# Thirty years of satellite derived bathymetry – The charting tool that hydrographers can no longer ignore

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## Preamble

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## Abstract

Thirty years after being introduced into national chart series, Satellite Derived Bathymetry (SDB) charts are still struggling to be recognised as valid navigation documents, capable of meeting the level of confidence required by the S-44 IHO standards for hydrographic surveys.

The advent of new generation satellite constellations, such as Sentinel-2*, provide improved geolocation and, thanks to higher revisit frequency, an almost unlimited capacity to detect natural dangers visible from space within the limits of the sensing instruments. Thus, this negative vision of SDB must change.

Written by Hydrographers, this article aims to provide a scientific background adapted to practical Hydrography; introduce the notion of "Perfect Image", first mentioned at the International Hydrographic Remote Sensing workshop (Ottawa, September 2018); and rehabilitate older concepts such as Depth of Penetration (DOP), which make SDB an incomparable instrument to chart the World's shallow waters (Fig. 1). Here, "incomparable" does not mean "perfect", as there are limits to SDB capacity to detect and quantify bottom structures that will be detailed later.

*The frequent mention of Sentinel-2 should not lead the reader to believe that the authors are focussing on this constellation. The intention is to show how satellite hydrography has evolved naturally from exploiting unique images to processing large collections that provide ever-improved information, the latest example happening to be Sentinel-2.

## Resumé

Trente ans après leur introduction dans les portefeuilles nationaux, les cartes issues de la bathymétrie par satellite (SDB) rencontrent toujours des difficultés à s'imposer en tant que documents satisfaisant aux exigences de sécurité de la navigation, requises notamment par la publication S-44 (Normes de l'OHI pour les levés hydrographiques).

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Or, l'avènement d'une nouvelle génération de constellations satellitaires telles que Sentinel-2*, offre une géolocalisation améliorée et, grâce à leur haute fréquence de répétitivité, une capacité presque illimitée de détection des dangers naturels visibles depuis l'espace dans les limites des performances des capteurs embarqués. Aussi, cette vision négative de la SDB doit-elle changer.

Écrit par des hydrographes, cet article vise à fournir un contexte scientifique adapté à la pratique de l'hydrographie, à introduire la notion de «Perfect Image», mentionnée pour la première fois lors de l'atelier télédétection hydrographique, Canada 2018, et à réhabiliter des concepts plus anciens comme la profondeur de pénétration (DOP), qui fait de la SDB un instrument incomparable pour cartographier les eaux peu profondes du monde (Fig. 1). Ici, «incomparable» ne signifie pas «parfait», puisqu'il y a des limites à la capacité de la SDB à détecter et à quantifier les détails du fond. Ces limites sont argumentées dans l'article.

*La mention fréquente de Sentinel-2 ne devrait pas amener le lecteur à penser que les auteurs se concentrent sur cette constellation. L'intention est de montrer comment l'hydrographie par satellite est naturellement passée de l'exploitation d'images uniques au traitement de grandes séries qui fournissent des informations toujours meilleures, le dernier exemple étant Sentinel-2.

# Resumen

Treinta años después de haber sido introducidas en las series de cartas nacionales, las cartas de Batimetría satelital (SDB) siguen luchando por ser reconocidas como documentos de navegación válidos, capaces de cumplir con el nivel de confianza requerido por la norma S-44 de la OHI para levantamientos hidrográficos.

La llegada de las constelaciones de satélites de nueva generación, como Sentinel-2*, proporcionan una mejor geolocalización y, gracias a una mayor frecuencia de revisiones, una capacidad casi ilimitada de detección de peligros naturales visibles desde el espacio dentro en los límites de los instrumentos de detección. Por lo tanto, esta visión negativa del SDB debe cambiar.

Escrito por Hidrógrafos, este artículo tiene por objeto proporcionar antecedents científicos adaptados a la Hidrografía práctica; introducir la noción de «Imagen Perfecta», mencionada por primera vez en el Taller Internacional de Teledetección Hidrográfica (Ottawa, septiembre del 2018); y rehabilitar conceptos más antiguos como la Profundidad de Penetración (DOP), que hacen de la SDB un instrumento incomparable para cartografiar las aguas poco profundas del mundo (Fig. 1). Aquí, «incomparable» no significa «perfecto», ya que hay límites a la capacidad de la SDB para detectar y cuantificar las estructuras del fondo que se detallarán más adelante.

* La frecuente mención de Sentinel-2 no debería hacer creer al lector que los autores se centran en esta constelación. La intención es mostrar cómo la hidrografía satelital ha evolucionado naturalmente de la explotación de imágenes únicas al procesado de grandes colecciones que proporcionan información cada vez mejor, siendo el último ejemplo Sentinel-2.

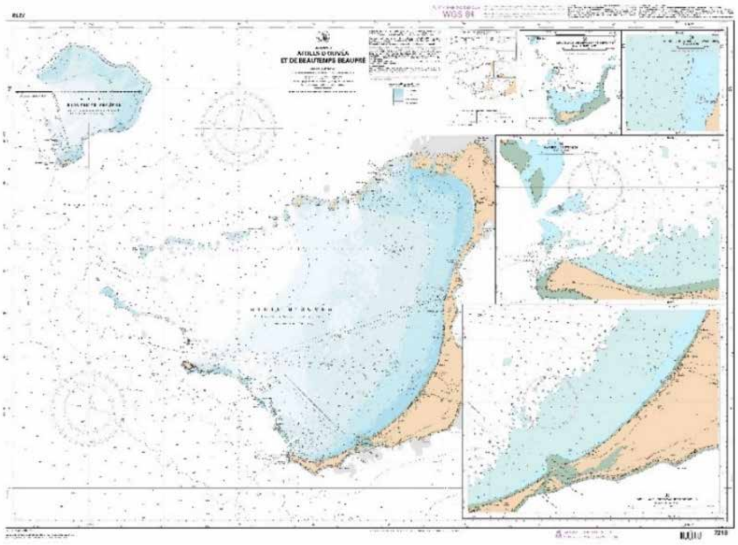

**Fig. 1** The first SDB official chart. Source: 2010 SHOM, publication 1990 based on a 1988 SPOT image.

## 1 Background

Since the beginning of seafaring, careful visual watching of dangers has been the Navigator's best asset for survival in shallow waters. During his search for traces of the unfortunate Lapérouse expedition, Beautemps-Beaupré, who would become Napoleon's Hydrographer, had refined Captain Cook's geometrical method of determining South Pacific reefed coastlines from a safe distance by taking sights with a sextant from the ship crow's nest. Replace the lookout with an optical sensor, human appreciation of shoals' glow by stricter measurements of reflectance, and rule of thumb by bathymetric modelling, and you have all the ingredients of today's Satellite Derived Bathymetry.

The main drivers for the use of SDB are the need to achieve full bottom coverage, ability to provide horizontal precision comparable with the ship's positioning systems, and provision of a reliable image-based alert system when shallow dangers are suspected in the absence of traditional field surveys, irrespective of vertical measurement that SDB is unable to yield with the precision required by the IHO S-44 Standards. None of these can be achieved unless the environment conditions are adequate, i.e. clear skies and waters transparent enough to see the bottom, which were also Captain Cook's preconditions and are now remote sensing's major constraints, somewhat attenuated by the availability of larger collections of images.

If one waits long enough to meet these requirements with ever improving satellite constellations, sustained by practical scientific considerations, all based on empiric observations, there is no reason not to be able to chart most of the World's coastal areas, which up to the present time have remained 99 % unsurveyed according to the GEBCO database. Funding such a major undertaking has always been, and shall remain, an issue however, compared to traditional methods that would take hundreds of years and require massive resources, SDB images and processing are affordable[1], easy to use and accessible to all. Provided they have been cleared of cloud cover and impenetrable turbid patches, and given enough images, a SDB time series can theoretically track everything within the DOP, extricate permanent bottom structures from transient background, and yield validated, although vertically imprecise, bathymetric information. No costly classical survey methods limited to one single swath could deliver the same. When validated by professional hydrographers, SDB seems good enough to fill the World's empty coastal databases and fulfil developing countries' mapping requirements. Further, if regulated by sworn Hydrographers sanctioned by the IHO, SDB can lend added confidence to the qualitative information needed by Mariners for safer navigation.

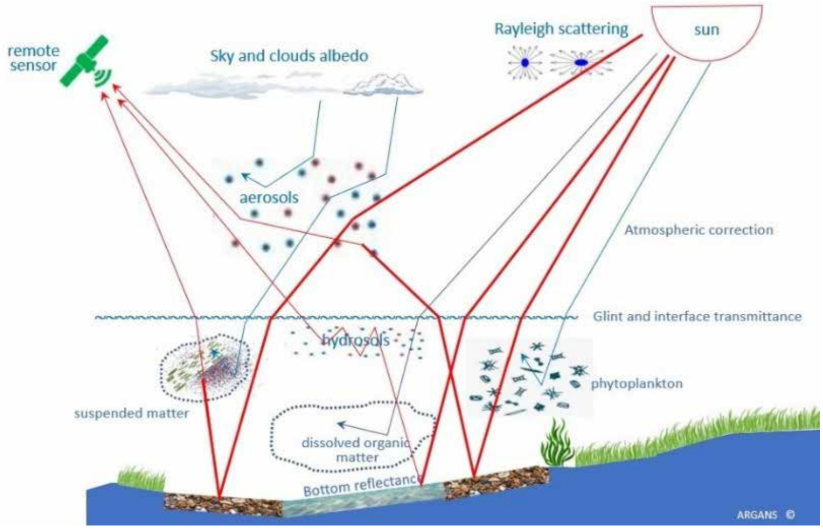

**Fig. 2** SDB fundamentals: only red paths may contain attenuated depth information.

## 2 C-13 Manual on hydrography update

Although broached superficially by the C-13 Manual on Hydrography, last updated in 2011, satellite imagery has been used since the 1980 by Hydrographic Offices, mainly for topography updates and survey planning. Since then, Space Agencies have significantly improved Earth Observation (EO) sensors, spatiotemporal resolution and image quality, whilst laboratories developed their own requirements for habitat classification and environmental monitoring. Despite non-existent IHO procedures, SDB products also started to be promoted and delivered by private service providers for large environmental projects such as a survey of the Great Barrier Reef. With the exception of the International Hydrographic Remote Sensing workshop organised in 2018 by the Canadian Hydrographic Service, the Hydrography community remained conspicuously absent during these developments, which seems indicative of a lukewarm interest despite early support from IHO leaders.

However, by making use of the latest EO satellite improvements, notably revisit time and sensor spectral performances, hydrographic research and development entities, mainly supported by the European Space Agency and few advanced HOs, have developed new tools and gathered sufficient evidence to confirm the benefits SDB can offer toward improving coastal water cartography, i.e:

- Near absolute capability to detect natural bottom structures in shallow waters up to depths of about 20 metres, providing the bottom is unambiguously visible from space;
- 11 metres or even better absolute horizontal precision without further ground control;
- spectrally calibrated composite images free of corrupted pixels. To designate these spatiotemporal objects, the term "Perfect Images" was introduced incidentally at the 2018 Remote Sensing workshop mentioned earlier;
- the potential to develop Depth of light Penetration statistics applicable to optical remote sensing worldwide;

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[1] About the real cost of free satellite images, please refer to the footnote at the end of paragraph 4.

- and, thanks to the elimination of corrupted pixels, improved depth assessment, in spite of being generally outside S-44 standards except in small areas endowed with a well-controlled environment.

## 2.1 Methodology

### 2.1.1 SDB theory

Before plunging headfirst into abstract formulae, the Hydrographer must bear in mind that SDB is not a pure mathematical science, but is the art of rigorously interpreting natural phenomena characterised by an almost infinite quantity of unknowns. Achieving the true water depth from multi-spectral imagery depends on the analyst but, their interpretation, supported by physics-based equations governing the propagation of photons from the source of energy to the sea bottom and back to the satellite (Fig. 2), categorises SDB as an applied science.

To solve the simple depth equality (Z is a function of an almost infinite quantity of unknowns), the analyst disposes of a limited set of equations provided by the sensor's spectral bands, five at the most: blue and/or coastal blue, green, yellow and two near infrareds. This system can't be resolved unless the number of unknowns is reduced drastically by selecting small areas characterised by similar environmental conditions, leaving only those unknowns necessary to find a solution to the basic equation of radiative transfer, which extracts the bottom signal; i.e. the Remote Sensing Reflectance Rrs  observed by the satellite after travelling though the water column, across the surface, and through the atmosphere.

For the record, the remote sensing reflectance Rrs above the surface, which is provided by satellite missions' L2A products , is linked to the reflectance in the water by:

$$R_{rs}\left(0^{+}, \Theta^{air}_{obs}, \Theta^{air}_{sun}, \Phi\right) = \frac{t}{n^{2}}\frac{E_{0}(0^{-})}{E_{0}(0^{+})} r_{\infty}\left(0^{-}, \Theta^{w}_{obs}, \Theta^{w}_{sun}, \Phi\right)$$

where $t$ is the transmittance of radiance from water to air, and n is the index of refraction of water: $t \cong 0.96$, $n \cong 1.34$ and the ratio of irradiances $E_0(0^-)/E_0(0^+)$ is close to 1 when the sun is vertically overhead.

In short, calculating Reflectance is all about counting bottom-reflected photons reaching the sensor against a noisy background. Optimising the Signal to Noise Ratio (SNR) depends on increasing the number of photons comprised in the signal, using a performing sensor, and filtering noises. This in turn calls attention to the pixel size and the image spectral resolution, which cannot be extended indefinitely at the expense of SNR.

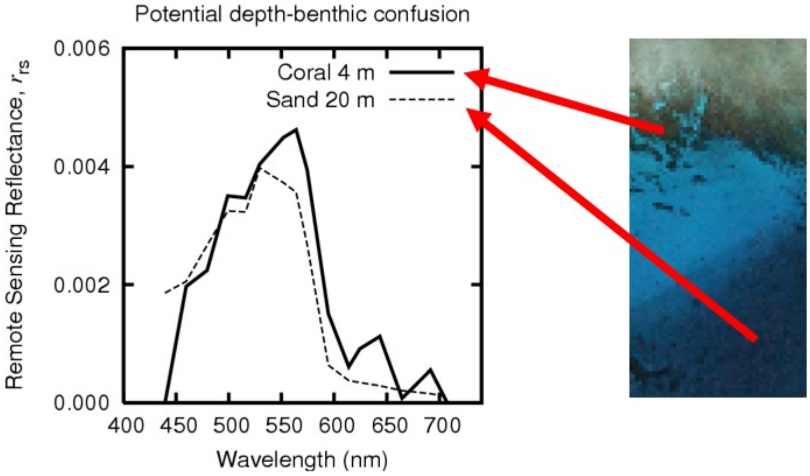

**Fig. 3** SDB Fundamental Uncertainty: Only the analyst can decide whether the same dark pixel corresponds to a deep sandy bottom or a shallow dark bedrock. Source: Dr Hedley's IDA tutorial 2019.

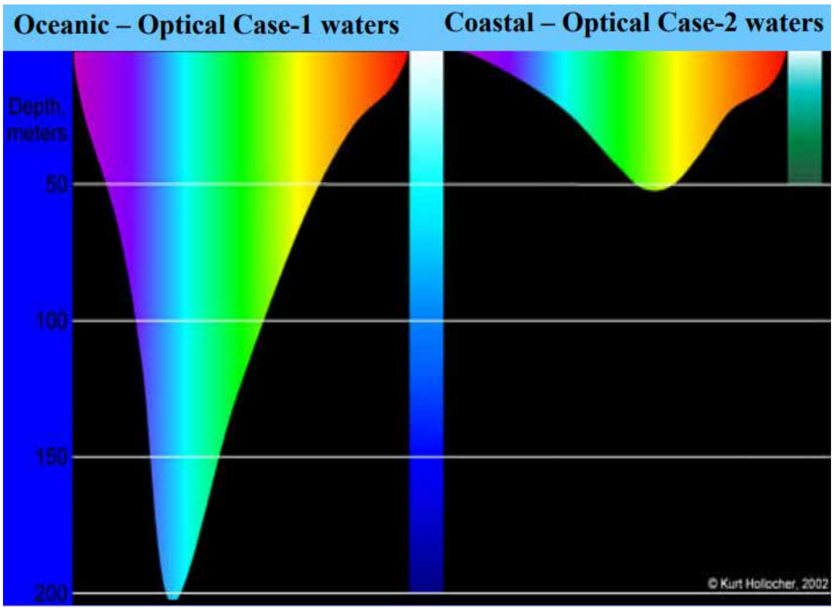

**Fig. 4** SDB fundamentals: Light penetration in Cases 1 and 2 waters. Image courtesy of Kyle Carothers, NOAA-OE.

A last point, possibly the most important, is the paramount predominance of human supervision over models. SDB techniques process the colour of each pixel individually and are incapable of establishing a correlation with the next pixel and surrounding environment. Only an experienced analyst can form an intelligent judgement and decide between two solutions (Fig. 3) which is the most plausible. With the advent of Landsat-8 and Sentinel-2 time series, this supervised approach can be substantially simplified by machine learning methods, such as Random Forest (Breiman, 2001), trained to generate optimal solutions amongst numerical models.

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[2] The reflectance *R(z,λ)* of the surface of a material is the fraction of incident radiant flux reflected by that surface.

[3] Sentinel-2 L2A: Bottom-Of-Atmosphere (BOA) reflectances in cartographic geometry.

[4] $E_0$ = scalar irradiance; $R$ = irradiance reflectance; $0^+$, $0^-$ = altitudes $0$ above and under the surface; $\theta$ = direction; $\Phi$ = power. These are further developed at Table 1.

**Table 1** A selection of common RTE symbols and abbreviations (Miller et al., 2005).

| | |
|---|---|
| AOP | Water Apparent Optical Properties, related to IOP through the RTE |
| DOP | Depth of Penetration. Depends on IOP, air/sea interface, sky radiance, sun viewing angle and irradiance. |
| IOP | Water Inherent Optical Properties, i.e. concentrations in Chlorophyll, CDOM, etc. |
| OAC | Optically Active Components |
| RTE | Radiative Transfer Equation |
| $E_d^{0+}(S_{ky}\Theta_S)$ | Irradiance measured on the sea-surface, combining skylight ($S_{ky}$) and sunlight ($\Theta_S$) |
| $E_d(z,\lambda)$ | Downwelling irradiance |
| $K_d(z,\lambda)$ | Diffuse attenuation coefficient, i.e. decrease with depth of the ambient downwelling irradiance |
| $\phi_v$ | Viewing azimuth angle from the solar plane |
| $L_w$ | Water leaving radiance. This measures light intensity of light, i.e. the luminance emitted from a surface per unit area (solid angle) |
| $\lambda$ | A wavelength in the $\Omega_{VNIR}$ region |
| $0^+$ | A position of observation just above the sea-surface |
| $0^-$ | A position of observation just below the sea-surface |
| $R_{rs}(\theta,\phi,\lambda)$ | Spectral Remote Sensing Reflectance of the ocean |
| $R(z,\lambda)$ | Irradiance Ratio ($E_u/E_d$), a measure of how much of the radiance $E_d$ traveling in all downward directions is reflected upward into any direction $E_u$ |
| $S(z,\theta,\phi,\lambda)$ | Source light term |
| $S_{ky}$ | Skylight with sources (light diffusion on molecules and aerosols) and sinks (clouds, attenuation on molecules and aerosols) in the whole semi-hemisphere |
| $\rho$ | Light reflectance (ratio of radiances) on sea bottom |
| $\Theta',\phi'$ | Incident direction |
| $\Theta,\phi$ | Scattered direction |
| $\Theta_v$ | Viewing angle from nadir |
| $\Theta_s$ | Subsurface solar viewing angle from zenith |
| $\Omega_{VNIR}$ | Visible and near infrared spectral band, between 400 and 1100 nm |
| $z$ | Depth z at position *Lat*, Long |

### 2.1.2 Equations, notations, models, and software

Rather than going through the mathematical developments needed to describe the laws of radiative transfer, we shall review the ingredients used in the SDB cooking recipe, i.e. the light propagation basic principle, the Radiative Transfer Equation, the variables at play and their mathematical notations, the unknowns, and finally the software.

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### *Maximum depth achievable in coastal waters*

Considering that photons must travel a round-trip, 25 metres is the maximum depth achievable in Case-2 shallow waters as shown by the NOAA light absorption diagram (Fig. 4).

### *The Radiative Transfer Equation (RTE)*

The useful depth information has to be extracted from the radiance components received by the satellite detector. Presuming that data have already been corrected for atmospheric and air/water interface effects, the relationship between the water Intrinsic Optical Properties (IOPs) and the radiance can be described by the formula that Curtis Mobley calls **the formidable integro-differential Radiative Transfer Equation** (Mobley, 2001).

$$\begin{aligned}\cos\theta\frac{dL(z,\theta,\varphi,\lambda)}{dZ} &= -c(z,\lambda)L(z,\theta,\varphi,\lambda)\\ &+\int_{4\pi} L(z,\theta',\varphi',\lambda')\times\beta(z,\theta',\varphi',\theta,\Phi,\lambda)d\Omega'\\ &+S(z,\theta,\varphi,\lambda)\end{aligned}$$

Rather than discussing the RTE in detail, we shall give an idea of the variables at play by displaying Mobley's notations, familiar to environment scientists who normally prefer focusing on practical software applications than cross-questioning already established fundamentals.

### *Mobley's notations*

The table below gives a rough idea of the variables at play and the symbols most commonly used by Mobley and the RTE.

### *RTE basic function and algorithms*

To retrieve depths in shallow-waters, remote sensing must simultaneously combine the effects of bottom reflectance, water-intrinsic optical properties, atmospheric corrections, interface transmittance (characterised by surface glint) and the various scattering and absorption properties depicted in Fig. 2.

SDB's basic assumption is that all power fluxes, i.e. the various radiances and irradiances, decrease exponentially with depth in homogenous water, free of local boundaries effects. Using Mobley's notation, the relation between depth and radiant energy due to this exponential decrease can be written conveniently as:

$$E_d(z,\lambda)\equiv E_d(0,\lambda)\exp\left[-\int_0^z K_d(z',\lambda)dz'\right]$$

in which appears the SDB's most important function $K_d(z,\lambda)$, e.g. the diffuse attenuation for spectral irradiance. K functions depend mainly on water properties (IOPs), and marginally on environmental conditions such as sun incident light and sea state. K functions are computed using Mobley's Hydrolight radiative transfer numerical model that gives analysts the ability to simulate different environmental conditions and adjust their parameters.

Bottom detection occurs when the optical sensor sees a fluctuation due to a photon hit. The fluctuation might be on one pixel $\delta L_b(\vec{x}_0)$ or a few pixels $L_b(\vec{x}_0)$ where $V(\vec{x}_0)$ is a vicinity of $\vec{x}_0$. Bottom detection occurs when $\mathrm{mes}\,\{\delta L_b(\vec{x})\}\geq\Delta^{\mathrm{trh}}_{\mathrm{mes}(L)}$ where mes is a measure of the water leaving radiance $L_w$, and $\Delta^{\mathrm{trh}}_{\mathrm{mes}(L)}$ is a threshold.

### *Unknowns and the obligation to restrain analysis to small areas*

As said earlier, there is almost infinite unknowns at play to characterise the layers that photons have to pass through during their transit from the sun and sky to the sea bottom and back to the satellite sensor. Most SDB parameters are determined by field observations and plotted on spectral diagrams, found in scientific papers, where they can be retrieved and be fed into SDB models.

These parameters include absorption, scattering in the water column and Rayleigh scattering in the upper atmosphere, reflection from the bottom and the surface, emissivity from the sun and the sky above, transmissivity across the air/water boundary, glint corrections depending of the force and direction of the wind and swell, water organic and inorganic constituents, types of aerosols, ad *libitum*.

To find a solution to such a large system, the ocean has to be subdivided into small homogeneous areas of similar composition, each of which can be described by a simple forward model of the form:

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

where $R_{rs}(\lambda)$ is the remote sensing reflectance of the ocean as seen from space, $P$ is the concentration of phytoplankton, $G$ is the inorganic Gelbsdorf absorption, $X$ is the particle backscattering, $H$ is the depth, $E$ is an endmember characterising the types of bottom (sand, mud, rocks, algae; etc.) and $m$ is their mixing ratio.

It might be tempting to use *n*-bands hyperspectral instead of *m*-bands multispectral sensors to augment the number of equations $(n > m)$ but this is an illusion (Miller et al., 2005) as the signal to noise ratio would then become indistinct and unable to provide exploitable solutions. Satellite hyperspectral sensors, with their well-known ability to classify bottom structures, have very narrow bands (1:10th to 1:100th those of multispectral captors such as Sentinel MSI or Landsat OLI) and receive less photons, making them comparable to VHR satellites that deliver less depth information due to their lower SNR.

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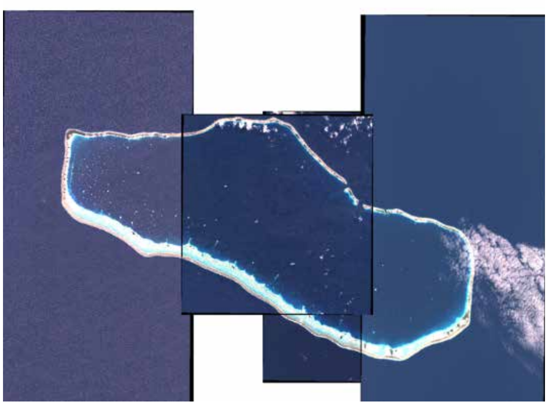

**Fig. 5** A Pleiades 4-images mosaic: In spite of appearances, the two left scenes are worthless because of glint.

### *The two empiric and physics-based approaches*

All SDB models must be able to match convincingly the solutions they have provided with the observed reality. Unfortunately, due to the quasi-infinity of unknowns and the limited availability of observations, there can't be any solution unless carefully thought simplifications are introduced. These in turn entail differences between the model's results and the field observations that define an uncertainty interval characterised as best as possible by error bars.

There are traditionally two types of SDB models based on spectrum-matching; the first, called "Empiric" or data-based, after Lyzenga (1978) and upgraded by Stumpf et al. (2003), requests establishing, by Monte-Carlo experiments, a linear regression between observed points and modelized pixels of known radiance and assumes that the behaviour law thus defined can be applied across the whole image; the second, called "Physics-based" after Lee et al. (1999) relies on direct radiative transfer models simplified by the use of semi-analytic formulae.

In fact, both approaches are empiric and physics-based. Both assume that the light attenuation with depth is approximately exponential, require some preliminary knowledge of the water column constituents and spectral behaviour of the substrate, and both are of the form:

$$R_{\mathrm{rs}}(\lambda) \approx B + A^{\exp(-k \cdot \mathrm{depth})}$$

where the coefficient A, B and the k function are deduced by regression to empirical data for the whole image by Lyzenga and constrained within every pixel by what is physically possible in physics-based methods.

### *Software*

Software methodologies leave aside the problem of atmospheric correction and focus on analysing the separation between the signals from the water column and seabed. There are two groups of methods depending whether radiances are measured (e.g., absorption and scattering coefficients), or pre-defined.

The table below quotes twenty known models referred to in the list of publications in fine, but there seems to be no limit to the number of candidates (ARGANS internal R&D; Zoffoli et al., 2014).

## *2.1.3 Satellite images*

### *Image selection*

There cannot be good SDB modelling without excellent images. Twenty years ago, good images were so rare that it could take up to five years to select, at great cost, a reasonably exploitable scene (Fig. 5), but things have changed for the better. EO analysts now have access to a large supply of images of various resolutions and performances.

Further, the advent of high-resolution, high-revisit, free-access constellations, such as the Sentinel family of the Copernicus programme, have considerably changed the traditional approach by offering calibrated time series that can be merged into co-registered and spectrally normalised "Perfect Images", free of clouds and transient artefacts.

Although not as simple as it looks, downloading large numbers of images can be realised from ESA or NASA open-access hubs, but is best achieved by non-commercial applications such as CODE-DE (https://code-de.org/) that offers more than 15 PB of Sentinel and Landsat data, or at cost through commercial service providers, such as Amazon, Sinergise and others, who offer additional facilities such as full visualisation of scenes allowing for a preliminary selection according to cloud cover, glint and water turbidity.

### *HR or VHR imagery?*

Until very recently, it was assumed that best results could only be obtained with expensive, very high-resolution (VHR) imagery, rather than using free HR satellites such as Landsat 8 or Sentinel 2. This changed dramatically after extensive tests, covering a large number of sites, images and constellations carefully selected by a Hydrographic Office, established that better results were in fact obtained with time series of lesser resolution, and not occasionally but systematically. Although results are generally protected by Intellectual Property Rights, the test results obtained in 2019 under the aegis of the European Space Agency can be made available to the public.

This can be explained in simple terms by considering how an HR 10 × 10 metre pixel receives more photons than a VHR 0.5 × 0.5 metre's, resulting in a better Signal to Noise Ratio. But this is not all as better captors such as Sentinel-2 MSI endowed with more spectral bands and band shift control have been developed. And further, one may speculate whether a

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**Table 2** A selection of twenty SDB models.

| Reference | Approach | Resolution | Output | Applicability |
|---|---|---|---|---|
| Lyzenga | Band combination | Multispectral | Combination of bands | First “empiric” model (1978) applicable in high transparency waters and homogeneous bottoms. Poor in shallow waters. |
| Spitzer & Dirks | Band combination | Multispectral | Composition of 2 to 3 bands | Developed for SPOT and Landsat. Same as Lyzenga. |
| Tassan | Band combination | Multispectral | Combination of bands | Sequential application to turbidity gradients. |
| Sagawa et al. | Band combination | Multi and Hyperspectral | $\rho$ index | Suitable to poor transparent waters but needs good map references. |
| Conger et al. | Band combination | Multi and Hyperspectral | Pseudo-colour bands | Assumes homogeneous environment. Ineffective in red band. |
| Gordon & Brown | Algebraic | Multi and Hyperspectral | $\rho$ index | Assumes homogeneous environment and empirical determination of parameters. |
| Maritorena et al. | Algebraic | Multi and Hyperspectral | $\rho$ index | Assumes homogeneous environment and high transparency. |
| Bierwirth et al. | Algebraic | Multi and hyperspectral | $\rho$ derivation | Needs clear waters. Yields composite maps of depths structure and bottom reflectance. |
| Purkis & Pasterkamp | Algebraic | Multispectral | $\rho$ index | Assumes high transparency and needs good map references. |
| Lee et al. | Algebraic | Multispectral | $\rho$ index | Semi-analytical. Uses detailed IOP and assumes homogeneous environment. |
| Yang et al. | Algebraic | Multispectral | $\rho$ index | Analytical. Suitable to multi layered water column. |
| Louchard et al. | Optimized matching | Hyperspectral | Bottom types, Z and OAC | Requires careful preparation of spectral library. |
| CRISTAL | Optimized matching | Hyperspectral | Bottom types, Z and OAC | Requires careful preparation of spectral library. |
| BRUCE[5] | Optimized matching | Hyperspectral | Bottom types, Z and OAC | Requires careful preparation of spectral library. Useful in low diversity areas. |
| SAMBUCA[6] | Algebraic | Hyperspectral | Bottom types, Z and OAC | Assumes that bottom is a linear combination of two substrates. Derived adaptation of Lee et al inversion scheme to optimise depth retrieval. |
| SWAM[7] | Algebraic | Hyperspectral | Bottom types, Z and OAC | Adaptation of SAMBUCA developed for integration into SNAP/Sentinel-2 toolbox. This still needs software optimisation to make it performing and user-friendly. |

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[5] Bottom Reflectance Un-mixing Computation of the Environment model, an inversion method derived from the algorithm (Klonowski et al., 2007).

[6] Semi-Analytical Model for Bathymetry, Un-mixing and Concentration Assessment, an inversion method derived from the algorithm by Brando et al. (2009).

[7] Software User Manual (SUM) of the SEOM S2-4Sci Land and Water: Coral Reefs (Sen2Coral) project funded by the European Space Agency (ESA).

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| | | | | |
|---|---|---|---|---|
| BOMBER | Algebraic | Hyperspectral | Bottom types, Z and OAC | Derived adaptation of Lee et al inversion scheme to optimise bio-optical outputs. |
| Hedley's Image Data Analysis (IDA, ex-ALUT) | Optimized matching | Hyperspectral | Bottom types, Z and OAC | Derived adaptation of Lee et al inversion scheme. A user-friendly workhorse that optimizes computing time by subdividing parameters space. |
| PIF | Multitemporal analysis | Multi and hyperspectral | Normalised time series | Pseudo Invariant Features using DNs (digital numbers) of co-registered time series of same satellite. |
| Bertels et al. | Geo-morphologic | Multi and hyperspectral | Maps of bottom types | Suitable to reefs of consistent bottoms and environment. |

**Table 3** Comparison of HR and VHR assets.

| Assets | HR (Sen-2) | VHR (WV, Pleiades…) | Comments |
|---|---|---|---|
| Sensor performance | ✓ | ✓ | CNES would advocate rightly that Pleiades and S-2 MSI performances are similar, but then, the use of HR time series confers an advantage over single VHR images in SDB applications. |
| Band shift control | ✓ | | |
| Photons count | ✓ | | HR pixels contain at least 100 times more information than VHR's |
| Interpixel Signal to Noise ratio | Low | High | |
| SDB usable Spectral bands | 5 | 3 to 5 | |
| Revisit time at Equator | 5 days | | |
| Suppression of clouds and transients | ✓ | | Time series can yield "Perfect Images" |
| Deglinting | | ✓ | HR cannot correct glint effect for waves < pixel size ≈10 m |
| Absolute horizontal precision without ground control points | 11 m | | VHR can achieve far better precision but this needs geodetic control |
| Performance on same computer | 15 minutes | 8 hours | Computing time 30 times faster |
| SDB Value-for-money | ✓ | | VHR minimum charge ≈ € 20/km2 |

0.5 × 0.5 metre resolution is really necessary when natural microstructures eventually detected by VHR images are included in the same generalised contour, stretched for security reasons at scales <1:50 000 sufficient to fill adequately the World's poorly surveyed areas. This might be objected by surveyors mainly concerned by large scales needed for harbours and berthing usage bands for which SDB, even at VHR resolution, is unlikely to comply. However, the risk of giving undue precedence to vertical precision over broader portrayal is intentionally to leave blanks on the charts while a wealth of satellite information useful to Safety of Navigation is available. The need to achieve a fair compromise between these two apparently conflicting priorities points at the importance of applying informed hydrographic judgement in conjunction with Safety of Navigation common goals. The SDB cartographer's guideline will be to comply with the CATZOC requirements, a composite criterion that comprises horizontal position accuracy, vertical accuracy and seafloor coverage. Considering the mediocrity of SDB vertical performances against the two other criteria, the analyst will apply conservative judgment to isolate potential dangers by stretching

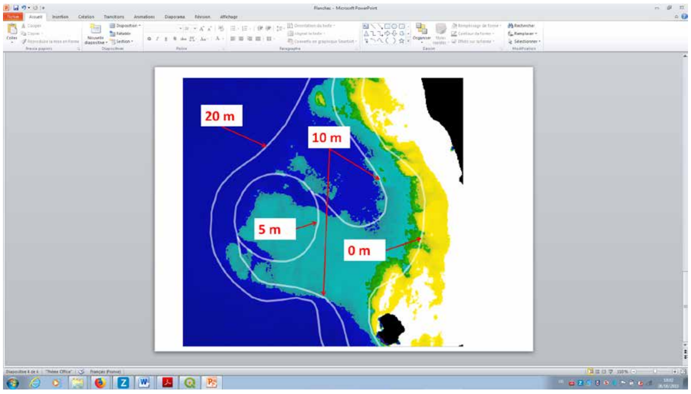

**Fig. 6** Rehabilitation of a vintage chart: The "Perfect Image" on the left confirms and completes the ancient chart on the right with an almost 100 % guarantee of shoal detection and surface coverage.

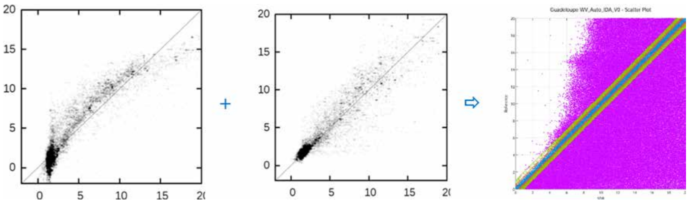

**Fig. 7** SDB depths TVU Scatter plot: Merging too many S-44 compliant areas usually ends-up with a larger non-compliant zone.

depth contours so as to discourage navigation in potentially shallow areas.

The advantages of HR time series over single VHR images have been listed and commented in the following table.

Whilst HR images, thanks to time series, are sufficient and comparatively more efficient for most hydrographic surveys at scales <1:50 000, one must not dismiss lightly the specific advantages of VHR, be they for large scale surveys or co-registration to improve HR mosaics' horizontal precision, when phenomena such as coastal erosion have to be observed. Setting aside the prohibitive computation time due to the number of pixels, if there were no limit to the amount of VHR images that could be viewed and merged, there is no doubt that marginally better results could be achieved. However, these would unfortunately come at a cost and remain unaffordable to most users, making the HR time series a unique opportunity for Hydrographic Offices and for meeting developing countries coastal charting essential requirements.

### 2.1.4 SDB novel performances

*A new paradigm…*

Hydrographers, so far, have been focussing on SDB poor vertical precision falling short of the S-44 Total Vertical Uncertainty (TVU) standards and being unlikely to improve when processing large areas. However, this vision, driven by the need to achieve high precision at large scales >1:50 000, has to change as SDB's main asset is not TVU, rather its aptitude to provide an advanced capability to detect shoals in large areas, assuming the sea bottom is visible from space. By offering 100 % coverage and very precise determination of visible structures, satellite "Perfect Images" can contribute decisively to safety of navigation by detecting dangers that can be depicted on charts and thus avoided by Navigators.

*…characterised by a near 100% guarantee of shoal detection…*

Thanks to sufficiently extended time series, the need to achieve total coverage, even in Arctic waters and, if one waits long enough, in frequently cloud-covered coasts, can now be met over large areas and avoids confusion with transient artefacts. SDB provides a guarantee, dubbed provisionally "Optical Wire Sweep", combining full surface coverage and quasi-unlimited horizontal precision of relatively large natural features, but somewhat imprecise depth assessment and inability to detect small human-made structures. (Fig. 6).

The key to detecting features is being able to see the sea floor from space, which led to the development of a DOP algorithm that will be detailed later.

*…unfortunately associated with a relatively poor vertical precision…*

TVU varies with the size of the area of interest (AOI). If the AOI is small enough and environment conditions and parameters are properly appraised, then S-44 TVU standards can be met, as shown in a recent Japanese study (Sagawa et al., 2019) using Landsat-8 time series in exceptionally clear waters. But this cannot be extended indefinitely to larger zones. Based on time considerations, a compromise has to be found between S-44 compliant micro-processing and blurry over-simplification (Fig. 7) consisting of merging areas characterised by different environments.

*…but a better control of uncertainties…*

Effective SDB applications, such as Dr. Hedley's Image Data Analysis model, depict uncertainties as error bars, but it has been determined these have been simplified for the users' convenience and could be slightly improved for better depth control. For instance, increased turbidity makes the bottom look deeper while spectral errors affect the apparent re-

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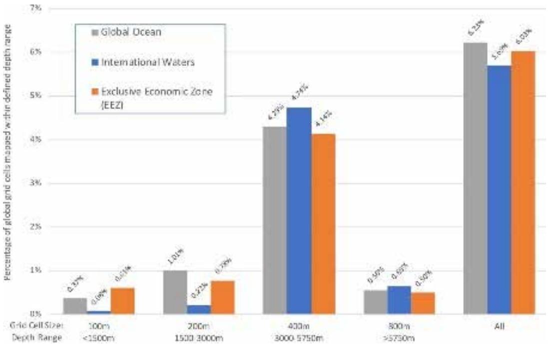

**Fig. 8** GEBCO Histogram of the World ocean percentage covered.

flectance. Failing to take into account minor sources of radiated energy, such as those generated by boundaries effects, impacts depth retrieval. All these adverse consequences necessitate exploring the models' parameters in detail and going back to Mobley's formidable RTE. Non-Gaussian processes might elicit several solutions that cannot be averaged but could be submitted with their range of uncertainties to the analyst who would then make an informed final choice.

Uncertainties sustained by an arduous examination of probability laws have been studied with the intention to qualify SDB results with improved percentages of errors. This gave rise to complex mathematical developments compiled in a number of internal research notes that can be communicated to those interested. As a principle, uncertainties distributions calculated for one image and one pixel only have to be extended to a whole batch in order to determine possible solutions, which cannot be approximated by simple arithmetic averages.

*….at an affordable cost.*

The financial criteria will likely limit the use of expensive VHR systems to specific large-scale applications despite their merits. In a global ocean bordered by coastal waters that have hardly been properly surveyed according to GEBCO records (Fig. 8), only satellites that can extract stable information from a large collection of swaths may be considered to fill the World's charting gaps systematically.

Not only do HR time series have the potential to deliver a first answer, but they can deliver it quickly, as long as the sea floor is visible from space. Looking forward, once validated and standardised, SDB methodology, which is more reliable than traditional reconnaissance survey techniques, could easily and affordably provide the required information to replace the ancient charts that still clutter our official chart series. Further, the methodology could easily be disseminated worldwide through Capacity Building initiatives and help developing countries to fulfil, with minimum help, their own cartographic needs.

## 2.2 Applications

### *2.2.1 Present-day*

With the exception of the French Hydrographic Office, who has been adding SDB-enhanced charts into the national chart series for thirty years and has developed its own procedures in the absence of IHO standards, hydrographic offices have deemed SDB to be reliable only for survey planning and topography complements to traditional charting. However, SDB is now starting to be used by the United Kingdom Hydrographic Office Admiralty charts and the United States National Oceanic and Atmospheric Administration, and is regularly tested by the Canadian Hydrographic Service with a goal to document safe navigation channels in the Northwest Passage with proper navigational charts.

In parallel, non IHO-compliant mapping services have been offered by private companies with various success, ranging from an impressive geomorphologic survey of the whole Great Barrier Reef in support of Australian Universities (Hamylton et al., 2015) to the exploration of future Marine Highways in uncharted waters[8] and determination of precise UNCLOS baselines[9].

Very recently, SDB time series have been successfully employed to reduce risk in the deployment of towed arrays in shallow waters, and tested in their ability to rehabilitate ancient charts (based on leadline surveys) in order to turn them, at minimum cost, into up-to-date navigational documents.

### *2.2.2 In future*

In the near future, it is envisaged to test the ability of Sentinel-2 time-series to reduce the considerable lack of coastal material in the GEBCO database. If successful, this test could be extended to the World database and online mapping websites would be approached to disseminate the information globally.

Sentinel-2 revisit time has been harnessed to the task of monitoring coastal erosion. To this end, time series have been combined with VHR satellites to obtain a sub-metric horizontal precision. Sentinel-2 provides 5 days revisit time and broader coverage, while WorldView or Pleiades bring the precision required to observe small coastal changes, almost in real time.

Lack of funding notwithstanding, nothing at this juncture should prevent developing countries to improve their cartographic schemes by rehabilitating older charts and filling in the blanks along their coasts with new satellite navigational charts on which the in-

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[8] GEF Concept Note: WESTERN INDIAN OCEAN Marine Electronic Highway Development and Coastal and Marine Contamination Prevention Project Phase II (2011).

[9] Benin, the Republic of Congo, Cote d'Ivoire and Togo submissions to the UN Division for Ocean Affairs and the Law of the Sea (DOALOS), 2015–2019.

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**Table 4** Excerpt of tentative SDB standards (ongoing contribution to the S-44 HSPT Proposal): The critical point is to make sure that no validation can be pronounced without sworn Hydrographers' approval.

| Parameter / Data Type | 3 | 5 | 6 | 8 |
|---|---|---|---|---|
| *EARTH OBSERVATION AND REMOTE SENSING* | | | | |
| **Capability of system to measure Depth [range in m]** | 20 | 10 | 5 | |
| **DOP (Depth of Light Penetration) [m]** | Optional | 10 | 5 | 1 |
| **Resolution (e.g. pixel size) [m]** | 20 | 10 | 5 | 1 |
| **Revisit period [days, hours]** | > 15 d | 5 to 9 d | 1 to 4 d | < 12 h |
| **Overall validation and professional expertise [FIG/IHO category, other credentials]** | Cat B | Cat B | Cat A | Cat A |

famous label, "NOT TO BE USED FOR NAVIGATION", would be removed and replaced by a less conspicuous and more subtle warning.

## 3 Latest SDB breakthroughs

### 3.1 Circumstances

SDB breakthroughs were initiated by the launching of Sentinel missions (2014) and the rapid accumulation of a large collection of satellite images demonstrating the benefits of revisit time sensed earlier by Landsat-8. It took time to fill the Sentinel database, which now occupies on the order of ten petabytes of data, and for research and development hydrographers to take advantage of newly available "Perfect Images". Testing of this concept has just been completed thanks to ESA initial funding through projects such as Sen2Coral and Sentinel Coastal Charting Worldwide tutored by knowledgeable technical officers.

Sentinel-2 was originally focussed on land but Sen2Coral, the first maritime project consisting of observing coral bleaching, demonstrated that coastal applications such as environmental mapping and nautical charting were possible and could be just as important.

In parallel, the IHO has initiated a revision of its S-44 publication on Standards for Hydrographic Surveys, offering the opportunity to introduce Earth Observation satellites as an additional instrument to the Hydrographers' and Nautical Cartographers' toolbox.

### 3.2 Time series

By introducing Sentinels' short revisit time, ESA has revolutionised a way of thinking shaped by centuries, not days. To quote two examples, in Western Europe, the chart of Northern Britany first surveyed by Napoleonic Hydrographers -and actually amazingly precise- has only been replaced recently by a modern survey using multibeam echosounders, while in West Africa the International chart series are still using coastal data collected under sail by Georgian Royal Navy Hydrographers.

The main advantage of revisit time is that, by stacking scenes of the same spot, it allows to identify and suppress transient details such as clouds, sediment plumes and other artefacts that obscure the observation of plain bottom, making it possible to merge layers of georeferenced and radiometrically normalised pixels to obtain "Perfect Images".

Two recent tests, the ESA "Sentinel Coastal Charting Worldwide" and a simultaneous extensive "Bathysat" project conducted on about ten different sites and using VHR and HR images have established that depths calculated with SDB software fed with "Perfect Images" combining up to fifty Sentinel-2 scenes are better than those derived from single VHR images (Fig. 9) selected with care.

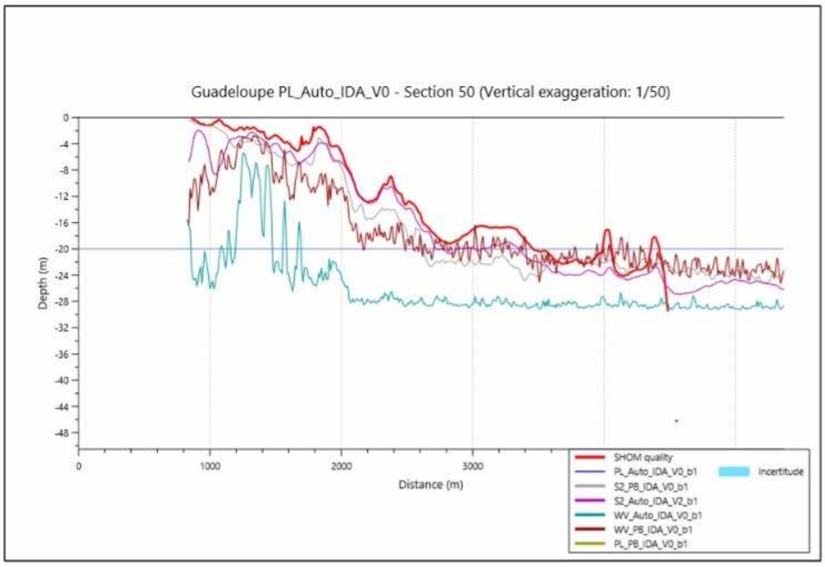

**Fig. 9** Comparison of a Sentinel-2 "Perfect Image", with Ground Truth, Pleiades, and World View cross sections: The purple trace (S2_Auto_IDA_V2_b1) follows better the red sonar profile than single VHR images WW_Auto and PL_PB.

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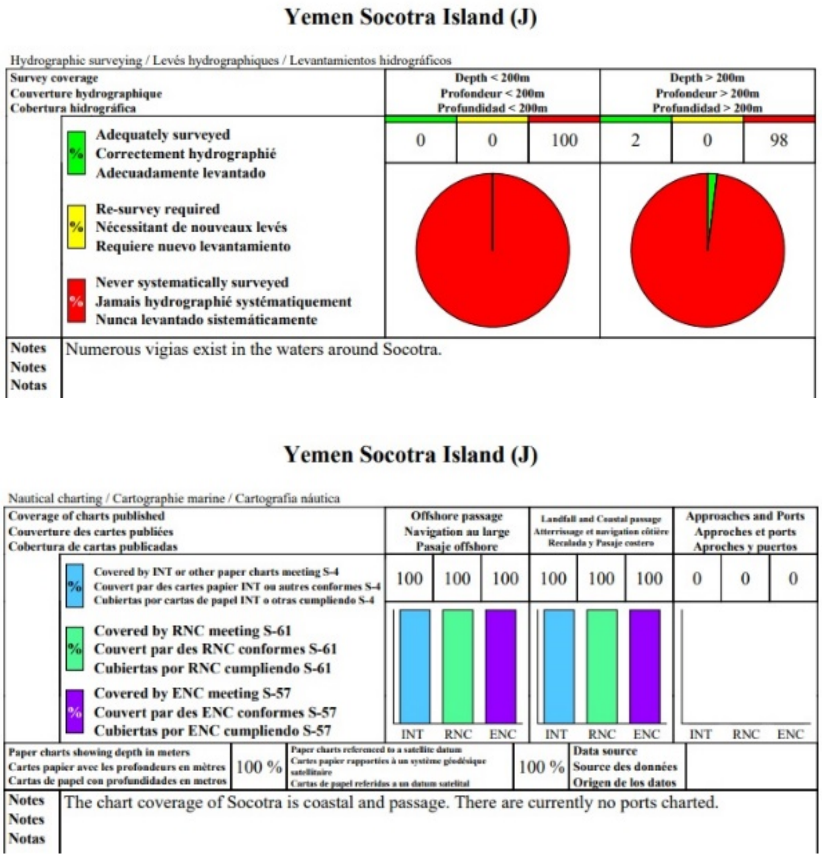

Yemen Socotra Island (J)

Hydrographic surveying / Levés hydrographiques / Levantamientos hidrográficos

| Survey coverage<br>Couverture hydrographique<br>Cobertura hidrográfica | Depth < 200m<br>Profondeur < 200m<br>Profundidad < 200m | | | Depth > 200m<br>Profondeur > 200m<br>Profundidad > 200m | | |
|---|---|---|---|---|---|---|
| | 🟩 | 🟨 | 🟥 | 🟩 | 🟨 | 🟥 |
| 🟩 % Adequately surveyed<br>Correctement hydrographié<br>Adecuadamente levantado<br>🟨 % Re-survey required<br>Nécessitant de nouveaux levés<br>Requiere nuevo levantamiento<br>🟥 % Never systematically surveyed<br>Jamais hydrographié systématiquement<br>Nunca levantado sistemáticamente | 0 | 0 | 100 | 2 | 0 | 98 |
| Notes<br>Notes<br>Notas | Numerous vigias exist in the waters around Socotra. | | | | | |

Yemen Socotra Island (J)

Nautical charting / Cartographie marine / Cartografia náutica

| Coverage of charts published<br>Couverture des cartes publiées<br>Cobertura de cartas publicadas | Offshore passage<br>Navigation au large<br>Pasaje offshore | | | Landfall and Coastal passage<br>Atterrissage et navigation côtière<br>Recalada y Pasaje costero | | | Approaches and Ports<br>Approches et ports<br>Aproches y puertos | | |
|---|---|---|---|---|---|---|---|---|---|
| 🟦 % Covered by INT or other paper charts meeting S-4<br>Couvert par des cartes papier INT ou autres conformes S-4<br>Cubiertas por cartas de papel INT o otras cumpliendo S-4<br>🟩 % Covered by RNC meeting S-61<br>Couvert par des RNC conformes S-61<br>Cubiertas por RNC cumpliendo S-61<br>🟪 % Covered by ENC meeting S-57<br>Couvert par des ENC conformes S-57<br>Cubiertas por ENC cumpliendo S-57 | 100 | 100 | 100 | 100 | 100 | 100 | 0 | 0 | 0 |
| | INT | RNC | ENC | INT | RNC | ENC | INT | RNC | ENC |
| Paper charts showing depth in meters<br>Cartes papier avec les profondeurs en mètres<br>Cartas de papel con profundidades en metros | 100 % | Paper charts referenced to a satellite datum<br>Cartes papier rapportées à un système géodésique satellitaire<br>Cartas de papel referidas a un datum satelital | 100 % | Data source<br>Source des données<br>Origen de los datos | | | | | |
| Notes<br>Notes<br>Notas | The chart coverage of Socotra is coastal and passage. There are currently no ports charted. | | | | | | | | |

**Fig. 10** One of the two hundred and sixty-three C-55 world areas displaying the state of surveys (top) and charting (bottom).

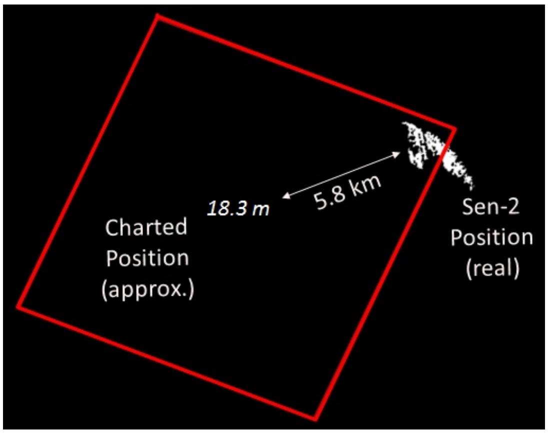

**Fig. 11** Sentinel-2 conformation of a misplaced shoal: By peering at blue spectral bands, this shoal was found on three out of five Sentinel-2 images carefully selected from a large time series of over 50 scenes spread over several months.

### 3.3 Depth of Penetration (DOP)

In order to process "Perfect Images" with their bathymetric models, Hydrographers must make sure they will be able to see the sea floor with passive EO satellites or reach it with active LiDAR.

By assessing the depth of penetration of light in a water column characterised by its intrinsic optical properties, a DOP software[10] adapted from earlier water transparency modules has been developed to determine, at a given time and for a given satellite, if the bottom is visible from above and thence, whether optical methods can be applied. To this end, before deciding to start an SDB or LiDAR survey, analysts should be able to consult the reference IHO document, the C-55 Status of Hydrographic Surveying and Charting Worldwide completed with DOP statistics (Fig. 10).

By using the colour of the ocean to determine the Intrinsic Optical Properties of any water body and applying the classical logarithmic absorption curve across the light spectre, DOP can calculate the light penetration and determine the cut-off threshold beyond which the reflected bottom signal is lesser than the noise. DOP can be used to confirm whether optical bathymetry is feasible in coastal regions inaccessible to boats equipped with multibeam echosounders.

Depending on the precision required, DOP can use colour of the ocean data retrieved from MERIS, Sentinel-3/OLCI or Sentinel-2/MSI.

### 3.4 Confirmation of visible shoals by making use of revisit time

Revisit time confers an entirely new detection capability to satellites, making them a survey tool on their own and not just a complement to sonar surveys. Until recently, disproving doubtful shoals depicted on charts would have required a new hydrographic survey whilst now, provided that the bottom is visible and analyst have access to large collection of images, SDB detection can provide a remote sensing confirmation of existence (Fig. 11). Indeed, identical pixels observed in the same place at different times categorises them as belonging to a permanent feature, however, analysts must be certain that the bottom is visible, hence the importance of evaluating DOP in all optical control methods. DOP is becoming the key criteria to validate optical detection.

### 3.5 SDB costs considerations

Be they powerful oil and gas companies or impoverished coastal States, cost considerations are important for potential users of SDB. Reducing risk in its geophysics surveys to support deployment of very large towed arrays mentioned earlier, a supermajor classified SDB exploration along "Best achievable"

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[10] This software is an output of the "Sentinel Coastal Charting Worldwide" project mentioned earlier. It has been delivered to ESA under the name "Impact of field-proven SDB on the world uncharted waters (DOP)".

**Table 5** Sentinel-2 Pros & Cons.

| Pros | Cons | Comments |
|---|---|---|
| Value-for money[11] | | Sentinel-2 offers an open and free access to its imagery compared to an average 20€/km$^2$ for VHR commercial images. |
| Radiometric calibration | | Control of spectral shift is essential to be able to compile images shot at different times. |
| 5 days Revisit time at Equator | | |
| Suppression of transients | | Production of “Perfect Images” by compilation of large collections of images |
| 11 metres absolute horizontal precision | | No more topographic surveys for scales <≈1:50 000 for sufficiently clear shallow waters properly assessed by DOP analysis. |

and “Good enough” criteria, using commercial VHR images in the first case and free HR time series in the latter. Much to the buyer’s surprise, there was no significant differences between results and a better detection capacity in favour of time series. “Good enough” surveys were in fact cheaper and faster to process while “Best achievable” led to never ending developments. As a result, this dual approach was finally abandoned.

## 4 Conclusions: HR time series Pros & Cons

Based on 2019 extensive tests results following dozens previous satellite surveys conducted with less performing constellations, the HR time series pros and cons, best represented by Sentinel-2, can be listed as follows in Table 5.

Although slightly less performing due to their earlier entry in service (2013), these conclusions are valid for Landsat-8, as observed in the ESA Sen2Coral earlier project (Hedley et al., 2018).

With the advent of performing new generation satellites offering global revisit time such as Landsat-8 and Sentinel-2, SDB has moved from being an exploratory methodology, usable with great circumspection, to becoming an indispensable method for improving safety of navigation in shallow waters, provided that the sea floor can be observed unambiguously from space. This prerequisite can be met with the emerging concepts of “Perfect Images” and Depth of Penetration.

SDB awareness shared by too few Hydrographic Offices is now spreading globally thanks to the support offered by authoritative voices such as IHO and the European Space Agency.

All that is left is for Hydrographers to rigorously develop and standardise a method, already widely used by Biologist and Environment Scientists, that has the potential to extend sufficiently precise coastal mapping to the World’s uncharted waters.

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[11] With regards to value-for-money, one has to be aware that there are hidden costs to Sentinel-2 open-access images supported by ESA’s 22 Member States. *“The vision of ESA is to enable the maximum benefit of Earth observation for science, society and economic growth in Europe, served by European industry. ESA will implement this vision through its Earth observation programmes, working in close cooperation with Member States, the EU, EUMETSAT and European industry within the widest international framework.”*

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## Authors' biographies


Jean Laporte

A former Naval Aviator and senior Cat A Hydrographer, Jean Laporte is ingénieur général (Flag Officer, Reserve Service) of the Armament Corps. He has spent most of his career as Charge Hydrographer in the French Hydrographic Office and is currently Chairman of the IHO Hydrographic Dictionary Working Group and ARGANS Managing Director. His scope of expertise encompasses hydrography, charting, air and shipborne surveys, satellite bathymetry (SDB) and remote sensing, International laws of the sea (UNCLOS & SOLAS), EEZ border agreements, bilateral co-operation agreements, Marine Electronic Highways, Capacity Building and finally, Chinese history and culture.


Henri Dolou

A FIG/IHO/Cat A Hydrographer, Henri Dolou spent 30 years as Engineer and Charge Hydrographer in the French Hydrographic Office where he was involved in surveys covering the world's oceans and seas. He remains an IHO Advisor in African Capacity Building and Professor on hydrography and oceanography in various French institutions. His scope of expertise encompasses hydrography, data Quality Control, charting, satellite bathymetry & remote sensing, spatial oceanography, International laws of the sea (UNCLOS & SOLAS), EEZ border agreements, Capacity Building, Risk management & Auditing.


Joseph Avis

Joseph Avis received his BSc in Physical Geography before completing his MSc in Remote Sensing and GIS at Aberystwyth University, Wales, UK. His MSc thesis was researching the impact of suspended sediment on mangrove forests through remote sensing data. In 2018 Joseph joined ARGANS as an Earth Observation Scientist where he applied his expertise in hydrological and geomorphology applications on a range of Earth Observation projects. Joseph has since taken on the role as Technical Lead of ARGANS Satellite Derived Bathymetry projects working with ESA and a national hydrographic agency where he manages a team split between UK and France.


Olivier Arino

Dr Olivier Arino received his PhD in Remote Sensing with maximum honours from the Institut National Polytechnique de Toulouse in 1990. After a postdoc at CNES/CNRS focussed on the International Geosphere Biosphere Programme of the European Commission, he joined the European Space Agency in 1991, where he worked as ENVISAT product engineer for the next seven years, then Head of Project section and Application section. He initiated the GlobSeries projects that led to ESA's Climate Change Initiative and authored more than 100 Scientific papers in different fields such as Albedo, Vegetation, Land Cover, Active Fire Detection and recently, Coastal Charting.

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