM	Rhone Plume
NIVA	Transect/Ferrybox	Ed, Ld, Lu, CHL, CDOM	Color Fantasy, Port and Starboard radiometry
NIVA	Stations/Ferrybox	Ed, Lu, Ld, CDOM, SPM	Trollfjord, Herdla, Bow and Stern radiometry
RBINS	Stations	CHL, RHOW, SECCHI, SPMGFFA, TUR, dRHOW, dSPMGFFA, dTUR	Mediterranean
RBINS	Stations	CHL, RHOW, SECCHI, SPMGFFA, TUR, dRHOW, dSPMGFFA, dTUR	Scheldt
RBINS	Stations	CHL, RHOW, SECCHI, SPMGFFC, SPMGFFA, SPMGFF, TUR, dRHOW, dSPMGFFA, dTUR	Southern North Sea
RBINS	AERONET-OC platform	Lwn	Belgian coastal waters: MOW-1
RBINS	AERONET-OC platform	Lwn	Belgian coastal waters: C-POWER
U HULL	AERONET-OC platform	Lwn	North Sea: Blyth

Table 2-2. Overview of datasets collected by partners.

2.3 WP6 Image Processing

Objective:

The main objective of WP6, image processing, was to develop prototype image processing chains for the new S2plus and GEO HIGHROC products and derived multi-sensor and multi-temporal products, integrated with the existing S3plus products.

Results:

Highroc produced three main prototype image processing chains: S2plus, GEO and S3plus and a derived multimission processor. The overall concept and data flow is presented in Figure 11. The S2plus processor, which includes Sentinel-2 and Landsat-8 runs at VITO, the GEO processor runs at RBINS and the S3plus processor which includes MODIS, VIIRS and Sentinel-3 runs at BC. For all processors a dedicated workflow was developed including pre-processing, atmospheric correction and the derivation of L2W products. The L2W products feed into the Multimission processor producing multi-temporal and multi-mission synergy products. All processors share a common image and metadata format.

All products produced by the processors were made available to the HIGHROC partners, who added further value and distributed them to their end users as specified in the Service Level Agreements. The processors were operationally in the period of the User Service Trials from October 2016 to October 2017.

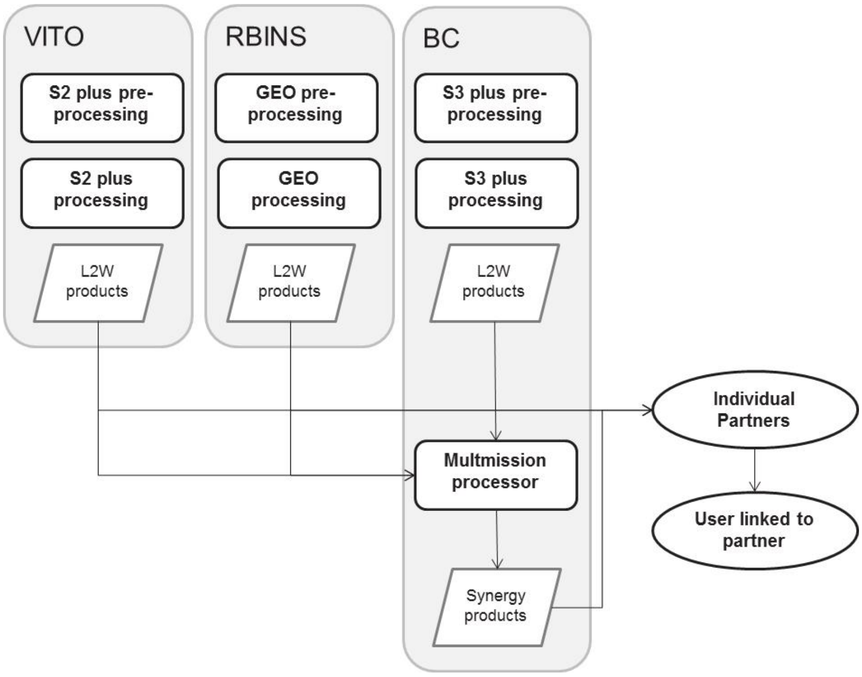


Figure 11 Data flow between the Highroc processors and partners

S2 plus prototype processor

The S2plus processor ran operationally in Near Real Time (NRT) during the period of the user service trials and produced data for more than 15 sites (72 unique Landsat-8 tiles and 67 unique Sentinel-2 tiles).

The L8 workflow is presented in Figure 12. Landsat L1 data is downloaded from USGS. The data is then processed in several steps including pre-processing, atmospheric Correction (A/C) and Level 2 Water (L2W) processing. Post processing includes building of the NetCDF file, archiving and distribution via FTP. In total more than 1050 tiles have been processed resulting in a total volume of 1 TB.

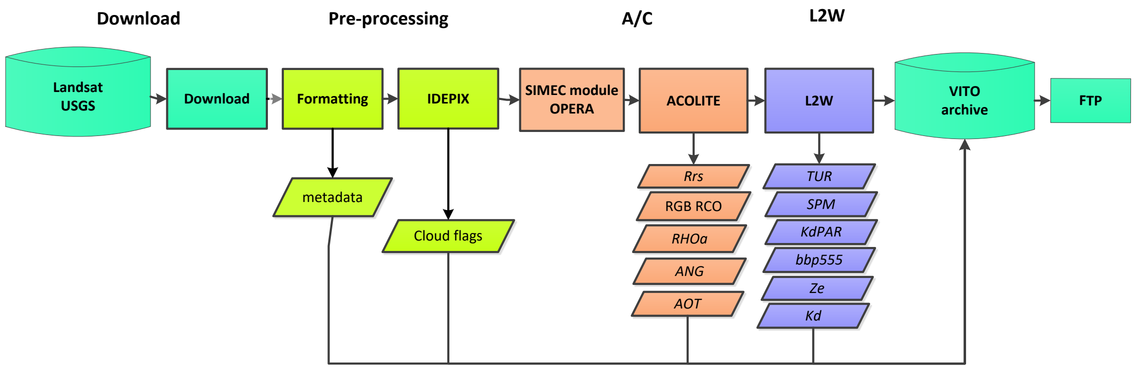


Figure 12. Landsat-8 workflow

The Sentinel-2 workflow is shown in Figure 13. Level 1C data is downloaded from the ESA hub and further processing is done similarly to the L-8 processing. The L2W processor delivers 2 additional outputs compared to the L-8 processor.

In total more than 8000 tiles have been processed resulting in a total volume of 16 TB.

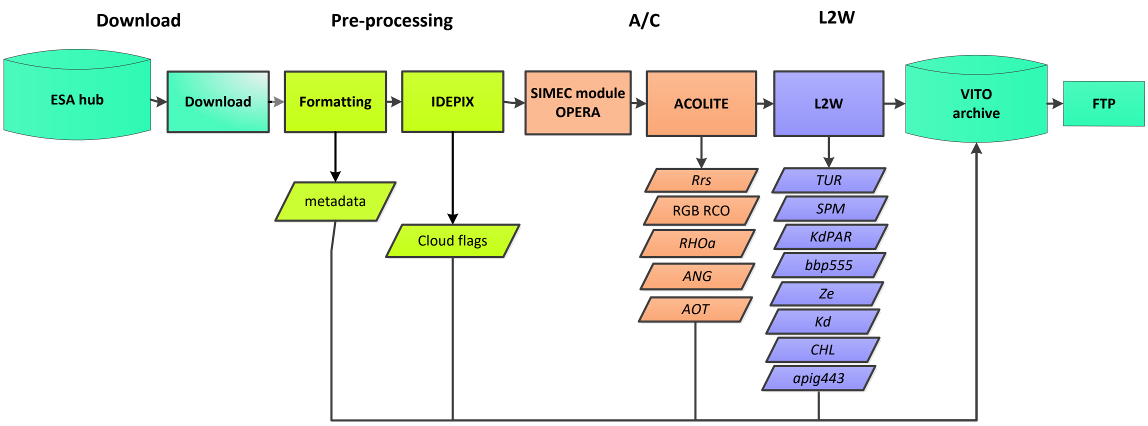


Figure 13. Sentinel-2 workflow

GEO prototype processor

The operational version of the GEO processor ran in near real time (NRT) during the whole User Service Trial period (Oct. 2016 to Dec. 2017). The NTR GEO processor is composed of the 3 modules to (1) process raw files, extract and save the European waters region, (2) apply the atmospheric correction in 4 local regions (Southern North Sea, Bay of Biscay, Golf of Lion and Skageratt region) and (3) produce image file of the SPM distribution for each product - see Figure 14. At the end of each day, daily netcdf are produced. They also contain time-filtered (5 data points) time-series. After that, all GEO products created during the daytime are copied to a ftp server shared with all partners. The GEO processor is coded in IDL (atmospheric correction processor), bash and python. It is run every 15 minutes. During the User Service Trial, 88640 tiles have been processed and HIGHROC GEO products produced during the period Oct. 2016 - Dec. 2017 represent 49 GB of data.

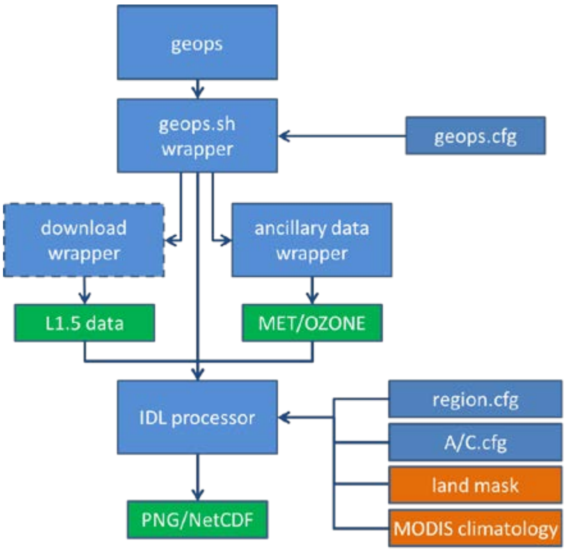


Figure 14. Work flow of the GEOPS processor. Upload of the final L2 PNG/NetCDF outputs to the FTP is not shown.

S3plus prototype processor

At BC, the near real time (NRT) processing for the S3plus chains consisted of several steps: setting up a download order for the predefined regions (15), running the preprocessor (Idepix, subsetting) and respective L2 processor(s) with region specific parameterisation(s), applying the HIGHROC water algorithms, and finally uploading the dedicated ftp.

Processing chains for MODIS Aqua, and VIIRS, were finalised and ran by the start of the Service Trials. MODIS Terra processing was implemented during the course of the Service Trials upon request from a few partners. As for OLCI, since the launch was delayed, the availability of standard L2 products was also delayed for the project (July 2017, too late for the Service Trials). It was then decided to implement a processing chain based on the C2RCC processor, which is equivalent to the one used in the ground segment for the alternative atmospheric correction products (chl_nn and tsm_nn). A similar process as with MODIS and VIIRS was as such implemented for NRT OLCI delivery on the ftp

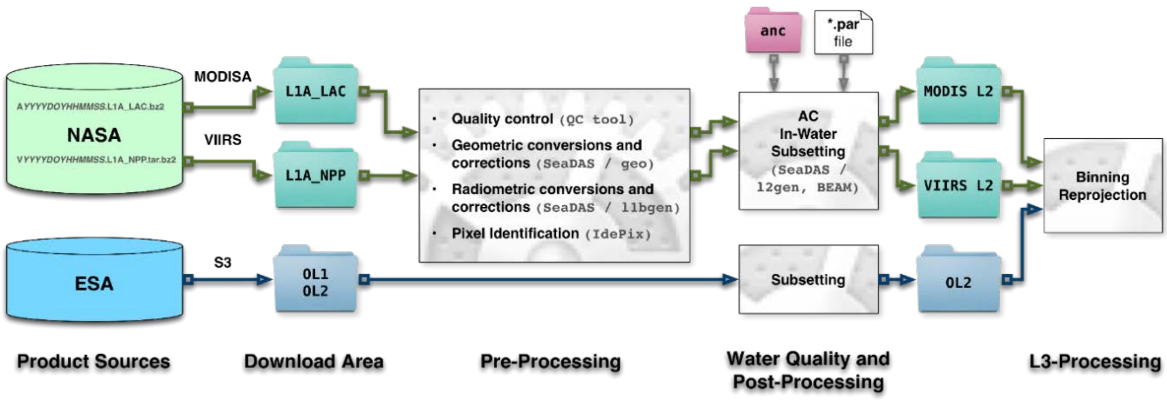


Figure 15. Integrated multimission prototype processor

Two kinds of multi-temporal products were offered to HIGHROC users, a temporally aggregated (L3, daily, monthly, seasonally, yearly aggregated) product derived from each sensor of the S3+ stream to observe and analyse trends, or a temporally aggregated GEO product to reduce the inherent noise of the individual 15 minutes products.

The multi-sensor product integrated in the multimission processor (Figure 15) is a S3plus/GEO synergy product. The algorithm for the multisensor synergy product was implemented in python for on-demand processing.

2.4 WP7 Product Validation

Introduction

The quality of the HIGHROC satellite products was assessed based on the field datasets acquired and/or compiled as part of the HIGHROC project, and the corresponding satellite-derived measurements generated from the prototype processors (Figure 16). The different field test sites covered various types of European coastal waters, from clear to highly turbid environments (Figure 17). For each test site, taking into account the regional specifications defined in terms of satellite data processing and match-up protocol, the satellite-derived water reflectance and biogeochemical products were compared to the corresponding quality-checked products measured in the field.

Based on the scatterplots produced, the differences between the satellite-derived and field measured values were used to express statistically the confidence (uncertainty) level in the satellite products taking into account the uncertainty associated to the field data (Figure 18, Figure 19 and Figure 20). The results obtained were analysed to give recommendations on where algorithm improvements are required or validation techniques need adjustment.

Satellite data and products included:

- high spatial resolution data (called S2plus) provided by the S2-MSI and L8-OLI sensors
- medium spatial satellite data (called S3plus) provided by the MODIS and VIIRS sensors
- high temporal resolution data (called GEO) provided by the MSG-SEVIRI sensor.

The different satellite data and products considered are illustrated in Figure 16. S2plus satellite data have a spatial resolution of about 30 m and a temporal revisit of about 5 days. S3plus satellite data have a temporal resolution of about 300 m and a temporal revisit of 1 day. GEO satellite data have a much coarser spatial resolution (about 4 km) but a high temporal revisit (15 min).

Figure 16. Three types of satellite data are considered: S2plus (high spatial resolution), S3plus (medium resolution standard ocean colour data) and GEO (high temporal resolution) data. Illustrations here with S2-MSI (left, showing the Gironde Estuary), MODIS-Aqua (center, here the southern North Sea) and MSG-SEVIRI products (right, here the Bay of Biscay).

The first step in the validation exercise was the validation of the atmospheric corrections applied to the satellite data to retrieve the water reflectance, here the remote sensing reflectance (Rrs) or normalized water-leaving radiance (Lwn). The second step in the validation exercise was the validation of the derived water biogeochemical products, typically the water turbidity, concentrations of suspended particulate matter (SPM) and chlorophyll-a (Chla).

Field datasets

Only a part of match-ups between field and satellite data were obtained using field measurements carried out during regular field (shipborne) campaigns. Most of the match-ups were obtained using field data recorded by autonomous sensors onboard moving such as ferries[1] or fixed platforms such as Smartbuoys[2], Aeronet-OC stations[3] and the instrumented Mesurho platform[4].

[1] https://www.niva.no/en/water-data-on-the-web/ferrybox-ships-of-opportunity
[2] https://www.cefas.co.uk/cefas-data-hub/smartbuoys/
[3] https://aeronet.gsfc.nasa.gov/
[4] http://www.ifremer.fr/medicis/projets/mesurho.html

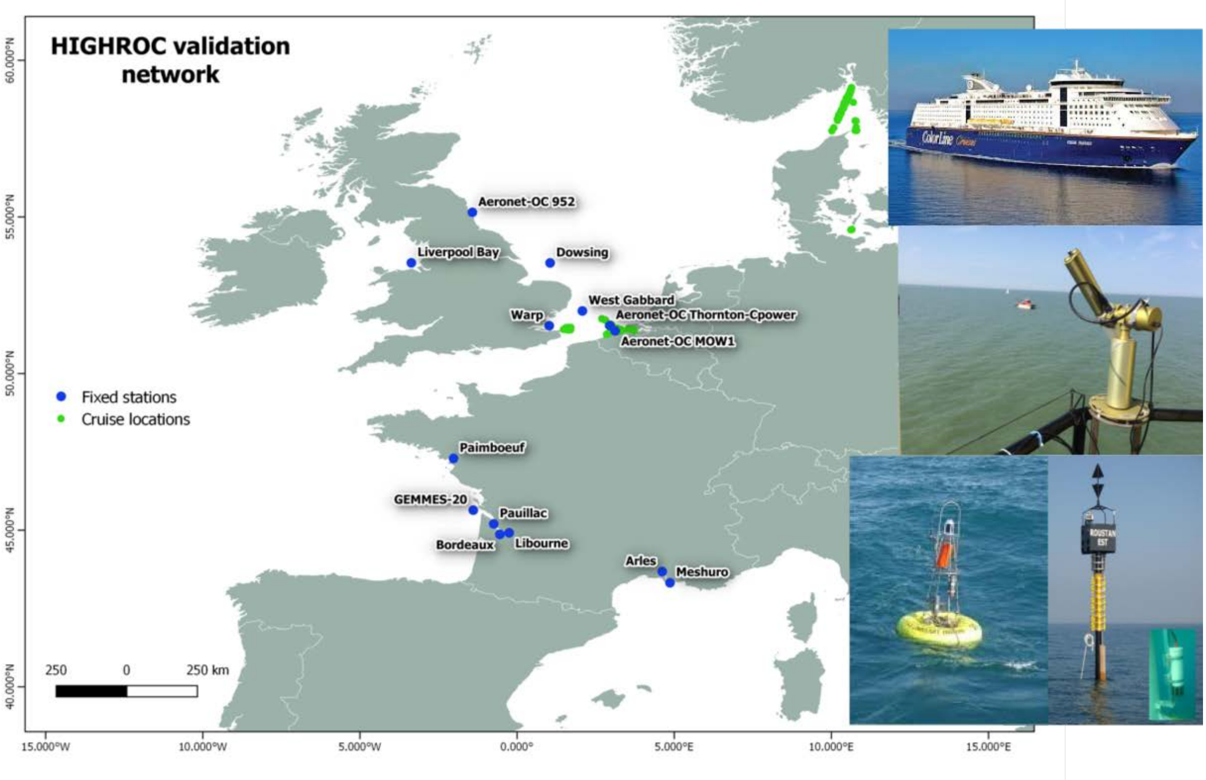


Figure 17. Map of the field measurements used to validate the HIGHROC satellite products in European coastal waters. In addition to field oceanographic campaigns, data were recorded onboard autonomous platforms such as ferries (FerryBox network in Norwegian coastal waters), AERONET-OC stations (Southern North Sea and UK waters), SmartBuoys stations (Southern North Sea an UK waters) and Mesurho (NW Mediterranean Sea).

<u>Results</u>

The first part of the exercise provided satisfactory results in terms of validation of the atmospheric corrections applied to satellite data. As could be expected, applying appropriate atmospheric corrections (here the MUMM algorithm) to S3plus data recorded over moderately turbid waters resulted in quite limited differences (<25%) between field and satellite data, at least in the green and red spectral regions (not shown). The atmospheric corrections applied to S2plus satellite data recorded over moderately to highly turbid waters could also be validated (Figure 18), which represents a step forward in the remote sensing of coastal and estuarine waters. GEO satellite products were also validated based on direct comparisons with simultaneous S3plus satellite products (not shown).

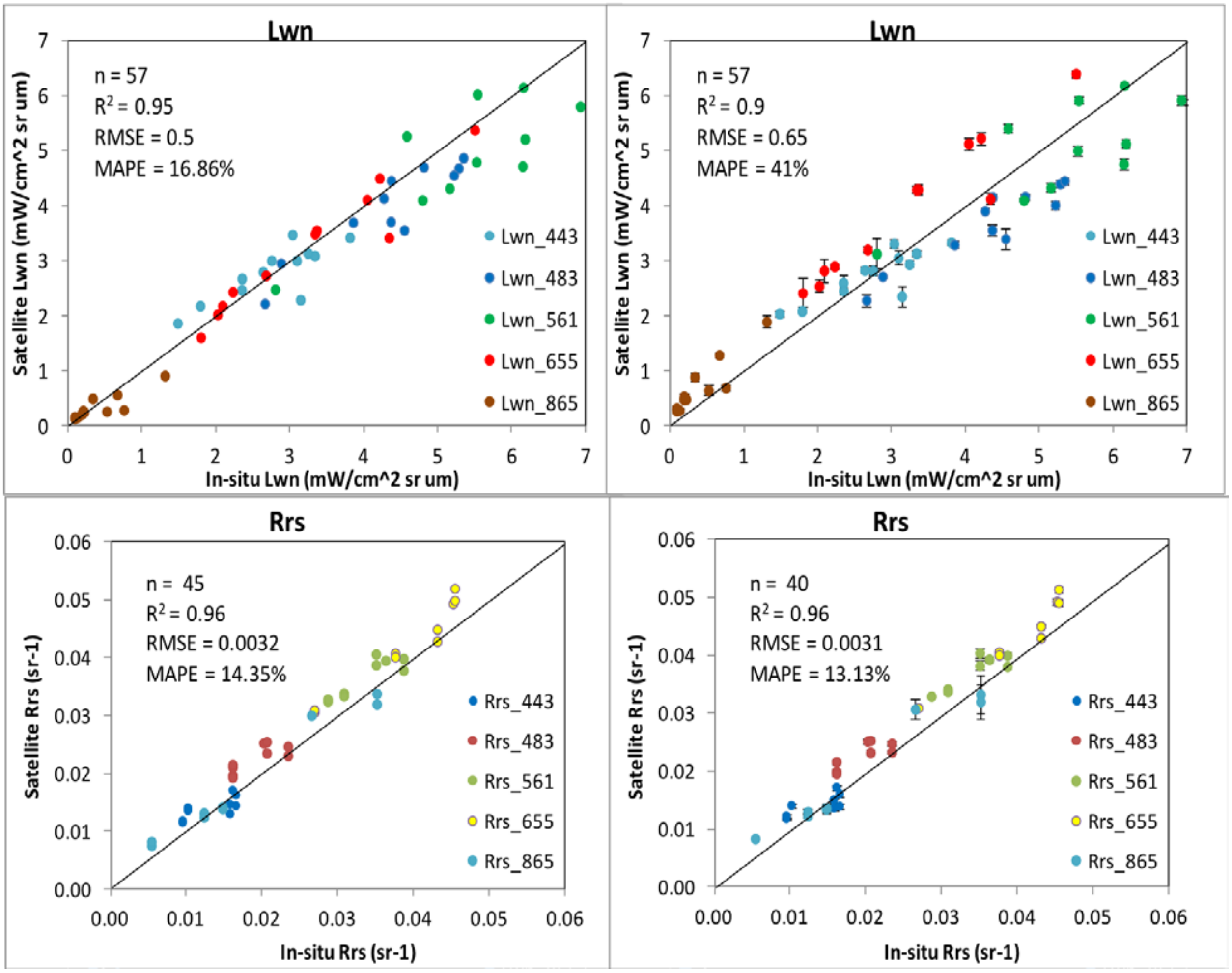


Figure 18. Typical match-ups between satellite-derived and field-measured water-leaving radiance (top, southern North Sea) or remote-sensing reflectance (bottom, Gironde estuary). The observed differences in the visible and near-infrared spectral regions are usually lower than 20%, which represents a validation of the atmospheric corrections applied here to S2plus satellite data using the ACOLITE software.

The next step was to analyse match-ups between field data and satellite biogeochemical products. Both the water turbidity and SPM concentration are functions, as a first approximation, of the water reflectance in the red spectral region (or the near-infrared in the case of highly turbid waters). It was not surprising to obtain good results in terms of turbidity (Figure 19 top), SPM concentration and diffuse attenuation coefficient (Kd) remote sensing retrievals. Over a 13-year period, numerous match-ups were obtained between S3plus and Smartbuoy data, resulting in a robust validation of these key products (Figure 19). The good agreement between field and satellite observations support the future monitoring of seasonal to multi-year dynamics of SPM concentration in coastal waters.

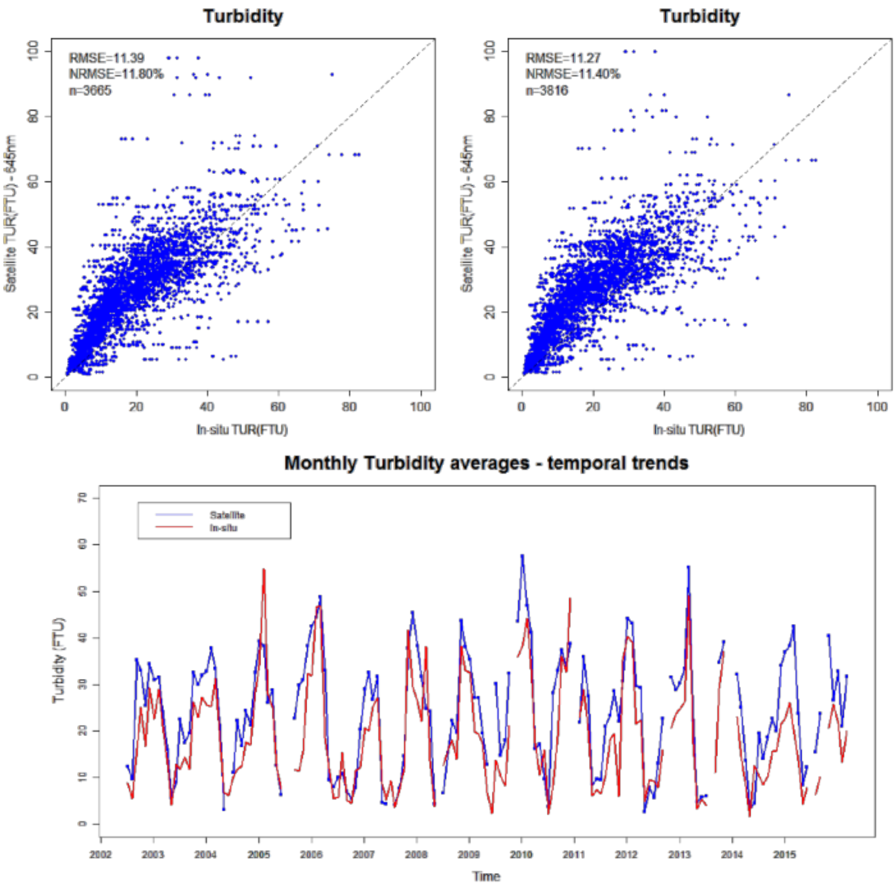


Figure 19. **Typical match-ups between satellite-derived and field-measured water turbidity. Data from Smartbuoys in the southern North Sea have provided numerous match-ups with S3plus (here MODIS) satellite data (1*1 (left) and 3*3 (right) pixels). Statistics show the good agreement between the two datasets (differences lower than 12%).**

It is *a priori* more difficult to remotely sense Chla concentrations in turbid coastal waters where non-algal particles and dissolved substances contribute significantly to both light absorption and backscattering. The contribution of Chla to the water reflectance is more difficult to detect and the blue-to-green Chla algorithms usually fail. This failure has been often observed based on HIGHROC datasets. Another issue to deal with when using in situ Chla fluorescence measurements to validate satellite products is the quenching effect on phytoplankton cells around mid-day. Despite these issues, a quite satisfactory agreement was observed between field-measured and satellite-derived observations of the seasonal dynamics of Chla (Figure 20). Best results were usually obtained considering weekly-averaged field and satellite observations in test sites with low turbidity.

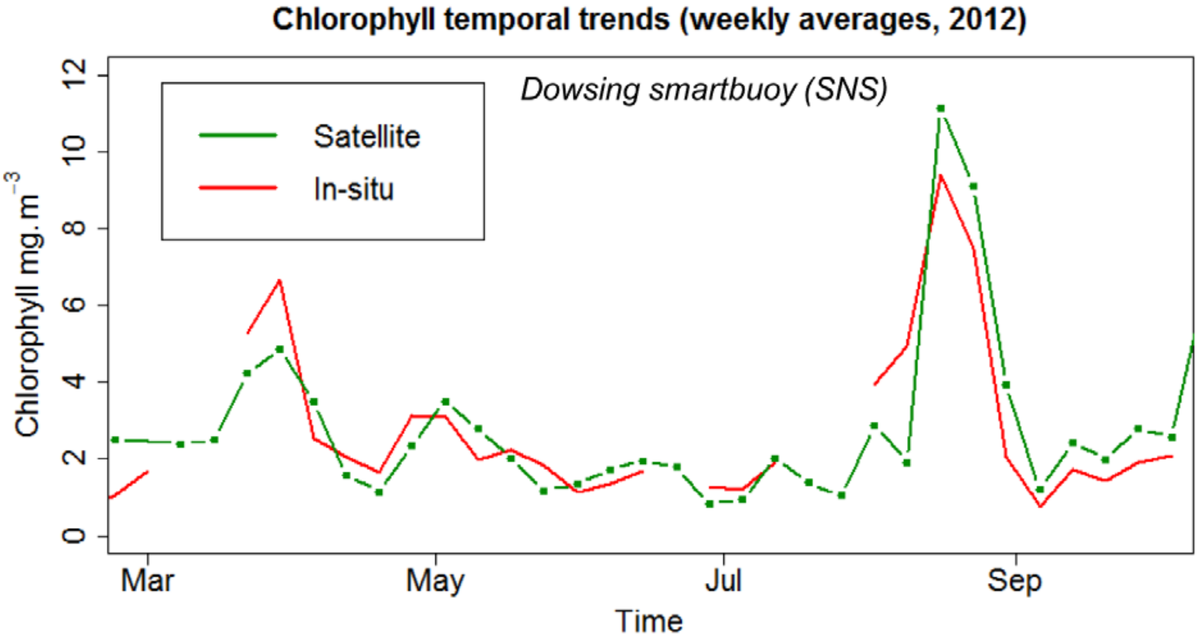


Figure 20. Temporal (seasonal) trend of Chla concentration variations in the southern North Sea captured by in situ measurements (Dowsing Smartbuoy) and by satellite (MODIS-Aqua) data.

<u>**Conclusions and perspectives**</u>

This multi-sensor and multi-site match-up exercise conducted for S2plus, S3plus and GEO satellite products provided many satisfactory results and also highlights required improvements in the development and validation of future algorithms.

Results obtained in terms of atmospheric corrections of satellite data demonstrate that algorithms specifically designed for turbid coastal waters are now quite mature and operational in the visible and NIR parts of the spectrum. SPM concentration, turbidity and Kd algorithms also proved to operational but are still regional or at least require prior knowledge of the turbidity water range.

At the end of this validation exercise, most of the OLI, MODIS and VIIRS satellite products can be considered as 'validated' thus operational for delivery to users. More quality match-ups and maybe even algorithm development are required to assess the uncertainties associated to MSI and especially OLCI satellite products in the near future.

In all sites, improvements are required to minimize the uncertainty on the satellite-derived Chla concentration. The validation of future Chla products in turbid coastal waters require: (i) an efficient correction or filtering for Chla-fluorescence measurements affected by quenching effects; (ii) more complex Chla algorithms able to first remove the optical contributions of NAP and CDOM from reflectance spectra to accurately retrieve the Chla spectral signature. Neural network and/or multi-step regional algorithms could represent solutions.

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Neukermans G. Optical in situ and geostationary satellite-borne observations of suspended particles in coastal waters. Ph.D. dissertation, Université du Littoral – Côte d'Opale, Wimereux, France. Academic and Scientific Publishers, Ravensteingalerij 28, 1000 Brussels, Belgium. ISBN 978 90 7028 949 2 (2012)

Neukermans G. & Ruddick K. & Bernard E. & Ramon D. & Nechad B. & Deschamps P.-Y. Mapping total suspended matter from geostationary satellites: a feasibility study with SEVIRI in the Southern North Sea (2009) Optics Express, Vol. 17(16) pp. 14029–14052.

3 Project impacts, dissemination and exploitation

3.1 Potential impact of results on marine user community

HIGHROC project and activities had an important impact to the marine user community by providing quality control, high resolution, maps of seawater parameters such as suspended particulate matter (SPM), Chl-a, etc. During the one-year period of the User Service Trials, the full suite of HIGHROC products was supplied to key users in order to assess the utility of HIGHROC products and service. Feedback was collected from those users.

The key-users involved in the HIGHROC user trial are listed below.

- Environment Agency (EA) in the UK is a non-departmental public body, sponsored by United Kingdom Government's Department for Environment, Food and Rural Affairs (DEFRA), with responsibilities relating to the protection and enhancement of the environment in England.
- SUMO is a research group of the RBINS (OD Nature) institute. Its aim is to better understand sediment transport and dynamics in Belgian waters.
- SHOM (Service hydrographique et océanographique de la marine) is in Brest, France. It is the national hydrographic service. Its objectives are to support the Navy on environmental information and to support public policies.
- The Scientific Service Management Unit of the Mathematical Model of the North Sea (MUMM, RBINS-OD Nature) has the objective to improve knowledge of the North Sea and provide scientific marine services. It is in charge of reporting about coastal water quality for the WFD and MSFD
- International Marine and Dredging Consultants (IMDC) is a Belgian engineering and consultancy company specialised in a vast range of water related projects. The main topics of their studies are: dredging, offshore energy, flood Risk, waterways, coasts & estuaries and ports & offshore structures. The main clients are governmental agencies, dredging companies, marine industries and LNG companies.
- BSH, the German Federal Hydrographic Agency, is obliged to assess the state of the North Sea and Baltic Sea at every time, and to give reports about the state for defined observation periods.
- Brockmann Geomatics (BG), Sweden, is a service provider itself and serves several Swedish Authorities responsible for water management and water quality, such as SwAM (Swedish Agency for Marine and Water Management), the Swedish Water Authorities and the regional County Administrative Boards.
- The Norwegian Environment Agency (NEA) is a government agency under the Ministry of Climate and Environment working for a clean and diverse environment. Their primary tasks are to reduce greenhouse gas emissions, manage Norwegian nature, and prevent pollution with principal functions including collating and communicating environmental information, exercising regulatory authority, supervising and guiding regional and local government level, giving professional and technical advice, and participating in international environmental activities.

- i-Sea, in France, is a private company created in 2004 from the GEO-Transfert Institute, a technology transfer cell of the Université de Bordeaux 1 and ADERA. The RIVERCOLOR project is considered as an (intermediate) user of the HIGHROC project.
- Pierre Gernez (University of Nantes, France) oversees the remote sensing of environmental parameters in the Bourgneuf Bay for the GIGASSAT project.

User expectations and needs were very different in the HIGHROC service trial. Some of the users were only interested in a final product (e.g. averages over time of SPM, chlorophyll concentrations, or Kd), while some wanted to use intermediate products issued from the HIGHROC processing chain. Nevertheless, the general feedback of the service trial was very positive (80 % satisfaction on average) despite the diversity of the products requested and the expertise of the provider. In general, all the users acknowledge the scientific quality of the consortium, the communication and the reactivity to problems in the partnership. The service trial presented the highest score for communication (83.3%) followed by the benefits (82%) and the performance (77%). Users recognised the benefits of remote sensing information to complete scarce in situ observations. They are happy to continue to discuss with the consortium and they recognized its scientific expertise.

3.2 Potential impact and dissemination of results in scientific community

HIGHROC project had an important impact in the scientific community with the publication of 11 papers in peer-review journal (see Table A1 for an exhausting list). HIGHROC results have also been presented in numerous remote sensing oriented scientific meetings, including strong participation in major events such as IOCS conferences in 2015 and 2017, the Ocean Optics conference in 2016, the Sentinel 3 for Science symposium in 2015, etc. The HIGHROC consortium was also very active in the international working groups such as Sentinel-2 Validation Team (S2VT) and Sentinel 3 Validation Team (S3VT) with presentations from different partners during S2VT and S3VT meetings.

The HIGHROC Science conference, open to all experts from the scientific community, was organised in Brussels from 7 to 9 November 2017. It allowed presentation of the HIGHROC results to the scientific community but more importantly opened up the discussion with the international community about new challenges for coastal ocean color remote sensing. The scientific committee was composed half of HIGHROC partners and half of external experts in coastal ocean colour.

The scientific program was divided into 4 main sessions:

- In situ measurements and validation
- Coastal water applications
- Satellite data processing
- New satellite sensors and algorithms

Regarding participation, over the 68 confirmed registrations (80 participants were expected at maximum), 62 participants attended the conference. Participants came from 17 different countries (14 Europeans countries + South Korea, Canada and Argentina). 47 scientific abstracts were submitted to the conference (25 oral presentations and 22 poster presentations). Most of the scientific contributions were of very high quality, stimulating a state-of-art discussion during the last meeting session. The conference was also the opportunity to train and advertise to the scientific community the software developed during the HIGHROC project such as ACOLITE and iCOR which are both dedicated to atmospheric correction of S2 and L8 images over inland and coastal waters.

3.3 Dissemination of HIGHROC activities to users, public and relevant organisations

A website has been created and updated throughout the project to describe HIGHROC activities (www.highroc.eu). It describes the project and its general objective, shows some user stories, presents the HIGHROC products and lists all the HIGHROC publications.

Two brochures have been produced to describe the HIGHROC project, one at the beginning emphasis the objective and one at mid-project with some results (http://www.highroc.eu/assets/pdf/highroc_brochure.pdf , http://www.highroc.eu/assets/pdf/highroc_brochure_2.pdf). These brochures have been distributed to potential users and are available online.

HIGHROC partners also attended conferences to meet and present HIGHROC products to external communities which might be interested by products as potential users (e.g. dredging community during the CEDA dredging days 5-6 Nov 2015; FerryBox community during a Workshop on MS Colro Fantasy on October 2017).

Two users workshop were organised during the project. The first HIGHROC User Workshop "Earth Observation methods for the coastal zone: progress and opportunities" was held in London on 8-9 June 2015. The aim of the workshop was to bring together as wide a range as possible of potential end-users for the project, including marine policy makers, marine environmental agencies and the marine/maritime industrial sector.

The workshop was organised in four sessions to answer:

(1) What is the state-of-play for the measurement of *in situ* data for remote sensing validation purposes?
(2) What are the current applications of Earth Observation (EO) data to solve marine policy questions?
(3) What will HIGHROC bring to the field?
(4) How will we make the most of the new Sentinel data?

With more than 30 participants from five different countries representing the core user base of HIGHROC, and 18 presentations over the course of 1 ½ days, the workshop was successful in engaging HIGHROC with a strong user base in the UK, as well as showcasing (potential) HIGHROC user applications in e.g. France and Belgium.

The second HIGHROC User Workshop was held in Hamburg on 9-10 October 2017. The aim of the workshop was to give the floor to the HIGHROC core users after the one-year Service Trials period to report about the usage and integration of EO and HIGHROC products into their daily work. The workshop was successful in gathering over the course of 1 ½ days 22 participants from six different countries, to hear presentations and discuss coastal applications and how HIGHROC products were used. The discussions focussed on the usability of the HIGHROC products in pre-existing working schemes for each user and the combination of different data sources, among others HIGHROC products and other EO based results.

HIGHROC was also presented to external organisations such as the CMEMS community with several presentations during the project period, (e.g. Copernicus workshop for coastal zone monitoring and management, Brussels, 29/06/2017, Copernicus Marine week, Brussels, 28/09/2017), and the space agencies (e.g. ESA, EUMETSAT and active participation in S3VT and S3VT groups).

3.4 Future Exploitation of the results (software)

HIGHROC atmospheric correction algorithms developed by partners RBINS and VITO were integrated into publicly available software, ACOLITE and iCOR respectively, to be used by a larger community. In addition, specific training sessions were organized during the HIGHROC Science Conference.

HIGHROC processing chains will be use in the DSC4COP project whose aim is to propose integrated oceanographic data layers to Intermediate Business Users in a pre-commercial licensing framework. Each HIGHROC product will consist of a specific data layer. Hence, HIGHROC results will be used in an operational mode in the future.

3.5 Project website

The project web site can be found at www.highroc.eu and will be maintained until December 2020. Most pages will remain unchanged from January 2018 with the exception of the publications page, which will be updated with any publications which appear after the end of the project. This may include 2-3 peer-reviewed publications which are in preparation at the time of writing of this Final Report.

4 Publications

Project publications are listed on the project website, which will be updated until December 2020. Most of these papers are publicly available as downloadable PDF files by following the hyperlinks in the following subsections. At the time of writing the following papers have been published.

4.1 Published in 2017

Moses, W.J., Sterckx, S., Montes, M., De Keukelaere, L. and Knaeps E. (2017). Chapter 3 Atmospheric Correction for Inland Waters In D. Mishra, I. Ogashawara and A. Gitelson (Eds). Bio-optical modeling and remote sensing of inland waters, Elsevier, ISBN: 9780128046449.

Lavigne H and Ruddick K. (2017). The potential use of geostationary MTG/FCI to retrieve chlorophyll-a concentration at high temporal resolution for the open oceans. International Journal of Remote Sensing, In press.

Forster R., Creach V., Conaill S. (2017). A new AERONET-OC site for the North Sea EuroGOOS conference, 3-5 Oct. 2017, Bergen, Norway.

Collingridge K., Forster R., Capuzzo E., Schluter L., Hull T., Creach V (2017). A new database of quality-controlled phytoplankton pigments for the European north-west shelf.EuroGOOS conference, 3-5 Oct. 2017, Bergen, Norway.

Morin G.P., Marty S., Doxaran D., Ody A., Harmel T., Constantin S. (2017). Exploring the capabilities of Landsat8-OLI and Sentinel2-MSI satellite data to remotely sense the size distribution and composition of suspended particles in rivers plumes. International Ocean Colour Science Meeting 2017, Lisbon, Portugal, 15-18 May 2017

Vanhellemont Q. and Ruddick K. (2017). Atmospheric correction for coastal and inland water application of very high resolution satellite imageryInternational Ocean Colour Science Meeting 2017, Lisbon, Portugal, 15-18 May 2017

Ruddick K., Vanhellemont Q., Dogliotti A., Lavigne H. and Van der Zande D. (2017). High resolution (1-30m) optical remote sensing of processes in coastal and inland waters – new opportunities and challengesoral presentation at International Ocean Colour Science Meeting 2017, Lisbon, Portugal, 15-18 May 2017

Doxaran D., Constantin S., Ody A., Novoa S., Lebreton C., Creach V. Capuzzo E., Collindridge K., Hull T., Sorensen K., Ledang A.B., Marty S., Forster R., Knaeps E., Van der Zande D., Ruddick K.(2017). Validation of multi-mission ocean colour satellire products in European coastal waters as part of the EU-FP7 HIGHROC project. International Ocean Colour Science Meeting 2017, Lisbon, Portugal, 15-18 May 2017

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Gernez P., Doxaran D. and L. Barillé (2017). Shellfish aquaculture from space: potential of Sentinel2 to monitor tide-driven changes in turbidity, chlorophyll concentration and oyster physiological response at the scale of an oyster farm. . Frontiers in Marine Science, 4, 137; doi:10.3389/fmars.2017.00137

Vanhellemont Q. and K. Ruddick (2017). A near-shore phytoplankton bloom in Belgian waters observed from space. . VLIZ Marine Scientist Day 2017, Brugge, Belgium, 3 March 2017.

4.2 Published in 2016

Ody A., Doxaran D, Gentili B., Vanhellemomt Q., I. Pairaud, Verney R. & P. Ruddick(2016) Fluxes and dynamics of suspended particles in a river plume by combining in situ autonomous measurements and multi-sensor ocean colour satellite data. extended abstract submitted for the 2016 Ocean Optics Conference, Victoria, BC, Canada, 23-28 October 2016

Vanhellemont Q. & Ruddick K. (2016) ACOLITE processing for Sentinel-2 and Landsat-8: atmospheric correction and aquatic applications extended abstract submitted for the 2016 Ocean Optics Conference, Victoria, BC, Canada, 23-28 October 2016

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Ruddick K., Vanhellemont Q., Dogliotti A. (IAFE), Nechad B., Pringle N. and Van der Zande D. (2016) New opportunities and challenges for high resolution remote sensing in turbid watersoral presentation at the 2016 Ocean Optics Conference, Victoria, BC, Canada, 23-28 October 2016

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M. Baeye, R. Quinn, S. Deleu, M. Fettweis, (2016). Detection of shipwrecks in ocean colour satellite imagery. Journal of Archaeological Science,v. 66, p. 1–6. DOI: http://dx.doi.org/10.1016/j.jas.2015.11.006.

Doxaran D. & Leymarie E. & Nechad B. & Dogliotti A.-I. & Ruddick K. & Gernez P. & Knaeps E. (2016). Improved correction methods for field measurements of particulate light backscattering in turbid waters . Optics Express, Vol. 24(4) pp. 3615–3637.

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Lebreton C. & Stelzer K. & Brockmann C. & Bertels L. & Pringle N. & Paperin M. & Danne O. & Knaeps E. & Ruddick K. (2016). Cloud and cloud shadow masking of high and medium resolution optical sensors - an algorithm inter-comparison example for Landsat-8 . Submitted for the proceedings of the 2016 ESA Living Planet Symposium held in Prague, Czech Republic, 9-13 May 2016, ESA Special Publication SP-740.

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