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-SDB
Date: 09/12/2019

Customer: ESA

Contract Ref.: 4000126603/19/I-LG

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Version and Signatures

Version	Date	Modification
	02/12/2019	review
	05/12/2019	review
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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

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

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1 Overview and Background Information

1.1 Product requirement

1.1.1 Information content quality and value

End-users require (see URD) some volume products such as bathymetry for the Integrated Coastal Zone Management (ICZM) of areas further offshore. Volume products are required to produce datum-based shoreline indicators (DSI) and assess volumetric sediment change. Satellite-derived bathymetry (SDB) 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.

Bathymetric charts need to characterize the all 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.

Satellite Derived Bathymetry 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. SDB should provide information on the near-shore morphology (between C and D line in figure 1.1) 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.

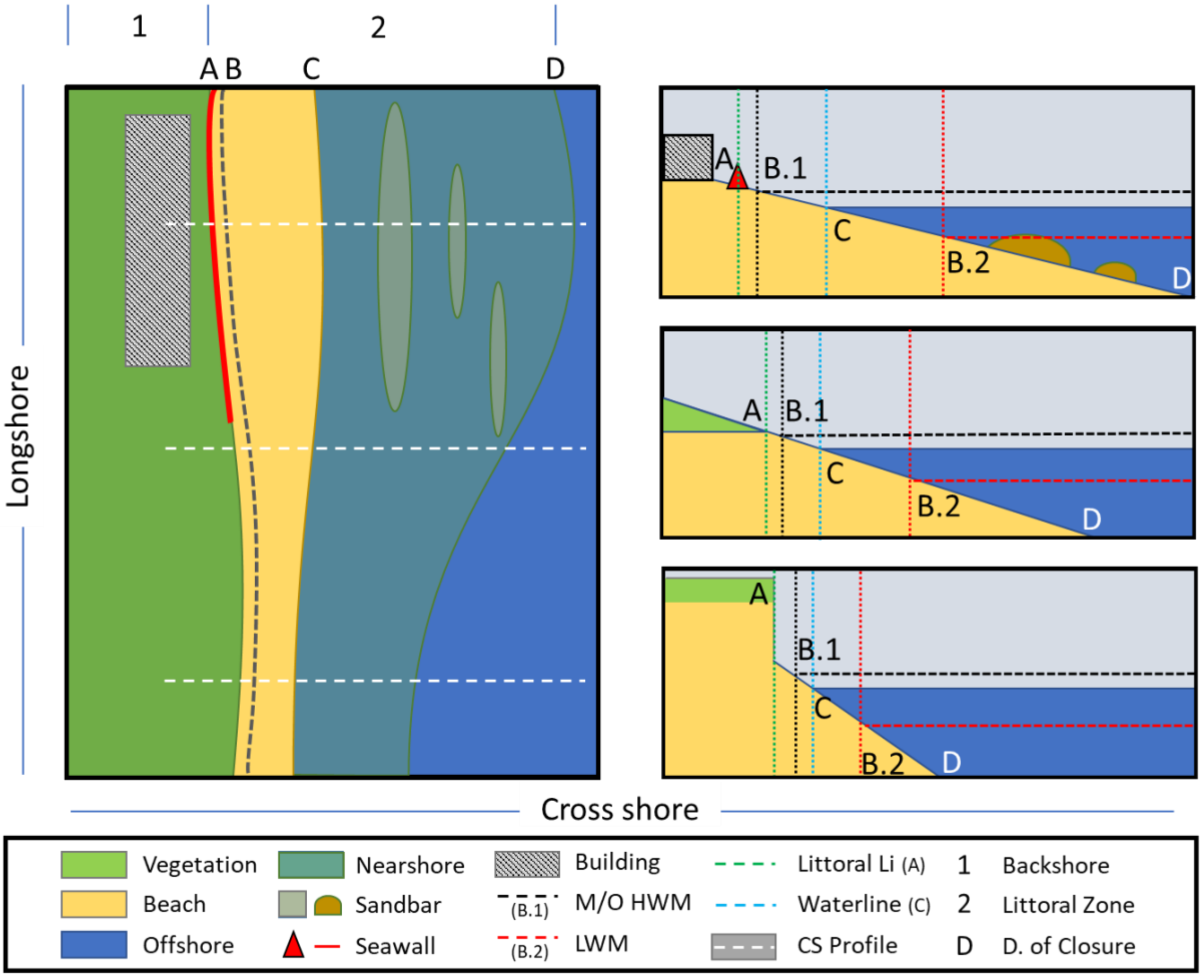

Figure 1.1: Shore and coastal features diagram

Spatial resolution is a particularly important factor in the SDB 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.

Ground- truth (in-situ) bathymetric point data (e.g. from an echo sounder) and nautical charts can be used as a training data set. Additional in-situ bathymetry data is desirable for to use as an 'independent' validation data set for assessing the derived bathymetry.

1.1.2 Product order & delivery services

Topo-bathymetric digital elevation models (TBDEM) will be delivered in raster format containing a time stamped Digital Elevation Model (DEM) of the coastal zone (including backshore, foreshore and nearshore).

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.

The SDB processor is used to assess geomorphic change and volumes of sediment eroded and deposited by subtraction of two independent DTM surfaces to produce a DTM of Difference (DoD), with each grid cell value representing a measure of the vertical elevation difference, but also to monitor coastal erosion, dredging activity and environmental awareness, active coastal erosion in a urban area, coastal dynamics, estuary dynamics, sea level and submerged landscapes.

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.

SDB analysts have identified 8 steps in the image processing and subsequent production of satellite derived charts[2]. 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),
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.

The latter two points have been added to complete the standard cartographic process.

Physics-based models are derived from full equations of optical radiative transfer[3]. 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

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

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

[3] 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)

that ii. suitable bands from multi- or hyperspectral data are used simultaneously to find an optimal solution over all unknown factors[4].

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 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[5].

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.

1.2.3 Auxiliary data

Bathymetry measurements can be derived by satellite imagery and by auxiliary data[6] that allow also to assess whether the results obtained represent reality. Examples of such data are probe measurements, echo-sounding measurements and nautical charts can be used. In-situ measurements are a well consolidated method to determine the water depth, but their limitation is linked to the small amount of measurements that can be performed for each site. Furthermore, this method provides extremely localized results and cannot be extended to larger areas. Echo-sounding measurements is extremely accurate but highly expensive and limited to a certain area where the echo-sounding is performed. The results obtained from the SDB process

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

[5] 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)

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

are generally compared to values reported on nautical charts[7] as they are easy to access on dedicated websites and constantly updated.

1.2.4 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 take the full 8 to 12 bits dynamics. Sensor signal, as well as signal-to-noise ratio, are 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 losing 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 a 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. It is also difficult to merge several satellite images (mosaics) and 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 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

[7] Joy, R., "An Assessment of the Potential Role of Multispectral Imagery in Bathymetric Charting", 98, (1984).

and attenuation during transit through the atmosphere and the water column[8]. The atmospheric correction is one of the main issues of the SDB 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 sediments 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.

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.

[8] 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)

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 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.

1.4 Product Specifications

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

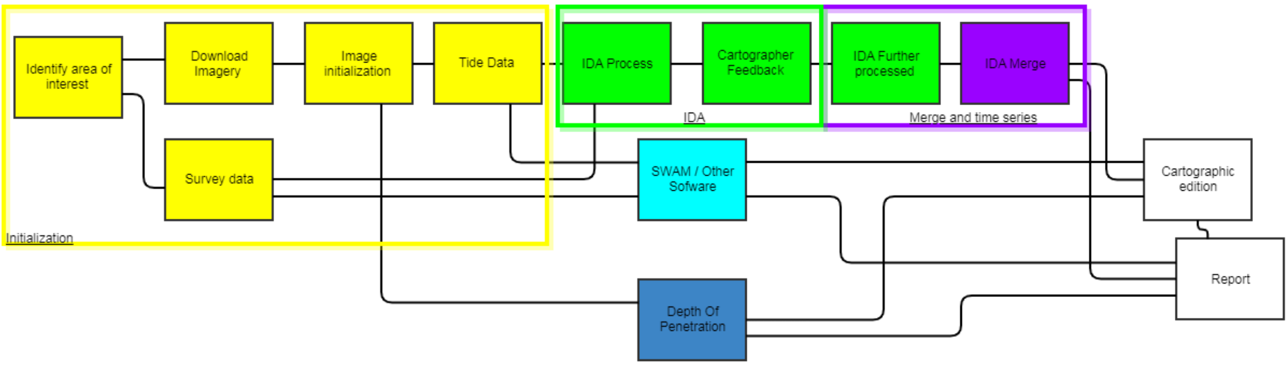

Figure 1.2: SDB processor workflow

The processor comprises various tools. Level-1C data face multiple steps in which they are deglinted and the atmospheric correction is applied. The bathymetry is then derived from image data using an inversion method model and the results filtered. The processor produces two types of output: Level-2 and Level-3 (merged images).

For shallow water, two different approaches are considered depending on the tidal regime of the area. For macro and meso tidal area, the bathymetry might be retrieved using waterline and shoreline position at low water mark. For micro-tidal area a method using stereo imaging to get depth information.

1.4.1 Level-2 Products

The final product of the entire SDB process is a Digital Terrain Model (DTM) which represents the bare ground surface without any other object.

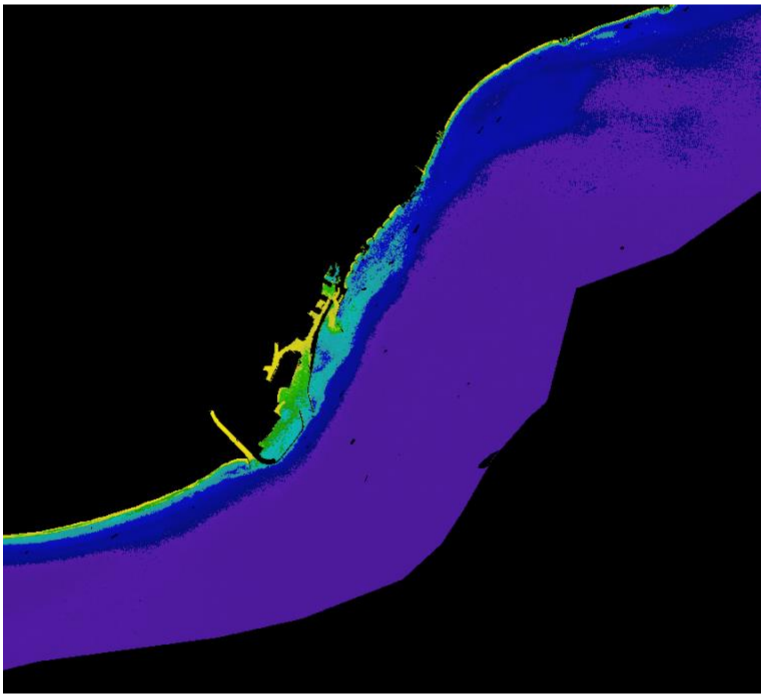

Figure 1.3: Level-2 Barcelona El Prat filtered SDB 22-06-2017

1.4.2 Level-3 Products

DTMs 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.

A merging processor is already available and it gives the user the chance to compute different values, such as: arithmetic average, uncertainty weighted average, minimal average distance to other points, Root Mean Square, range intersection. The choice of the merging option is highly site dependant. After having performed all of the options the results must be compared with ground truth data and it is then possible to assess which one has a better agreement with the in-situ measurements.

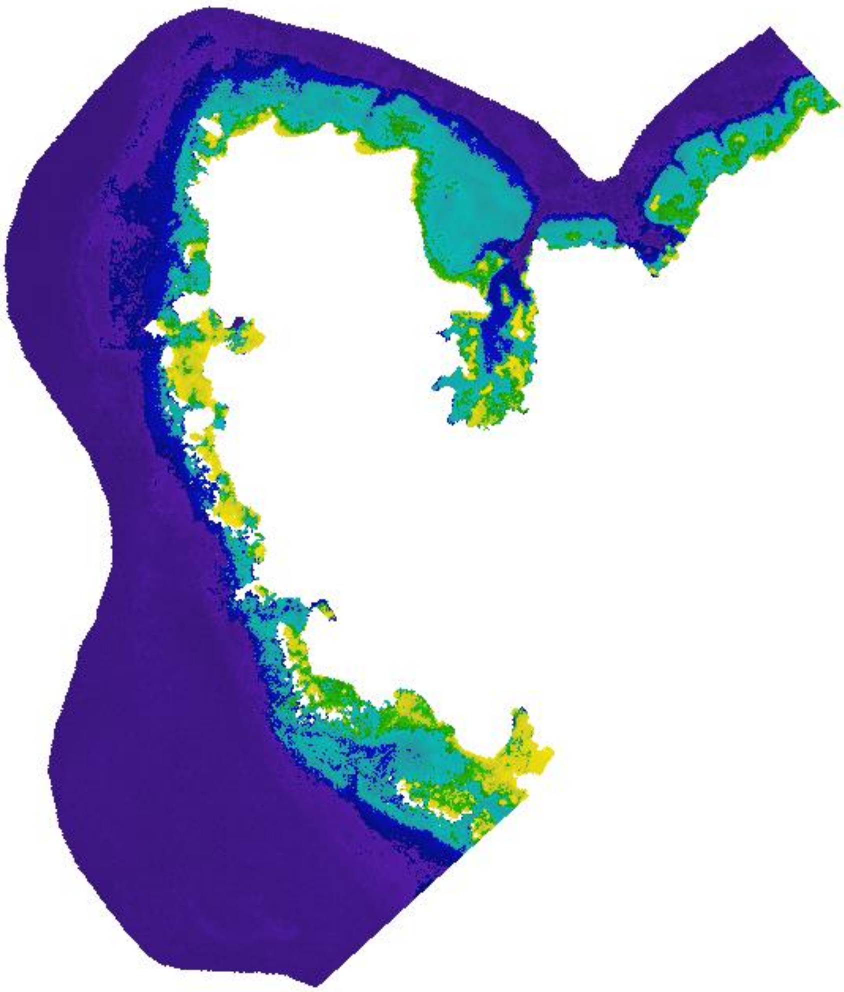

Figure 1.4: Martinique merged image calculated with the *Root Mean Square* option.

Algorithm Description

1.5 Data Processing outline

1.5.1 *Sketch of the computer program*

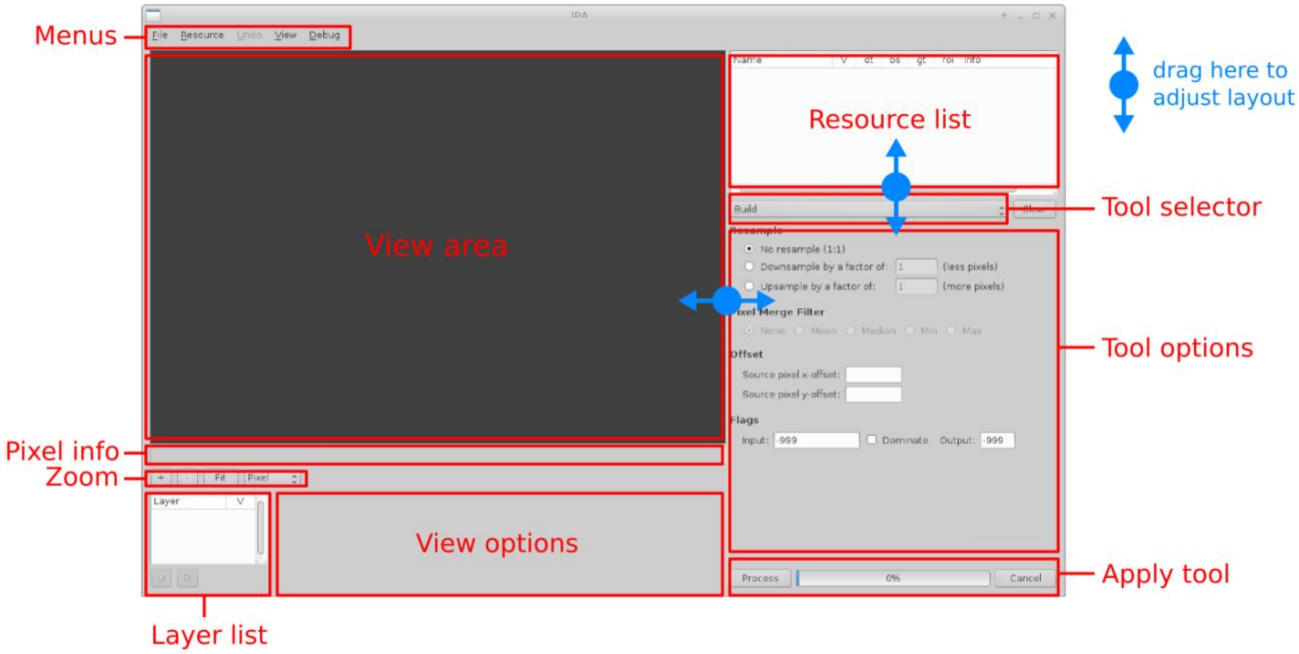

Figure 0.1: IDA processor window

The labelled areas function as follows[9]:

- 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.
- Tool selector – selects the tool to apply.
- Tool options – the options for the currently selected tool.

[9] Check "IDA Manual", John D. Hedley, (2019).

- Apply tool – applies the tool to the selected resources and shows processing progress.

1.5.2 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)[10] 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 SDB product to customers.

Each step of the SDB 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[11]. 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[12].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 radius of

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[10] 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).

[11] 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).

[12] 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).

particles is RH-sensible (99% for this model). The free troposphere and the stratosphere are considered free of any aerosol[13].

1.6 Algorithm Input

Another model used in the bathymetry step (from figure 2.4 below) 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[14].
- 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 estimations of *P*,

[13] 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).

[14] 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).

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.

1.7 Theoretical Description

1.7.1 Physical Description

The depth of a specific site can be extracted by the radiance components received by a satellite detector. 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 $R_{x,y}^{\infty}$ 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: $A_{x,y}^{\lambda}$, $g_{x,y}^{\lambda}$ and $R_{x,y}^{\infty,\lambda}$. Depth is related to the radiance at this wavelength by:

$$z_{x,y} = a_0 + a_1 \ln\left(R_w^m - R_{x,y}^{\infty}\right)$$

Where R_w^m is the estimate of the reflectance at the position (x, y) [15].

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) [16] and, once the

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

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

spectral responses are in agreement the processor inverts the spectral remote sensing reflectance equation in order to determine the depth value H[17].

1.7.2 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: $h_{\mathrm{meas}}(\vec{x},t) = h_{\mathrm{sf}}(\vec{x}) + h_{\mathrm{meas}}^{\mathrm{bias}}(\vec{x}_L,t) + \delta h_{\mathrm{meas}}^{\mathrm{noise}}(\vec{x}_L,t)$ with $h_{\mathrm{meas}}(\vec{x},t)$ the measurement at the position $\vec{x}$ ant time t.

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

In the deglint step, when performed, the mean NIR from the ROI is considered to be the baseline for the process[18].

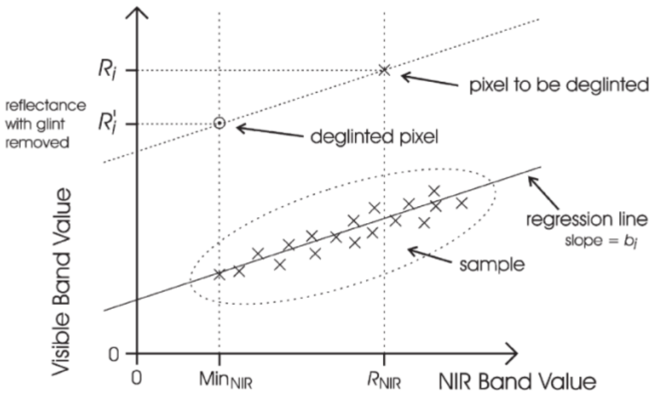

Figure 0.2: Graphical interpretation of the deglint correction.

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[17] 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.

[18] 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).

In figure 2.2 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)[19]. 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.

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 value must 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.

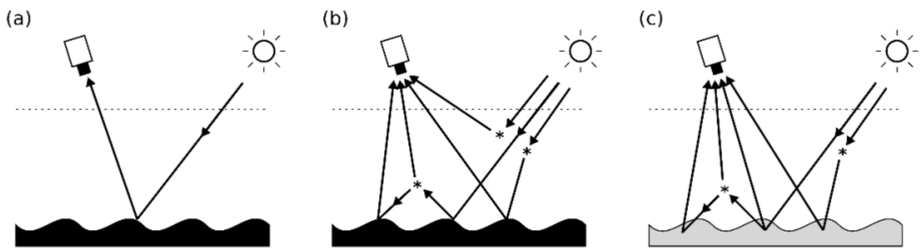

Figure 0.3: Different paths from sun to sensor through the atmosphere. (a) Direct reflected path from air-water interface. (b) Atmospheric reflectance and indirect reflected paths from the air-water interface. (c) Paths that penetrate the water surface and hence carry useful information

[19] 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).

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.

1.7.3 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[20,21].

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, Nosy Be - 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.

1.7.4 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 ($\tau 550$) and the water surface 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

[20] 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).

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

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 endmembers 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 SDB, 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 $p_{\text{meas}}(\vec{x}, t)$.

1.8 Algorithm output

The products created by the processor can be found in the complimentary TSD as:

[EO]-L2_3D_BTM/SDB_{area/date/hour} [Alg(L2)]

[EO]-L2*_1D_BTM/m_{area/date/hour}

The possible outputs form IDA are:

- Digital 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.

1.8.1 Product content

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

- Timestamp; date of data collection of images used to create TBDEM
- Spatial Reference System
- Datum
- Digital Surface Model; raster surface elevation model
- Digital Terrain Model; raster relief elevation (i.e. excluding structures and vegetation)
- Uncertainty in the elevation of DSM
- Uncertainty in the elevation of DTM

The information layers in the output raster for Level-3 products also add:

- Bathymetry maps for all sites and year.
- Bathymetry Model
- Uncertainty in the water depth of the bathymetry model
- Uncertainty in the positioning of the bathymetry
  Information on Z data points density (per pixel)

1.8.2 Product organisation

The default outputs for the processors are:

- Image_dg
- Image_dgmask
- Image_LEboa

- Image_LdivE
- Image_LEboa_z
- Image_LeEboa_z_F5

1.9 Algorithm Performance Estimates

1.9.1 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.

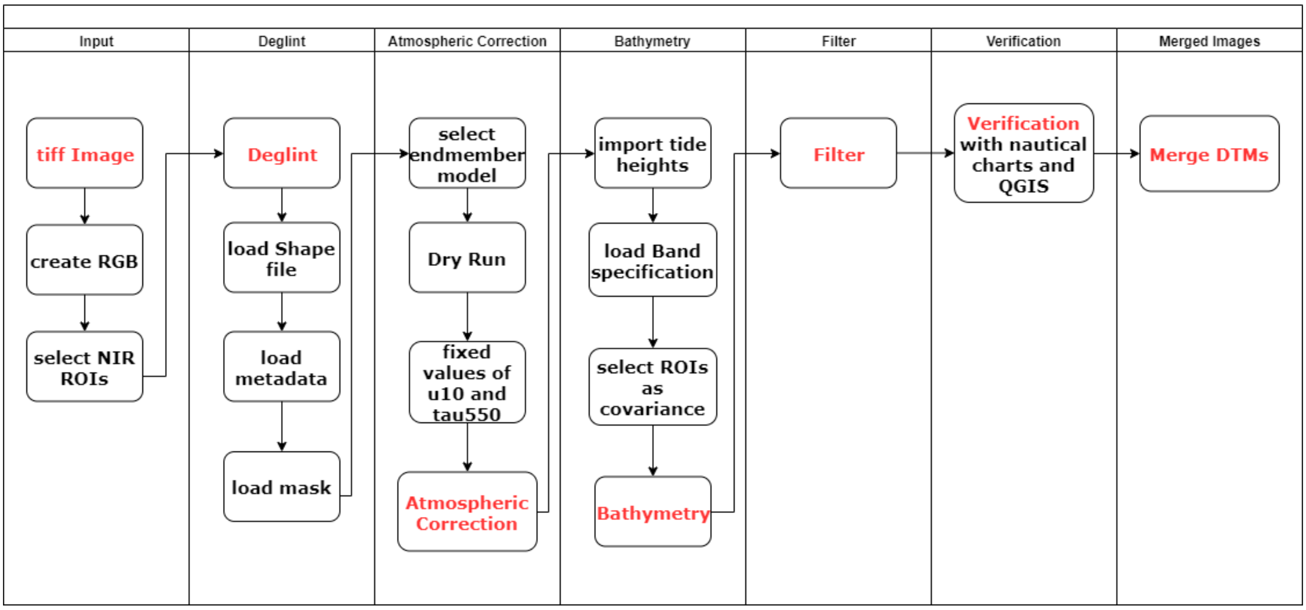

Figure 0.4: Workflow of IDA processor

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

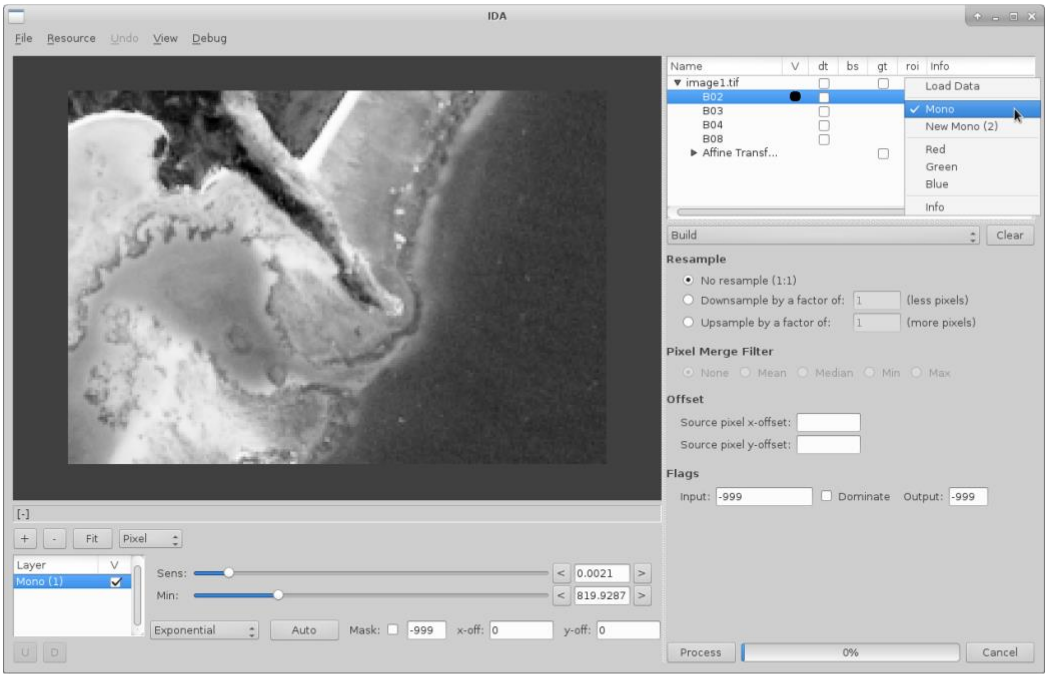

Figure 0.5: IDA processor window with input data image1.tif

1.9.2 Test Datasets

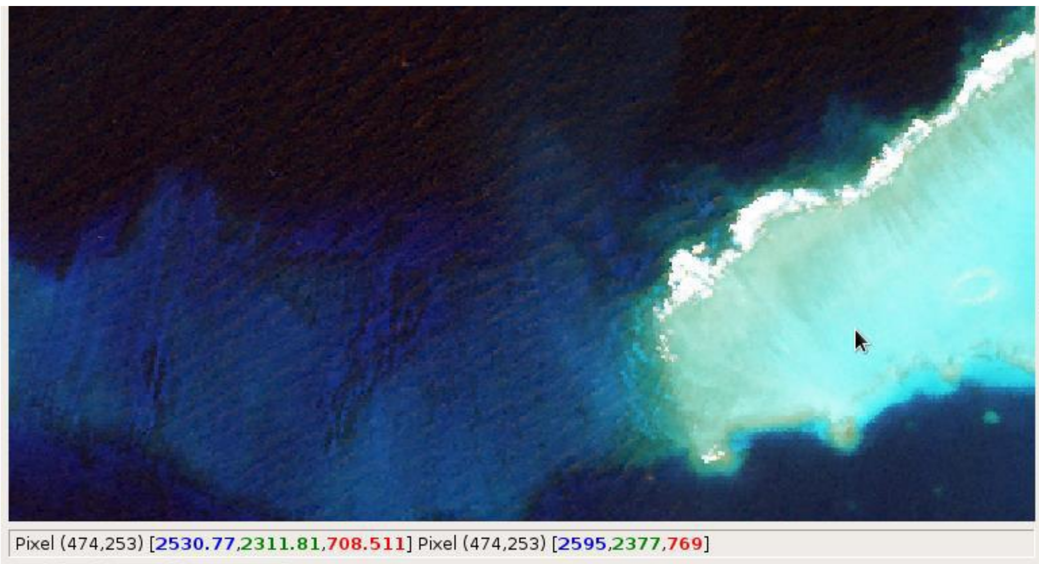

Figure 0.6: Deglinted image1.tif.

Figure 0.7: image1.tif after the Atmospheric Correction.

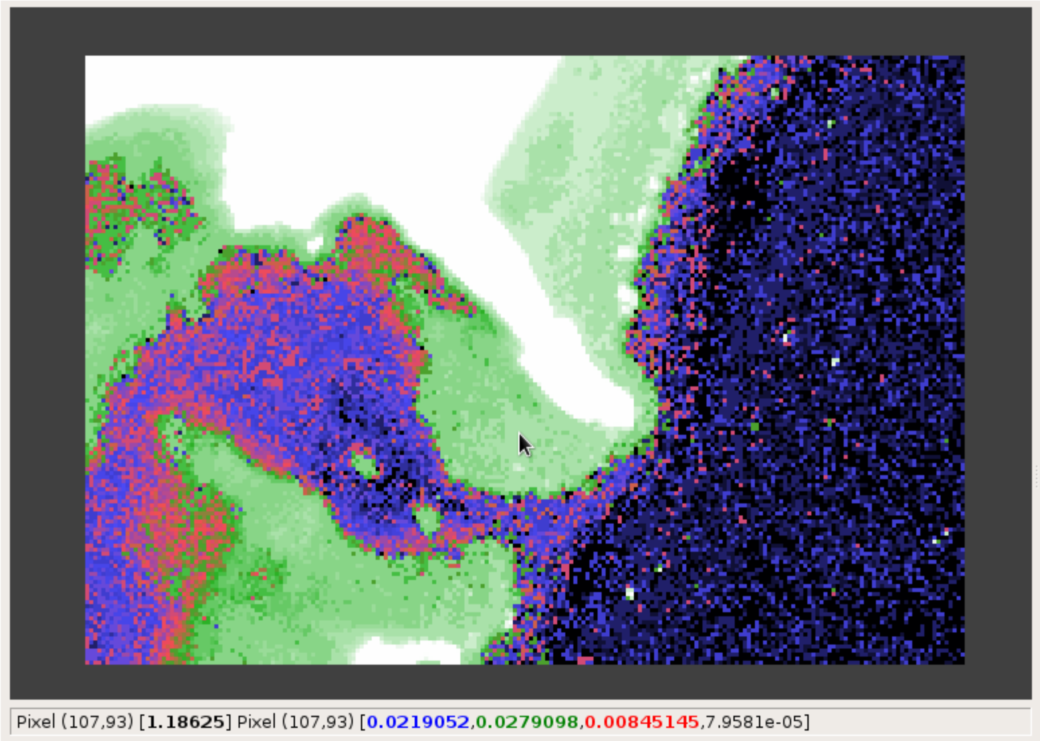

Figure 0.8: Bathymetry derived from the atmospherically corrected image1.tif

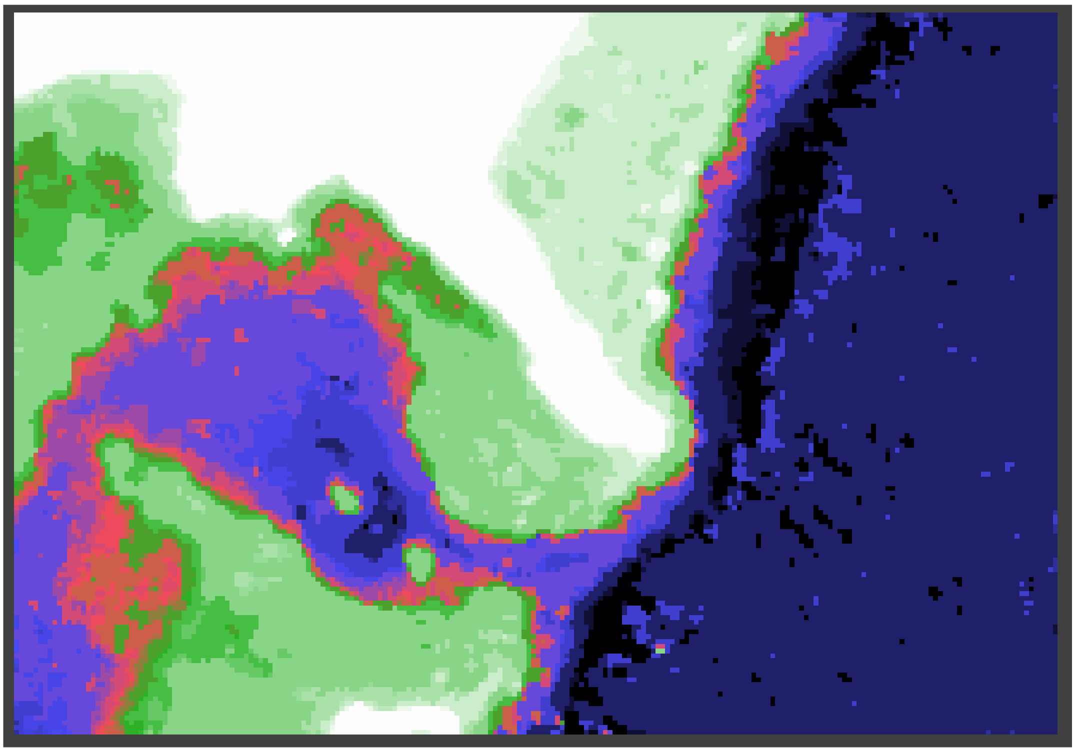

Figure 0.9: Filtered Bathymetry derived from the atmospherically corrected image1.tif.

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.

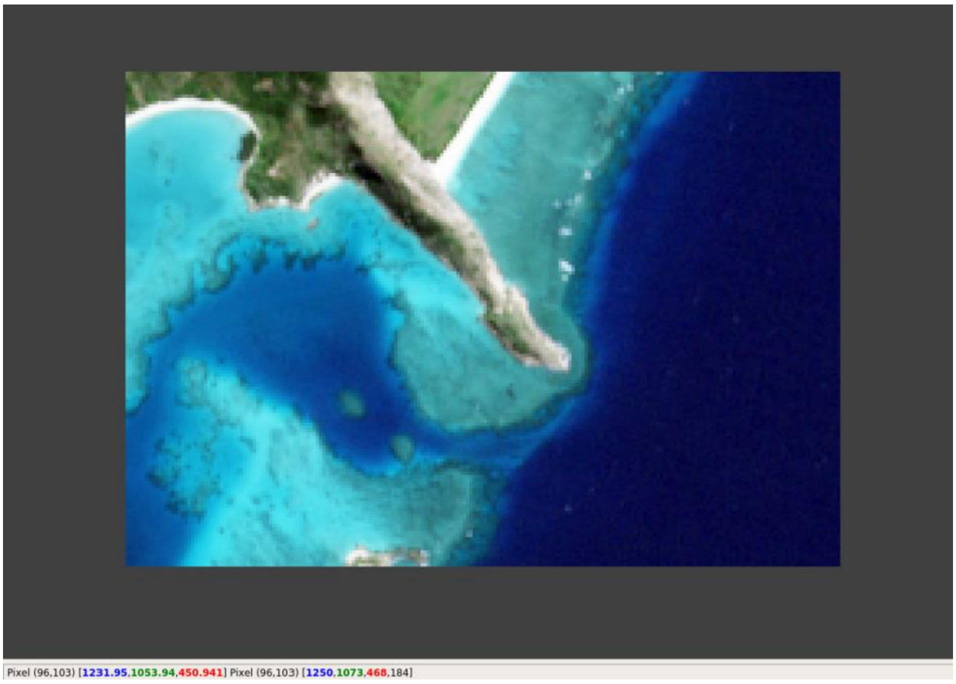

Figure 0.10: Comparison of two RGBs (example and elaborated) that have both been deglinted

1.9.3 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.

1.10 Products Validation

1.10.1 Test specifications

Product validation tests will mainly be a comparison of our SDB chart with in-situ data.

1.10.2 Test Datasets (identification & description)

Data from the partners and in-situ surveys are needed to run tests for each location sites.

1.10.3 Validation

1.10.4 Practical Considerations

Sentinel-2 has 12 detectors which work in threes at different angles. To correct this difference there is a time delay in the acquisition that can produce artefacts. Indeed, if a wave is moving perpendicular to the ascending node in the data image is possible to see strips within the footprint.

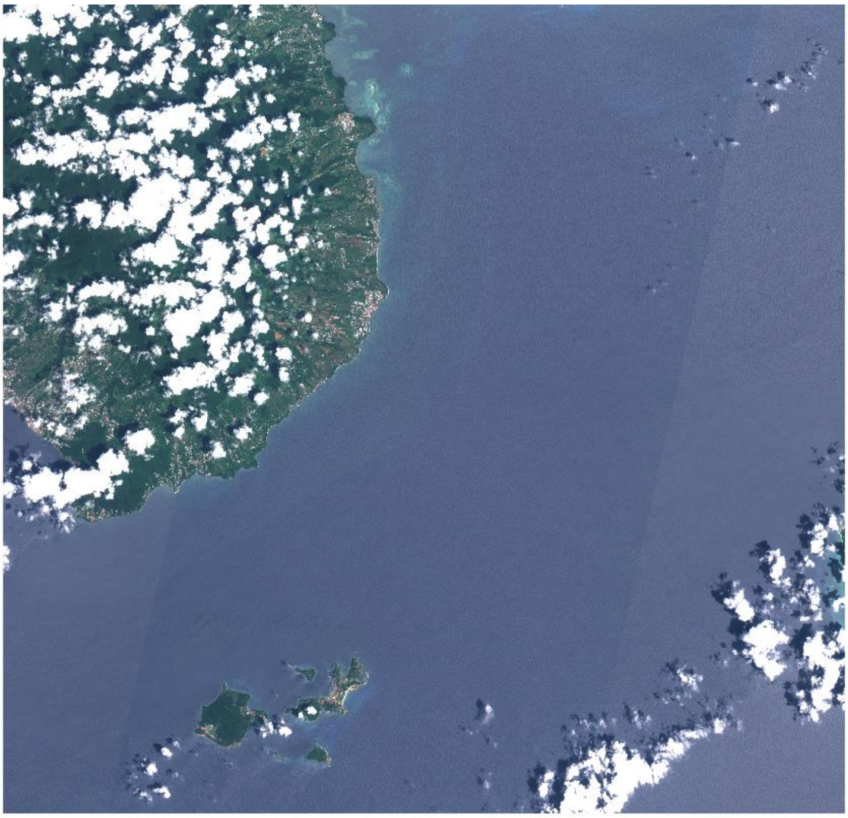

Figure 0.11: Three sensor bands as seen in Sentinel-2 images.

As previously said, one of the main issues to take into consideration during the process is the Atmospheric Correction. A better understanding of the models used by the processor would be required. Furthermore, water based atmospheric corrections should be used when processing SDB images.

Empirical models perform better when a large amount of in-situ data is available rather than physical-based models.

The Quality Control consists on verifying that each model, parameter and value is properly selected. The choice of these is described in previous sections.

2 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.

The SDB products that will be delivered to the partners add more information about the coastal change. Indeed, they will allow the user to study both long-shore processes and sediment transport. Both of them are crucial to identify erosion processes.

2.1 Assessment of limitations

The limitations of the processor are:

- Cloud/boat masks must be performed manually by the user.
- Atmospheric Correction.
- Water properties.
- 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[22].

2.2 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.

[22] 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)

3 References

4 Appendix

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