Coastal Erosion from Space

Coastal Erosion events:

in Nerja (Spain) *in Kilkee (Ireland)* *in St Laurent mouth (Canada)*

Algorithm Theoretical Baseline Document

Ref:SO-TR-ARG-003-055-009-ATBD-BMTM
Date: 20/01/2021

Customer: ESA

Contract Ref.: 4000126603/19/I-LG

© 201719ARGANS

This page is intentionally left blank

© 2019ARGANS

Version and Signatures

Version	Date	Modification
0.5	02/12/2019	review
0.6	05/12/2019	review
0.6	11/01/2021	Final Review
0.7	10/02/2021	Final Review
Verification by	François-Regis Martin-Lauzer	
Authorisation	Craig Jacobs	

© 2019ARGANS

Acronyms

ALUT: Adaptive Look-Up Table

ARCSI: Atmospheric and radiometric correction of satellite imagery

CDOM: Coloured dissolved organic matter

CNES: Centre national d'études spatiales (Fr)

DEM: Digital elevation model

DoD: DTM of difference

DSI: Datum-based shoreline indicators

DTM: Digital terrain model

EO: Earth observation

GRD: Ground range detected

HR: High resolution

ICZM: Integrated Coastal Management

IDA: Image data analysis

IOPs:Inherent optical properties

MSI: Multi-spectral imager

NIR: Near infra-red

OLI: Operational land imager

SAR: Synthetic-aperture radar

SDB: Satellite derived bathymetry

TBDEM: Topo-bathymertric digital elevation model

URD: User requirement document

VHR: Very high resolution

© 2019ARGANS

Abstract

The Coastal Erosion Project is focussed on delivering a global service for monitoring coastal erosion, environmental risk assessment and research on the potential impact of climate change on the coast. It is a project lead by ARGANS with the objective of determining the feasibility of using satellite images to monitor coastal change, to detect when and where erosion and/or accretion have occurred. A consortium of end-users is also part of the project and they have provided a series of requirements to fulfil the objectives. One of the requirements is the bathymetry for the Integrated Coastal Zone Management (ICZM) of areas further offshore. Bathy-morpho terrain models (BMTM) have been chosen as the selected product that will be delivered, providing bathymetric data in a cost-effective way in some areas. It is necessary to point out the difference existing between the well-known satellite derived bathymetry (SDB) and BMTMs. In the former, the objective is to provide a navigationally safe surface, but in the frame of this project, we are looking at providing trends of features that can be observed to monitor coastal changes. Thus, BMTMs have been selected as the approach followed in this project, considering also the challenges to be faced when working in the selected study sites due to the extremely opaque nature of the water column and sediment loads, a key feature in erosion/accretion.

Two different approaches exist when estimating BMTMs, empirical models and physics-based models. Empirical models allows to estimate the various unknowns, such as the depth, from comparison with field measurements, however, we are interested in features trends, which are more unlikely to be observed if empirical models are used. Thus, a physics-based model is used under the framework of this project.

Image Data Analysis (IDA) software is used, which is based on Hedley et al., 2009. The procedure for the estimation of BMTMs follows three different steps: pre-processing, IDA process and Confidence maps estimation. The pre-processing consists of the download and selection of the images to work with in each study area according to the environmental conditions. The IDA process consists of different steps: the clouds and boats mask estimation, a deglint step, an atmospheric correction step and depth estimation. Then a final stage, the confidence map estimation, has been added to the project to add a reliability value in terms of water clarity to the BMTM maps. Photons that penetrate the ocean and interact with water molecules and other constituents of the water column, such as coloured dissolved organic matter (CDOM) and suspended particulate matter (SPM), could not reach the bottom. Therefore, a confidence map is delivered together with BMTM maps to provide the end user with information for each image related to water clarity. It is necessary to point out that the confidence maps are an indicator of the water clarity, so the possibility of the photons to reach the bottom, but the depth estimated in the BMTMs still needs to be validated in those areas selected as good and medium.

© 2019ARGANS

Applicable and reference documents

Id	Description	Reference
AD-1	Requirement Baseline Document	SO-RP-ARG-003-055-006-RBD_v1.0_20190916
AD-2	Pre-processing ATBD	SO-TR-ARG-003-055-009-ATBD-PP

© 2019ARGANS

Contents

© 2019ARGANS

List of Figures

© 2019ARGANS

1 Overview and Background Information

1.1 Product requirement

1.1.1 Information content quality and value

End-users require (see URD) products such as bathymetry for the Integrated Coastal Zone Management (ICZM) of areas further offshore. Bathy-morpho terrain models (BMTM) could potentially provide bathymetric data in a cost-effective way in some areas. Coastal erosion within the coastal zone has been identified by coastal stakeholders worldwide as an issue that needs urgent attention, and the consulted champion user organization agreed on limiting the spatial scope of the products requirements to the coastal zone. The term BMTM is used in this Project instead of Satellite Derived Bathymetry (SDB), as the objective is not to replicate a navigationally safe surface but to detect trends or features that could be observed in coastal environments under erosion or accretion.

Bathy-morpho terrain models need to characterize the shore area, from the land/sea delineation to the Secchi depth. The study area thus varies between 0 and 5 or 30m depth depending on the conditions.

BMTMs is a part of remote sensing that is useful to determine depths and other seabed features of coastal marine environments by measuring the reflectance of the sea bottom extracted from the upwelling light signal. BMTMs should provide information on the near-shore morphology (between C and D line in Figure 1) with vertical accuracy of $1\ m$ and horizontal accuracy of $10\ m$ for Sentinel-1 or -2 data, or vertical accuracy of $1\ m$ and horizontal accuracy of $1\ m$ for Very High Resolution (VHR) satellite data.

© 2019ARGANS

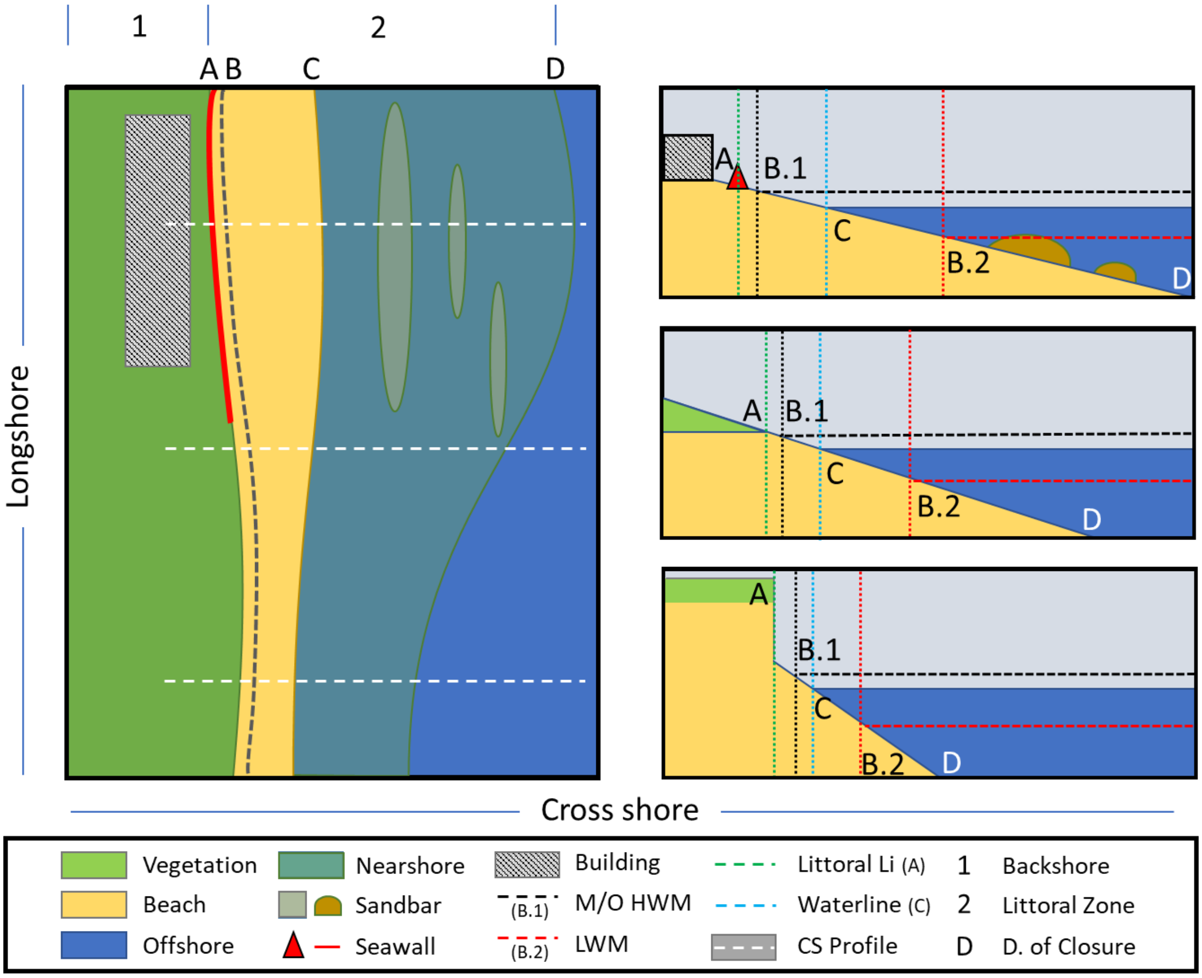

Figure 1. Shore and coastal features diagram

Spatial resolution is a particularly important factor in the BMTM process as it influences the information about the actual depth of the sites of interest that can be derived from the process itself. In particular, VHR images may not be the best choice for this type of process as the products can be very noisy. Images from Sentinel-2 with a high spatial resolution of 10 m are more likely to be used as they capture less features such as waves. Less noise will therefore be introduced in the final product.

1.1.2 Product order & delivery services

Bathy-morpho terrain models will be delivered in raster format together with a metadata file, containing information about the time and the area, and the values of the parameters used for processing each one of the BMTS delivered. Besides, a confidence map, containing information about the water clarity, is also delivered in a raster format.

© 2019ARGANS

Output format will be compatible with GIS software as ArcGis and QGIS and products will be available on a geoportal and delivered by an ftp transfer.

1.2 Quick Review – Feasibility

Please refer to the pre-processing ATDB (ref: SO-TR-ARG-003-055-009-ATBD-PP)

1.2.1 Existing EO Products

Please refer to the pre-processing ATDB (ref: SO-TR-ARG-003-055-009-ATBD-PP)

1.2.2 Models specifications

Two basic approaches can be used to extract bathymetry from radiance signals received by satellites sensors, including:

- Empirical models,
- Physics-based models.

The empirical models, are based on the exponential attenuation of light set by the Beer-Lambert law that can be simply expressed by the depth-log attenuation rule: $I(z) = I(0)e^{-Kz}$, where z is the depth, I the transmissivity of light through the water and K is the attenuation coefficient[1]. Empiric modelling consists of calculating the various unknowns in the equation from comparison with field measurements using statistical estimates, and assuming that the conditional probability law thus defined can be extended to the entire area that is surveyed.

Satellite Derived Bathymetry (SDB) analysts have identified 8 steps in the image processing and subsequent production of satellite derived charts2. An additional initial step for image selection has also been included:

1. Selecting image based on sufficient suitability for SDB (e.g. low cloud cover, low glint, low water turbidity),

[1]David R. Lyzenga, "Passive remote sensing techniques for mapping water depth and bottom features", Appl. Opt. 17, 379-383, (1978).

© 2019ARGANS

2. Eliminating instrumental noises and applying threshold mechanisms to the selected scenes,
3. Correcting atmosphere and water surface reflection (deglinting),
4. Applying geometric corrections in regions where geodetic data are often non-existent and ground controls (radiometric and/or geodetic),
5. Re-sampling & interpolating pixels, creating false colour composite layers, calculating various indexes,
6. Creating land, inter-tidal and cloud/shadow masks to remove artefacts and data excluded from depth extraction,
7. Performing statistical analysis leading eventually to the production of a bathymetric model,
8. Capture of objects and compilation with ancient data,
9. Production of SDB charts.

Physics-based models are derived from full equations of optical radiative transfer[2]. They do not require field calibration data and are far more robust in terms of transferability between different waters and atmosphere optical properties. The key differences with empirically calibrated methods are that i.water optical properties and bottom reflectance are treated as 'constrained unknowns', i.e. observationally constrained estimates, and that ii. suitable bands from multi- or hyperspectral data are used simultaneously to find an optimal solution over all unknown factors[3].

Spectral calibration to known depths is not required because the model that is developed attempts to capture the full physical process of light transfer without any unknown scaling factors to be calibrated.

Basically, it is a forward model that estimates the reflectance from a parameterised model of all the radiative transfer components of the system. The model has at least one degree of freedom for each unknown factor, i.e. depth, water optical properties and benthic reflectance. All these unknown variables can be constrained because the ranges of water optical properties and benthic reflectances are not infinite.

The models compute spectral radiance distributions for natural water bodies as a function of depth and direction, including both the water-leaving radiance and that part of the incident direct and diffuse sky

---

[2]Zhongping Lee, Kendall L. Carder, Curtis D. Mobley, Robert G. Steward, and Jennifer S. Patch, "Hyperspectral remote sensing for shallow waters. I. A semianalytical model," Appl. Opt. 37, 6329-6338 (1998)

[3]Hedley, John,"Hyperspectral Applications", 10.1007/978-90-481-9292-2_4, (2013).

© 2019ARGANS

radiance that is reflected upward by the wind-blown sea surface (sun glint), and taking into account the absorbing and scattering properties of the water body and the reflectance of sea-bottom boundary[4].

All forward model variants are based on the same equations and are almost numerically identical. Their results depend therefore only on the details of how the model is parameterised and inverted.

It is important to point out that the approach followed in this project distinguished from the one followed when calculating Satellite Derived Bathymetry. In our case, we intend to provide information about coastal evolution, and for that, and due to the different areas selected for each country involved, the physical approach has been chosen. As the empirical approach uses in situ data to calculate the unknowns and as we want to detect features trends, the physics-based model is the best option.

1.2.3 Currently known issues

The floor below the sea-surface is much dimmer than land so that the total radiance, from the Top-Of-Atmosphere (TOA), is much larger over land, and the atmospheric contribution to the total is less, while the EO signal recorded on the satellites takes the full 8 to 12 bits dynamics. Sensor signal, as well as signal-to-noise ratio, is lower over open ocean & coastal waters.

Depending on the spatio-temporal structure of the images and the type of satellite, a model can be calculated for an image, a segment, a block or a combination of the three. A first issue to be aware of is that images can be down- or over-sampled loosing information induced by the transform.

Clouds and boats must be masked from the input image before performing the whole process. The masking itself is a laborious task as each image has different features. If the masking does not occur the output image will be contaminated with artefacts containing false information about the actual depth of a pixel.

It is practically impossible to assess the error from the empirical model analysis as corrections are calibrated for one given dataset and one given location and are not homogeneously valid for all bottom-types. The constraints of near-verticality, dynamic range and atmosphere clarity affecting satellite images are particularly hard to identify. The empirical method is neither repeatable, nor transferable worldwide. SDB charts are indeed limited to inter-reefal areas of similar nature. Addressing different bottom structures and

[4] Zhongping Lee, Kendall L. Carder, Curtis D. Mobley, Robert G. Steward, and Jennifer S. Patch, "Hyperspectral remote sensing for shallow waters: 2. Deriving bottom depths and water properties by optimization," Appl. Opt. 38, 3831-3843 (1999)

© 2019ARGANS

water of various qualities, although feasible in theory, means different laws of probability, more field surveys and more expenses for in-situ sampling.

The changes of physics-based methods compared to empirical ones is the need for radiometrically calibrated spectral remote-sensing radiances/reflectances, which are easily obtained from low and medium spatial resolution EO satellites, but seldom from high resolution satellites. As inversions are done at pixel level, the image needs to be properly processed – in particular corrections for atmospheric effects and white-sky correction. Indeed, remote sensing reflectance measured by a satellite instrument is affected by scattering and attenuation during transit through the atmosphere and the water column[5]. The atmospheric correction is one of the main issues of the BMTM models. There are two distinct aspects to the need to correct for the effects of atmospheric aerosols:

I. Pixel to pixel variations, such as thin cloud,
II. Atmospheric effects that can be considered uniform image-wide, such as the basic molecular Rayleigh scattering.

Radiative transfer models require these latter corrections to be made, while image uniform effects are less critical for empirically calibrated methods, they may cause issues for mosaicking if scenes are collected at different times. Both forms of correction imply an associated uncertainty that will impact on the bathymetric estimations and that can be propagated to the error budget assessment in the bathymetric assessments.

The key to bathymetric estimation is to relate the reflectance of the water column to its depth; this requires the forward model to capture the variation in the optical properties of the water and its constituents, and also of the benthic reflectance. Another important issue comes with the fact that both the methods endure the same fundamental uncertainty, i.e. similar reflectance can be consistent with different depths. Pure water has a distinctive spectral attenuation that varies over several orders of magnitude in the visible range from clearest wavelengths (blue-green) to being close to opaque in the NIR, whether constituents such as chlorophyll, coloured dissolved organic matter (CDOM) and suspended particulate matter (SPM) affect the attenuation and backscatter of the water column. Inherent optical properties are stored in large databases of in-situ spectral measurements made in various environments; however, it is hard to locate the laboratories that keep such data and gain access to it. Besides, low water clarity (in terms of concentration

[5] James A. Goodman, ZhongPing Lee, and Susan L. Ustin, "Influence of atmospheric and sea-surface corrections on retrieval of bottom depth and reflectance using a semi-analytical model: a case study in Kaneohe Bay, Hawaii," Appl. Opt. 47, F1-F11 (2008)

© 2019ARGANS

of constituents such as CDOM and SPM in the water column) could hamper the estimation of the bottom reflectance that will allow the estimation of the depth.

Moreover, satellite derived bathymetry using model previously announced (section 1.2.3) are only accurate between 3m and the Secchi depth. Indeed, in shallow-waters, remote sensing is impacted by seafloor depth, by the seafloor reflectance as well as the water column absorption and viewing condition (sunlight, observation angle, etc.). Other methods need to be implemented for bathymetry retrieval between 0 and 3m depth.

1.3 Potential Solutions

Constituents such as chlorophyll, coloured dissolved organic matter (CDOM) and suspended sediments affect the attenuation and backscatter of the water column. The variation of water constituents can be expressed in a number of ways:

I. by three parameters that express the relative amounts of CDOM, chlorophyll and the particulate backscatter slope,
II. by datasets of Inherent Optical Properties (IOPs), which can be directly ingested. IOPs are spectral measurements of the beam attenuation and scattering of the water.

Potential variation in benthic reflectance from sand, mud, rock, corals, and other marine biotas must be captured by the model. A possible solution consists of analysing the image at a sub-pixel scale. In this case in each pixel it would be possible to identify a fraction for every different component of the seabed resulting in more information.

Some water based atmospheric correction models can better describe the atmospheric parameters and composition with respect to a land based one. Examples of them are:

- Atmospheric and Radiometric Correction of Satellite Imagery (ARCSI). This software provides a command line tool for the generation of Analysis Ready Data (ARD) optical data including atmospheric correction, cloud masking, topographic correction etc. of Earth Observation optical imagery (Blue-SWIR). The aim of ARCSI is to provide as automatic as possible method of generating analysis ready data.
- 6s Atmospheric Correction. The 6S code is a basic RT code used for calculation of lookup tables in the MODIS atmospheric correction algorithm. It enables accurate simulations of satellite and plane observation, accounting for elevated targets, use of anisotropic and lambertian surfaces and

© 2019ARGANS

calculation of gaseous absorption. The code is based on the method of successive orders of scatterings approximations and its first vector version (6SV1), capable of accounting for radiation polarization. It was publicly released in May, 2005.

- Sen2Cor.It is a processor for Sentinel-2 Level 2A product generation and formatting; it performs the atmospheric-, terrain and cirrus correction of Top-Of- Atmosphere Level 1C input data. Sen2Cor creates Bottom-Of-Atmosphere, optionally terrain- and cirrus corrected reflectance images; additional, Aerosol Optical Thickness-, Water Vapor-, Scene Classification Maps and Quality Indicators for cloud and snow probabilities. Its output product format is equivalent to the Level 1C User Product: JPEG 2000 images, three different resolutions, 60, 20 and 10 m.
- DOS Atmospheric Correction. Dark Object Subtraction (DOS) is one of the most common used atmospheric correction methods. Various sets of input parameters are available such as the atmospheric transmittance. You can set pixel value (Digital Number) of a dark object (often water bodies) from your scene.

A way to improve the quality of the results obtained would consist of introducing one or more of these more atmospheric correction methods to the existing algorithm.

Water clarity has been tagged as a currently known issue, as it could hamper the detection of the bottom reflectance. A way to provide information of the water clarity would consist of the estimation of the concentration of the different constituents of the water column, such as the suspended particulate matter (SPM) and the coloured dissolved organic matter (CDOM). This would provide information of those concentrations that will hamper the visualization of the bottom reflectance using satellite data, which will imply that the depth obtained for those areas will be based on the water constituents rather than the bottom reflectance.

1.4 Product Specifications

The processor currently used to retrieve the bathymetry between 3 and 30m, is the IDA (Image Data Analysis) 2019 software from Natural Optics Ltd. The processor workflow is shown in the following picture.

© 2019ARGANS

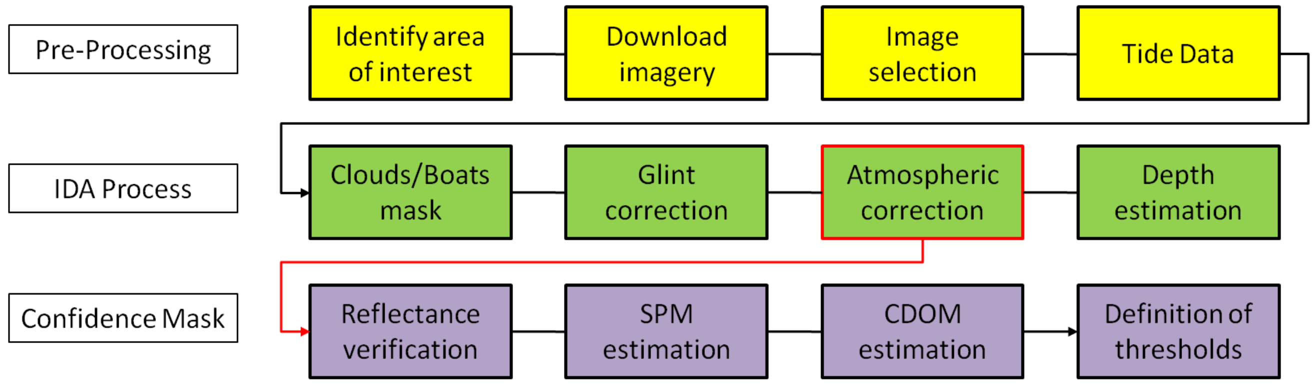

Figure 2. BMTM processor workflow

The processor comprises various steps. The Pre-Processing procedure is an important step, as even though several images for an area will be available, not all of them will be suitable for the estimation of BMTMs. The images should be chosen considering the presence of clouds, glint, waves, or the presence of high concentrations of water constituents by a visual inspection of all the images by the person processing them.

Once the images to work with are selected, Level-1C data face multiple steps in which they are deglinted and the atmospheric correction is applied, in the context of the IDA Process procedure. The bathymetry is then derived from image data using an inversion method model. The processor produces two types of output: Level-2 (Depth estimation) and Level-3 (merged images, only possible when the quantity of images available allow us to do so).

The last step, the confidence mask procedure, consists of the estimation of the concentration of the water constituents of each image. Then, the estimation of the thresholds for each country involved in the project will allow the definition of the values of concentration that would hamper the visualization of the bottom reflectance.

1.4.1 Level-2 Products

The final product of the entire BMTM process is a depth map which represents the bare ground surface without any other object.

© 2019ARGANS

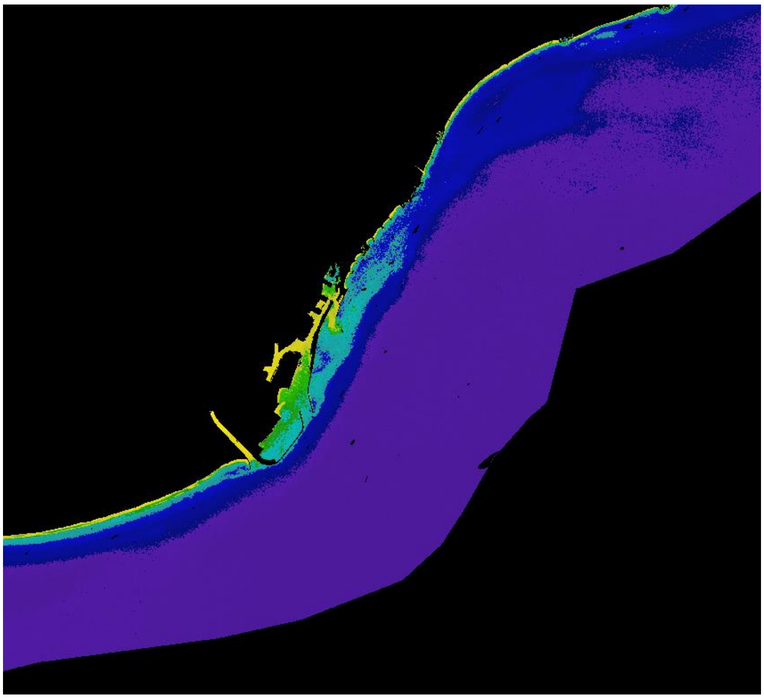

Figure 3. Level-2 Barcelona El Prat filtered BMTM 22-06-2017

1.4.2 Level-3 Products

BMTM maps elaborated for different days, months or seasons can be used to derive whether the depth of a studied site has changed in time. Pixels are compared and by simply subtracting the most recent image with an older one it is possible to determine the depth variations in time.

It is necessary to point out that this product will be restricted to the environmental conditions of the area under study. Areas highly affected by cloud cover, or with high concentrations of water constituents, for example, will not be suitable for the estimation of Level 3 products due to the number of BMTM maps with good quality available.

1.4.3 Confidence maps

The final product of the confidence maps procedure is a water clarity and reflectance indicator with three different levels of confidence. Areas presenting good water clarity (bottom reflectance can be observed) and realistic reflectance values (after the atmospheric correction), are classified as 1; areas presenting bad water clarity (high concentration of water constituents) or non realistic reflectance values, are classified as 3; and finally, areas presenting mean water constituents concentration (bottom reflectance can be observed in certain cases) and realistic reflectance values, are classified as 2; the end user should consider these areas carefully.

© 2019ARGANS

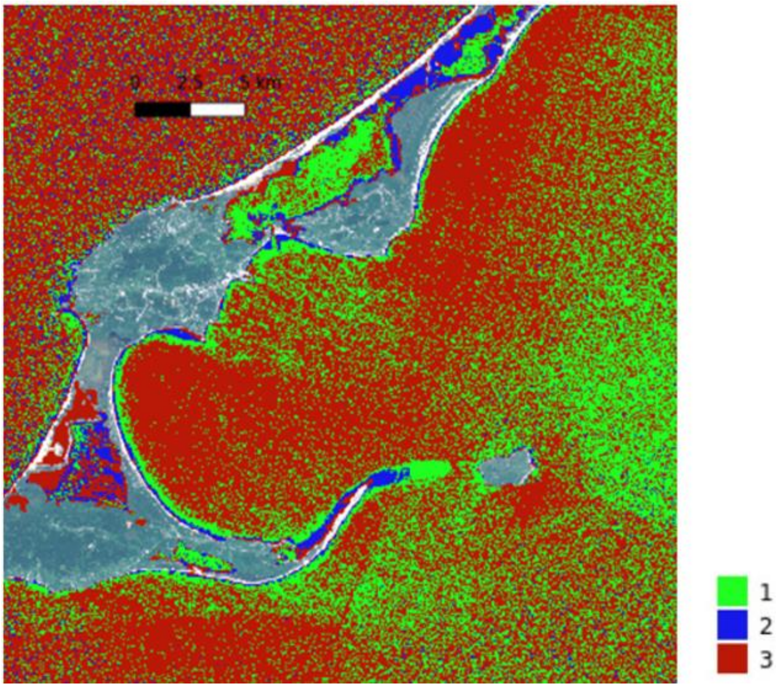

Figure 4. Iles de la Madeleine confidence map

© 2019ARGANS

2 Algorithm Description

2.1 Data Processing outline

2.1.1 *Sketch of the computer program*

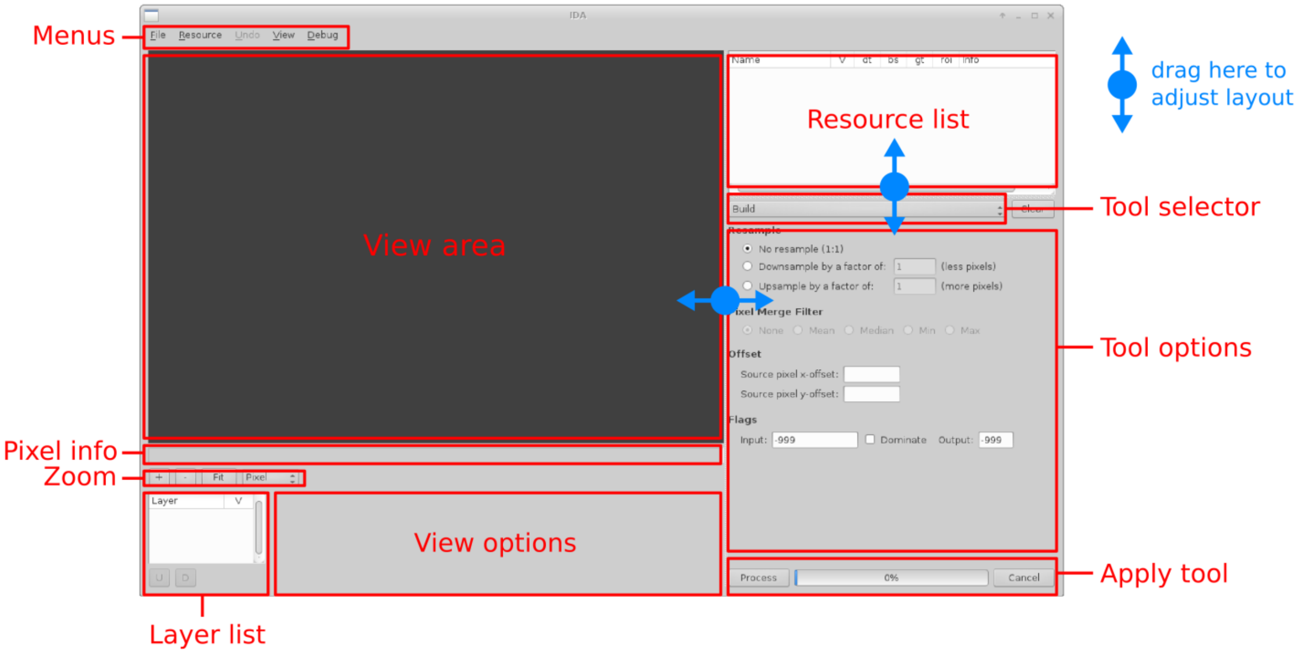

Figure 5. IDA processor window

The labelled areas function as follows[6]:

- Menus – standard menus to open files etc.
- View area – images are viewed here.
- Pixel info – shows details of the pixel the mouse is currently over.
- Layer list – the list of layers in the view, can be re-ordered and switched on and off.
- Zoom – for zooming in or out on the image view.
- View options – when viewing an image contrast and brightness can be adjusted here.
- Resource list – lists the currently loaded resources and selects resources for use in tools.

[6] Check “IDA Manual”, John D. Hedley, (2019).

© 2019ARGANS

- Tool selector – selects the tool to apply.
- Tool options – the options for the currently selected tool.
- Apply tool – applies the tool to the selected resources and shows processing progress.

2.1.2 Pre-requisite

The requirement for the product is a co-registered image (see the Pre-processing ATBD, Ref.: SO-TR-ARG-003-055-009-ATBD-PP)[7]which provide the true location of every identifiable feature within the satellite imagery, with a minimum of three bands in the RGB, i.e. in visible wavelengths: blue ($\sim 497\ nm$), green ($\sim 560\ nm$), red ($\sim 665\ nm$); images including the Near Infra-Red ($\sim 835\ nm$) can be useful but not compulsory in the process. Clouds and boats must be masked in order to avoid artefacts from the output image.

Level-1C data are used as EO data for the process. They include radiometric and geometric corrections including ortho-rectification and spatial registration on a global reference system with sub-pixel accuracy. Data have to be elaborated with specific models in order to deliver the final BMTM product to customers.

Each step of the BMTM process is performed by using consolidated methods to obtain the best results out of the available data. The deglint step, when needed, consists of identifying one or more regions of interest (ROI) where the NIR reflectance is minimum[8]. This NIR value is the one that would be expected in the absence of glint and is what the correction 'pulls back' the reflectance to.

Starting from deglinted images the Atmospheric Correction must be performed. This step is the one that introduces the biggest error to the final product. The model used in this step is generally MAR99, which stands for Maritime 99% Relative humidity model[9].The model considers for the aerosol a mixture of sea salt solution in water, plus a contribution of tiny continental particles. The index of refraction and the mean

[7] Scheffler, Daniel & Hollstein, André & Diedrich, Hannes & Segl, Karl & Hostert, Patrick, "AROSICS: An Automated and Robust Open-Source Image Co-Registration Software for Multi-Sensor Satellite Data", *Remote Sensing*, (2017).

[8]Hedley, JD, Harborne, A. R., Mumby, P.J., "Simple and robust removal of sun glint for mapping shallow water benthos", *International Journal of Remote Sensing* 26, pp 2107-2112, (2005).

[9]Antoine D. and Morel A., "A multiple scattering algorithm for atmospheric correction of remotely-sensed ocean colour (MERIS instrument): principle and implementation for atmospheres carrying various aerosols including absorbing ones", *Int. J. Rem. Sens.,* 20(9): 1875-1916, (1999).

© 2019ARGANS

radius of particles is RH-sensible (99% for this model). The free troposphere and the stratosphere are considered free of any aerosol[10].

2.2 Algorithm Input

Another model used in the bathymetry step considers six predefined spectral response curves (coral, sand, dead coral, macroalgae, seagrass, benthic microalgae) in order to discriminate these features from the seabed. These reflectances can be adapted to the geographical location and geological conditions in order to better match the real marine ecosystems. However, this algorithm allows for input of custom spectral response curves for different benthic types. The parameters available as input in the *bathy*tool are:

- P = phytoplankton concentration (proxy, absorption due to phytoplankton at 440 nm).
- G = dissolved organic matter concentration (proxy, is absorption due to CDOM at 440 nm). CDOM is a complicated mixture of organic macromolecules Brezonik, Menken and Bauer 374 with aromatic, carboxylic acid, and phenolic groups derived primarily from decomposition of plant material in soils and wetlands[11].
- X = backscatter (particulate backscatter coefficient at 470 nm).
- H = depth in metres.

For *P*, *G* and *X*, zero is always a sensible minimum value but the upper limit will be site specific. The default values have proven to work well at many coral reef sites, and for such sites they are at least suitable for an initial analysis. At other sites it may be necessary to research for information about the site or guess at different upper bounds. Actual in-situ measurements are only of use if you have a dataset that covers the time and spatial domain the image may be from. If in doubt simply enter large upper limits that certainly cover what might be expected, but bear in mind the cost of this is higher uncertainty in the bathymetry estimates, and with too much potential variability the results may become completely degenerate. The estimated outputs for *P*, *G* and *X* can be checked to see if the value limits are sufficient. However, the

[10]Shettle, E.P. and Fenn, R.W., "Models for the Aerosols of the Lower Atmosphere and the Effects of Humidity Variations on Their Optical Properties", Optical Physics Division, Air Force Geophysics Laboratory, Hanscom Air Force Base, Mass, (1979).

[11]Brezonik, P., Menken, K. D., & Bauer, M. E., "Landsat-based remote sensing of lake water quality characteristics, including chlorophyll and colored dissolved organic matter (CDOM)", *Lake and Reservoir Management*, *21*(4), 373-382, (2005).

© 2019ARGANS

estimations of *P*, *G* and *X*, given by the software user manual, may not be very accurate anyway, since there is not sufficient information in the imagery to estimate them.

2.3 Theoretical Description

2.3.1 Physical Description

The depth of a specific site can be extracted by the radiance components received by a satellite detector.

The key variables in the remote sensing of shallow waters to retrieve the variable of interest, the bathymetry, the water depth or vertical distance between the sea floor and a virtual still water surface, are: the reflectance of light by the sea-bottom (seabed and habitats), the water column's absorption and scattering of light by dissolved or organic and mineral suspended matter, the reflection and transmission of light through the more-or-less rough sea-surface (whether sun-light, sky-light or water leaving light), and the atmosphere's absorption and scattering of light by gas molecules, vapour, aerosols and ice crystals. In short we have ten variables:

- z_{sf} , the water depth
- ρ_b , the light reflectance (ratio of radiances) on the sea bottom, i.e. a marine demersal habitat, which is made of 3 parameters
  - ρ_{seabed}
  - ρ_{hab} where inhabitants are the vegetation (algae, seaweeds…) or living non-migratory animals (corals, shellfishes…)
  - α the ratio of sea bed surface which is illuminated and radiates to the sea-surface (not shadowed by inhabitants)
- a_b^w and b_p^w the attenuation and scattering of light in the ocean waters
- r_s the reflection of light through the sea surface
- a_b^{at} and b_p^{at} the attenuation and scattering of light in the atmosphere.

Assuming already deglinted and atmospherically corrected images the relationship between the radiance at the BOA L_w, the observed radiance R_w, the downwelling irradiance E_d entering the sea surface, the depth z at position (x, y) where x is the latitude and y is the longitude, and the sea bottom albedo ρ_z can be described as:

$$R_w(x, y) = \frac{\pi L_w}{E_d} = \left(\rho_{x,y} - R_{x,y}^{\infty}\right)e^{-g \cdot z} + R_{x,y}^{\infty}$$

Where $R^{\infty}_{x,y}$ is a calibration factor (similar to the radiance of deep waters) and g is a function of attenuation of both downwelling and upwelling light.

For each wavelength λ or band centred on λ, this equation is the same but with various coefficients: $A^{\lambda}_{x,y}$, $g^{\lambda}_{x,y}$ and $R^{\infty,\lambda}_{x,y}$. Depth is related to the radiance at this wavelength by:

$$z_{x,y} = a_0 + a_1 \ln\left(R^m_w - R^{\infty}_{x,y}\right)$$

Where R^m_w is the estimate of the reflectance at the position (x, y)[12].

In order to calculate the depth associated to a pixel the processor checks for the spectral response and tries to match it with the predefined ones using a 6-endmember inversion model. To do the matching it changes each value of P, G or X. By doing so the processor builds an Adaptive Look-Up Table (ALUT)[13] and, once the spectral responses are in agreement the processor inverts the spectral remote sensing reflectance equation in order to determine the depth value H[14].

2.3.2 Mathematical Description and calculation procedures

As the true depth is not directly accessible, we need to calculate it from measurement, we thus access to a measured depth which cannot call true depth due to bias and noise: $h_{\text{meas}}(\vec{x}, t) = h_{\text{sf}}(\vec{x}) + h^{\text{bias}}_{\text{meas}}(\vec{x}_L, t) + \delta h^{\text{noise}}_{\text{meas}}(\vec{x}_L, t)$ with $h_{\text{meas}}(\vec{x}, t)$ the measurement at the position $\vec{x}$ant time t.

From the measurement value we can estimate the depth h_{est},$h_{\text{est}}$is a statistics estimation based on h_{meas} value from different images or surveys. We set $T_n = T\left(H_{\text{meas},1}, H_{\text{meas},2}, \ldots, H_{\text{meas},n}\right)$the estimator of h_{sf} with *n* the number of measurements and $h_{\text{meas},i}$ with $i \leq n$is available ($H_{\text{meas},i}$ is the random variable related to $h_{\text{meas},i}$), and it converges to the true value when the size of the sample *n* grows.

Each tool described uses specific mathematical equation to elaborate the input data.

---

[12] IHO "Manual of Hydrography", chapter 3 – Depth determination. International Hydrographic Bureau, Monaco (2005)

[13]Hedley, John D., Christiaan M. Roelfsema and Stuart R. Phinn., "Efficient radiative transfer model inversion for remote sensing applications." (2009).

[14]Hedley, J.; Roelfsema, C.; Phinn, S.R.,"Propagating uncertainty through a shallow water mapping algorithm based on radiative transfer model inversion.", In Proceedings of the Ocean Optics XX, Anchorage, AK, USA, 25 September–1 October 2010.

© 2019ARGANS

In the deglint step, when performed, the mean NIR from the ROI is considered to be the baseline for the process[15].

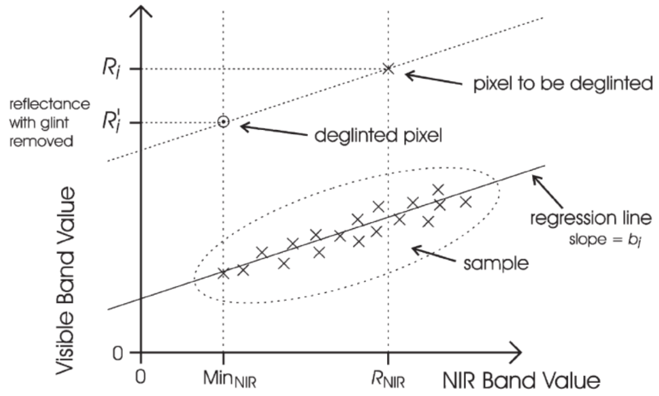

Figure 6. Graphical interpretation of the deglint correction.

In Figure 6 it is shown that for each visible band all the selected pixels are included in a linear regression of NIR brightness (x-axis) against the visible band brightness (y-axis)[16].To deglint a visible wavelength band, a regression is performed between the NIR brightness and the brightness in the visible band using a sample set of pixels selected by the user, which would be homogeneous if not for the presence of sun glint (e.g. deep water).If the slope of this line for band i is b_i, then all the pixels in the image can be deglinted in band i by the application of the following equation:

$$R_i' = R_i - b_i(R_{NIR} - M_{in_{NIR}})$$

Where $R_i'$is the sun-glint corrected pixel brightness in band i and it is obtained by subtracting $R_i$by the product of regression slope $b_i$and the difference between the pixel NIR value, R_{NIR}, and the ambient NIR level $M_{in_{NIR}}$, which represents the NIR brightness of a pixel with no sun glint and can be estimated by the minimum NIR found in the regression sample or alternatively as the minimum NIR value found in the whole image. In general, the minimum NIR pixel is less prone to problematic outliers than the maximum NIR pixel.

[15] Kay S, Hedley JD, Lavender S., "Sun glint correction of high and low spatial resolution images of aquatic scenes: a review of methods for visible and near-infrared wavelengths",*Remote Sensing* 1: 697-730,(2009).

[16]Hedley, JD, Harborne, A. R., Mumby, P.J., "Simple and robust removal of sun glint for mapping shallow water benthos", *International Journal of Remote Sensing* 26, pp 2107-2112, (2005).

© 2019ARGANS

The atmospheric correction provided by the atmospheric correction tool is spatially homogenous, and it reduces in each band to a simple linear transform:

$$P_i'(x,y) = [P_i(x,y) - s_i] \times m_i$$

Where $P_i(x,y)$ is the input value in the pixel(x,y) in the band i and $P_i'(x,y)$ is the atmospherically corrected value. The P_i valuemust be in units of upward radiance divided by downwelling irradiance at TOA (sr^{-1}). After correction $P_i'(x,y)$values are the remote sensing reflectance,R_{rs}, in band i, which is the water-leaving radiance divided by the downwelling irradiance at BOA.

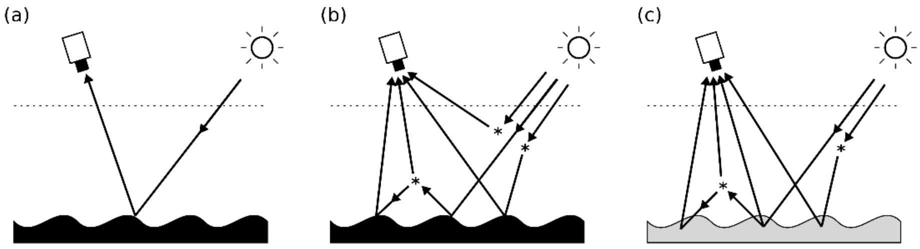

Figure 7. Different paths from sun to sensor through the atmosphere. (a) Direct reflected path from air-water interface. (b) Atmospheric reflectance and indirect reflected paths from the air-water interface. (c) Paths that penetrate the water surface and hence carry useful information

The atmospheric correction tool attempts to remove paths in (a) and (b) from the reflectance, and correct for any losses (absorption and out-scattering) in the atmospheric section of the paths in (c).

Although different terms are involved, aerosols, ozone, surface reflectance etc. ultimately the atmospheric correction applied here reduces to the simple linear transform of the equation previously written applied the same to all pixels. Therefore, the task is to estimate a single set of values for *m* and *s* in each band.

2.3.3 IDA software

IDA software is based on Hedley et al., 2009, which is a modified inversion scheme as proposed by Lee et al., 1999. It considers that bottom reflectance spectrum could be one of many different curves resulting from the linear mixture of a few most common substrate types (sand, live and dead coral, algae and seagrass, as indicated before). The algorithm proposed an efficient subdivision of the parameter space (any parameter of interest) once the real range of variability is known. For example, consider changes in the reflectance as a function of depth: it can be observed that in the first depths, small changes can lead to greater diminution in measured reflectance; however, at greater depths, small changes lead to lesser impacts in the measured reflectance, therefore, the algorithm proposes a more detailed subdivision of the depth in shallow areas than in deeper ones.

© 2019ARGANS

2.3.4 Acceptance of the Models

The processor has been used and validated in multiple occasions. Literature shows that the processors performs well and can create accurate outputs[17,18].

ARGANS have successfully delivered the ESA contract No. 4000124860/18/I-NB under the EO Science For Society Permanently Open Call For Proposals EOEP-5 BLOCK 4 called “Sentinel Coastal Charting Worldwide”.

In the context of the project both the sentinel system and the processor have been tested for 4 different sites (Puerto Morales – Mexico, NosyBe - Madagascar, Lampi Island - Myanmar, Coral Harbour – Canada) and the results show a good agreement with the Electronic Navigational Charts (ENC) used as a comparison method.

However, the procedure followed in the previous Project is not exactly the same as the one used under this Project as the objectives are not the same. In the latter one, they intended to provide Nautical Charts, proving good results when compared to ENC. For that, a merge step was added to the Procedure, providing a single nautical chart for each area of interest at the end of the project.

In the actual project, coastal variations related to erosion or accretion want to be detected. For that, the merging step is not an option, as it will put together the final results of each available map in a final map version, which will not allow us to detect any movement of the different features, such as sand bars, for example, that characterize coastal areas. Thus, a BMTM map is provided for each selected satellite image, using the same model that showed accurate results in the Project “Sentinel Coastal Charting Worldwide”, but without the merging step.

2.3.5 Error estimation

The main error source in the process is the Atmospheric Correction. Common models are generally not able to give a good representation of the atmospheric conditions present in coastal area. Those models are terrestrial based and are not accurate enough for coastal areas. One variable is the ozone concentration in Dobson unit (DU) which has values on average confined in a range between $300\ DU$ and $500\ DU$. The increase in accuracy of this variable over the default value of $300\ DU$ may not have significant effect on downstream products. The other two values are the aerosol optical thickness ($\tau550$) and the water surface

[17] Hedley, J.D., Roelfsema, C., Phinn, S., “Propagating uncertainty through a shallow water mapping algorithm based on radiative transfer model inversion”, *In Proceedings of the Ocean Optics XX*, Anchorage, AK, USA, (27 September–1 October 2010).

[18] Hedley, J.D., “Satellite derived bathymetry of Tahanea atoll using Pleiades imagery and in-situ bathymetric point data”, - , (2014).

© 2019ARGANS

roughness in terms of wind speed ($u10$). Running the model approximate values of these two variables are determined but eventually these results are not ultimate as it may be necessary to change them manually multiple times in order to obtain results that should better approximate the expected values. The last decision of these two values is however up to the user, so there is not an accredited method that can explain how these variables should be chosen. Furthermore, there are many interferences between water vapor and other aerosols, especially in coastal regions at the border between land and water, which the model is not able to properly represent.

Another issue comes with end-members values of the spectral response curves. At the moment six curves are present in the bathymetry model but the elements present on the seabed and their spectral responses strongly depend on the geographic location of the studied area. Furthermore, adding more known reflectance curves could introduce even more confusion in the understanding of the sea features in the studied area.

Measurement comes also with errors due to the measurement system, bias $h_{\text{meas}}^{\text{bias}}$which impacts the accuracy and noise $\delta h_{\text{meas}}^{\text{noise}}$which impacts the precision.For BMTMs, usually the biases are coming from the choice of the seabed-types and from restricted ocean colour equations when modelling radiative transfer. The only possibility is to consider a global inversion of the image (all pixels together) instead of a pixel-based inversion, with different length scales for the atmospheric transmission and scattering properties ($L_{\text{atm}} = O(100\text{km})$for mesoscale weather phenomena and $L = O(100m)$for katabatic winds), the sea-surface ruggedness properties ($L_{\text{seasurf}} = O([1\text{cm}, 100m])$from capillarity waves to train waves in swell), the optical properties of the water ($L_w = O(15\text{m})\,, O(10\text{km})\,, O([30\text{km},50\text{km}])$).

Because of these errors for$h_{\text{meas}}^{\text{bias}}and\delta h_{\text{meas}}^{\text{noise}}$, h_{meas} can be considered as the output of a random variable H_{meas}or a stochastic process $H_{\text{meas}}(\vec{x}, t)$, the occurrence of h_{meas} obeying probability functions $P_{H_{\text{meas}}}(\vec{x}, t)$ or probability density functions $p_{\text{meas}}(\vec{x}, t)$.

2.3.6 Confidence maps

The IDA software is used to estimate BMTMs, that is useful to determine depths and other seabed features of coastal marine environments by measuring the reflectance of the sea bottom extracted from the upwelling light signal. However, it has been seen that the estimation of depth and other seabed features can be hampered under certain environmental conditions. As shown in the Figure 2, it is necessary to pre-select the images used to estimate BMTMs to avoid the possible causes that will impact depth retrieval and select those ones presenting the optimal conditions to estimate depth and seabed features. Even though the best images are selected, BMTM results could be considered as bad in some areas of the images due to different

© 2019ARGANS

causes such as the environmental conditions. Some photons that penetrate the ocean can interact with water molecules and other constituents of the water column under certain environmental conditions (coloured dissolved organic matter, suspended particulate matter…), but do not reach the bottom. Thus, confidence maps provide information about the constituents of the water column and those areas of the image where the concentrations are such that the photons will not reach the bottom. Besides, it provides also information of the reflectance used to estimate depth values after the atmospheric correction. If the values are not realistic (lower than zero), depth values are not considered as valid. Therefore, this section provides the steps follow to the estimation of the confidence maps, which will provide guidance to the end users for those areas with a good reliability on the depth values obtained in terms of water clarity and reflectance.

Atmospheric correction

The passage of light from its source to the surface and subsequently from the surface of the earth, or the sea surface, to the sensor is affected by the atmosphere in two ways: 1) light received at the sensor is reduced by absorption and scattering of photons out of the 'beam' that travels from the surface to the sensor; and 2) conversely, the received light is increased by photons that are scattered into the path of the beam. This is considered a really important step for the depth retrieval, as IDA uses the water leaving reflectance to estimate the depth. The main error source in the process is the Atmospheric Correction (AC). The two variables that need to be adjusted are the aerosol optical thickness ($\tau 550$) and the water surface roughness in terms of wind speed ($u10$). The main impact when selecting these two latter variables, is the quantity of negative reflectance values, which is related to an overestimation of the parameter $\tau 550$. Because of that, those areas presenting negative values will be flagged (value of 3 in the confidence map), as the depth estimation cannot be guarantee.

Water constituents

The bio-optical properties for surface waters could impede the estimation of depth values, as depending on the concentration of the biogeochemical-optical products (coloured dissolved organic matter and suspended particulate matter), the bottom reflectance will not be detected. As a consequence, the confidence map should provide reliability of the depth values depending on the concentration of these products in the different areas of the image.

- Suspended Particulate Matter (SPM) can hamper the estimation of SDB depending on its concentration present in the water column. To identify those areas of an image that will present high SPM concentrations and will impede the visualization of the bottom reflectance, an algorithm

© 2019ARGANS

has been applied to the reflectance obtained using IDA processor. The chosen algorithm is a semi-analytical one developed by Han et al., 2016. This algorithm has been chosen because it covers four orders of magnitude, from clear to very turbid waters, so it would cover the different areas of study in this project (Canada, Ireland, U.K. and Spain sites). Besides, it was developed for several sensors, including Sentinel 2. SPM maps have been obtained for all images that has been processed using IDA. An analysis of the different concentrations of SPM present in ultra-near shore coastal areas, in estuarine waters and in coastal waters have been performed to assess its impact on depth estimation for each country involved in the Project. It is here proposed a mask that will flag depth values as a function of SPM concentration ranges. Depth retrieval in those areas with low SPM concentration (concentration estimated empirically and will vary for each country) will be considered as good values. In case we have medium SPM values (concentrations estimated empirically, which will vary for each country), depth retrieval should be considered as medium quality values, as a SPM plume could be present. In this case, it will be up to the user to choose if the depth corresponding to those pixels will be used. The depth estimated in pixels showing high SPM values (threshold to determine high SPM values estimated empirically for each country) will be classified as bad values. The ultra-near shore coastal areas need a special assessment, as the SPM algorithm could mislead bottom reflectance with water column backscatter. This part will be assessed together with the coloured dissolved organic matter (CDOM), which will allow to identify ultra-near shore pixels.

- Colored Dissolved Organic Matter (CDOM) is also an important biochemical product, which will provide information about the river plumes existing in the images which will impede the detection of the bottom reflectance used to estimate BMTMs. To estimate this product, an algorithm based on the paper of Kutser et al., 2005 is used. This algorithm is based on the ratio between the green (B3) and the red (B4) bands. As in the case of SPM, CDOM maps have been estimated for all areas of study in each country and they have been used to assess the CDOM product in different coastal areas. As a consequence of the observed values and the impediment of observing the bottom reflectance in some of the cases due to CDOM presence, a classification for the confidence map according to the concentrations is here proposed. All the depth values associated to pixels presenting CDOM concentrations bigger than a defined threshold (empirically estimated for each country) should be flagged as bad values. In the case the concentration is lower than a defined threshold (empirically estimated for each country), the bottom reflectance is detected, and the pixels could be flagged as good. For those pixels with concentrations varying in between the previous defined thresholds (empirically estimated for each country), a medium value is going to be

© 2019ARGANS

given to those pixels in the flagging mask. As mentioned in the previous SPM point, in the ultra-near shore coastal areas, CDOM values are higher than expected due to the consideration of the bottom reflectance to estimate the concentrations. In these areas, a medium value is going to be given to the pixels, as the end user should decide if they use the depths for these areas or not. The classification for them is done considering both SPM and CDOM concentrations and the thresholds have been estimated empirically for each country.

The consideration of the atmospheric corrected reflectance and the concentration of the water constituents, that allow us to determine the water clarity of the different areas of study, have been used to build the confidence maps. Three different values ranging from 1 to 3 as follows: good values, attention values (mean concentrations) and bad values; have been considered using the thresholds empirically defined for each country and following the previous points.

2.4 Algorithm output

The possible outputs form IDA are:

- Bathy-morpho terrain models for bathymetry;
- Water constituents, the estimated phytoplankton concentration, dissolved organic matter concentration, backscatter values in each pixel;
- Bottom cover, the estimated proportion of each of the bottom cover types in each pixel;
- Bottom reflectance, the estimated bottom reflectance in the source image bands, i.e. like a 'water column corrected' reflectance;
- Relative PAR, and estimate of the transmission of photosynthetically available radiation (PAR) from the top of the water column to the bottom.
- Spectral match fit, various outputs to show the spectral matching that was achieved by the model.

2.4.1 Product content

Level 2 products: BMTMs

The information layers in the output raster for Level-2 products are:

- Timestamp; date of data collection of images used to create BMTMs
- Spatial Reference System

© 2019ARGANS

- Datum

Metadata

The information in the json file containing the metadata of each BMTM is:

- Product name
- Product Type
- Product Category
- Product Level
- Product Qualifier
- Last Modified Date
- Acquisition Date Time
- Time Series Start Time
- Time Series End Time
- Location Name
- Location Long Name
- Image Bending Box
- Coordinates System
- Sensor Instrument
- Solar Zenith Angle
- Solar Azimuth Angle
- View Zenith Angle
- View Azimuth Angle
- Processor Name
- Processing Sate Time
- BT_Wind Speed U_{10}
- BT_Aerosol Optical Thickness
- BT_Depth Reference Value
- BT_Phytoplankton
- BT_CDOM
- BT_BackScatter
- BT_Aerosol Type
- BT Quality Indicator Map

© 2019ARGANS

Confidence maps

The information layers in the output raster for the confidence map product are:

- Spatial Reference System
- Map containing 4 values classifying the water quality for each BMTM provided:
  - Land: 0
  - Good values:1
  - Attention values: 2
  - Bad values: 3

2.4.2 *Product organisation*

The default outputs for the processors are:

- Image_dg
- Image_dgmask
- Image_LEboa
- Image_LdivE
- Image_LEboa_z
- Image_LeEboa_z_F5

2.5 Algorithm Performance Estimates

2.5.1 *Test specification*

The test performed is a general example used in the IDA training manual. The image used is a segment of a Sentinel-2 image of Lizard Island, Great Barrier Reef. Copernicus Sentinel data 2017, processed by the European Space Agency.

© 2019ARGANS

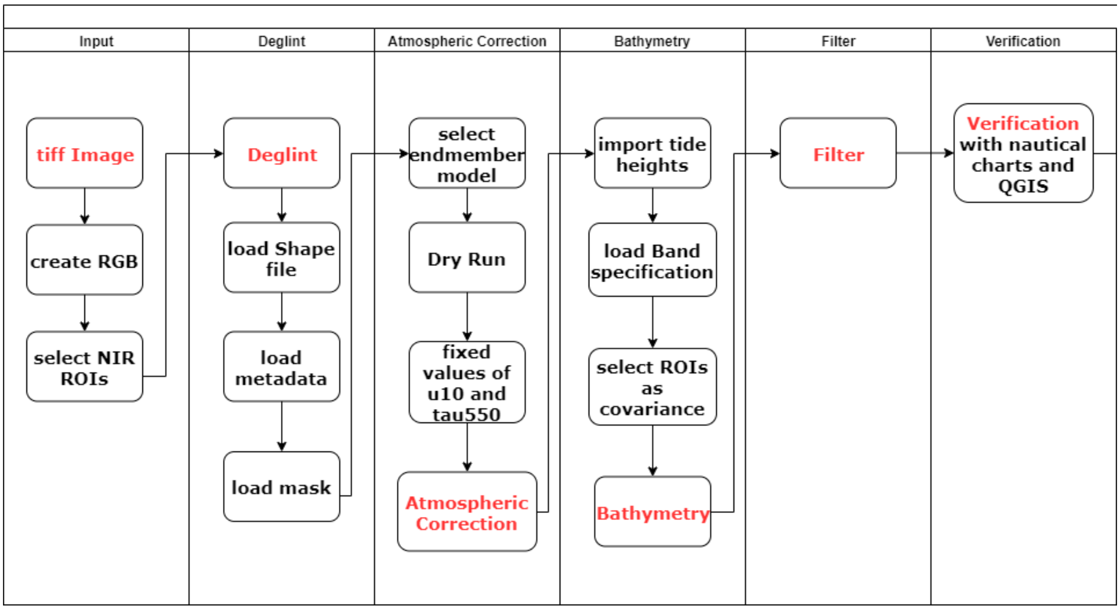

Figure 8. Workflow of IDA processor

The input data needed for the processor are:

- Tiff image;
- Image metadata
- Masks available for the image (cloud mask, land mask, etc.)
- NIR ROIs
- Shapefile
- Tide heights
- Band specification box

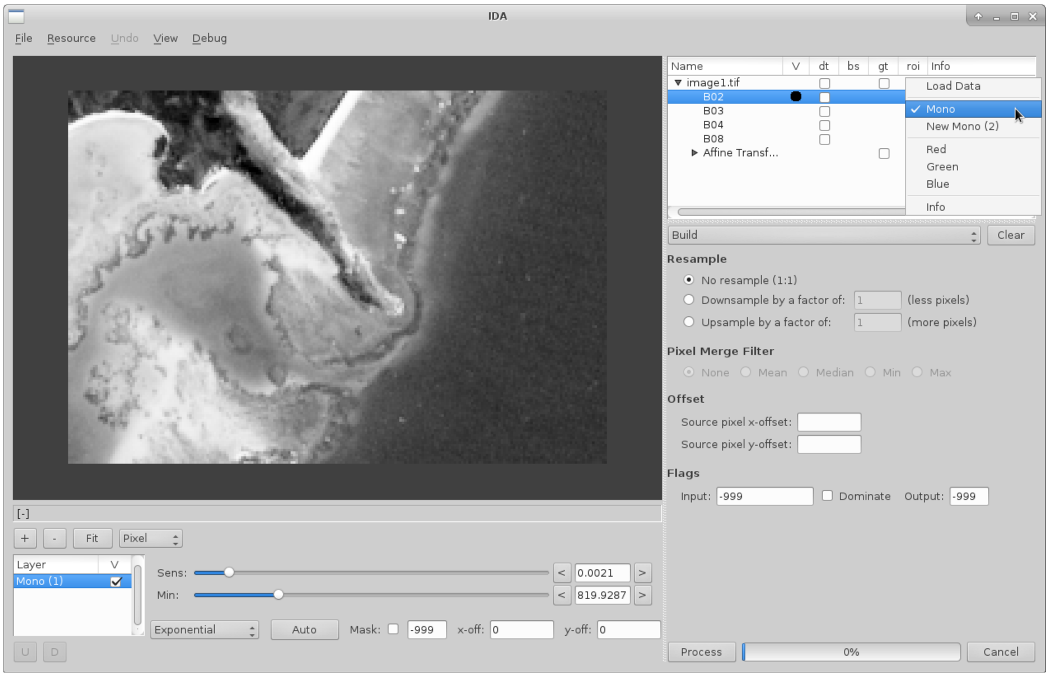

Figure 9. IDA processor window with input data image1.tif

2.5.2 Test Datasets

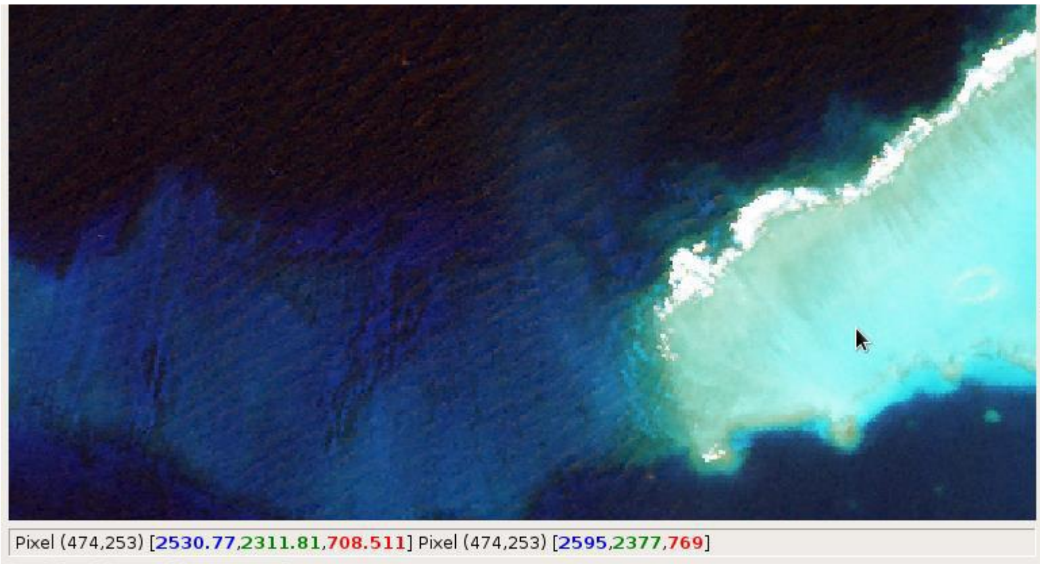

Figure 10. Deglinted image1.tif.

Figure 11. Image1.tif after the Atmospheric Correction.

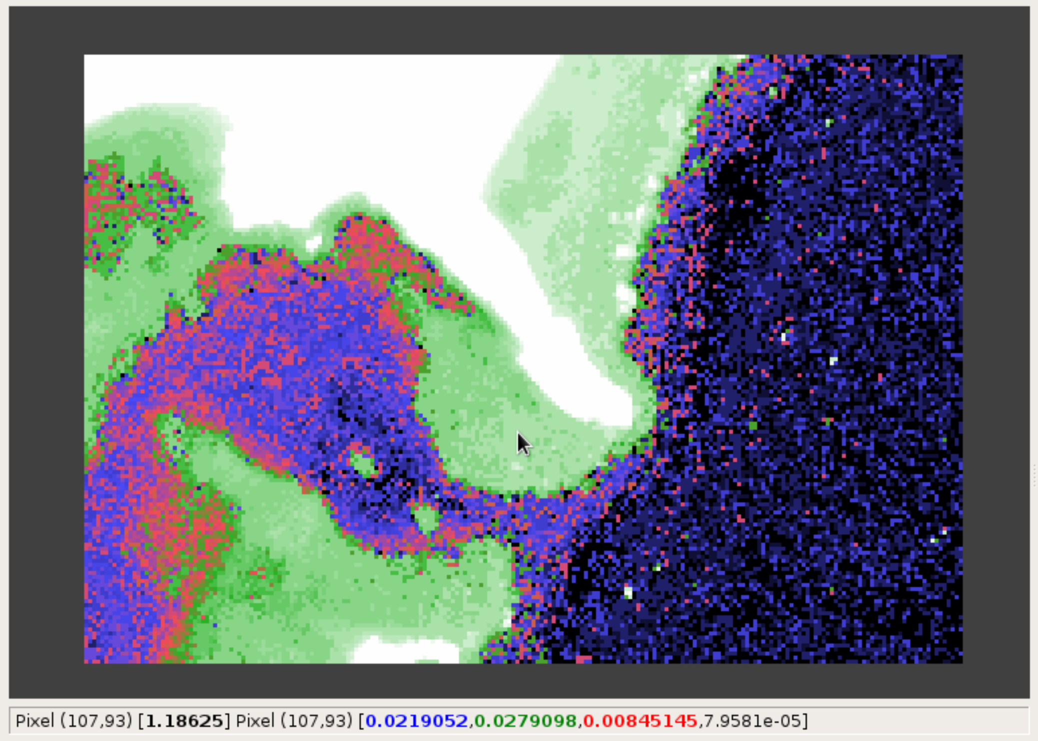

Figure 12. Bathymetry derived from the atmospherically corrected image1.tif

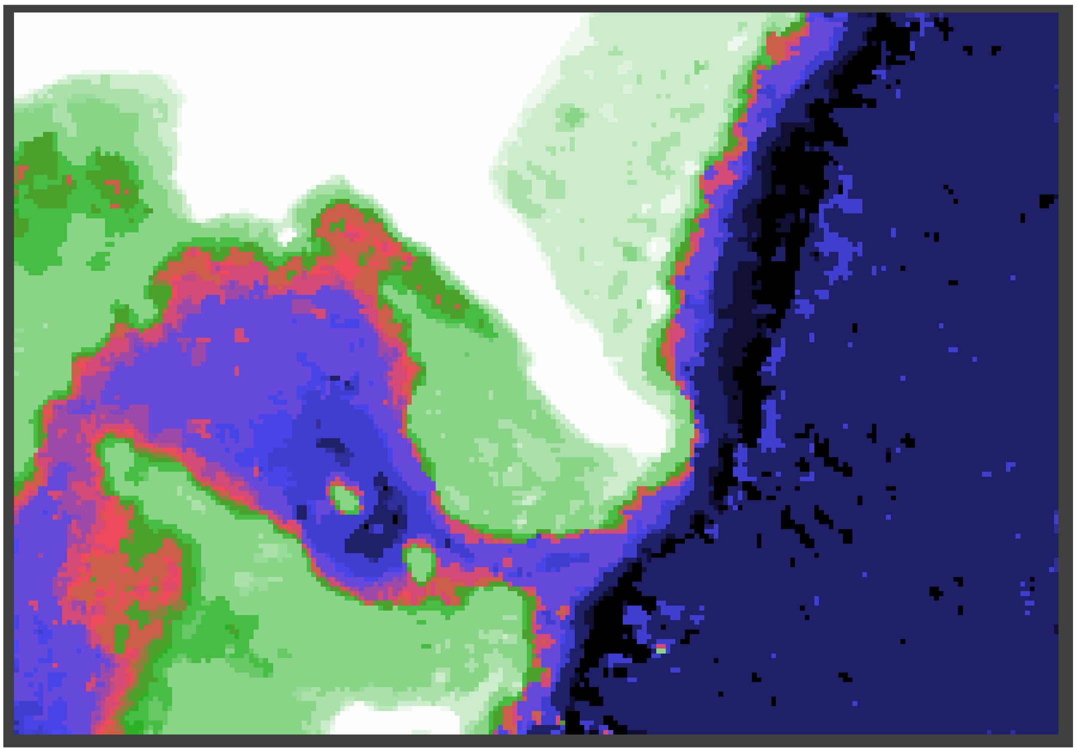

Figure 13. Filtered Bathymetry derived from the atmospherically corrected image1.tif.

Outputs can easily be compared to the example images with IDA. Overlapping layers that are supposed to contain the same information by simply selecting each pixel it can be shown whether the values in each band match to the expected values. Layers that have been processed with the same corrections should be compared, i.e. two an image that has been atmospherically corrected must be compared to the example image that has faced the same atmospheric correction.

© 2019ARGANS

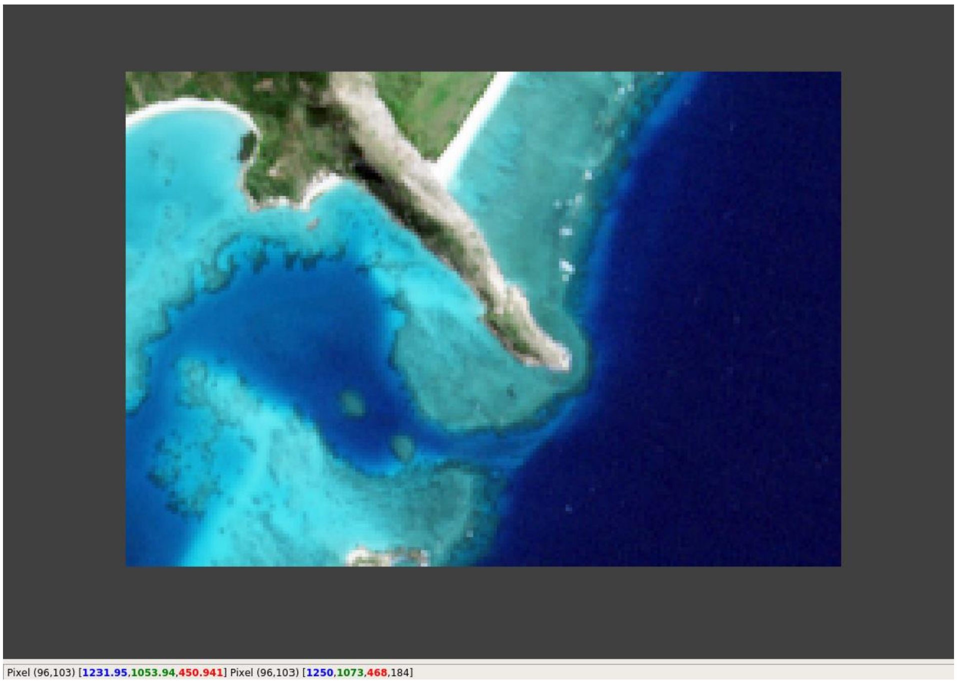

Figure 14. Comparison of two RGBs (example and elaborated) that have both been deglinted

2.5.3 Practical Considerations

At this stage the cloud and boat masking is not yet an automated process. Once the data have been downloaded and the files converted, and after the land and water mask has been performed clouds, boats and parallax must be masked manually on GIS software. This process costs time resources.

The results obtained can be different from the expected values due to multiple factors. During the various steps performed parameters can be set up in a different way or with different values with respect to the ones used for the test. Furthermore, a problem can occur if the input image is wrong or if the metadata is not the proper one.

2.6 Products Validation

Product validation tests will mainly be a comparison of the BMTM map with in-situ data when available. For this project we are not only considering a validation comparing in-situ data depth values directly with the depth values of the BMTM maps, but also the validation of the position of the different coastal features existing in each area. Due to the environmental conditions prevailing in some of the areas under study, a direct comparison between in situ data and BMTMs will provide errors that in some cases could be higher than 1m. This would be related to the procedure followed in this project according to the objectives fixed. The objective of the project was not to replicate a navigationally safe surface, but to look at trends or at the

© 2019ARGANS

features that could be observed, so because of that, a direct comparison is not possible for some of the areas. Thus, a validation checking the trends and evolution of the visible coastal features presenting in the different areas of study, is also considered as a validation option of the BMTM maps provided.

© 2019ARGANS

3 Conclusion

The Coastal Erosion from Space project has the ultimate purpose of describing the dynamic-state and evolutionary trends of coastal systems, in order to better understand coastal morphodynamics for interannual evolution as well as for short term respond to storms. With that purpose in mind, BMTM models are delivered to provide information about the evolution of coastal features under erosion/accretion.

3.1 Assessment of limitations

The limitations of the processor are:

- Cloud/boat masks must be performed manually by the user.
- Atmospheric Correction.
- Water properties and high concentration of different suspended particles
- The process is limited to GDAL images.
- Adding extra end members beyond the 6 default spectral response curves included in the selected bathymetry model will increase the processor's ability to detect a larger range of benthic environments. This will increase the accuracy of the depth estimations, however the overall bathymetric uncertainty from the inversion model will be higher because of a larger number of degrees of freedom[19].

3.2 Mitigation

An improvement to the actual processor would be the introduction of the HydroLight radiative transfer numerical model, which computes radiance distributions and related quantities in any water body, to better describe the water properties of specific environments studied. Also, water based atmospheric corrections could be used. New developments are needed in order to generate an automated cloud/boat mask.

---

[19] J.D. Hedley, C. Roelfsema, S. Phinn, "Propagating uncertainty through a shallow water mapping algorithm based on radiative transfer model inversion", Proceedings of the Ocean Optics XX Conference, Anchorage, AK, USA, 27 September–1 October 2010 (2010)

© 2019ARGANS

In relation to the confidence map, it will be necessary to combine the Depth of Penetration together with the concentration of SPM and CDOM, as especially in the very shallow coastal waters, the concentrations of these water constituents can be very high as the reflectance detected is the one corresponding to the bottom. In these shallow areas, the combination of both tools will allow us to identify those areas where the bottom is detected.

© 2019ARGANS

4 References

J.D. Hedley, C. Roelfsema, S. Phinn, "Propagating uncertainty through a shallow water mapping algorithm based on radiative transfer model inversion", Proceedings of the Ocean Optics XX Conference, Anchorage, AK, USA, 27 September–1 October 2010 (2010)

Hedley, J.D., Roelfsema, C., Phinn, S., "Propagating uncertainty through a shallow water mapping algorithm based on radiative transfer model inversion", *In Proceedings of the Ocean Optics XX*, Anchorage, AK, USA, (27 September–1 October 2010).

Hedley, J.D., "Satellite derived bathymetry of Tahanea atoll using Pleiades imagery and in-situ bathymetric point data", - , (2014).

Kay S, Hedley JD, Lavender S., "Sun glint correction of high and low spatial resolution images of aquatic scenes: a review of methods for visible and near-infrared wavelengths",*Remote Sensing* 1: 697-730,(2009).

Hedley, JD, Harborne, A. R., Mumby, P.J., "Simple and robust removal of sun glint for mapping shallow water benthos", *International Journal of Remote Sensing* 26, pp 2107-2112, (2005).

IHO "Manual of Hydrography", chapter 3 – Depth determination. International Hydrographic Bureau, Monaco (2005)

Hedley, John D., Christiaan M. Roelfsema and Stuart R. Phinn., "Efficient radiative transfer model inversion for remote sensing applications." (2009).

Hedley, J.; Roelfsema, C.; Phinn, S.R.,"Propagating uncertainty through a shallow water mapping algorithm based on radiative transfer model inversion.", In Proceedings of the Ocean Optics XX, Anchorage, AK, USA, 25 September–1 October 2010.

Shettle, E.P. and Fenn, R.W., "Models for the Aerosols of the Lower Atmosphere and the Effects of Humidity Variations on Their Optical Properties", Optical Physics Division, Air Force Geophysics Laboratory, Hanscom Air Force Base, Mass, (1979).

Brezonik, P., Menken, K. D., & Bauer, M. E., "Landsat-based remote sensing of lake water quality characteristics, including chlorophyll and colored dissolved organic matter (CDOM)", *Lake and Reservoir Management*, *21*(4), 373-382, (2005).

© 2019ARGANS

Scheffler, Daniel & Hollstein, André & Diedrich, Hannes & Segl, Karl & Hostert, Patrick, "AROSICS: An Automated and Robust Open-Source Image Co-Registration Software for Multi-Sensor Satellite Data", *Remote Sensing*, (2017).

Hedley, JD, Harborne, A. R., Mumby, P.J., "Simple and robust removal of sun glint for mapping shallow water benthos", International Journal of Remote Sensing 26, pp 2107-2112, (2005).

Antoine D. and Morel A., "A multiple scattering algorithm for atmospheric correction of remotely-sensed ocean colour (MERIS instrument): principle and implementation for atmospheres carrying various aerosols including absorbing ones", Int. J. Rem. Sens., 20(9): 1875-1916, (1999).

James A. Goodman, ZhongPing Lee, and Susan L. Ustin, "Influence of atmospheric and sea-surface corrections on retrieval of bottom depth and reflectance using a semi-analytical model: a case study in Kaneohe Bay, Hawaii," Appl. Opt. 47, F1-F11 (2008)

"IDA Manual", John D. Hedley, (2019).

Zhongping Lee, Kendall L. Carder, Curtis D. Mobley, Robert G. Steward, and Jennifer S. Patch, "Hyperspectral remote sensing for shallow waters: 2. Deriving bottom depths and water properties by optimization," Appl. Opt. 38, 3831-3843 (1999)

Heidi M. Dierssen and Albert E. Theberge, Bathymetry: Assessment, Encyclopedia of Natural Resources: Water, 10.1081/E-ENRW-120048588, (629-636), (2016).

Zhongping Lee, Kendall L. Carder, Curtis D. Mobley, Robert G. Steward, and Jennifer S. Patch, "Hyperspectral remote sensing for shallow waters. I. A semianalytical model," Appl. Opt. 37, 6329-6338 (1998)

Hedley, John,"Hyperspectral Applications", 10.1007/978-90-481-9292-2_4, (2013).

David R. Lyzenga, "Passive remote sensing techniques for mapping water depth and bottom features", Appl. Opt. 17, 379-383, (1978).

Tiit Kutser, Donald C. Pierson, Kari Y. Kallio, Anu Reinart, Sebastian Sobek. Mapping lake CDOM by satellite remote sensing, Remote Sensing of Environment, 94, 4, 535-540 (2005) https://doi.org/10.1016/j.rse.2004.11.009

Han, B.; Loisel, H.; Vantrepotte, V.; Mériaux, X.; Bryère, P.; Ouillon, S.; Dessailly, D.; Xing, Q.; Zhu, J. Development of a Semi-Analytical Algorithm for the Retrieval of Suspended Particulate Matter from Remote Sensing over Clear to Very Turbid Waters. *Remote Sens.* 2016, *8*, 211.

© 2019ARGANS

End of Document

© 2019ARGANS