The Nosy Be demonstrator

Sentinel Coastal Charting Worldwide

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Final Report

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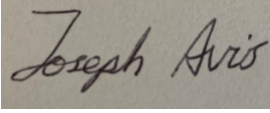
ARGANS

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0.1.   ACRONYMS

Acronym	Meaning
ALUT	Adaptative Look-Up Tree
ARGANS	Applied Research in Geomatics, Atmosphere, Nature & Space
COD	Cut-Off Depth
DN	Digital Number
DOP	Depth of Penetration
DTM(s)	Digital Terrain Model(s)
ENC	Electronic Navigational Chart
EO	Earth Observation
ESA	European Space Agency / *Agence spatiale européenne*
GEBCO	The General Bathymetric Chart of the Oceans
HO	Hydrographic Office
HR	High Resolution
HSPT	Project Team on Standards for Hydrographic Surveys
ICEC	RTE inversion software developed by ARGANS
ICZM	Integrated Coastal Zone Management
IDA	Image Data Analysis, RTE inversion software developed by Dr Hedley, formerly known as ALUT
IHO	International Hydrographic Organization
IHR	International Hydrographic Review
IOP(s)	Intrinsic Optical Property(ies)
IR	InfraRed
LAT	Lowest Astronomical Tide

MSI	MultiSpectral Instrument (the Sentinel-2 sensor)
NIR	Near-InfraRed
QC	Quality Control
R&D	Research and Development
ROI	Region of Interest
RSE	Remote Sensing of Environment, an Elsevier peer-reviewed publication
RTE	Radiative Transfer Equations
SDB	Satellite Derived Bathymetry
SWIR	Short Wave InfraRed
UNCLOS	United Nation Convention on the Law of the Sea
VHR	Very High Resolution
WG	Working Group
WP	Work Packages, as listed in the ARGANS Proposal
ZOC	Zones Of Confidence (cf. IHO Publication S-4)

0.2.   SUMMARY

It is widely and wrongly assumed that the World coasts are depicted with great precision by modern nautical charts. This optimistic feeling is not shared by the International Hydrographic Organisation who knows better and tries to keep track of the poorly surveyed areas. The IHO has been looking for years for an affordable method to fill the coastal gaps still affecting large sections of the world, especially in Developing Countries. Great hopes have been placed in the possibilities offered by Satellite Derived Bathymetry (SDB).

The Sentinel-2 Coastal Charting Worldwide project aims at proving that Sentinel-2 has the capacity to complete the costal gaps with reasonably reliable results, moreover, obtained for an affordable price.

To this end, four demonstrators have been processed and rendered by experienced cartographers familiar with the IHO latest standards to give an updated impression of what the future satellite coastal cartography, not limited to technically advanced countries, could look like.

If validated by the IHO, the implementation of SDB methodology should give rise to a new generation of nautical charts, where the traditional hydrographic 95% guarantee, often based on vintage surveys and sometimes only proven by the absence of ship groundings, could be replaced by a full optical coverage and a safe navigational threshold. Associated to a sensible Capacity Building scheme, SDB and Sentinel-2 have further the potential to fill most Developing Countries' ICZM charting requirements.

The Project will eventually be promoted by publications submitted to peer reviews: the International Hydrographic Review in the May 2020 issue and to the professional magazine Hydro International, completed by an article submitted.to the Elsevier's Remote Sensing of Environment.

The first publication should be focussed on the use of Sentinel-2 time series which, **without a single exception**, have proven far superior to any other VHR satellite images to construct "Perfect Images" capable of yielding optimised depth measurements.

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FIRST PART: SDB MODELLING

I.1. INTRODUCTION

This report describes the work completed by ARGANS on behalf of the European Space Agency regarding the use of Sentinel-2 imagery to produce nautical charts based on the Satellite Derived Bathymetry (SDB) methodologies.

Four characteristic areas have been selected across tropical and polar regions, each characterised by a nautical chart demonstrator developed for the following different purposes:

- The **Puerto Morelos demonstrator** aims at measuring the progress made by SDB processing for the past five years and compare Sentinel-2 to KOMPSAT VHR images.
- The extremely ambitious and time consuming **Nosy Be demonstrator** tries to make use of the Sentinel-2 revisit time to achieve a better bathymetry based on the construction of a "Perfect Image" free of transient artefacts. It further aims at assessing the SDB potential in Developing countries.
- The **Lampi Island demonstrator** complements the previous Sen2Coral project with a nautical chart based purely on SDB in the absence of ground truth. Can SDB deliver reasonably valid nautical charts in such areas?
- The **Coral Harbour demonstrator**, finally, tries to assess the potential of Sentinel-2 in the polar Northwest passage barely opened to maritime traffic and only documented to date by the Canadian Hydrographic Office.

As there are a lot of images, each demonstrator is detailed in four annexes numbered A to D, provided separately for convenience.

I.2. METHODOLOGY

I.2.1. Sentinel-2

Sentinel-2 is the main focus of this study, showing how Sentinel-2 can be used to produce accurate and reliable SDB results. Sentinel-2 provides a perfect sensor to capture environments best suited to SDB. SDB is primarily used in coastal environments where water depths can reach a maximum of about 30 metres. This is due to the light penetration into the water column not being sufficient enough after

30 metres to record accurate data. Due to Sentinel-2's global coverage of coastal environments many places around the world could benefit from the production of SDB from Sentinel-2.

Sentinel-2 offers 10 m spatial resolution and 12 m absolute horizontal precision. The satellites Multi Spectral Instrument provides 13 bands spectral resolution covering 443 – 2190 nm. Due to Sentinel-2 having two satellites (Sentinel-2A and Sentinel-2B) there is a 5-day revisit time at the equator. As a result there is a large database of images for each test sites that will be taken advantage of within this study in a novel experiment that could not take place before the Sentinel-2 first launching in 2015.

Calibration and orthorectification of Sentinel-2 is excellent and is a leading factor in the justification of ARGANS using Sentinel-2 imagery for many applications within SDB, either to fill the coastal charting gaps worlwide, or for commercial purposes. As every image and tile undergoes a very strict processing stage there is the highest confidence that these images are of a high standard and can produce excellent results for use in SDB. Many other SDB providers focus on the need for high spatial resolution, a choice that ARGANS challenges owing to the reduction in the image quality, absence of calibration and orthorectification, not to mention the adverse performances of applying RTE inversion models onto considerably larger datasets, resulting in punitive calculation time by a factor of about 30 compared to Sentinel-2 datasets. A frank discussion with the Canadian specialist of stereoscopic use of VHR data to determine depths of pinnacles further shows that the method itself is inconclusive, at least for the time being. Higher spatial resolution imagery such as WorldView also incurs a very large cost which makes working with a large data set extremely expensive; a huge benefit to ESA's Sentinel-2 image collection which comes with complete public access. By increasing the quality of the spatial resolution there comes a large amount of noise per pixel particularly seen within imagery of 2 m spatial resolution. This noise intensifies the impact of ocean glint therefore reducing the quality of the final SDB result.

Within this project, ARGANS has developed a new and novel methodology that encompasses a large data set of satellite imagery over a specific test site to produce one bathymetry data set from a large list of images. This method termed "*Merge*" merges the product of all SDB models per image together for each site. By producing this merge, it allows ARGANS to take advantage of Sentinel-2's data catalogue and remove errors from sediment plumes, clouds and other anomalies to yield what the satellite community starts to call the 'Perfect Image'.

I.2.2. Image selection and pre-processing

Image selection is highly important for SDB as the quality of the results are dictated by the quality of the image. During the image selection process all images were inspected closely to identify the best images to be used within the process. Images with high suspended sediment loads and sediment plumes, extreme ocean glint and high cloud cover were not included due to the negative impact these have on SDB. The following figure shows the number of Sentinel-2 images selected per site and DTMs subsequently produced.

Study site	Number of Sentinel-2 images selected	Number of DTMs produced
Puerto Morelos	31	6
Nosy Be	53	50
Lampi Island	15	9
Coral Harbour	21	19

Number of Sentinel-2 images selected per site and final DTMs

Pre-processing must be applied to the images selected to be used within the investigation. This step includes masking out any anomalies within the image and adjusting for tide and other variations. This step is required to increase accuracy of the SDB models and to reduce the processing time for each image.

For each test site one image was selected with the least cloud cover (in all cases this was zero cloud cover). A threshold was then data mined within the near infra-red band to compute a classification between land and water. This classification was then vectorised to become a mask for the land (not needed within the SDB process). This mask was inspected by the analyst after to ensure that all coastlines had been masked appropriately. Following this all remaining images per test site were inspected by hand for clouds, cloud shadow and large sediment plumes. If any were present these were masked by hand as they have a negative affect within the SDB process as will be explained later within this report.

I.2.3. Satellite Derived Bathymetry

ARGANS has utilised two physics based SDB models within this study; Image Data Analysis (IDA) and Shallow Water semi-Analytical Model (SWAM).

IDA has been used extensively by ARGANS for commercial production of SDB results in a range of research projects. IDA has been developed and tested for the last 10 years by ARGANS under its original name 'ALUT' referring to the adaptive look up table that is implemented within the software. Both IDA and SWAM implement similar methodologies and use the same Radiative Transfer Equations (RTE).

Within both models a similar workflow was used which includes three steps:
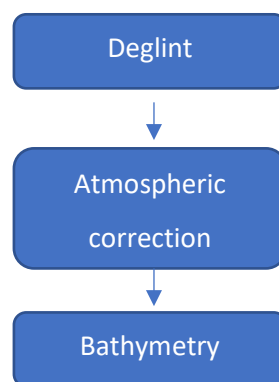
Figure 1: Flow diagram of the SDB production chain.

Both processes implement a deglint process which is used to reduce the effect of water surface sun-glint. An atmospheric correction is then used to correct for atmospheric reflection and transmission. Finally, a bathymetry model is applied to produce depth.

To remove glint from an image a training sample is provided to both IDA and SWAM which includes pixels with and without glint. By recording the pixel values in either the near infra-red (NIR) or SWIR the 'glint' over water can be quantified. This training area must be over deep water where the user would expect the reflectance to be homogenous without the glint. A regression is then performed between the values calculated in the NIR or SWIR to the remaining bands as shown below

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

Where R_i is the pixel value in the band, b_i is the product of the regression slope from training data and R_{NIR} the difference between the pixel NIR value and Min_{NIR} the ambient NIR level. Over removing of glint within shallow areas has in the past caused issue around shoreline bathymetry. As a precaution to reduce any error, a bathymetry layer was included during the de-glint to prevent areas less than 3 m deep to be affected by the de-glint.

The atmospheric correction for IDA corrects for atmospheric reflection and transmission with several aerosol models, indirect reflection from upper-side of the water surface and absorption from the ozone. The correction is homogenous and is applied in the same way to every pixel.

$$P'_i(x, y) = [P_i(x, y) - S_i] \times m_i$$

Where P_i *(x,y)* is the input value and P'_i *(x,y)* is the atmospherically corrected value. For each atmospheric correction, IDA allows for the testing of areas of interest to determine the bathymetry to ensure that the atmospheric correction was applied correctly. To monitor the quality of the atmospheric correction, tests were carried out over points of deep and shallow water to ensure the estimated bathymetry was correct before continuing.

Within the SWAM model, the Sen2Cor atmospheric correction was applied to the Sentinel-2 imagery which is a purpose-built atmospheric correction for Sentinel-2 imagery and for the use of SWAM.

Finally, a bathymetry model is applied to the images using a physics-based method:

$$r_{rs}(\lambda) \approx f(P, G, X, H, m, E)(\lambda)$$

Where $r_{rs}(\lambda)$ is the remote sensing reflectance, P is the concentration of phytoplankton, G is the dissolved organic matter concentration, X is the particle backscatter at 440 nm, H is the depth, λ is the spectral wavelength and m and E are the equations endmembers codes.

When applying bathymetry within IDA, the tool estimates bathymetry from image data using a model inversion method. The main model uses an Adaptive Look-up Table (ALUT) for model inversion. There are a range of different parameters that can be changed to be site specific [see $r_{rs}(\lambda)$ equation above].

These include phytoplankton concentration, dissolved organic matter concentration, backscatter, and depth. In all cases the minimum and maximum expected ranges should be provided per site and depth should be set to the maximum depth of interest.

The use of SWAM proved to be exceedingly laborious. It took ARGANS about a month to be able to implement this free software due amongst other things to the difficulty of identifying a compatible Python version. When this was done, thanks to the help of the Sen2Coral previous Beta tester, the software was very slow compared to IDA and thus, only applicable to very small zones. It was finally decided not to waste any more time on SWAM and the trial was stopped when it was demonstrated that both IDA and SWAM provided identical results when using the same parameters.

I.2.4. The "*Merge*" novel methodology

ARGANS has developed a new and novel concept which involves using ESAs large database of Sentinel-2 imagery for SDB, this technique has been called "*Merge*". In previous research projects, teams could be waiting years for the one perfect image that would be the best condition possible to produce SDB. However, these methods could take a large amount of time and in some cases vast expense to collect the imagery. ARGANS new "*Merge*" method attempts to take a large input of SDB models and merging these into one result and therefore producing the 'perfect model' from a large database. By using multiple satellite images, errors within the image can be removed. This includes sediment plumes, effects of turbid water and human artefacts such as boats. The "*Merge*" workflow is shown below.
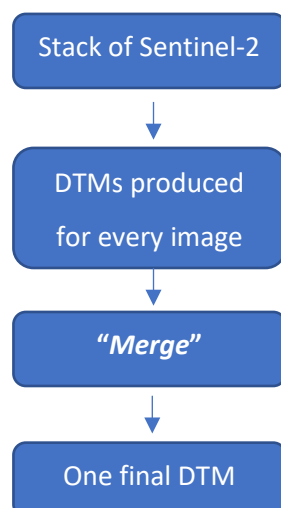
Figure 2. Workflow for **"Merge"** *methodology.*

ARGANS **"Merge"** method relies on all DTMs being in the same spatial setting. There are currently five methods of merging depth values from multiple DTMs to create one model:

    i.   Arithmetic average

Computes the mean for all pixels using the values from every DTM. This has to be used with extreme caution as the RTE inversion model might yield several solutions and the values spectrum is not Gaussian.

    ii.   Root mean square

Similar to the arithmetic average however computes a root mean square value from every value in the DTMS. As above, this has to be used with extreme caution as the RTE inversion model might yield several solutions and the values spectrum is not Gaussian.

iii. Uncertainty weighted average

This method applies a weight to every pixel in all DTMs corresponding to the uncertainty associated with the depth. The larger the uncertainty the smaller the weight. An average is then produced using these weighted values.

iv. Distance with others weighted

Compares the values of all depths. A weight is then applied to the depth with values that are found in 'clusters' having a higher weight compared to those which are found far from other values.

v. Range intersection

Detects the common space between the uncertainty values for every pixel. Where the most uncertainties overlap this will be computed as the depth.
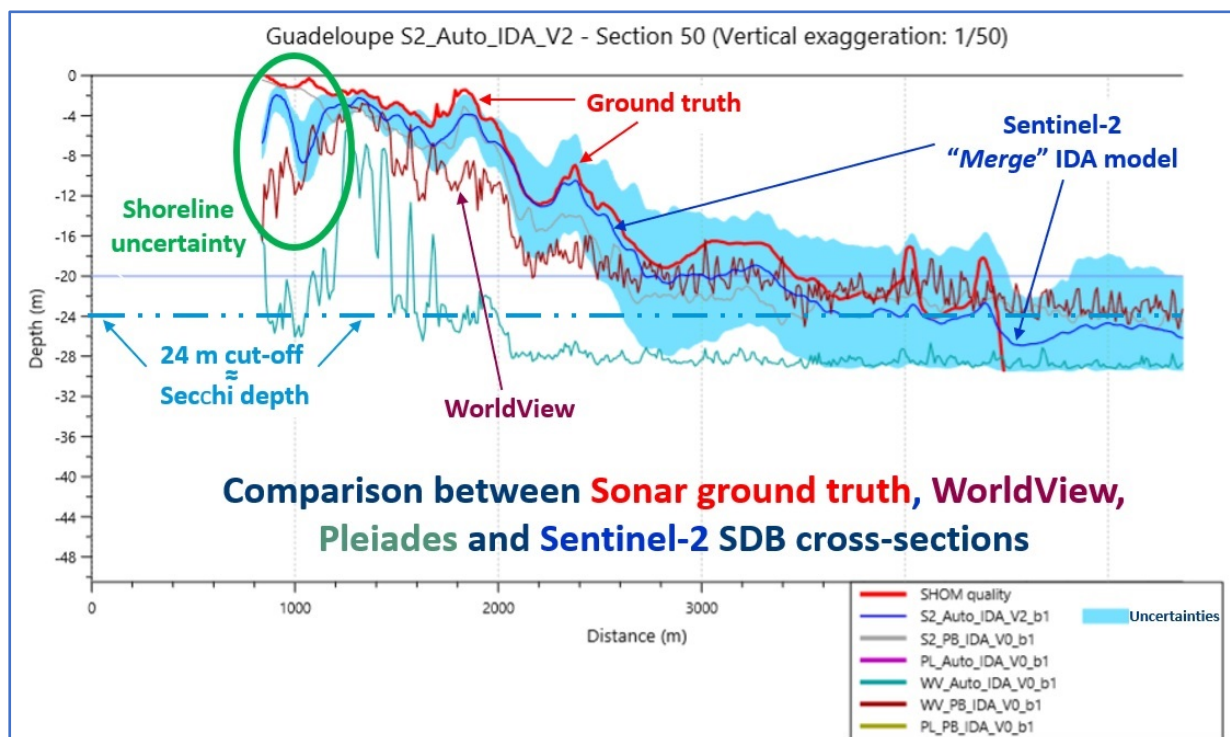
Fig 4   First comparison between Sentinel-2 "*Merge*" model and VHR satellite images

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SECOND PART: STUDY SITES

ARGANS has selected four study sites to demonstrate the ability of Sentinel-2 for the use of satellite derived bathymetry: Puerto Morelos, Mexico - Nosy Be, Madagascar - Lampi Island, Myanmar and Coral Harbour, Canada, as shown in the following planisphere:

Study sites
◆ Puerto Morelos
◆ Nosy Be
◆ Lampi Island
◆ Coral Harbour
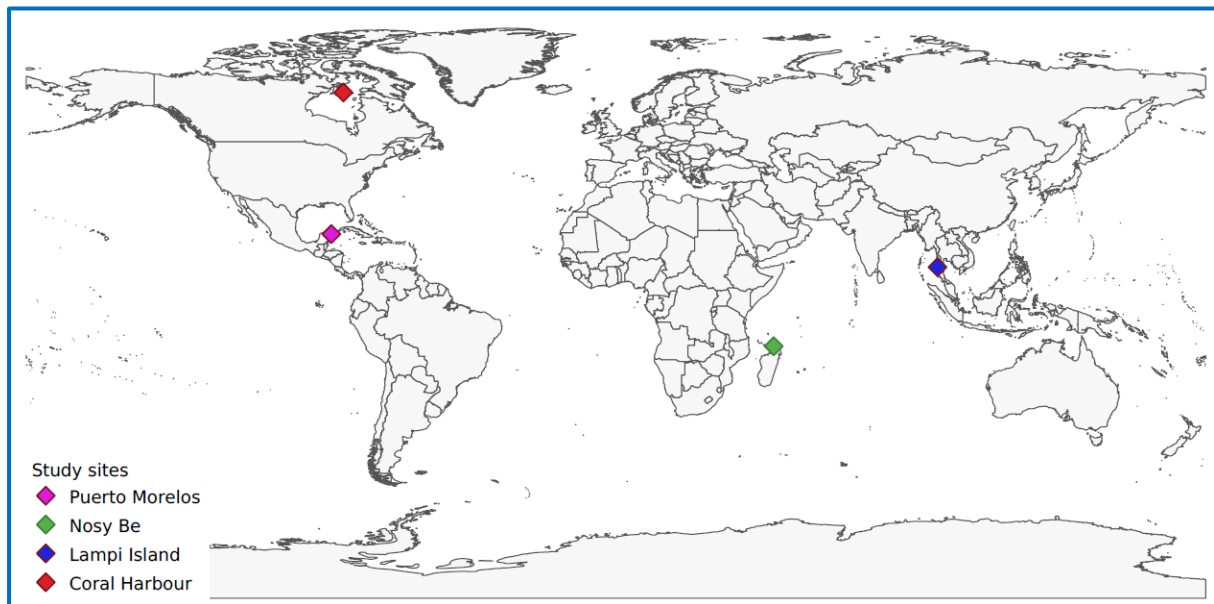
Fig 5   Map of the four study sites.

Each location provides a unique setting for SDB and a specific test per location. This has allowed for ARGANS to study and compare how SDB works in a range of different locations and settings while testing how Sentinel-2 performs in different locations.

II.1.   Mexico

Puerto Morelos, Mexico, has been selected to be used as a comparison between the Sentinel-2 SDB model and a pre-existing SDB chart produced using VHR imagery from KOMPSAT images shot in 2008 and 2009.

The Puerto Morelos detailed site report is at Annex A.
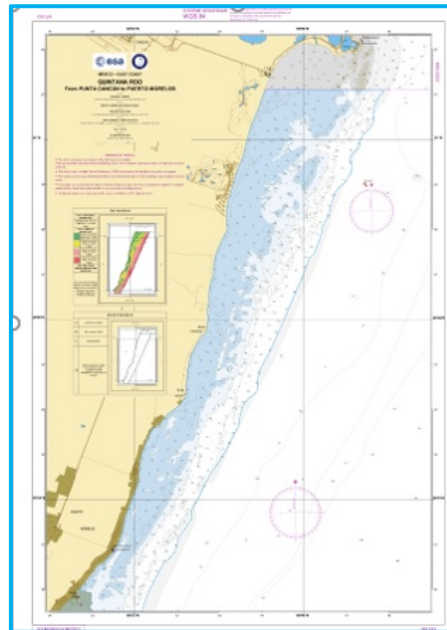
Fig 6 The Puerto Morelos demonstrator

II.2.   Madagascar

The **Isle of Nosy Be, Madagascar,** was chosen as an area deprived of recent field data or measurement, It was used as a test bed for the *"Merge"* method based on a large database made of 53 Sentinel-2 images and subsequent 50 DTMs. There was however a reliable ground reference provided by a professional lead survey performed at the end of the 19th century.

The Nosy Be detailed site report is at Annex B.
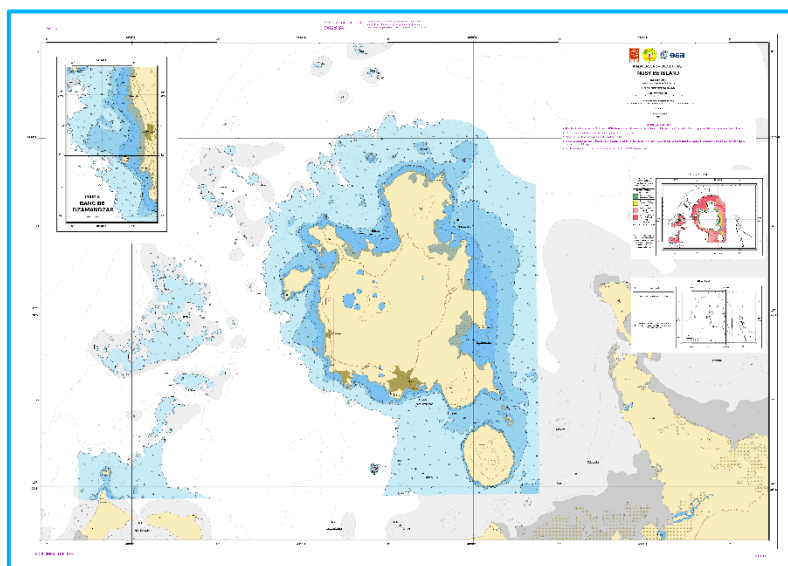
Fig 7   **The Nosy Be demonstrator**

II.3. Myanmar

Lampi Island, Myanmar was chosen to show the effectiveness of SDB within turbid waters and produces an experiment evaluating ARGANS **"*Merge*"** method in dealing with very turbid areas. This site was also used in the previous Sen2Coral ESA project, which did not include the production of a nautical chart.

The Lampi Island detailed site report is at Annex C.
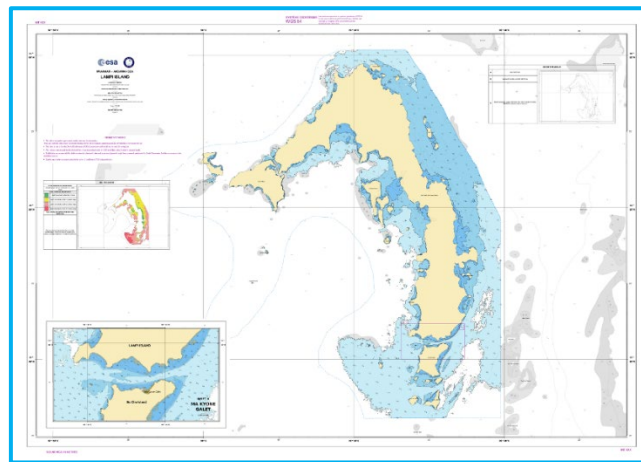
Fig 8   The Lampi Island demonstrator

II.4. Hudson Bay, Canada

Coral Harbour, Hudson Bay, Canada, is a new attempt at exploring how Sentinel-2 and SDB perform in Artic waters.

Much to ARGANS surprise, depths of penetration of about 16 metres were observed and confirmed in a later SDB survey performed off Newfoundland.

The Coral Harbour detailed site report is at Annex D.
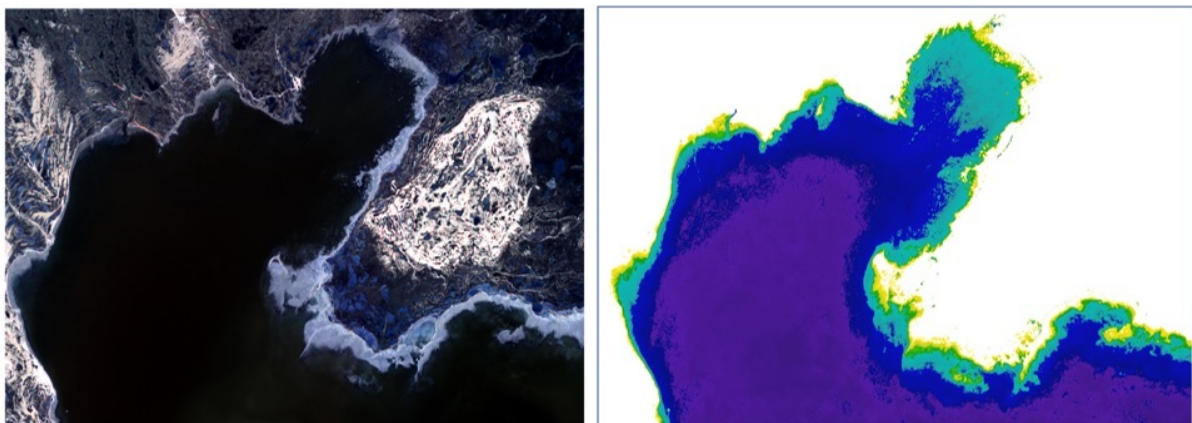
Fig 9   The Coral Harbour demonstrator

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THIRD PART: DISCUSSION

III.1. WHAT WENT WELL

III.1.1. Background

Originally, this project was planned with the best information available on satellite charting at the time it was submitted. ARGANS then only had a limited experience of Sentinel-2, gained during the unfinished Sen2Coral project that concluded somewhat casually that "*Radiometrically Sentinel-2 data can support good results in physics-based methods, such as bathymetric mapping, comparable to Landsat 8 and WorldView-2*"[1].

In the commercial tests that followed, performed in support of a Super-major oil company who was considering using SDB to "derisk" some of its geophysics survey, Sentinel-2 was first advertised as a poor-man's alternative to classical VHR images. ARGANS had managed to convince the Buyer to try two solutions called "Good-enough" with Sentinel-2, and "Best-achievable" with traditionally selected VHR images. There was a significant difference of price of about € 20 per sq.km as VHR images had to be bought. It quickly appeared that for a lesser price the "Good enough" method yielded comparable results to VHR.

Better results could even be achieved by making use of the Sen-2 time series. For instance, in an Andaman test survey, Sentinel-2 was able to detect an 18-metre shoal that was not visible on VHR images and that two contractors out of four had actually failed to observe.

This was a turning point and ever since, ARGANS has focussed on Sentinel-2, only looking at VHR images to make comparisons.

The decision to concentrate on Sentinel-2 times series gave access to entirely new methods and led ARGANS to develop unexpected applications, amongst which the "*Merge*" method, which applied to now almost "Perfect Images" could revolutionise the Coastal cartography.

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[1] Coral reef applications of Sentinel-2: Coverage, characteristics, bathymetry and benthic mapping with comparison to Landsat 8 - John D. Hedley1, Chris Roelfsema2, Vittorio Brando3, Claudia Giardino3, Tiit Kutser4, Stuart Phinn2, Peter J. Mumby5, Omar Barrilero6, Jean Laporte7, Benjamin Koetz8
Elsevier's Remote Sensing of the Environment – 28 July 2018
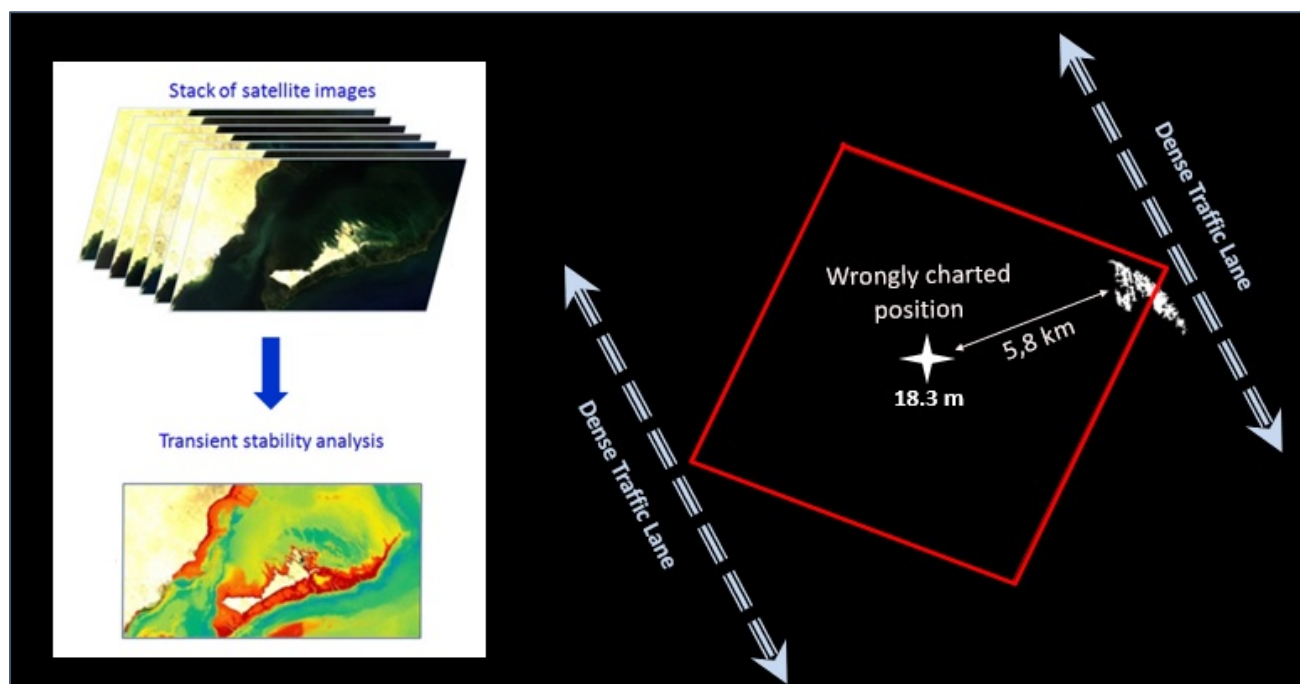
Fig 10   Detection of a misplaced shoal, thanks to Sentinel-2 time series

III.1.2.   Software and processing times

ARGANS currently operates three RTE software suites, based on the same semi-empirical equations that ultimately yield the same results when parameterised identically.

The ESA free SWAMPy inversion software developed within the Sen2Coral project requires a lot of efforts to be installed and is pretty laborious to run. It has been used nonetheless with a limited number of profiles to control the IDA and/or ICEC more user-friendly results.

The ICEC software developed internally and Dr Hedley's IDA have similar high performances although ICEC is only documented in French. It was finally preferred for simplification to use the English documented IDA model that ARGANS has been running regularly for about ten years.

Having processed hundreds of images and thanks to time series, the processing team is now very familiar with inversion software and can draw the following practical conclusions:

> ⇨   Sentinel -2 IDA or ICEC processing time ≈ 15 minutes
> ⇨   VHR IDA or ICEC processing time for same area ≈ 8 hours
> ⇨   Sentinel-2 DOP for same area≈ 20 minutes

Sentinel-2 images, on the one hand, are easier to process because they have much less pixels than VHR's and laptops do not crash as often as they would, say, with Pleiades or WV images. On the other hand, Sentinel-2 yields far more bathymetric models that take time to process if one selects all eligible images.

III.1.3.   Novel applications

The effort spent on handling large VHR databases are now diverted to analysing a greater number of HR bathymetric models with the intention to prove that because they are based on per-pixel analysis, Sentinel-2 SDB models are far superior than VHR's because of the MSI sensor's radiometric sensitivity and vicarious calibration.

The two applications have been developed to support these views:

III-1.3.1. DOP

The **Depth of Penetration (DOP) software** is a validation tool delivered to ESA separately, which consists of determining the theoretical maximum detection threshold, based purely on the colour of the ocean. As a very simple validation check, any modellised depth deeper than the DOP should be double-checked and eventually suppressed.

Applied originally to small ROI Sentinel-2 images, the DOP software is being assessed against other existing Ocean colour satellites (MERIS, MODIS, OLCI….).

Noting the importance of DOP, ESA recommends that penetration thresholds should be mentioned explicitly in any future SDB-based nautical charts.

III-1.3.2. "*Merge*" method

As explained at paragraph I.2.4 the **"*Merge*" method** is a natural, yet unexploited consequence of Sentinel-2 revisit time. It consists of selecting every valid image, applying a mask to each to suppress any interfering data such as land, clouds, shadows, transient sediment plumes and artefact, and finally create a "Perfect Image" made of tens of normalised[2] components.

Thanks to Sentinel-2 excellent 12 m absolute horizontal precision, all pixels can be compared and averaged over a long period of time and many different environmental conditions. Figure 4 shows that "*Merge*" results seem to be systematically better than any other results, be they either generated by one selected Sentinel-2 image or by any other 50 cm resolution VHR images. The only remaining

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[2] …especially with regards to tidal reductions.

problem is in shallow waters for depths, say, less than 5 metres where RTE inversion models can yield multiple solutions.

III-1.3.3.   Shallow water dispersion and multiple solutions

ARGANS Science expert has drawn the attention to the importance of theoretical multiple solutions that can render the "*Merge*" model inoperant and precludes calculating averages. Solutions have to be systematically tested and selected by the analyst, either with an expert system still to be developed or by comparison with an environment database adapted to the ROI containing such information as IOP, Seafloor properties, ancient nautical charts, etc.).
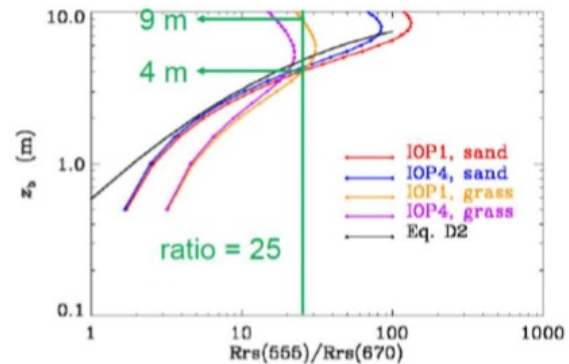
Fig 11   Hydrolight Remote Sensing Reflectance simulations for two sets of IOPs and two sand and grass bottoms showing different RTE solutions. (Source: C. Mobley)

It is envisaged for the moment to develop a cartographic application to optimise the "*Merge*" reliable profile made up of several images with a hand-selected single plausible Sentinel-2 profile without creating an artificial dogleg.

III.1.4.   The importance of cartographic experience over pseudo-science

There is a growing number of environment service providers offering commercial SDB solutions. As seen at paragraph III.1.1 above with the Thalia shoal, self-appointed SDB experts might miss important observations that hard-suffering marine cartographers prompted by their Safety of Navigation concerns would find eventually, although never with 100% certainty. Until strict standards have been discussed and implemented by the IHO, the situation is not likely to improve.

One has to keep constantly in mind that SDB endeavours to find a solution to a system of 3 equations provided by the blue, red and green spectral bands but containing an almost unlimited number of unknowns. SDB is thus the art of parameterising the RTE with the analyst best guesses to replace the unresolvable unknowns in a reasonably homogeneous area.

The cartographer and hydrographer's experiences are fundamental to interpret, or eventually replay the model by using different parameters until the final result, always a compromise, matches the existing nautical charts in similar environment. Except in rare cases such as closed lagoons, the local conditions can vary significantly and a given set of parameters might change considerably. The analyst

might then have to decide to subdivide the ROI into more homogeneous sub-zones. By doing so, he augments the processing time which further influences costs and makes a reasonable cost-assessment difficult to establish.

In short, the quality of SDB solutions depends more on the marine cartographer's experience and robust QC than on pseudo-scientific considerations.

III.1.5. Demonstration of Sentinel-2 marine cartography potential

With this proviso in mind, the project four demonstrators have confirmed the SDB and Sentinel-2 potential in marine cartography compared to all other satellites, thanks to a number of improvements unknown of previous constellations, amongst which one would find difficult to set a priority:

⇨ Revisit time, essential to get rid of transients and developing the "Perfect Image" and **"Merge"** concepts,

⇨ 12-metre absolute horizontal precision, allowing for multi- pixel integration over large periods of time,

⇨ Vicarious calibration,

⇨ Band shift control, making comparisons possible within time series,

⇨ MSI Radiometric performances, enabling deeper water penetration,

⇨ Practical 10 m resolution, better adapted to marine cartography scaling factors and replays,

⇨ Etc.

III.1.6. The need to modernise traditional cartographic concepts and methodology

Due to Government liability in the distribution of official charts to Mariners, Hydrographic Offices are extremely reluctant to take any risk by releasing unproven charts or disproving disputable dangers, sometimes depicted on charts over 100 years old. HOs proceed with field controls and multiply drastic QCs. Any not fully proven prototypes are considered to be unsafe. This applies to SDB charts which should display the very conspicuous and discouraging warning: ***Not to Be Used for Navigation***.

This extreme precaution is somewhat contradictory with the fact that a number of official International charts are still based on very ancient surveys, e.g. 1898 for the Nosy Be demonstrator, 1829 for the Guinea Conakry coastline, etc.

Should SDB be considered as the only viable system to fill the World coastal gaps, the International Hydrographic Community at large and the IHO must be convinced to adopt a less dissuasive approach. Whilst assuming the fact that satellite bathymetry will seldom meet the S-44[3] vertical criteria except in small homogeneous ROIs, a better adapted formulation will have to be accepted to replace vintage charts and fill the coastal gaps with new charting schemes including SDB charts similar to the project 4 demonstrators.

Satellite contribution to cartography should not be limited to producing entirely new charts out of nothing like the Lampi Island demonstrator, but should mostly consist of updating ancient charts with modern precise elements such as coastline, intertidal zones and confirmed visible shoals.

In many cases, SDB terrain models could actually be draped onto DTM made of reliable if patchy lead line measurements to provide equivalents to the S-44 full floor search as long as the bottom is visible from space.

III.2. WHAT COULD HAVE BEEN IMPROVED

III.2.1. The project poor timing assessment

Getting into the project proper took much longer than expected and producing the first demonstrator took over six months during which the SDB team had to get accustomed to the various software and methods. Once the production chain was in place, it should have been much faster to complete the initial work plan but in the meantime unexpected new possibilities appeared which had to be explored in the interest of the project.

The two most remarkable examples are provided by the development of the *"Merge"* method and the subsequent comparisons between satellites which were not included in the project, but are essential to promote Sentinel-2 amongst users and government agencies.

The latter was made possible thanks to another contract won with a European Hydrographic Office who intended to improve its own SDB production chain. Quite typically, this contract only required VHR satellite models and only tolerated Sentinel-2 as an option suggested by ARGANS.

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[3] S-44 Publication: **IHO Standards for Hydrographic Surveys.** (February 2008). S-44 is the professional Hydrographic Surveyors' Bible.

To be fair, this improvement contract should benefit in turn from the ESA project by gaining prime access to the latest Sentinel-2 findings.

Another minor difficulty was caused by the timing needed to apply to peer-reviewed publications who set their own tempo, regardless of the project GANTT chart that they have no reason to consider.

III.2.2. The difficulty to organise meetings involving several international organisations and working groups

An international organisation such as the IHO comprising 93 member states attends hundreds of meetings worldwide and the Secretary General and two Directors are seldom available. Organising a face-to-face meeting seemed an almost impossible task which was eventually achieved on the 11th of October in the Principality of Monaco[4]. It should be remembered that the IHO provided its written support to this project from the very beginning.

The standardisation task included in the ESA project concerns the HSPT working Group attended normally by over 40 member states and stakeholders. This WG held its fourth meeting in December 2019 in Monaco, attended by ARGANS representative who made a SDB presentation of their latest Sentinel-2 findings, together with a German company that ARGANS had had invited to provide another viewpoint. The SDB Standard proposal was discussed superficially and satellite methods should be included for the first time in the S-44 next edition.

4th meeting of HSSC Project Team on Standards for Hydrographic Surveys (HSPT4) in Monaco, 3rd to 6th December 2019

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[4] Post meeting remark: this meeting and ensuing seminar took place as expected in Monaco and the Project presentation was made, mainly to Member States representatives. It was further decided to include a public presentation on the occasion of the large IHO Assembly in April 2020, presided over by Prince Albert II and attended by the 93 Member States and most International maritime organisations and stakeholders.

Much to ARGANS surprise, it was found out that Sentinel-2 was very much ignored by the Hydrographic Community. The German company mentioned above, one of the World's most active and capable, still gives preference to WorldView images to the archives of which it seems to have unlimited access thanks to a privileged agreement with Digital Globe.

III.2.3.   The internal liaison between scientist and hydrographers

Although studied by laboratories since Lyzenga first 1978 publication[5], Scientists have shown little or no interest in Marine cartography. Conversely, Hydrographers tend to consider Scientists with suspicion as they seldom abide by the IHO strict standards and procedures and generally ignore the question of liability attached to the production of official nautical publications.

The two worlds had `to meet to complete this project. Whilst ARGANS Scientists had at the beginning a tendency to consider that their task was achieved when the model bathymetric layers had been calculated, cartographers were conducting lengthy statistical analysis and comparisons and had to produce the final charts in time. They often had to ask questions to their EO colleagues, complained about QC and their extreme concern for Safety of Navigation strict requirements was at first somewhat misunderstood. In spite of their geographical separation -the EO team was located in Plymouth while the cartographers were based in Brest- the system functioned reasonably well and would have functioned even better if they could have been collocated.

Working ratio have been established approximately as follows:

⇨ SDB models and developments: 30 %

⇨ Cartographic processing, statistical analysis and validation: 40 %

⇨ Management, exposure and publications: 30 %

III.3.   COST CONSIDERATIONS

III.3.1.   Hydrographic Offices' current practices

The production of nautical charts being an act of sovereignty entailing Government full responsibility, most Hydrographic Offices are Public Agencies, supported by national budgets, usually placed under the responsibility of Ministries of Defence.

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[5] Lyzenga, D. Passive remote sensing techniques for mapping water depth and bottom features.; Appl. Opt. 1978, 17, 379–383; Lyzenga, D. Passive remote sensing techniques for mapping water depth and bottom features, Appl. Opt. 1978, 17, 379–383;

Thanks to its broad commercial network, only the UKHO is sustainable and capable of generating a profit. All the other HOs are heavily subsidised, often in the region of 90%. This does not make them easy customers and they tend to be conservative and reluctant to accept new methods that could have adverse consequences on the safety of human life at sea (SOLAS), their protected status and their liability mentioned above. The same cautious approach was applied to new systems now fully accepted like MBES and lidar. To date, new SDB services are offered by private companies operating outside any standard and charging very variable costs for often disputable results.

This explains why SDB has difficulty to being recognised as a valid method and needs both support and regulation by the IHO and qualified HOs. In the meantime, HOs almost unanimously continue producing their national chart series and conducting national surveys with their own personnel, equipment and vessels and are highly suspicious of uncontrolled SDB surveys.

III.3.2. 2019 Cost assessments

As the first national HO to pioneer SDB in the eighties, and 20 years later to produce its own seamless coastal database, Shom, the French HO, established its own template based on its internal costs and from the observations he could collect here and there amongst private companies. The figures and template that follow are derived from this early assessment and have to be taken with caution.

⇨ **Electronic Navigation Chart 2019 production costs:**
  ➢ Publication ≈ € 80 K
  ➢ New Edition ≈ € 50 K
⇨ **Geophysical vessel (14 towed arrays – 57 crew) :** ≈ US $ 280 K per day
⇨ **Ocean survey vessel (including 10 Hydrographers survey team) :** ≈ € 70 K per day
⇨ **Survey of port and access:** about € 500 K per port
⇨ **Cost of coastal survey per sq. km:**

	Preliminary assessment (2004)	Now (2019)	Minimum charge
Lidar	1 000 €	€ 200 to 2 000 Greatly variable. Depends on survey and quality of post-processing	K€ 5 or 100 sq. km
MBES	10 000 €	€ 10 000 Up to 10 times this figure for overseas surveys requiring launches supported by large survey ship	On request
Satellite	50 €	Target prices: € 20 (Sentinel-2) to € 50 (VHR) (depends on quality of image)	K€ 5 or 250 sq. km

III.3.3.   SDB Business Plan and future customers

ARGANS has identified the following four types of possible customers:

III.3.3.1. National Hydrographic Offices

Depending on national policies, two type of services could be provided:

➢ **SDB surveys**, opened to qualified private companies operating within competitive tenders. Outsourcing is the UK policy as the UKHO does not intend to produce its own SDB charts but have these procured from private companies.

➢ **SDB production line update**, also based on competitive tenders amongst eligible contractors. This is the way chosen by Shom who will decide at the end of the current feasibility study whether production will be performed internally or outsourced to private companies, as chosen by the UKHO

III.3.3.2. ICZM and Regional Coastal Agencies

According to the GEBCO latest assessment, less than 1% of the World's coastal waters have been surveyed. Countries wishing to implement an ICZM policy might be recommended to use SDB as the only affordable alternative to unaffordable lidar or boat surveys.

In Developing Countries, progresses very much depend on the source of funding such as Regional Development Banks or the World Bank that can be identified to support these projects.

Re territorial disputes, ARGANS has won several contracts in West Africa, using SDB to determine the legal baseline used to determine the breadth of the Territorial Sea. It also been approached by countries wishing to develop their new coastal infrastructure.

III.3.3.3. Global Mapping Agencies

The Nippon Foundation/GEBCO intends to bring together all available bathymetric data to produce the definitive map of the world ocean floor by 2030. Providing the water is sufficiently clear to see the bottom, SDB is the only method that can cover the coastal areas at an affordable cost. ARGANS has been recommended by the IHO to approach the Nippon Foundation.

Global Mapping Providers such as Google, Bing, etc. could also be approached to depict shallow areas.

III.3.3.4. Geophysics Surveyors and Oil Companies

Super Major Oil Companies are investing the SDB potential to prepare their geophysics surveys and derisk the deployment of their expensive towed arrays.

Originally, these contracts included two options "Best-Achievable" with expensive VHR images and "Good Enough" with public Sentinel-2 data. ARGANS had won several such contracts in Eastern Africa, Myanmar, Algeria, etc. and discovered that the "Good Enough" solution yielded results at least as good as the "Best Achievable", and performed far better when Sentinel-2 time series could be used (see Figure 10).

These early commercial successes led ARGANS to recommend using Sentinel-2 systematically and, alone amongst other SDB service providers, argue that time series should be given preference over the VHR alternatives prescribed as a matter of routine by its clients.

FOURTH PART: DELIVERABLES

IV.1. SUMMARY

Deliverables consist of :

- The final report in "pdf" made of 5 components: the report proper and 4 annexes provided separately as a fully inclusive report would be to bulky.)
- Data:
  - DTMs , i.e. SDB models results in "TIFF" format
  - Nautical Chart demonstrators both in "pdf" and "TIFF"
- The previous technical studies, originally delivered in July
  - Sensitivity analysis and SDB models comparisons, V1.3
  - Impact of field-proven SDB on the world uncharted waters (DOP), V1.3
  - New S-44 Satellite Survey Standard, V1.1
- The Contract Closure Document provided separately.

Apart the Contract Closure Document, these deliveries are recorded in a directory : "ESA_Coastal charting_Deliverables_Report-Data" containing:

- The final report, V1.6 in pdf
- The 4 files labelled Annexes A, B, C and D, dedicated to study sites, all in pdf
- The 3 technical studies, all in pdf

IV.2. FINAL REPORT

Object	File's name
Final report (Without Annexes A, B, C and D)	ESA_Final_Report

Mexico - Puerto Morelos (Directory : "Deliverables_A_Puerto-Morelos")

Object	File's name
DTM	MergeV2_6DTM_Opt3

Chart in "pdf" format (Adobe Acrobat Document)	PuertoMorelos_2019-08-16
Chart in "GeoTiff" format (Image TIFF)	PuertoMorelos_2019-08-16
Annex A to final report	AnnexA_Puerto-Morelos_V1.0

Madagascar – Nosy Be (Directory : "Deliverables_B_Nosy-Be")

Object	File's name
DTM	ESA_NB_S2_AUTO_IDA_V2
Chart in "pdf" format (Adobe Acrobat Document)	Nosy Be-7000-2019-08-27
Chart in "GeoTiff" format (Image TIFF)	Nosy Be-7000-2019-08-27
Annex B to final report	AnnexB_Nosy Be_V1.0

Myanmar – Lampi Island (Directory : "Deliverables_C_Lampi-Island")

Object	File's name
DTM	ESA_LI_S2_Auto_IDA_v2
Chart in "pdf" format (Adobe Acrobat Document)	LampiIsland_2019-08-31
Chart in "GeoTiff" format (Image TIFF)	LampiIsland_2019-08-31
Annex C to final report	AnnexC_Lampi Island_V1.0

Canada – Coral Harbour ((Directory : " Deliverables_D_Coral-Harbour")

Object	File's name
DTM	ESA_CH_S2_Auto_IDA_Opt4_v0.tif ESA_CH_S2_Auto_IDA_Opt5_v0.tif
Chart in "pdf" format (Adobe Acrobat Document)	CoralHarbour
Chart in "GeoTiff" format (Image TIFF)	CoralHarbour
Annex D to final report	AnnexD_Coral Harbour_V1.0

FIFTH PART: CONCLUSION

This project intended originally to test the potential of Sentinel-2 in coastal charting. However, it did not turn as expected as it appeared in the course of the project that not only Sen-2 was well adapted to this type of usage, but Sen-2 time series should eventually supersede all known developments based on satellite imagery in general, and VHR images in particular.

At this juncture, and with the newly acquired experience of Sentinel-2 time series, going back to unique, even carefully selected, high resolution images seems preposterous.

0.5 metre resolution which is useful to depict detailed harbour structures is of no help when it comes to describe the coastal environment characterised by much larger natural features. It can even become a serious handicap as it draws too much time, money and effort to achieve a deceptive and often noisy bathymetric model.

The next step will be to convince the International Hydrographic community that updated satellite charts, often combined with ancient reliable surveys, is the solution for the future, not only by providing efficient tools to produce modern, IHO-compliant, nautical charts, but also to produce a new type of product covering the World's coastal gaps. These may be not as impeccably reliable as the traditional documents, but they would render a much better service to users confounded by the absence of charts and provide a practical and effective contribution to the IHO fundamental goal of Safety of Navigation.

<div align="center">END OF FINAL REPORT V2.0</div>