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International Hydrographic Organization
Guidance to Satellite-Derived Bathymetry

IHO

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About the cover page

In the spirit of using artificial intelligence (AI) technology, both the front cover image and its description are based on AI. The following description of the cover page is written by ChatGPT. “The cover illustration is an entirely computer-generated image created by a neural network model called DALL-E, developed by OpenAI. This model is capable of generating high-quality images from textual descriptions by using a combination of deep learning techniques, including transformer networks and generative adversarial networks (GANs). DALL-E's unique ability to create novel and imaginative images from textual input has generated significant interest and excitement within the AI and technology communities and are increasingly being used in artistic, scientific, and commercial contexts.”

PREFACE

This International Hydrographic Organization (IHO) Publication, (B-13) "Satellite-Derived Bathymetry Best Practice Guide", defines a guidance for Satellite-Derived Bathymetry. It is designed to improve the understanding of the technology and the use to map and monitor the marine environment.

Formal discussions on establishing an expert team began in early 2020. This then became a formal Project Team under the IHO's Hydrographic Surveys Working Group (HSWG) in 2021. In the creation of this first edition, the IHO Satellite-Derived Bathymetry Project team liaised with the Hydrographic Surveys Working Group (HSWG) membership and Satellite-Derived Bathymetry community.

Hydrographic technologies, including Satellite Derived Bathymetry (SDB) concepts and solutions are continually evolving, as is the expanding community of users. As such, the B-13 publication shall also evolve and expand to provide the most current information to hydrographers and other shallow water stakeholders.

This document provides technical best practices and guidelines. This document does not supersede national or international laws, standards, and regulations.

GLOSSARY

Cut-Off depth defines the transition depth zone where sunlight is reflected by the seabed or by the water column.

Band represents a segment of the electromagnetic spectrum.

Feature: Any object, whether natural or manmade, which is distinct from the surrounding area

Ground Control Points (GCP) are measured or clearly identified coordinates on the surface of the Earth.

High resolution (HR) satellite imagery are imaging satellites which have a spatial resolution / pixel size of 5-30m.

Hyperspectral sensors record the radiation in more than 100 bands.

Metadata are data describing a data set and its usage.

Multispectral sensors record the radiation in multiple bands. Currently 4-13 bands are common for multispectral satellite sensors which record wavelengths from blue to short wave infrared.

Optically shallow water zone is the water depth zone where sunlight is reflected by the seabed.

Optically deep water zone is the water depth zone where all sunlight is reflected by the water column and none is reflected by the seabed.

Panchromatic sensors record the radiation in one band. Commonly the spectral band covers all the visible wavelengths. Panchromatic imagery has typically a higher spatial resolution compared to multispectral data of the same sensor.

Radiative Transfer Equation (RTE) describes the sunlight propagation through a medium characterized by scatterers and absorbers.

Radiometric resolution is the differences in amount of radiation being reflected/emitted in the same wavelength band.

Spatial resolution describes the size of the pixel of an image in distance on ground. It defines the smallest object which can be detected by the image.

Spectral resolution describes its ability to discriminate differences in the amount of radiation. The finer the resolution, the more sensitive it is to detecting differences in the amount of reflected or emitted energy in a particular wavelength band.

Temporal resolution describes the frequency of a sensor to record the same place.

Turbidity is an optical measure of water transparency and typically defined as amount of light that is (back)scattered by suspended materials. It does not include absorption by algae pigments or organic materials, which also impacts the water depth retrieval limitations. According to the IHO dictionary it is defined as 'reduced water clarity resulting from the presence of suspended matter. Water is considered turbid when its load of suspended matter is visibly conspicuous, but all waters contain some suspended matter and therefore are turbid.'

Very-High Resolution (VHR) satellite imagery are imaging satellites which have a spatial resolution of 5m or better.

IHO FORWARD ON SATELLITE-DERIVED BATHYMETRY

David Parker: “Foreword (not statement) will be supplied by Mathias. ACTION Sam Harper when doc goes to HSWG for final review.”

INTRODUCTION

Satellite-Derived Bathymetry (SDB) is the calculation of shallow water depth from active or passive satellite sensors.

While it is difficult to collect information in shallow waters, knowledge about the depth and shape of the seafloor in these areas is critical for most maritime nations to identify navigational hazards and contribute to the blue economy. The necessity to better understand this depth zone has led coastal and maritime stakeholders to gain interest in SDB and the contribution it can make to the mapping and surveying toolbox. SDB technology allows users access to shallow water bathymetry at a lower cost compared to hydrographic survey campaigns and can be used for areas that are otherwise inaccessible or difficult to survey by other means. SDB can be especially beneficial in uncharted waters to improve safety prior to acoustic surveys.

The objective of this document is to provide background information on SDB techniques, and provide a framework for collecting, processing, analysing, interpreting, and sharing SDB data. It is intended to foster the best practices of SDB and provide important background information to SDB users.

This document also provides information on data uncertainties, to help SDB users better understand the quality, complexity, and uncertainties of SDB.

The techniques and methods which are presented to cover bathymetry retrieval can be used from airborne platforms with relevant sensors. The focus of this document however will be on satellite platforms.

This document is not intended to provide definitive guidance on how best to develop, integrate or use SDB, as the scope of SDB is far-reaching and has many applications. In the end, SDB data must be fit-for-purpose and align with the objectives of the applications that use them.

The document seeks to inform the SDB data users and to understand the principles and underlying assumptions, limitations and impacts on the usage of SDB data.

This document addresses several topics related to SDB.

Chapter 1: Satellite sensors and satellite data recording provides information on the satellite sensors and its recorded data.

Chapter 2: SDB concepts and methods describes current SDB concepts, methods and their assumptions and capabilities.

Chapter 3: Uncertainty delves into data quality issues and discusses how end-users can better understand the impact of various factors on the reliability of a dataset.

Chapter 4: Metadata describes the importance of data and metadata and details the information that is mandatory for documenting SDB results.

Chapter 5: SDB coverage and feasibility describes the potential of SDB analysis on a global scale and describes the regional potentials and environmental limitations.

Chapter 6: Applications of SDB discusses applications of SDB data and additional considerations.

CHAPTER 1 SATELLITE SENSORS AND SATELLITE DATA RECORDING

1.1 Introduction

Satellite-Derived Bathymetry requires a sensor (hardware) and relevant algorithms (software) to derive bathymetric data from the data recorded by the sensor.

Remote sensing systems which measure reflected solar radiation are called passive sensors (section 1.2). Active sensors (section 1.3) provide their own energy source for illumination and actively emit radiation which is directed toward the target to be investigated. The reflected radiation is recorded and measured by the sensor. The following subsections describe both categories.

1.2 Passive sensors

1.2.1 Introduction

Passive sensors can measure electromagnetic energy which travels in the form of waves through the atmosphere and water. These waves have different wavelengths and include the visible and infrared light which are detectable by satellite sensors and utilised for SDB studies. This subsection describes these sensors. Spectral resolution describes a sensor's ability to discriminate differences in radiation. The finer the resolution, the more sensitive it is to detecting differences in reflected or emitted energy. The level of detail on the target which can be recorded by satellite sensors is the spatial resolution. A satellite sensor records the Earth's surface radiation which ultimately is stored as numbers in a raster product with the smallest unit being a pixel. The term very-high resolution (VHR) refers to satellites which have a spatial resolution of 5m or better, the term high-resolution (HR) refers to data between 5-60m and any coarser satellite sensor refers to moderate to coarse resolution sensors. SDB analyses are typically based on VHR and HR sensors. Publicly accessible VHR sensors are commercial satellite sensors, and the licence to use satellite data can be purchased through the satellite owners. HR and coarser resolution sensors are often non-commercial and operated by national or international space agencies, such as the European Space Agency (ESA), and the U.S. Geological Survey (USGS) and National Aeronautics and Space Administration (NASA).

Passive satellite sensors measure the reflectance of the sunlight energy in different spectral bands. Spectral bands are the ranges of wavelengths which are recorded by a sensor. The higher the number of bands, the narrower the range of wavelengths of each band and the higher the spectral resolution of a satellite. Panchromatic (one broadband), multispectral (three to tens of relatively narrow bands) and hyperspectral (hundreds of very narrow bands) sensors are available in space. The wavelengths in the visible light region are of highest importance for SDB and seabed analysis because they penetrate the water column and can be reflected by the seafloor under the right conditions (see section 1.2.2).

The radiometric resolution of a sensor stands for the ability to store the radiance energy into multiple grey-scale values (bits). The finer the radiometric resolution of a sensor, the more sensitive it is to detecting small differences in reflected or emitted energy. Most modern satellite sensors have a typical bit depth of 12 bits which means that each band can store 2^{12} (4096) different values.

The temporal resolution of satellite sensors defines the capabilities of sensors to record the same place on Earth over a period of time. A high temporal resolution allows monitoring of coastal sites frequently, allowing changes of the seabed and intertidal dynamics to be identified by those sensors. The temporal resolution also specifies the ability to record at different tides and other environmental conditions.

A list of satellite sensors and their key specifications is provided in the annex.

Satellite imagery can be accessed at different processing levels. These processing levels describe the amount of data manipulation and processes which have been applied to the imagery by the image provider. Common processing levels are orthorectification, the correction of land terrain heights, or a constant base height above geoid without terrain correction. The latter is considered as more accurate for near coastal regions, especially for those backed by steep terrain. Other processing levels are the correction of atmosphere, image mosaicking of multiple satellite records, colour balancing, pan-sharpening or AI-model based increase of spatial resolution (super resolution). The definition and provided options of the processing levels depend on the satellite provider. The selection of the most meaningful processing level for SDB analysis depends on the analytical method and needs to be considered accordingly.

1.2.2 Impact of environmental conditions and recording geometry

Satellite imagery represents the foundational data of the SDB analysis, and the selection of the satellite scene(s) can have a significant impact on bathymetric coverage, its accuracy, and the amount of post-processing required. Care must be taken during image selection to minimize any factors that negatively affect SDB quality. In practice, it is rarely possible to identify a single satellite image acquired under perfect environmental and acquisition conditions. Algorithms that can use multiple satellite images as input are "multi-image" SDB approaches. These are typically used when environmental conditions are complex, and several satellite records are required to handle them. High temporal resolution is advantageous for a multi-image SDB analysis due to the repetition of imagery over a single area. Multi-image approaches to SDB are especially helpful for filling in gaps due to cloud cover, turbidity, breaking waves, and other episodic factors, as well as improving the accuracy and addressing false shoaling, due to periodic turbidity. There are either statistical methods of creating composite SDB (Caballero and Stumpf 2020[1]) or methods which use multiple imagery at the derivation of depth itself (Heege 2012[2]). It should be noted, however, that there are trade-offs to multi-image approaches. One challenge is that the different water levels need to be considered and that the seabed needs to be stable for the length of the time window over which the input scenes are aggregated or averaged. Longer time series can improve the

[1] Caballero, I. and Stumpf, R.P., 2020. Towards routine mapping of shallow bathymetry in environments with variable turbidity: Contribution of Sentinel-2A/B satellites mission. Remote Sensing, 12(3), p.451.
[2] Heege T, 2012. US patent US9613422B2 sing multispectral satellite data to determine littoral water depths despite varying water turbidity.

results but introduce the complication of seafloor change having occurred during the time window.

The following table describes the important factors for satellite image selection for SDB analysis.

Table 1: Important factors to identify satellite records for SDB analysis.

Factor	**Description**	**Impacts on SDB**
Adjacency Effect	Light reflectance from bright objects (coasts, clouds) which scatter into the path of upwelling radiance of the adjacent area (shallow waters).	A specific very localised atmospheric scattering effect which can introduce errors, especially at bright near-coastal sites and inland waters. It can be difficult to identify and mitigate for objects such as clouds just outside the edges of images.
Bottom reflectivity	Reflectivity of the top surface of the seabed	For all SDB methods which use the visible light spectra (except bathymetry from waves), the seafloor reflectivity is of highest importance for the SDB analysis. The higher the reflectance the better. In return, if the seabed has very minor to no reflectance, the SDB outcome is likely to have increased uncertainties. Basalt hard bottoms are examples of low-reflectance seabed. Additionally, vegetation cover, such as dense seagrass, can be very low reflectance.
Floating objects/obstructions/ ice cover	Whatever material staying/drifting on water surface	Floating objects reduce or hamper the reflectance of sunlight from the seafloor and thus limits the ability to map the seabed and needs to be masked in the QA/QC process. Floating objects can be vessels, floating sargassum mats, surface oil or debris.
Haze, clouds and cloud shadows	Haze refers to a condition of limited visibility caused by fine dust particles suspended in the air or light water vapours. Cloud refers to a visible collection of fine water droplets and frozen water crystals suspended in the atmosphere.	Haze causes the light reflected from the Earth to scatter in different directions, so the low-energy reflected light is lost and cannot be detected by the reflectance sensors on board the satellites. Clouds act like an opaque object in the path of both incoming sunlight and reflected light, absorbing most of the reflected light. The areas directly under the cloud are therefore masked out, leaving no meaningful data that could be available for analysis for SDB calculation. Cloud shadows, i.e. areas that are prevented from sunlight reaching the Earth's surface by the cloud above, result in lower light intensity in the affected areas and thus a proportional reduction in the reflected light that can leave these areas. The areas affected by cloud shadows are usually larger than the nominal size of the cloud itself and

Factor	Description	Impacts on SDB
		therefore have a negative effect on the reflectance available for the calculation of the SDB.
Submerged vegetation	Aquatic vegetation colonising the bottom substrates (e.g. dense kelp forests)	Areas with very dense submerged plant growth, such as dense kelp forests may absorb all incoming light and thus limit the ability of SDB methods to map the seabed and increase vertical accuracies. SDB data are in theory surface heights, including the height of the canopy of aquatic vegetation.
Sunglint	Mirrorlike reflectance of the water surface, caused by the recording geometries of sensor and sun	Sunglint significantly reduces the seafloor reflectance and thus increases vertical uncertainties and reduces the coverage of SDB processes.
Solar Elevation	Height of sun above the horizon	At very high polar latitudes, solar elevation might be so low as to not provide sufficient illumination through the water column. This may be a seasonal effect mitigated by choosing suitable months.
Turbidity	According to the IHO dictionary it is defined as 'reduced water clarity resulting from the presence of suspended matter.'	Interferes with the scattering and light penetration into the water column, hence impacting the retrieval of SDB and the maximum depth of SDB data.
Wave breaking	Wave breaking zones of the shallow waters	Wave breaking does not allow sunlight to be reflected by the seafloor. SDB data will be biased at locations with wave breaking, which need to be masked.
Waves	Up and down motion of water caused predominantly by the action of wind on the water surface	When sea water is whipped up by winds and other phenomena, the surface of the water body gets disturbed. The more the disturbance, the less it allows sunlight to penetrate deeper into the water column. Therefore, when wind speeds are high and wave-heights are significant, then the reflected sunlight would have significant noise, thereby affecting the process of ascertaining the actual depth at the affected area.

A visual example of each of those factors is provided in the following figures.

Table 2: Image examples of satellite records negatively affected by different factors.

Sunglint 	Wave breaking and resuspension of sediments 
Wave activities 	Turbidity 
Bottom reflectance and submerged vegetation 	Haze 
Floating objects (and wake) 	

Figure 1: Example of satellite imagery recorded in different environmental conditions. Imagery © Maxar, 2022

1.3 Active sensors

Active sensors use their own source of energy or emission source to illuminate objects or regions of interest. There are two types of active remote sensing for deriving bathymetry from ocean observation, 1) Synthetic Aperture Radar (SAR) sensors and 2) lidar (Light Detection And Ranging) sensors. These generate and focus electromagnetic radiation towards the Earth's surface and then measure the intensity and the travel time of those pulses after they are reflected or refracted back.

Lidar is an active remote sensing technology that combines laser ranges with sensor trajectory (position and orientation) and pointing angle measurements to obtain 3D spatial coordinates of points from which a laser pulse was reflected. While most lidar systems are topographic-only systems, bathymetric lidar systems use green-wavelength (typically, 532 nm) light and custom receivers and processing software to generate bathymetry. Lidar has the advantages of being highly efficient and cost effective for data collection, especially in shallow waters where multibeam sonar acquisition is inefficient (Guenther, 2007[3]). As with other optical remote sensing methods for mapping bathymetry, turbidity is the primary limiting consideration to derive depth. Most bathymetric lidar systems are airborne, but a notable spaceborne lidar that has proven highly effective for bathymetric profiling is NASA's ICESat-2 Advanced Topographic Laser Altimeter System (ATLAS).

SAR systems operate in the microwave and radio wavelengths ranging from 1 mm to 20 m. The main advantage in using microwaves is their ability to penetrate atmospheric gases and clouds, and to some degree, liquids and solids. However, these wavelengths cannot penetrate the water surface and all information is reflected by the water surface. Thus, SAR imagery has been used in bathymetric studies which focus on the identification of ocean waves and their shoaling in shallow waters (see section 9.3.1). In addition, SAR data have been utilized to define the shoreline and the boundary between land and water, thus providing information on the intertidal zone and its heights. The European Space Agency's Sentinel-1 or the TerraSAR-X are examples of SAR sensors.

[3] Guenther, G., 2007. Airborne Lidar Bathymetry in: in Digital Elevation Model Technologies and Applications: The DEM Users Manual, 2nd ed (David F. Maune, Ed). American Society for Photogrammetry and Remote Sensing, Bethesda, Maryland, pp. 253-307.

CHAPTER 2 SDB CONCEPTS AND METHODS

2.1 Introduction

Satellite-Derived Bathymetry requires a sensor (hardware) and corresponding algorithms (software) to generate bathymetric data. This section focuses on the algorithms and workflows of SDB with the aim to provide an overview of different techniques, their core assumptions and relevant information.

2.2 Pre-processing

Pre-processing describes the steps applied to satellite imagery prior to running the algorithms which improve the accuracy of the SDB analytics. The following processing steps are described for multispectral and hyperspectral satellite image analysis.

Geometric correction of satellite imagery aims to improve the horizontal geolocation accuracy of the satellite imagery. Overall, satellite imagery has high horizontal accuracy (see annex) but may vary depending on the level of processing (see previous section).

Access to local Ground Control Points (GCP) that intersect with the satellite imagery and are ideally evenly distributed over the area of interest can improve the horizontal accuracy. Methods for improving horizontal accuracy depend on the number and reliability of GCPs. The standard method is a polynomial fit of order 1. This process enables a shift of the satellite image in X, Y direction and rotation. Higher polynomial orders will introduce a warping effect which – depending on the distribution and accuracies of the GCPs – reduces the overall positional quality. An alternative to local ground control measurements is very-high resolution aerial images with higher horizontal accuracy, which – depending on the country – are available through government geodata agencies. These data can be used to identify GCPs, similar to those collected in the field.

Without access to GCPs or high-precision reference surfaces, the horizontal accuracies of satellite images are determined by the information provided by the satellite provider (see Annex).

After analysing SDB, horizontal accuracies can also be improved by considering refraction (see section 272.4.4) and acquisition geometry.

The analytical step of radiometric calibration turns the digital numbers of the image records into radiances, which is of importance when using multi- or hyperspectral satellite data and especially for Radiative Transfer Equation (RTE) SDB methods. Calibration coefficients, given by images providers, are required for this step.

Depending on the approach used, atmospheric and water surface effects can be considered as part of the preprocessing to obtain harmonised reflectance or radiance information: Different atmospheric correction methods of varying complexity, ranging from the assumption of a homogeneous atmospheric correction to the coupled retrieval of water and atmospheric parameters for each recorded pixel within a satellite image.

The correction of the so-called adjacency effect describes the increased radiance over water due to contamination of the signal from photons reflected by adjacent land, and their further scattering in the atmosphere. It is of importance for near coastal sites with bright surfaces (Kiselev et al 2015 [4]).

Sunglint correction of satellite images describes the removal of impacts of the mirror-like reflectance on the water surface. The sensor and acquisition geometry must be known for this procedure (often called de-glinting) and is usually specified in the metadata of the satellite data. Many de-glinting methods make use of the short wave (SWIR) and near infrared bands (NIR) which reflect most of the radiation at the water surface (Vanhellemont, 2019[5], Heege and Fischer 2000[6]). De-glinting is often but not always coupled with atmospheric correction.

The identification of water surfaces is a crucial procedure of all SDB analytics. It is based on the fact that water and land surfaces reflect visible and near-infrared light at different intensities and the separation of water and non-water surfaces can be done by a combination of these bands. The water identification is also important for atmospheric correction and for the identification of floating objects, such as ships or floating materials. Areas that are not water surfaces are not considered in the bathymetric processing analysis.

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[4]Kiselev, V., Bulgarelli, B. and Heege, T., (2015). Sensor independent adjacency correction algorithm for coastal and inland water systems. Remote Sensing of Environment, 157: 85-95. , ISSN 0034-4257, http://dx.doi.org/10.1016/j.rse.2014.07.025

[5] Vanhellemont, Quinten. (2019). Adaptation of the dark spectrum fitting atmospheric correction for aquatic applications of the Landsat and Sentinel-2 archives. Remote Sensing of Environment. 225. 175-192. 10.1016/j.rse.2019.03.010.

[6] Heege, T. & Fischer, J. (2000): Sun glitter correction in remote sensing imaging spectrometry. SPIE Ocean Optics XV Conference, Monaco, October 16-20.

2.3 SDB Methods

The following subchapter gives a brief introduction to the different methods that exist for calculating bathymetry with satellite sensors. It also lists the basic assumptions and important specifications of these methods.

2.3.1 Bathymetry from waves

Bathymetry from multispectral or panchromatic and radar satellite imagery can be estimated based on wave kinematics using the linear wave dispersion relation. The concept makes use of the fact that the length and period of gravity ocean waves change when they enter shallow waters. Thus, it is based on wave celerity, wave period, gravity acceleration and water depth. The length, speed and period of ocean waves can be measured by satellite imagery and therefore the equation can be solved for depth. Common methods for the analysis are based on fast fourier or radon transformation of satellite image subsets for which the average depth is calculated (Figure 3)

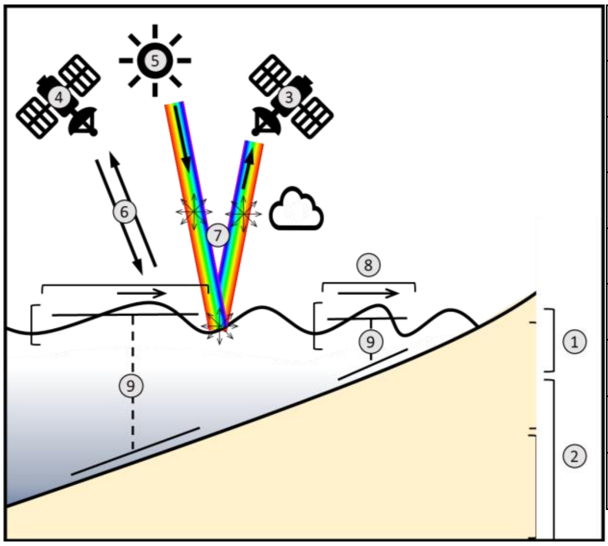
In theory, this method allows a user to construct bathymetry grids which are at least the size of the ocean wavelength. However typical bathymetry from waves is provided in coarse grids of 50-200m spatial resolution with a maximum depth of about 0.5 times the ocean wavelength (theoretically up to 40–60 m, but seldomly exceeding 25 to 35m depth) (e,g, Daly 2022[7]).

This technology is also known as WKB or WTA for respectively Wave Kinematics Bathymetry (Abileah 2013[8], Daly et al. 2022[9]) and Wave Transformation Algorithm (Danilo, 2016[10]). WKB requires at least two images in a short time delay (few seconds) whereas WTA relies simply on one image (optical or radar) that contain a deep water area for initialisation.

Core assumptions

The shoaling effect of waves can be measured by satellite data and the linear wave dispersion relation can be solved for depth.

[7] Daly, C., Baba, W., Bergsma, E., Thoumyre, G., Almar, R., & Garlan, T. (2022). The new era of regional coastal bathymetry from space: A showcase for West Africa using optical Sentinel-2 imagery. Remote Sensing of Environment, 278, 113084.
[8] Abileah, Ron, (2013). Mapping near shore bathymetry using wave kinematics in a time series of WorldView-2 satellite images, 2013 IEEE International Geoscience and Remote Sensing Symposium - Melbourne, Australia, 2274–2277.
[9] Christopher Daly, Wassim Baba, Erwin Bergsma, Gregoire Thoumyre, Rafael Almar, Thierry Garlan,
The new era of regional coastal bathymetry from space: A showcase for West Africa using optical Sentinel-2 imagery, Remote Sensing of Environment, Volume 278, 2022, 113084,ISSN 0034-4257,
[10] Danilo, C., & Melgani, F. (2016). Wave period and coastal bathymetry using wave propagation on optical images. IEEE Transactions on Geoscience and Remote Sensing, 54(11), 6307-6319.



1	Optically shallow water zone
2	Optically deep water zone
3	Passive, multispectral satellite sensor
4	Active, SAR satellite sensor
5	Sun and solar radiation
6	Emitted and reflected radar signal
7	Sunlight, reflected, absorbed, and transmitted through the atmosphere and at the water surface
8	Wave period, length and height derived by the satellite data
9	Water depth as a result of the wave dispersion relation for shallow waters.

Figure 2: Schema of the bathymetry from waves SDB method.

Key specifications

Spatial resolution: Bathymetry from waves methods create coarse resolution bathymetric grids of 50-200 m. The method results in 'smoothed' bathymetric surface and very little capability to identify single features. Video based high resolution satellite imagery could improve the resolution that can be reached in the future.

Depth range: The higher is the wave-period, the deeper the bathymetric estimate can be. Depth limitations to about 0.5 times the length of the ocean wave which results in theoretical depth down to 40-60m but seldomly exceeding 25 to 35m depth. Deep water areas cannot be addressed by the method. On the other hand, the wave dispersion relation becomes non-linear in very shallow water areas (typically for water depths less than wave period / 20) that can neither be addressed by the method.

Limiting factors: Sufficient gravity wave activity with at least 70-m of ocean wavelength and 7s wave period. Areas without sufficient wave activities, such as complex archipelagos without gravity waves, cannot be analysed. Unlike other SDB methods, there are no dependencies on water clarity.

Satellite sensors: WTA can be based on panchromatic, multispectral and radar images, WKB needs two acquisitions at a very short time delay. A sensor spatial resolution of at least 5-10 m is required.

Need for in-situ reference data: Not required.

Others: Potential challenge to identify the Cut-Off depth.

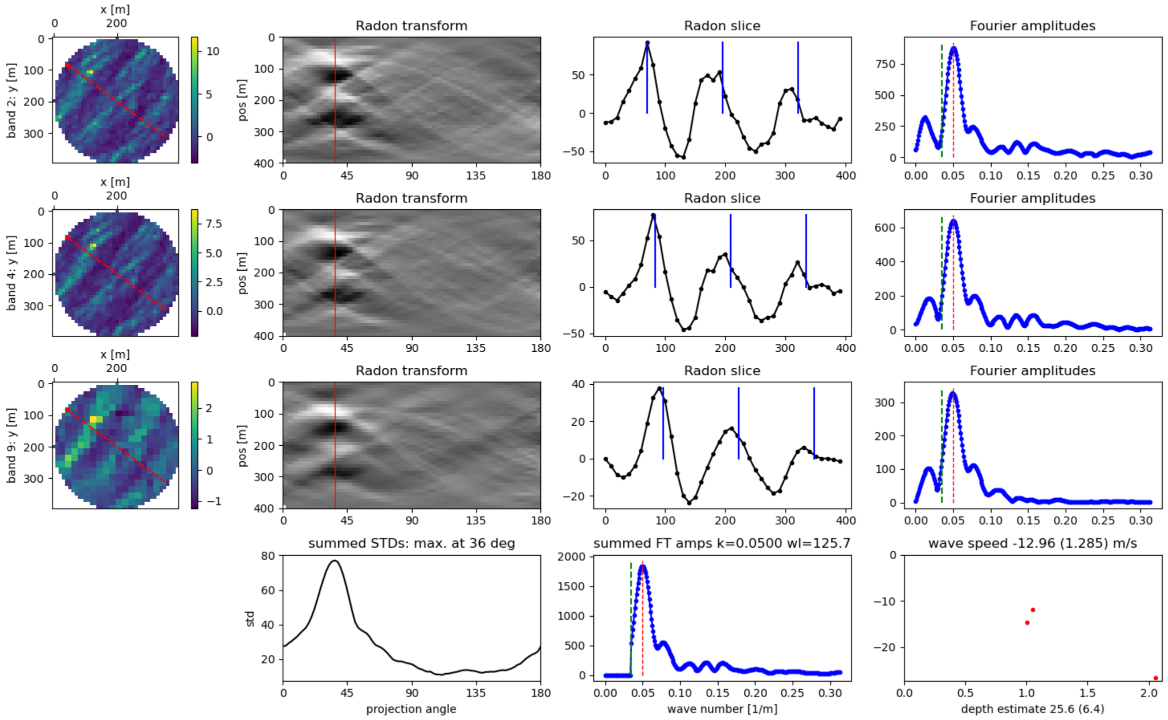
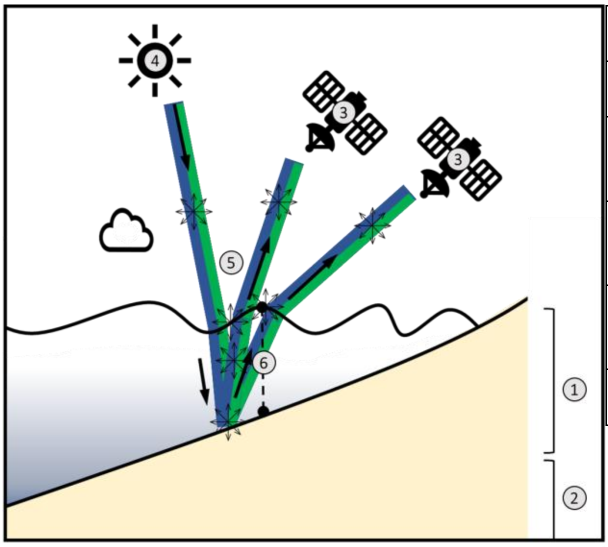


Figure 3: Concept of WKB. Image subsets (left) are analysed with radon transformation (mid left) and its wavelengths measured in meters (mid right), the time delta between – in this example – three different records allow to quantity the period (right) and a depth estimation is provide (bottom right). Image courtesy: EOMAP

2.3.2 Photogrammetric based SDB

Photogrammetry is the science of extracting 3D information from data acquired from a satellite stereo pair containing a different viewing geometry exhibiting parallax. Similar to human vision, the two images are combined to create a 3D model, allowing the XYZ coordinates of features in the imagery to be determined[11]. The identification of matching points in the triangulated stereo images and output derived depths can be applied to very-high resolution panchromatic or multispectral imagery which record the visible light spectrum. The identification of the matching points is of crucial importance for this method and can either be done by manual image interpretation or automatically. The manual approach requires the analyst to use stereo hardware to visually extract XYZ coordinates of features in the stereo pair. Through visual interpretation, the analyst extracts depths and interpolate them to a bathymetric model. The automatic approach combines the techniques of image correlation with photogrammetric triangulation principles and is less time consuming. Automatic and manual image interpretation can be biased by the water surface effects. All photogrammetry based SDB methods require very-high resolution satellite imagery and can use panchromatic and multispectral satellite data.



1	Optically shallow water zone
2	Optically deep water zone
3	Passive, multispectral satellite sensor(s) which record (multi-) stereo images in very-high resolution.
4	Sun and solar radiation. The wavelength which penetrates deepest into the water column (green and blue) is used for this approach.
5	Sunlight, reflected, absorbed, and transmitted through the atmosphere, the water surface, water column and seafloor.
6	Derived water depth

Figure 4: Schema of the photogrammetric based SDB method.

Core assumptions

Very-high resolution (multi-) stereo satellite imagery can be used to identify similar targets on the seabed and create a bathymetric surface for optically shallow waters.

Key specifications

Spatial resolution: Depends on the intensity of the identified matching points and varies with seabed colour or textual differences.

Depth range: 1 time Secchi Disc Depth, optically shallow waters

[11] Chénier, R.; Faucher, M.-A.; Ahola, R.; Shelat, Y.; Sagram, M. Bathymetric Photogrammetry to Update CHS Charts: Comparing Conventional 3D Manual and Automatic Approaches. *ISPRS Int. J. Geo-Inf.* 2018, *7*, 395. https://doi.org/10.3390/ijgi7100395

Limiting factors: Water clarity defines the maximum mapping depth of this method and it can only be applied for optically shallow waters. Low to no ocean wave impact and water surface reflectance so as not to impact the identification of matching points. The colour of the seafloor must be heterogeneous, so that reliable matching points can be identified. The water refraction impacts the multi-geometry/stereo approach and needs to be taken into account.

Satellite sensors: Very-high resolution satellite imagery with multi-stereo recording geometries is available.

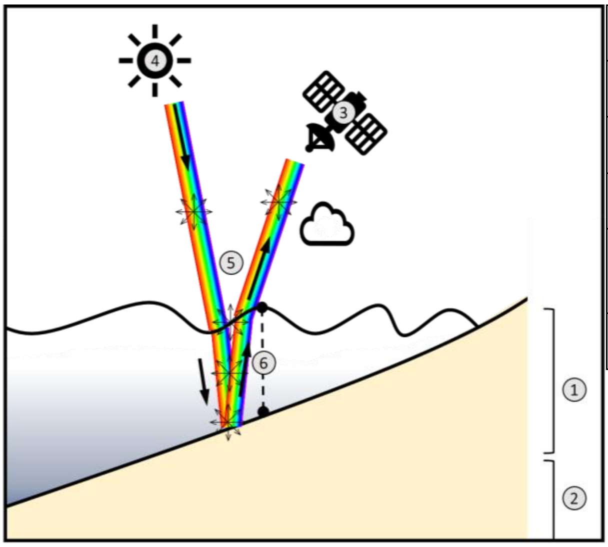
Need for in-situ reference data: Not required.

Others: Bathymetric surfaces derived from the photogrammetric approach represent modelled surfaces based on the triangulation (interpolation) of matching points.

2.3.3 Radiative Transfer Equation inversion method

The 'physics based SDB' or 'Radiative Transfer Equation (RTE) inversion' method describes the complete sunlight pathway based on the physical behaviour of the light. This requires an accurate, algorithmic physical description of all the environmental variables that influence the light signal pathway, including the atmosphere, sea surface, water column and seafloor optical properties. The propagation of sunlight is influenced by absorption, emission and scattering processes, which therefore need to be understood and modelled accordingly (e.g Kisselev and Bulgarelli, 2004[12], Heege et al. 2008[13]). For optically shallow waters the seafloor colour and the water depth significantly impact the radiation which is recorded at the satellite sensor. An oversimplified equation of this process is as follows: The radiation measured by the satellite sensor is a function of absorption, emission, and scattering in the atmosphere, on the water surface, in the water column, of the seafloor and of the water thickness. Since we know the radiation measured by the satellite, we can determine the water thickness, the depth, provided that all other parameters can be derived from the model itself. This also results in a significant advantage of the RTE models, namely the possibility of creating bathymetric grids and their vertical uncertainties without necessarily having to rely on information in the field.

Physics-based data analytics can be applied consistently to both multi- or hyperspectral satellite or airborne data. Such systems are called sensor agnostic or sensor independent and can also include simultaneous analysis of multi-temporal data (Heege 2008 and 2015[14]).



1	Optically shallow water zone
2	Optically deep water zone
3	Passive, multispectral or hyperspectral satellite sensor(s).
4	Sun and solar radiation.
5	Sunlight, reflected, absorbed, and transmitted through the atmosphere, the water surface, water column and seafloor.
6	Derived water depth

Figure 5: Schema of the RTE based SDB method.

[12] Kisselev, V.; Bulgarelli, B. (2004). Reflection of light from a rough water surface in numerical methods for solving the radiative transfer equation. Journal of Quantitative Spectroscopy and Radiative Transfer 85, 419-435.

[13] Heege T, Kobryn H., Harvey M, 2008: How can I map littoral sea bottom properties and bathymetry? In: Fitoka E & Keramitsoglou I 2008 (editors). Inventory, assessment and monitoring of Mediterranean Wetlands: Mapping wetlands using Earth Observation techniques. EKBY & NOA. MedWet publication.

[14] Heege, T. 2015/2017: Using Multispectral Satellite Data To Determine Littoral Water Depths Despite Varying Water Turbidity. US Patent 9046363 and 9613422

Core assumptions

The RTE can be solved for water depth and result in bathymetric grids for all optically shallow waters without any bathymetric pre-knowledge of the site.

Key specifications

Spatial resolution: Depends on the native spatial resolution of the satellite image. Currently multispectral satellite imagery is accessible with 1.3m to 10m or coarser spatial resolution.

Depth range: It can be applied for optically shallow waters.

Limiting factors: Water clarity defines the maximum mapping depth of this method. In contrast to empirical solutions, RTE methods have a demand for well calibrated and high signal to noise satellite sensors.

Satellite sensors: Based on multi- or hyperspectral satellite images covering the visible and near-infrared range. The more spectral bands available, the more accurate the result.

Need for in-situ reference data: The method can be applied in the absence of on-site depth information or where on-site information is not reliable.

Others:

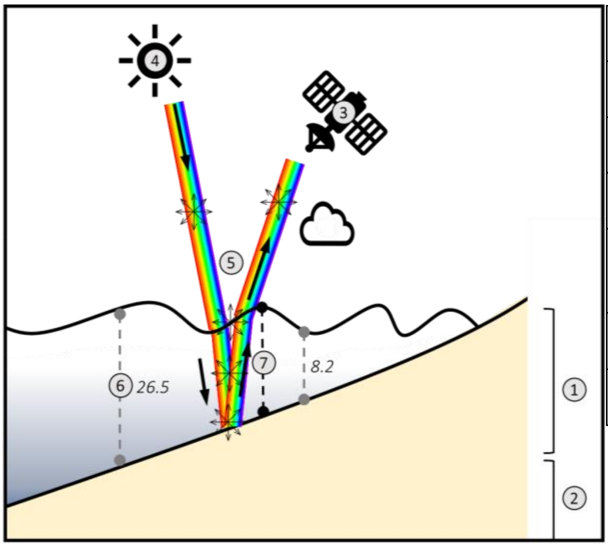
- The radiative transfer model includes databases or a model of major relevant environmental factors of atmosphere, Inherent Optical Properties (IOPs), or seabed reflectance for each common recording geometry of the sensor(s). The RTE inversion is often performed on a pixel-by-pixel basis.
- Can reduce subjective, manual parameter tuning and provide an automatic processing solution.

2.3.4 Machine Learning approach

Whereas RTE and empirical regression methods for calculating SDB make use of mathematical models established through classical scientific research, Machine Learning (ML) approaches - a subset of Artificial Intelligence (AI) - rely upon computers to make their own associations within large datasets.

In the case of SDB, a ML model would establish its own associations between satellite images and bathymetric depths through a process of learning from an initial input set of training data. The trained model would then proceed to derive bathymetry from across the rest of the image(s) where there was no pre-existing bathymetric data.

There are numerous different Machine Learning models, for example random forest regressors, Convolutional Neural Networks, Support Vector Machine, U-Net, etc, but the common requirement to all is the need for an initial training-learning stage which allows the machine to establish a model to explain the known depth with provided satellite imagery and ancillary data (Niederjasper et al. 2020[15], Guo et al. 2022[16]). All Machine Learning methods are either based on multi or hyperspectral satellite images.



1	Optically shallow water zone
2	Optically deep water zone
3	Passive, multispectral satellite sensor(s)
4	Sun and solar radiation.
5	Sunlight, reflected, absorbed, and transmitted through the atmosphere, the water surface, water column and seafloor.
6	Training data / known depth data for training purposes.
7	Derived water depth

Figure 6: Schema of the ML based SDB method.

Core assumptions

ML or AI methods can use known depth and multispectral satellite data (and other ancillary data) to train a mathematical model which can predict the depth for optically shallow waters located nearby the known depths data.

[15] Niederjasper, Marina & Hartmann, Knut & Steinsiek, Moritz & Bödinger, Christian & Rump, Stephen & Filippone, Marco & Stender, Manfred & Lampe, Christian & Adhiwijna, Dhira. (2020). HN116 Satellite-derived bathymetry in practice. 116. 40-47. 10.23784/HN116-06. URL: https://www.researchgate.net/publication/343344660_HN116_Satellite-derived_bathymetry_in_practice

[16] Guo, X.; Jin, X.; Jin, S. Shallow Water Bathymetry Mapping from ICESat-2 and Sentinel-2 Based on BP Neural Network Model. Water 2022, *14*, 3862. https://doi.org/10.3390/w14233862

Key specifications

Spatial resolution: Depends on the native spatial resolution of the satellite image. Currently multispectral satellite imagery is accessible with 1.3m to 10m or coarser spatial resolution.

Depth range: It can be applied for optically shallow waters.

Limiting factors: Water clarity defines the maximum mapping depth of this method and it can only be applied for optically shallow waters. A trained model can only work well for situations and environmental conditions shown during the training process. Therefore, the training data should be a representative sample for different conditions in terms of depth, bottom types, turbidity, (atmospheric conditions, satellite types, etc). Application to unknown situations will most likely produce less accurate results. Given the large variation of global environmental conditions, a ML model trained with non-representative overall training data risks not being transferable to other regions.

Satellite sensors: Based on multi- or hyperspectral satellite images covering the visible and near-infrared range. The more spectral bands available, the more accurate the result.

Need for in-situ reference data: There must be a good representative spread of local bathymetric data to train the model, covering as full a range of depths and bottom types as possible.

Others:

- Unlike all other SDB methods, a trained ML model's inner workings can often remain opaque to the user, meaning it can be challenging to fully understand why the model either works or fails.

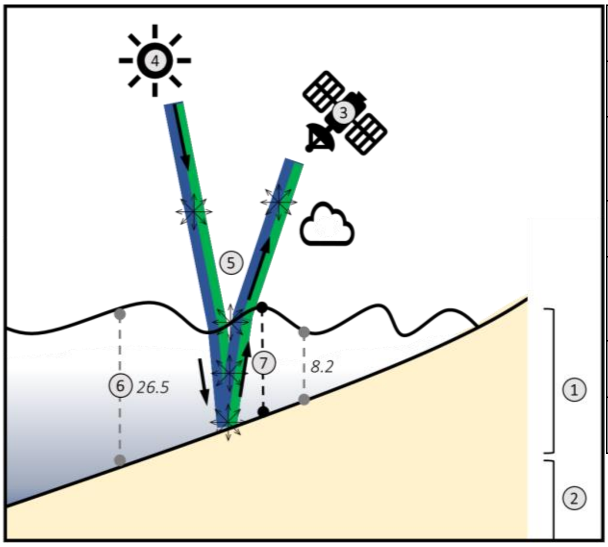
- A potential advantage of Deep Learning ML models is the ability to recognise contextual information. For example, recognition of seabed structures could improve the accurate depiction of shoals based on shape as well as pixel spectral returns alone.

- ML methods are particularly computationally intensive during training phases, however, fast to generate data products.

- Facing the wide range of ML methods applied to SDB with diverse outcomes, "ML-methods" for SDB and their quality might vary significantly.

2.3.5 Empirical methods

Empirical SDB methods describe mathematical models which are trained on local bathymetric information. A common method of the empirical SDB approach is referred to as the 'ratio approach' (IHO-IOC Gebco cookbook[17]). This method for deriving bathymetry from satellite imagery is a non-linear solution using a band ratio calculation (Stumpf et al., 2003[18], Lyzenga et al., 2006 [19]). Specifically, it uses a ratio of log-transformed water reflectance of bands having different water absorptions, so the ratio of reflectance will change with depth. The log-transform accounts for the exponential decrease of light with depth. The calculated ratio indicates the relative but not absolute depths. On-site bathymetric information is needed to correlate it to known depth and calculate bathymetric surfaces based on this correlation. Figure 8 provides an example of such a relationship, published in the IHO-IOC Gebco cookbook. Other empirical methods are using Machine Learning regression models to relate multispectral satellite records with known bathymetric data (see section 2.3.4). All empirical methods are either based on multi- or hyperspectral satellite images.



1	Optically shallow water zone
2	Optically deep water zone
3	Passive, multispectral satellite sensor(s), only the green and blue wavelengths are required for this approach.
4	Sun and solar radiation.
5	Sunlight, reflected, absorbed, and transmitted through the atmosphere, the water surface, water column and seafloor.
6	Training data / known depth data to calibrate the empirical equation
7	Derived water depth

Figure 7: Schema of the empirical 'ratio approach' SDB method.

Core assumptions

A non-linear regression of the ratio of blue and green light reflectance measured by the satellite can be correlated to known depth and predict water depths for optically shallow waters, which are located close to the known depth data (see next figure).

[17] International Hydrographic Organization, Intergovernmental Oceanographic Commission, The IHO-IOC GEBCO Cook Book, IHO Publication B-11, Monaco, Sep. 2018, 416 pp - IOC Manuals and Guides 63, France, Sep. 2018, 429 ppG
[18] Stumpf, R.P., Holderied, K., Sinclair, M., 2003. Determination of water depth with high-resolution satellite imagery over variable bottom types. Limnol. Oceanogr. 48 (1 part 2), 547–556.
[19] Lyzenga and Malinas D. R. Lyzenga, N. P. Malinas and F. J. Tanis, "Multispectral bathymetry using a simple physically based algorithm," in IEEE Transactions on Geoscience and Remote Sensing, vol. 44, no. 8, pp. 2251-2259, Aug. 2006, doi: 10.1109/TGRS.2006.872909

Key specifications

Spatial resolution: Depends on the native spatial resolution of the satellite image. Currently multispectral satellite imagery is accessible with 1.3m to 10m or coarser spatial resolution.

Depth range: Water clarity defines the maximum mapping depth of this method, and it can only be applied for optically shallow waters.

limiting factors: The metadata on vertical datum are known. The vertical uncertainties of the bathymetric surface are highly dependent on the quality and representative coverage across the study region, their representation over the various environmental conditions.

Satellite sensors: Based on multi- or hyperspectral satellite images covering the visible and near-infrared range. The more spectral bands available, the more accurate the result.

Need for in-situ reference data: Local bathymetric data covering a range of depths are accessible to train the empirical model. A strong dependency upon the local bathymetric training data exists. Local bathymetric data shall have a high reliability. Low quality or unsuitable representation of training data can lead to unknown vertical uncertainties.

Others: -

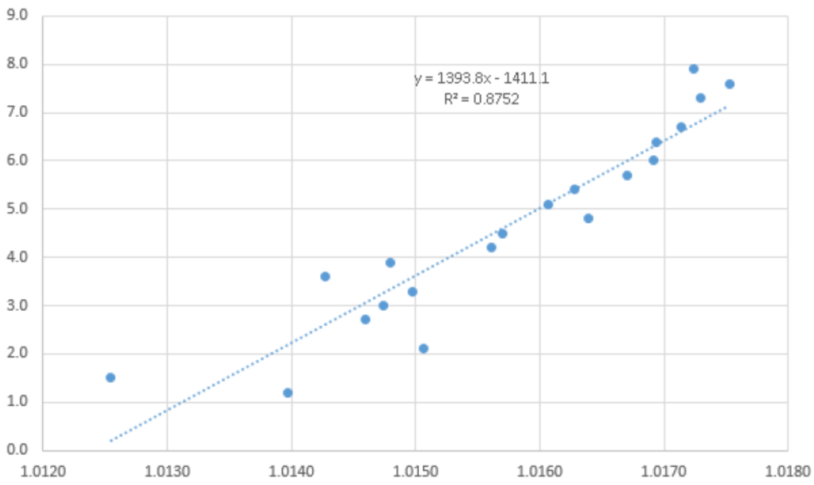


Figure 8: Example of the satellite-derived ratio value (X-axis) and chart soundings (Y-axis). The linear relationship is used to predict depth for the satellite data for optically shallow waters (8m in this example). Image courtesy: IHO GEBCO Cook Book

2.3.6 Satellite-Lidar Bathymetry (SLB) from ICESAT-2 ATLAS

NASA's ICESat-2 satellite launched in Sept 2018 features ATLAS, a green photon-counting lidar with a 10kHz pulse repetition rate and nominal 17m diameter footprint[20]. It is a profiling lidar and records photon returns in discrete track lines covering the entire globe that are capable of measuring bathymetry. ATLAS by itself cannot create a dense spatial grid as each trackline can be up to hundreds of kilometres apart. A proprietary cluster algorithm separates seafloor photon returns from both the water column and water surface. Correction routines need to be applied to the ICESat-2 seabed photon returns to account for the water refraction and recording geometry as well as effects on water heights. SLB information extracted along each trackline serves as a valuable check and as training dataset for other SDB methods.

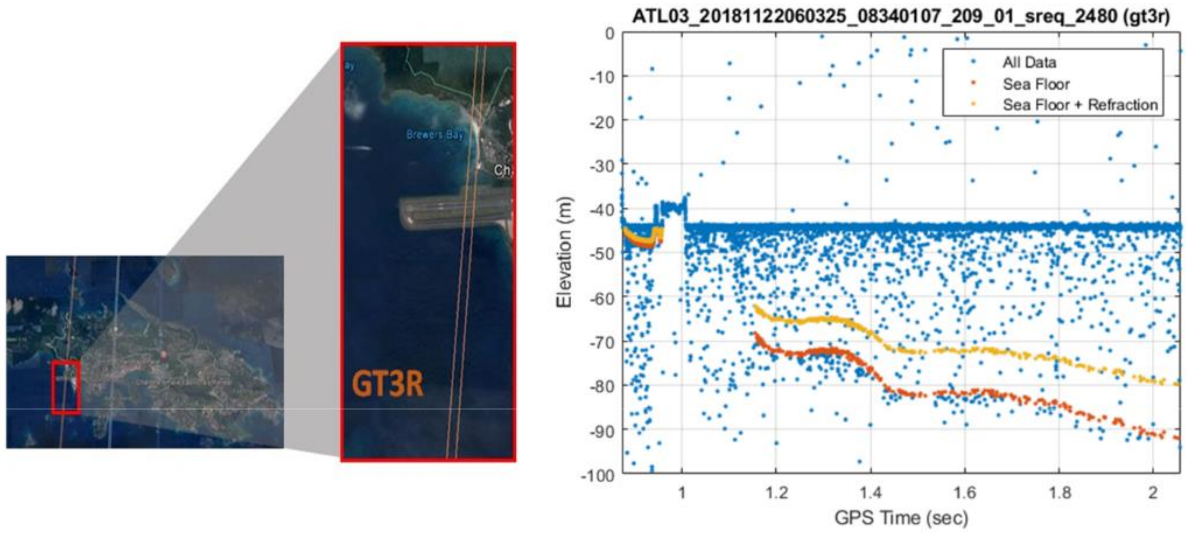


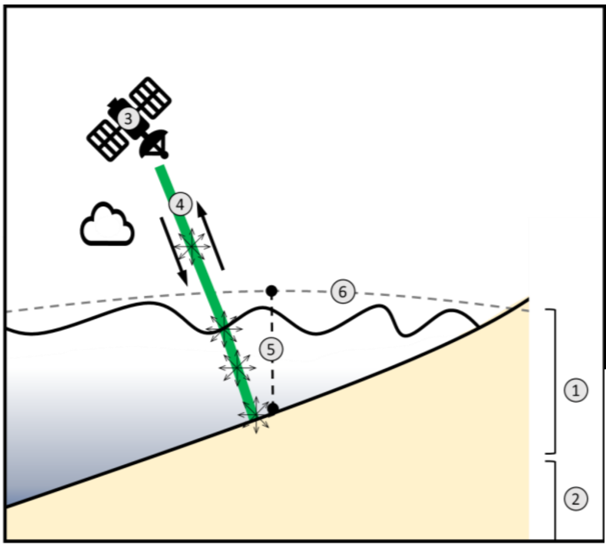
Figure 9: Left: St. Thomas site, crossing Runway 10/28 at the St. Thomas airport (STT). Right: profile of geolocated photon returns, with the bottom return photons, both pre-refraction correction (dark orange) and post-refraction correction (light orange). Image courtesy: Parrish et al. 2019[21].

Core assumptions

IceSat-2's green laser is reflected be the seabed and the time delta between the emission and return provides information on geoid height of the seabed.

[20] Neumann T., Brenner A., Hancock D., Robbins J., Saba J., Harbeck K., Gibbons A., Lee J., Luthcke S., Rebold T. 2021. CESat-2 Algorithm Theoretical Basis Document for Global Geolocated Photons (ATL03). Release 004. https://icesat-2.gsfc.nasa.gov/sites/default/files/page_files/ICESat2_ATL03_ATBD_r004.pdf

[21] Parrish, C.E.; Magruder, L.A.; Neuen schwander, A.L.; Forfinski-Sarkozi, N.; Alonzo, M.; Jasinski, M. Validation of ICESat-2 ATLAS Bathymetry and Analysis of ATLAS's Bathymetric Mapping Performance. Remote Sens. 2019, 11, 1634. https://doi.org/10.3390/rs11141634



1	Optically shallow water zone
2	Optically deep water zone
3	Active, green lidar.
4	Green laser reflected, absorbed, and transmitted through the atmosphere, the water surface, water column and seafloor..
5	Derived water depth (vertical datum: Geoid)
6	Geoid surface

Figure 10: Schema of the SLB from ICESat-2.

Key specifications

Spatial resolution: SLB is based on a profiling lidar and cannot provide a spatial coverage, depth information can be provided for single tracklines (profiles). Each trackline might be up to several 100m apart.

Depth range: SLB data are impacted by water clarity and can map depth down to 0.8 to 0.9 time Secchi Disc at time of recording and therefore valid for optically shallow waters.

Limiting factors: Density of the seabed photon returns and thus the quality of the depth measures is dependent on turbidity, atmospheric conditions, seabed reflectance.

Satellite sensors: ATLAS, a green photon-counting lidar on iceSat-2 satellite.

Need for in-situ reference data: No

Others: SLB outputs are geoid heights.

2.3.7 Others

The following are other satellite-based methods and are listed for completeness:

- Satellite radar altimeters which can be used to map the mean sea surface heights from which geoid undulations and gravity anomalies are estimated. These can be used to predict bathymetry over a wavelength band of 15–200 km (Smith and Sandwell, 1994[22], Smith and Sandwell, 1997[23]). As such, it provides a coarse resolution bathymetric grid which provides general depth information for the coastal regions.

[22] Smith, W.H.F. and Sandwell, D.T. (1994) Bathymetric Prediction from Dense Satellite Altimetry and Sparse Shipboard Bathymetry. Journal of Geophysical Research, 99, 803-821.
[23] Smith, Walter & Sandwell, David. (1997). Global Sea Floor Topography from Satellite Altimetry and Ship Depth Soundings. Science. 277. 1956-1962.

- Shoreline Correlation - Multispectral or radar imagery which detect the shorelines at different water levels. By linking the multiple shorelines with known water level records one can create contour lines of the intertidal bathymetry.

2.4 SDB post-processing and Quality Management

2.4.1 Introduction

Like any other survey method, SDB data requires post-processing and Quality Management (QM), which includes Quality Assurance (QA) and Quality Control (QC) procedures. Successful design and application of QA methods shall ensure compliance of final products to defined accuracies. QC validates if the product satisfies the requirements on coverage, accuracy, or other elements. QC procedures must be derived from the QA methods so that the validated quality elements of the products match with the purpose of the QA itself.

In general, QA design is based on the identification of all sequences involved in the generation of SDB products. These include but not limited to the followings:

1. Selection of satellite imagery (see section 1.2.2)
2. Data pre-processing, such as correction (see 2.4)
3. Data post-processing, involving mainly horizontal and vertical positioning accuracies.

QC procedures are part of the QA and can be applied to any elements in the SDB production sequence. The ideal QC would be the comparison of the SDB product with depth measured in-situ by means of standard hydrographic techniques, e.g., multi-beam echo sounding operation. In the comparison and for the purpose of the estimation of SDB uncertainties, in-situ data is often assumed as the true value.

Additionally, for the purposes of nautical charting and the safety of navigation, there may be an additional requirement for the use of independent control data for the purposes of validation (see section 6.3). Ultimately the user will need to satisfy themself that the SDB data is fit-for-purpose and assign appropriate uncertainty values in the metadata particularly where liability may be a significant consideration.

Data selection and pre-processing have been highlighted in the previous sections. This section highlights the data post-processing sequence as part of the QA design (sections 2.4.2 to 2.4.6) and the QC procedure according to in-situ hydrographic survey data (section 2.4.7).

2.4.2 Datum, coordinate system, and projection

In geodesy, datum is the reference frame that describes positions in three-dimensional space by means of a coordinate system. The datum of most satellite imagery is based upon the WGS84 ellipsoid. Transformation to any other horizontal datum will need to be carried out with care, (note, most modern charting is based on WGS84). Choice of a suitable coordinate system is up to the individual project; however users should take care if there becomes a need to transform from one coordinate system to another. For example, satellite imagery is often supplied on a coordinate system based on the Universal Transverse Mercator (UTM) projection. The horizontal position of any depth is specified according to the x and y coordinates as well as the assigned zone. Nautical charts often use Mercator projection for coastal and ocean navigation based on latitude and longitude coordinate systems.

It should be noted that with the use of WGS84, the description of the vertical component of position in three-dimensional space refers to the surface of the ellipsoid. Such a description is fully mathematical and not true in the physical sense. Therefore, vertical datum is used to describe the vertical positioning and enables true description of height or depth of any object on Earth. In hydrography, lowest tides, often such as Mean Lower Low Water (MLLW), Mean Low Water Spring (MLWS) and Lowest Astronomical Tide (LAT) have been used in nautical charting as the vertical reference plane termed as chart datum (CD). All depths hence refer to CD. CD represents a reference plane in which the actual water level at any time would rarely fall below it. It is a common practice to describe CD as the vertical separation to the Mean Sea Level (MSL) termed as Z0, so that:

$$CD + Z0 = MSL$$

with CD = chart datum, Z0 = the vertical separation between CD and MSL, and MSL = mean sea level.

An important consideration when using satellite data is that the imagery will likely have been projected onto a WGS84 ellipsoid. At off-nadir angles this can introduce a further horizontal displacement which can be very significant in areas of the world where the local vertical separation between geoid and ellipsoid heights are greatest. The best advice here is to consult with the satellite image vendor to ensure imagery has already been projected onto a suitable geoid model such EGM08. Translation of geoid to MSL or LAT can be done by means of HSM as it has been described in the section 2.4.3.

2.4.3 Depth reduction

SDB data which are derived from satellite data represent the depth, i.e., vertical distance between the sea level and seafloor/bottom, at the time of recording. Information on water level at the time of recording of the satellite imagery is mandatory to translate the SDB data to any hydrographic vertical datum. Common vertical references for Satellite-Derived Bathymetry are Lowest Astronomical Tide (LAT) or Mean Sea Level (MSL). Recommended approaches to access tidal information are from historic tidal gauging stations if those are accessible for the time of the satellite data records. All satellite data records are time tagged, so that a time match between the water level information and satellite records can be correlated at the time of recording.

Given that information of hydrographic vertical datum is available in the respective station, one can apply tidal corrections with respect to the given datum, i.e. LAT or MSL. Depending on the complexity of the tidal regime one or multiple tidal stations or predicted tidal stations can be used. An alternative to on-site measurement of tidal gauges is to access water level information from predicted tidal information using either predicted tidal stations or global or local tide models. In many locations, information on hydrographic datum might not be available or is inaccessible. MSL or LAT could be approximated according to the available tidal data. Users are advised to seek guidance for carrying out MSL or LAT approximation from IHO C-13.

For SDB data with referenced heights to the geoid (EGM-2008), e.g. IceSat-2’s SLB data, a translation of geoid height to a hydrographic vertical datum such as LAT or MSL is required and can be done with the help of a Hydrographic Separation Model (HSM). HSMs are available in some regions, such as VORF (UK), HyVSEPs (Canada), VDatum (USA), BathyElli (France), and BLAST (North Sea). In locations where a HSM is not available, the translation of heights referenced to the geoid to MSL could be done by applying correction due to the mean dynamic ocean topography (MDOT). Global model for MDOT is available from multiple sources, such as GRACE Tellus, Asia-Pacific Data-Research Center (APDRC), Aviso+, European Space Agency (ESA), and Technical University Denmark (DTU) Space.

2.4.4 Water refraction and off-nadir correction

Very high-resolution commercial satellites are typically agile in their ability to 'tip and tilt' as they gather image scenes on the course of their orbit. Consequently, very-high resolution imagery is rarely collected looking vertically downwards but has an 'off-nadir' viewing angle. This may typically fall anywhere between 0 and 30 degrees but may be as much as 45 degrees. SDB depths are necessarily a measure of observed path length from surface to seabed and as such off-nadir satellite imagery will be subject to errors due to a combination of diagonal view angle and refraction through the water surface, both of which will need to be accounted for. The following figure shows schematic illustration of depth correction applied to compensate for light deflection due to off-nadir view and the refraction of light path in the water column.

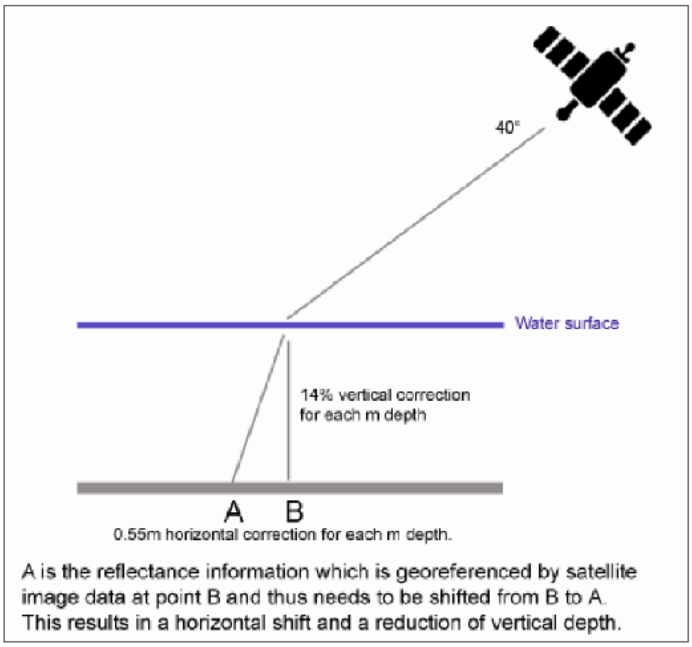


Figure 11: Vertical correction of depth due to off-nadir view and refraction of light path in the water column. Image credit: EOMAP

Observed depth points will likely need to be corrected to give depths vertical to the water surface to account for diagonal view-angle geometry and refraction effects. For very-high resolution imagery at steeper off-nadir angles there may also be a need to correct for the horizontal position of observed depths. These corrections will need to be carried out as a separate calculation after depth retrieval, which is a relatively simple trigonometric process (see figure 11). High resolution imagery such as Sentinel-2 does not require these corrections due to the lower pixel resolution and their less oblique viewing geometry.

2.4.5 Filtering

Data filtering is applied mainly in the QC processes for the purpose of removal of outliers or noises or unwanted signals. The criteria might be based on the statistical approach, for instance the z-score method. Different approaches could also be applied, such as spectral filtering or machine learning outlier detection. There is no specific SDB filter method or procedure and filter methods which have been used for other bathymetric surfaces can be applied to SDB. IHO publication C-13 (Manual on Hydrography) provides guidance.

2.4.6 Quality flagging

Data quality control flagging or quality flagging classifies depth data depending on the different processes applied in the acquisition, processing, and assessment of accuracy. In general, quality flagging separates data into two categories: Data that has undergone QC or no QC. Additional categories might be used to identify different attributes entailed in the data, such as the different level of accuracy. Quality flagging anticipates and systematically organises the increasing volume of data quantity from multiple sources and with different methods.

2.4.7 Validation and comparison with survey data

SDB quality and accuracy is affected by many factors, from the collection of suitable imagery and favourable environmental conditions, through to the ability to adequately model uncertainty, all of which is described elsewhere in this document.

If SDB will be used to support navigational products and services, comparison against independent control (‘validation data*)* survey data is an essential element to control and assess the accuracy of any given SDB dataset. Independent control data is useful for:

- Ensuring the highest possible level of accuracy for the SDB data.
- Assessing the overall accuracy
- Determining the Cut-Off depth beyond which SDB is considered too inaccurate for use on navigation products.

SDB without validation data may be of use for planning, situational awareness, and other non-safety critical uses. However, for use on navigational charts there is a need to quantify and demonstrate overall accuracy which enables charting authorities the ability to determine its fitness-for-purpose and ultimately to manage risk and liability in nautical products and services.

This leads to the further consideration of what makes good control data. For bathymetric data to be suitable for validation data it needs to:

- Hold a high level of accuracy.
- Enable a reasonable like-for-like comparison. For example, the time interval between validation data collection and satellite image acquisition should not be so long as to risk the seabed having changed over the intervening period, whether through gradual change or from any major environmental event such as significant storms, tsunamis,

dredging works, etc. It should essentially be from a seabed that is likely to be the same as that in the imagery.

- Cover enough of the area of SDB data. Validation data does not need to be dense, however it does need to be spread over the area of SDB, covering the full range of depths down to the anticipated extinction depth and representative seabed types and variable water conditions within the SDB survey area.

- Be considered on an image-by-image basis.

Pre-existing validation data can be used, or it can be gathered specifically for an SDB project, if it meets the requirements above. Spot soundings taken from existing nautical charts are generally not suitable.

Examples of good and bad located validation data are illustrated in figure 12.

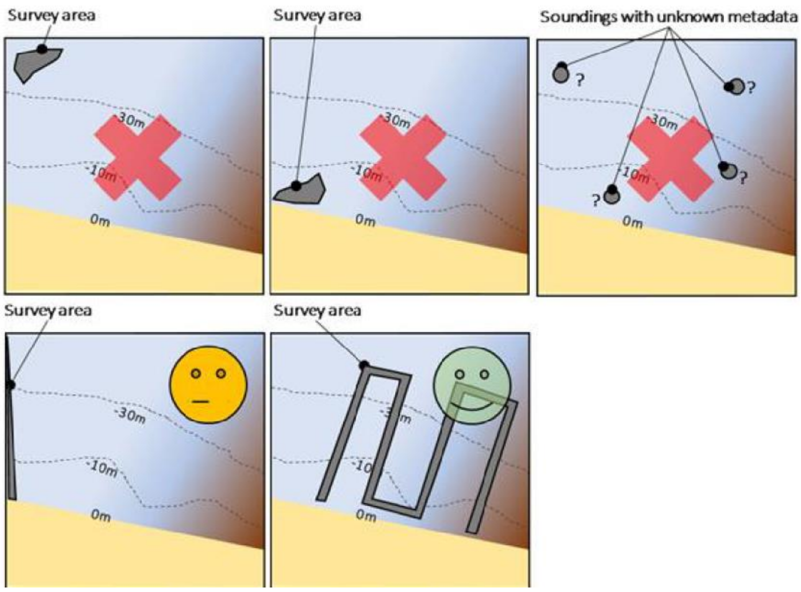


Figure 12: Unsuitable independent control (ground truth) surveys might not cover an adequate range of depths, or sufficiently coincide with the SDB survey area or may be taken from surveys with inadequate supporting metadata or unknown provenance. A well designed in-situ survey need not necessarily be dense but will have a good representative cover of the SDB survey area. Image credit: EOMAP

For some SDB computation algorithms, such as the empirical and machine learning methods described in section 2.3, survey data may also be a core requirement. Optionally, control data may be useful for fine tuning the coefficients within the Radiative Transfer Equation inversion method. Where these are the cases, survey data should be divided up into separate sets of soundings for training and validation stages.

CHAPTER 3 UNCERTAINTY

3.1 Introduction

There are many variables that could cause SDB to differ from the true depth of the seafloor and SDB uncertainties can vary depending on the environmental conditions of the satellite record, the recording geometry and on the applied method and QA/QC procedures. E.g., complex turbid waters will introduce higher depth uncertainties compared to clear water environments.

Depth uncertainties are known as vertical uncertainties. The horizontal uncertainties are defined by the source of the satellite sensor and its processing level. E.g., satellite sensors with lower spatial resolution have greater horizontal and vertical uncertainties than those of very high spatial resolution.

The topic of uncertainty can become quite involved. This document provides an overview of the topic, but IHO Special Publication S-44[24] (Standards for Hydrographic Surveys, Edition 6.1 2022), IHO Publication C-13 (currently updated document on Manual on Hydrography), and JCGM 100:2008[25] and JCGM 101:2008[26] contain additional background material and may be consulted for further details. Especially the specification matrix of S44 supports the flexible combination of different criteria, such as total horizontal uncertainty or total vertical uncertainties. Those categories can be applied flexible, to the entire SDB dataset, to individual depth zones, or, in an extreme scenario, at the pixel level for SDB results.

Currently there is no established or global error budget for SDB, due to the complexity and variability of the different methods used and the variety of environmental conditions on which the uncertainties depend. Uncertainties of SDB are modelled or estimated uncertainties, unless verified with survey data (see previous section).

3.2 Vertical uncertainties

3.2.1 Modelling and estimating vertical uncertainties

This subsection presents the aspects of modelling the vertical uncertainty of SDB.

3.2.1.1 Modelling vertical uncertainties of RTE methods

The Radiative Transfer Equation (RTE) methods aim to model the radiative transfer as precisely as possible. They rely – amongst others - on assumptions on absorbers and (back)scatterers in the different media and different environmental and recording conditions which introduces internal model uncertainties. These uncertainties depend on the accuracy and precision of the underlying assumptions and data. Therefore, a general statement on the

[24] https://iho.int/uploads/user/pubs/standards/s-44/S-44_Edition_6.0.0_EN.pdf
[25] https://www.bipm.org/documents/20126/2071204/JCGM_100_2008_E.pdf/cb0ef43f-baa5-11cf-3f85-4dcd86f77bd6
[26] https://www.bipm.org/documents/20126/2071204/JCGM_101_2008_E.pdf/325dcaad-c15a-407c-1105-8b7f322d651c

RTE internal uncertainties cannot be provided as it depends on the set-up and its ability to describe the RTE in detail. Important factors to understand the internal model uncertainties are the ability to account for bi-directional reflectance and none lambert reflector, ability to solve for the adjacency effects and the quality of the underlying inherent optical properties (IOP) model and the angular parametrizations. The uncertainties of the radiance measurements at the satellite sensor are also a source of uncertainty and varies with the satellite sensors.

A common method to better understand the internal uncertainties of the RTE model and its precision is based on Monte Carlo simulations. Monte Carlo simulations for vertical uncertainty propagation take the uncertainty distribution for each variable, such as the variability of the IOPs, as input and perform multiple model runs for (randomly) defined deviations of the input variables. For each of the model runs a slightly different output – water depth – will be created and statistics of the outcomes can be provided, such as the standard deviation or LE levels. The uncertainties of the radiance measurements at the satellite sensor are also a potential source of uncertainty and varies with the satellite sensors.

Another method is to propagate the sources of errors in the process and analytically derive the uncertainties using tools coming from the estimation theory (Jay, 2018[27]). The interest of using analytical tools resides in the fact that uncertainties can be a priori derived in a realistic computer time. It should be noted that the RTE in the water column being non-linear, propagation of errors through the RTE lead to non-symmetric maximum likelihood uncertainties, arguing that variance-based uncertainties may be irrelevant for inferring uncertainty on satellite bathymetric products (Sicot, 2021[28]).

Monte Carlo or analytical modelling of SDB uncertainties using uncertainties coming from the sensor reveals the asymmetry of the uncertainties and allows the lower and upper bounds of the asymmetric modelled 95% uncertainties (LE95) to be estimated (see next figure).

In addition, the stability of the inversion algorithms and the ability to independently predict uncertainties, e.g. by full error propagation, are further improved, e.g. to correctly resolve ambiguities and error levels over spectrally similar but different targets. This may be the case for sensors with limited spectral resolution, e.g. similar spectral shapes over shallow, dark vegetation or optically deep and dark water.

In post-processing, the external uncertainties of predicted tidal information lead to further uncertainties.

[27] S Jay, M Guillaume, M Chami, A Minghelli, Y Deville, B Lafrance, (2018) Predicting minimum uncertainties in the inversion of ocean color geophysical parameters based on Cramer-Rao bounds. Optics Express 26 (2), A1-A18

[28] Sicot Guillaume, Ghannami Mohamed Ali, Lennon Marc, Loyer Sophie, (2021). Likelihood ratio statistic for inferring the uncertainty of satellite derived bathymetry, 11th Workshop on Hyperspectral Image and Signal Processing : Evolution in Remote Sensing, Whispers 2021, 24-26 March 2021, Amsterdam

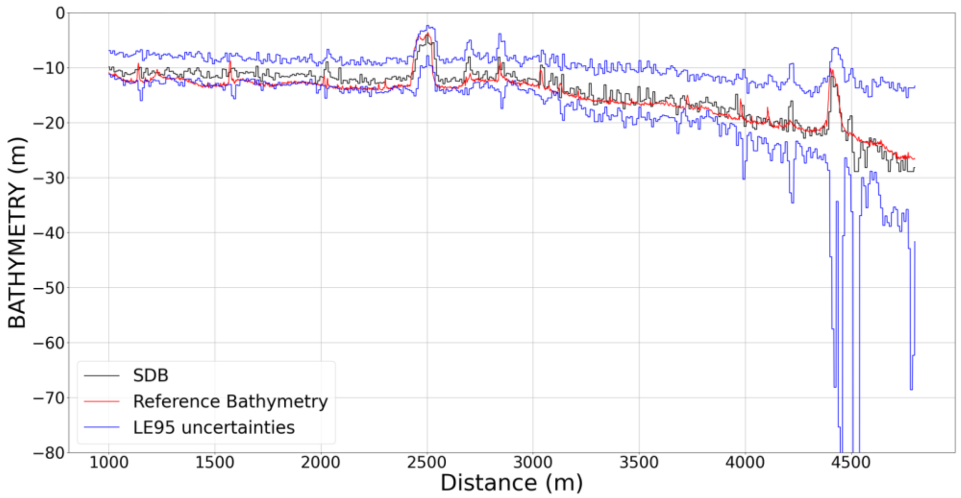


Figure 13: Transect of estimated SDB from a Sentinel-2 image (black), with reference MBES data (red), and the two bounds of the asymmetric modelled 95% uncertainties (blue). Image credit: SHOM and Hytech-imaging.

3.2.1.2 Vertical uncertainties of empirical, ML methods

The ML and empirical SDB models are necessarily trained or tuned with known bathymetric data. Therefore, the vertical uncertainties of the SDB results of these methods cannot be better than those of the training data. For example, an empirical method trained with low-quality nautical chart data cannot provide highly accurate depth information. Vertical uncertainties of empirical and ML methods can be estimated by using measures of the empirical fits to the training data, such as deviations from the calibration line for the ‘ratio approach’ or by separating training and validation datasets before the training procedures. The transferability of those uncertainties to other sites is limited. Similar to the transferability of the empirical and ML SDB models it depends on water clarity, water level, seabed colour and other environmental parameter being consistent with the reference site.

3.2.1.3 Vertical uncertainties of active lidar satellite sensors

No error model or modelling of the vertical uncertainties of the SLB has been published yet. The following factors need to be considered: (a) deviation of photons at the seabed from the derived seabed surface, (b) density of photon returns, (c) clarity of the water at the time of recording, and the (d) vertical uncertainties in transferring geoid height data to hydrographic vertical datum.

3.2.1.4 Vertical uncertainties of bathymetry from waves

The modelling of the vertical uncertainties of bathymetry from waves methods have not been published so far. Publications of journal articles, generally have the RMSE for the estimated depths and range from 10% – 20% of the mean ground-truth depth in the study, with most in the 20% range.

This section describes the theoretical errors which are introduced by the underlying assumptions of the bathymetry from wave methods.

The water depth of the bathymetry from wave methods depends on the wave dispersion methods, and namely on the ocean wavelength and its speed. Of those, the critical parameter is the wave speed for two reasons. First, it is in a power of two in the wave dispersion equation, and second, the wave speed can be derived from the consecutive snapshots of the different multispectral satellite bands, or separate satellite image recordings, or from a single image that includes deep water, and has typically a larger relative error than the wavelength.

The sensitivity of the models to wave speed is shown in figure 14. In this example an 80m long ocean wavelength, which is a common length near the shore, it is shown that the calculated water depth is a function of wave speed. Assuming a wave speed of 10 m/s and an uncertainty of 10% (1 m/s) in its derivation, we obtain a water depth of 14.2 with ± 5.9 m. Thus, a 10% error in the wave speed translates to a 40% error in the water depth calculation. At larger wave speeds, the estimated water depth as well as the uncertainty increase substantially until the function diverges at a wave speed of 11.2 m/s - always assuming a constant wavelength of 80 m.

The uncertainty of the ocean wave speed can be estimated from the satellite data itself by using different combinations of spectral bands and their known delay time between recordings. From these multiple measurements, an effective wave speed and wave speed uncertainty can be determined, allowing a vertical error estimate.

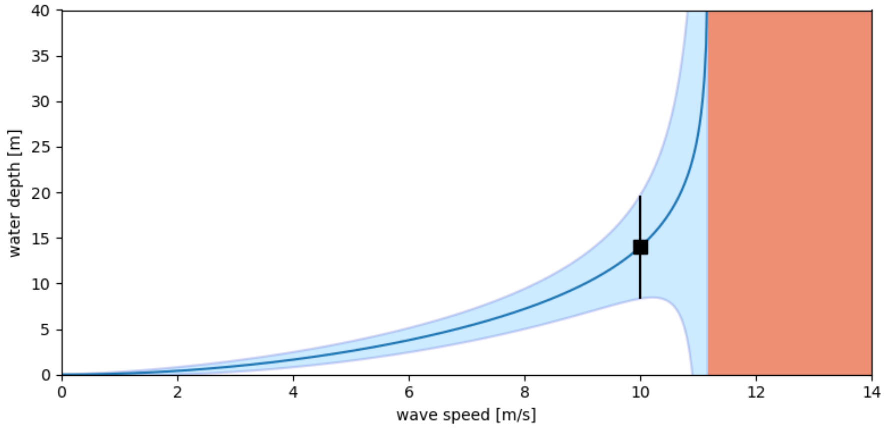


Figure 14: Water depth as a function of wave speed for a constant wavelength of 80m/s (dark blue line) with a vertical error estimate for a fixed uncertainty in the wave speed of 10% (1m/s), shown as blue area. For wave speeds above 10 m/s, the water depth is calculated as 14.2m with ± 5.9 vertical uncertainty. Image courtesy: EOMAP

3.2.2 Calculating uncertainties, measuring the error

Calculating the uncertainty of a measurement conducted with a standard method is ideally carried out with a benchmark measurement from a comparable system of higher and known precision and accuracy. In the case of SDB, there are no direct bathymetric measurements. SDB, as the term states, provides a derived result and not a direct measurement. In addition, SDB provides derived bathymetry of not a single point but of a relatively large area when compared to areas that are generally covered by conventional sounding methods. Therefore, when benchmarking a SDB result for precision and accuracy, the best method that lends itself as a reference is bathymetry that has been measured by a surface vessel, ideally, Multibeam

Echosounder (MBES). When compared to a single beam survey, multibeam surveys provide a wide coverage for any given pass in any given area and therefore is a more robust reference than a single beam survey. Being a direct acoustic measurement, the MBES survey result is bereft of uncertainties that affect reflected sunlight and therefore a more reliable source of reference data. The quality of surface vessel surveys is indicated in the sounding error budgets prepared during the survey, the actual results that were obtained and the degree of confidence that could be derived based on the quantum of depth-dependent and depth-independent errors that have been quantified and accounted-for in the survey. Once the confidence levels on a MBES survey have been established and comparable sets of data are available, then reference data for the areas of interest may be established for which the uncertainty of measurements of the SDB is to be determined.

The below figure depicts an example of how two sets of data between MBES and SDB compare for an area of interest in the 0m to 5m depth band covering areas mentioned in (a) and (b) above.

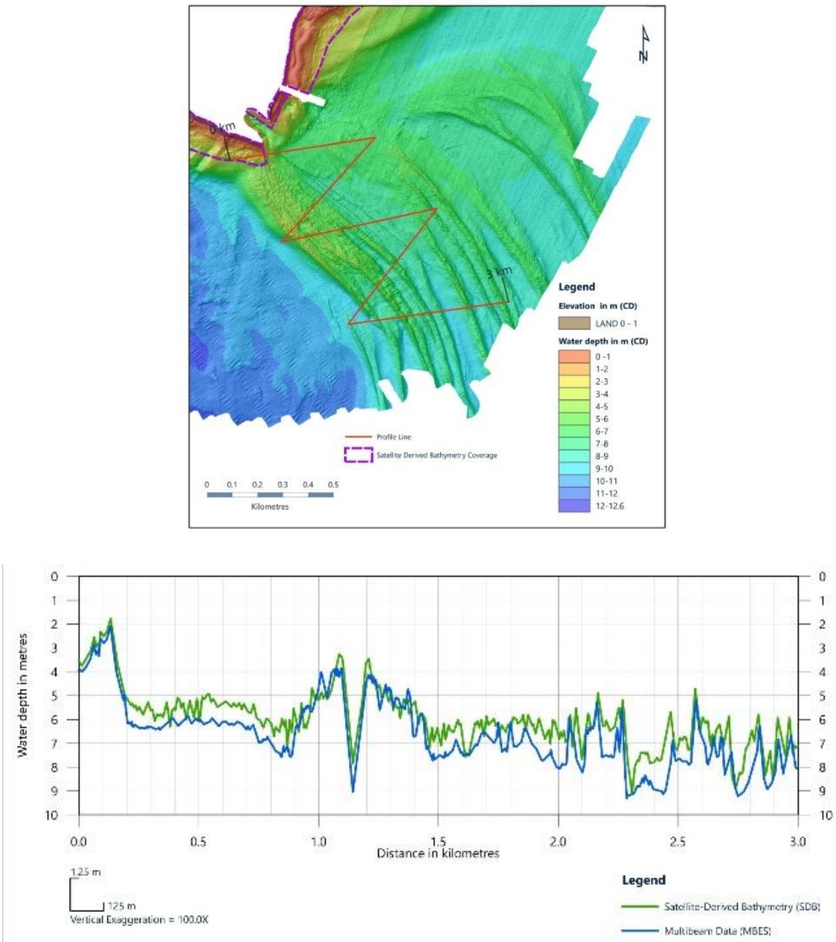


Figure 15: SDB grid overlaid by MBES survey lines (red lines) and the transect of the two surfaces (right). Image courtesy: Jayaprakash and Srinivasan[29].

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[29] Athmaram, Jayaprakash , and Ashish GS Srinivasan (2017) Acquisition of Satellite Derived Bathymetry Data for Offshore Engineering Projects - Island Case Study. Paper presented at the Abu Dhabi International Petroleum Exhibition & Conference, Abu Dhabi, UAE, November 2017. doi: https://doi.org/10.2118/188714-MS

3.2.3 Depth bias reduction

Reducing the vertical uncertainties of the SDB models is possible if high quality survey data - such as MBES data - intersect the SDB project area. Depending on the SDB model and the divergence between the two data sets, it may be a matter of gain and offset correction of the SDB surface or a more sophisticated refinement of the SDB model settings to reduce the uncertainties as much as possible.

Satellite lidar bathymetry (SLB) data could be used as further bathymetric information from space and also serve as a bathymetric dataset to refine the SDB model. However, this requires a comprehensive understanding of the vertical uncertainties of the SLB data and a comparison with the MBES data itself.

The importance of the location and understanding on the heterogeneity of the seabed, water and recording conditions is of high importance in this process.

3.3 Horizontal uncertainties

The horizontal uncertainty of SDB data from satellite imagery depends on several aspects, which are listed in this section.

- The satellite sensor - Annex 14 provides a list of the horizontal accuracies of the satellite vendors which varies across the satellite sensors.

- The processing level of the satellite imagery – The satellite imagery can be accessed at different processing levels, some might consider a correction for terrain heights for land surfaces or the mosaicking of multiple imagery. Depending on the morphology of the coastal terrain and the underlying terrain model, the satellite image may be subject to additional horizontal uncertainties.

- The availability of local Ground Control Points (GCPs) – With access to GCPs that can be identified in the satellite image, one can improve the horizontal uncertainties of the satellite image prior to an SDB calculation. The improvements can improve the horizontal uncertainties to be in the range of one time the cell size of the satellite image.

- The correction for viewing geometry and water refraction – Depending on the viewing angle and the water depth a correction might be relevant for very high-resolution satellite imagery and its derived SDB product to reduce horizontal uncertainties (see section 2.4.4)

CHAPTER 4 METADATA

4.1 Data vs. Metadata

It is important to understand the difference between data and metadata. Data is the core output of the SDB model, and metadata describes the data. For SDB, the data are the georeferenced depths. Information on satellite sensors, along with the date and time that they were collected, analytical methods and routines which were applied to correct for tides and related information are metadata.

Metadata provides information to data users that helps determine the quality of the data, and therefore the ability to use the data for more applications than would be possible with depth information alone.

Metadata should preferably be an integral part of the digital survey record and conform to the 'IHO S-100 Discovery Metadata Standard' when this is adopted. Prior to the adoption of S-100, ISO 19115 can be used as a model for the metadata. If this is not feasible, similar information should be included in the documentation of a survey.

4.2 Metadata and Data Formats

This section provides guidance about the minimum information on SDB data and metadata.

Table 3: The required information on data and metadata for SDB

Data	Description	Example
Depth	Z value with negative down. The calculated depth stored in negative value, in meters, with two decimal places.	-9.25 m
Coordinates	Coordinates in X, Y	25.235019 N, 55.235495 E
Uncertainty value	Calculated or Estimated Uncertainty (for each point) with description of the uncertainty measure	0.7m LE95
Spatial reference systems	Description of the spatial reference systems, including EPSG code	World Geodetic System 1984, epsg code 4326

Metadata	Description	Example
Date and time of satellite record(s)	The date and UTC time stamp for date of the satellite image record. If multiple satellite records are used, all shall be listed.	2021-01-15T10:30:15
Horizontal Datum	Horizontal datum of the SDB dataset	WGS84
Vertical Datum	Vertical datum of the SDB dataset	Lowest Astronomical Tide
Tidal information	Description of the tidal station and water level at time of satellite data record(s). If multiple satellite records are used, all shall be listed.	Sharjah, +0.2m above Lowest Astronomical Tide
Satellite sensor	Name of the satellite sensor	Sentinel-2A
Satellite scene number	Unique identifier of the scene(s) from which SDB was derived.	10100100045D38
Satellite off-nadir angle	Off-nadir angle, as distinct to satellite elevation angle (which is different!)	14.5 degrees
Satellite look azimuth	Angle of satellite look angle relative to north	230 degrees
Sun azimuth	Angle of the sun relative to north	125 degrees
SDB method	The analytical method of SDB	RTE method
SDB software name/version	Specific software name and version	WATCOR-X v1.2
Quality assurance	Procedures which have been applied to assure data quality	Validation with single beam lines
Vertical accuracy	Statement on vertical accuracy (SOUACC)	2.0m LE90
Horizontal accuracy	Statement on geolocation accuracy (POSACC)	5.0m CE90

Spatial resolution	The spatial resolution of the SDB grid	1.3m
Geographic Coverage	Extent of the SDB data (typically as a series of four corner points or centre point)	UL: 45.93N, 10.37E; UR: 45.92N, 10.97E; LL: 45.41N, 10.36E; LR: 45.41N, 10.95E
Producing organisation	Company or organisation responsible for producing SDB data	UK Hydrographic Office
Point of contact	Contact details to the SDB analyst or entity	P. Mitchell (mitchell@abcdef.xy)
Validation data data applied	State whether validation data was applied during the SDB process	True. Calibration-Validation process with single beam XYZ dataset.
Depth Coverage	Depth range covered by the SDB data, relative to vertical datum	Min: +2 m Max: -12 m
Data Cleaning	Statement on data cleaning performed on SDB	All systematic errors and obvious outliers are removed from the delivered dataset.
Comments	Statement on general issues that may limit the quality of SDB	Numerous floating objects limited SDB coverage

CHAPTER 5 SDB COVERAGE AND FEASIBILITY

The potential coverage and mapping potential of SDB depends on multiple environmental factors which impact the sunlight reflectance from the seafloor. The most important of those is turbidity, seabed coverage and seafloor vegetation, sea state and cloud cover.

Turbidity limits the maximum detection depth of passive and active sensors that measure the visible light spectrum. Turbidity varies with the influx of sediment from the coastal zone and resuspension and is spatially and temporally dynamic. The Secchi Disk Depth (SDD) and diffuse attenuation coefficient (Kd) are considered an indicator of turbidity and clarity of the water. It is generally considered that the SDB which relies on the seafloor reflectance (ML, empirical, RTE, photogrammetry and SLB) has a maximum depth coverage that is related to the SDD. Figure 16 illustrates the estimated maximum mapping depth based on 20-year time series for water clarity analysis (Hartmann et al., 2022). It can be understood as a general feasibility map for those SDB methods. It is important to understand that water clarity and turbidity are dynamic and can vary depending on the season or individual events and wave activities. This fact is not taken into account in the figure and the maximum mapping depth can differ from the map. Therefore, a preliminary study of water clarity conditions and satellite records of the site at times of low water clarity is recommended for any SDB project site.

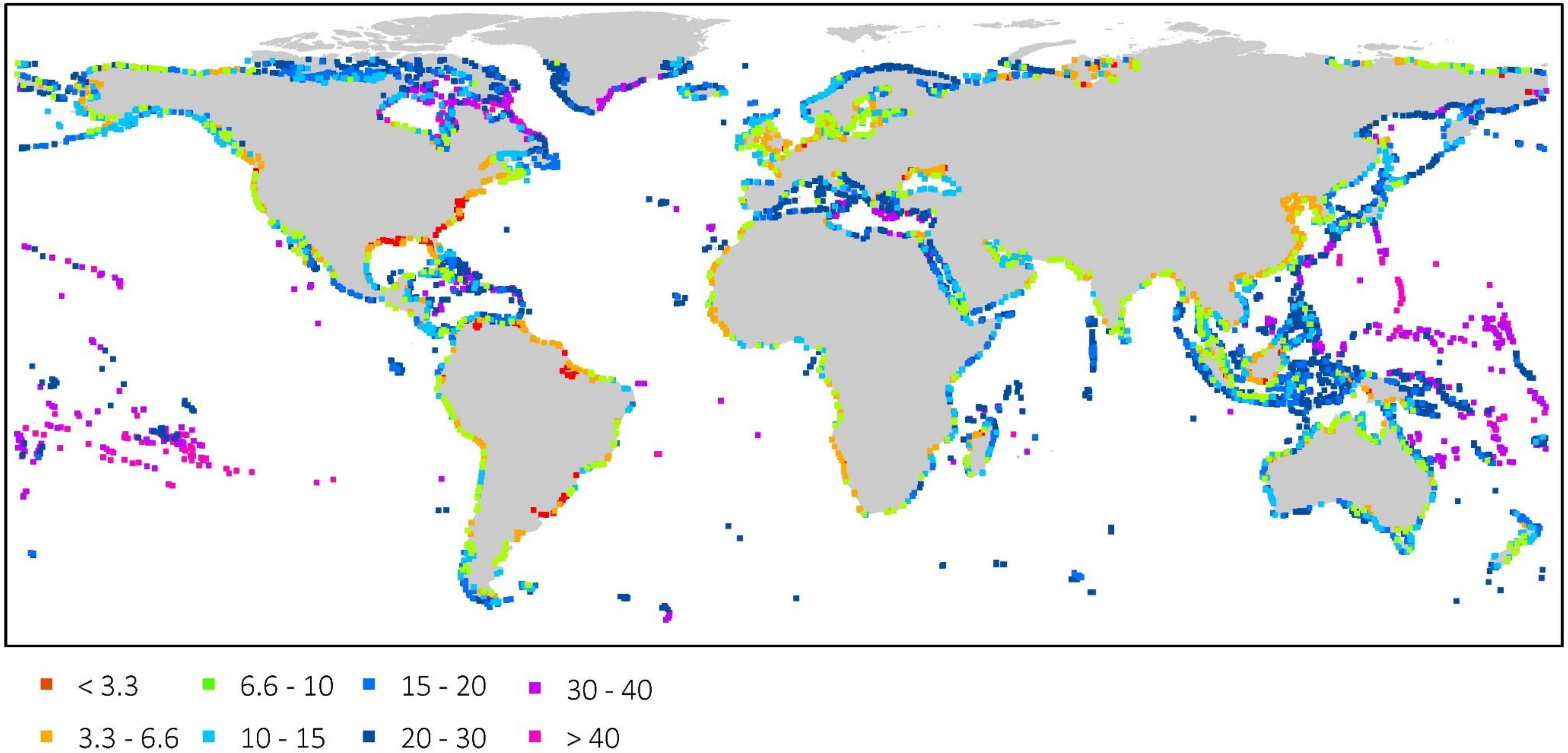

Figure 16. Estimated mapping depth/Cut-Off depth of SDB in meters based on global Secchi Disc Depth analysis. Image courtesy: Hartmann et al. 2022[30]. This map does not include the seasonal variations of water clarity which must be taken into consideration.

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[30] Hartmann, Knut, Reithmeier, Mona, Knauer, Kim, Wenzel, Julian, Kleih, Christoph Kleih, Heege, Thomas: SATELLITE-DERIVED BATHYMETRY ONLINE. International Hydrographic Review (28), 53-75 (2022). https://doi.org/10.58440/ihr-28-a14

While wave activities are mandatory for the bathymetric wave derivation method (see section 2.3.1) they reduce the SDB potential for other methods in areas with continuously strong wave breaking and whitecaps. Figure 17 illustrates the average annual wave height based on Copernicus Marine. It shows zones with higher wave heights, such as the Pacific coast of North and South America and most offshore islands. It also shows zones with low wave activity, such as the Baltic Sea, the Red Sea and Indonesia.

The map does not show the dynamics of wave activity, which vary with weather, currents and tides and may result in more favourable wave conditions for one or another SDB methods.

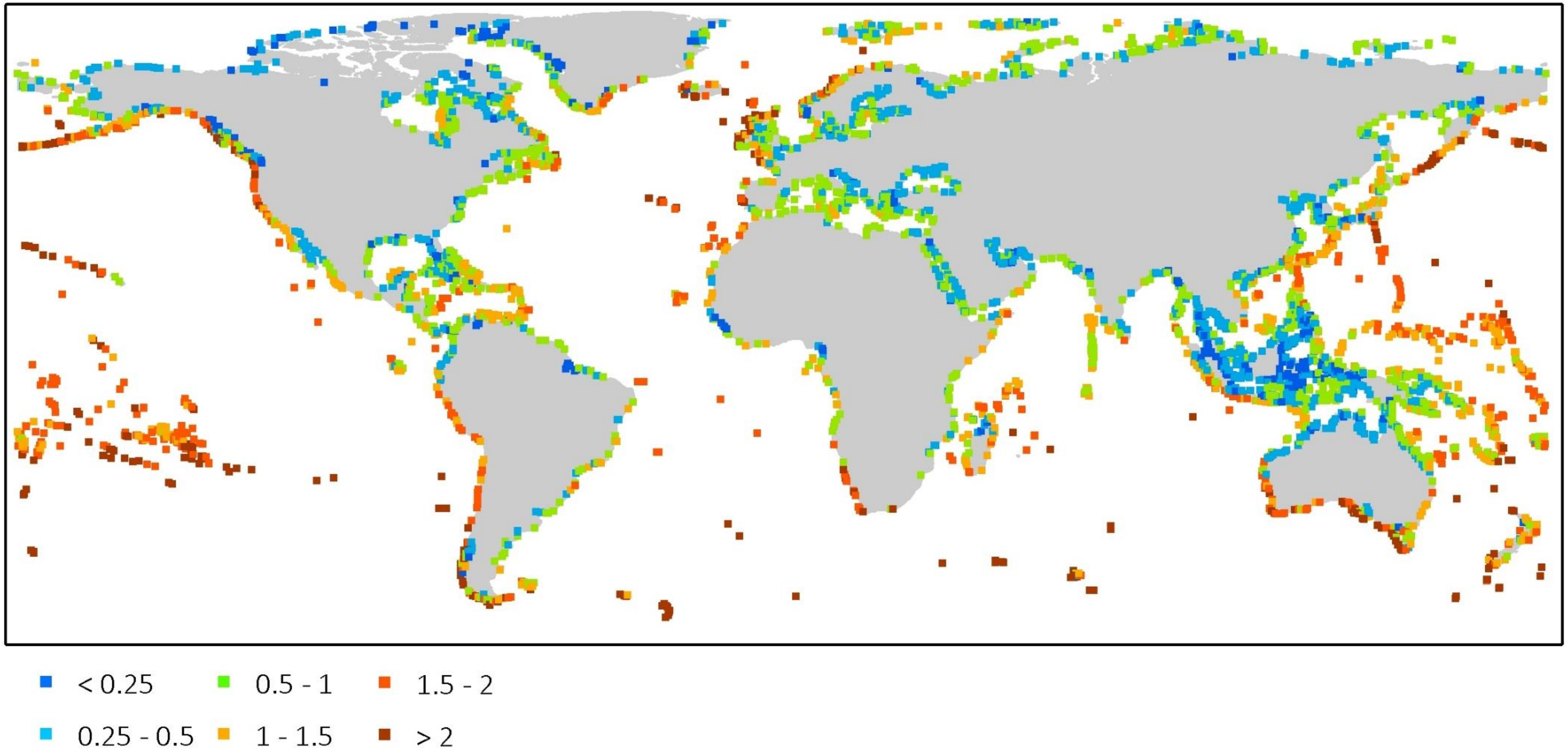

Figure 17. Average wave height in meters. Image courtesy: EOMAP, analysis based on Copernicus marine data.

Seabed colour and seafloor vegetation have a local impact on SDB detection when they absorb a significant amount of sunlight, limiting the SDB capability of active and passive sensors. Sites with very dark seabed exist in all coastal areas and their cover and intensity varies regionally. Dark seabed types are usually one of the following types: very dense seagrass beds, kelp forests or dark bedrock or volcanic rock. In extreme cases, a very dark seabed does not allow for SDB methods even if the water clarity is excellent.

Clouds and haze reflect the sunlight and do not allow for any surface or seafloor reflectance. The average cloud cover of the Earth is highest close to the equator and in the mid to higher latitudes but depends on seasons and weather events. Figure 18 provides an overview of the annual global cloud cover. The lower the average cloud cover, the higher the chances to access cloud free satellite records (archived and new). The current archives of the satellite data have recorded the Earth in cloud free conditions in most locations several if not hundreds to thousands of times. The map of the average cloud coverage provides an indication of the potential success of cloud free new image records and therefore the ability to monitor coastal zones in high frequency.

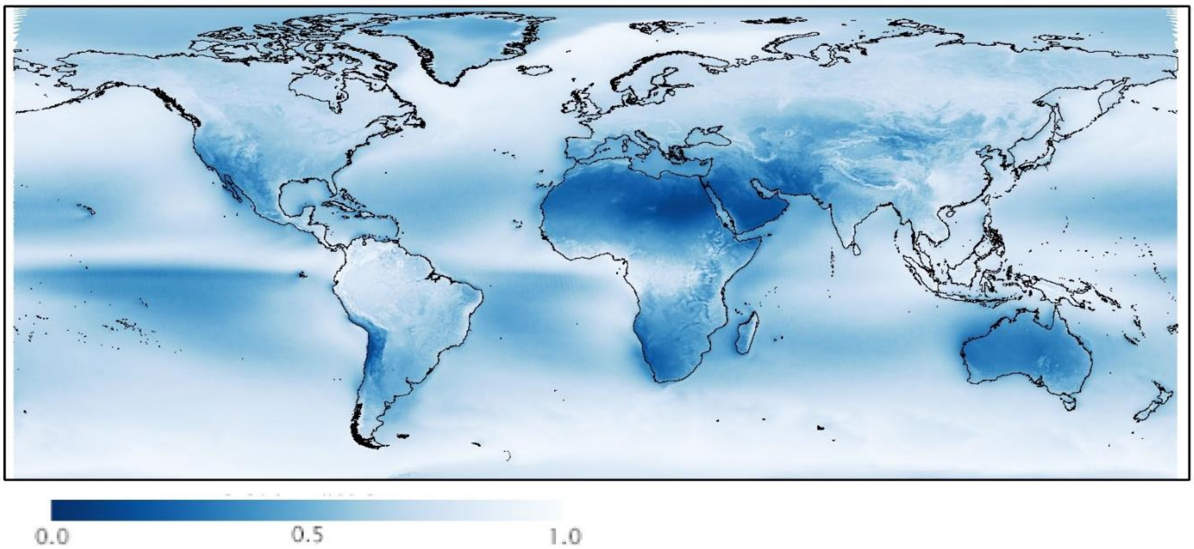

Figure 18. Average cloud cover from 0 to 100 (shown as 1.0) percent. Image courtesy: Nasa / Earth Observatory[31]

Ice coverage reflects all sunlight meaning no bathymetric data can be derived for areas which are covered by ice at time of satellite image recording. This, and the fact that sunlight intensities are highest at summer months, implies that SDB mapping of Arctic and Antarctic regions needs to be based on satellite records which are recorded in peak summer months. Figure 19 illustrates the average and minimum extent of the sea ice for the peak summer months for the Arctic and Antarctic.

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[31] URL: https://earthobservatory.nasa.gov/images/85843/cloudy-earth

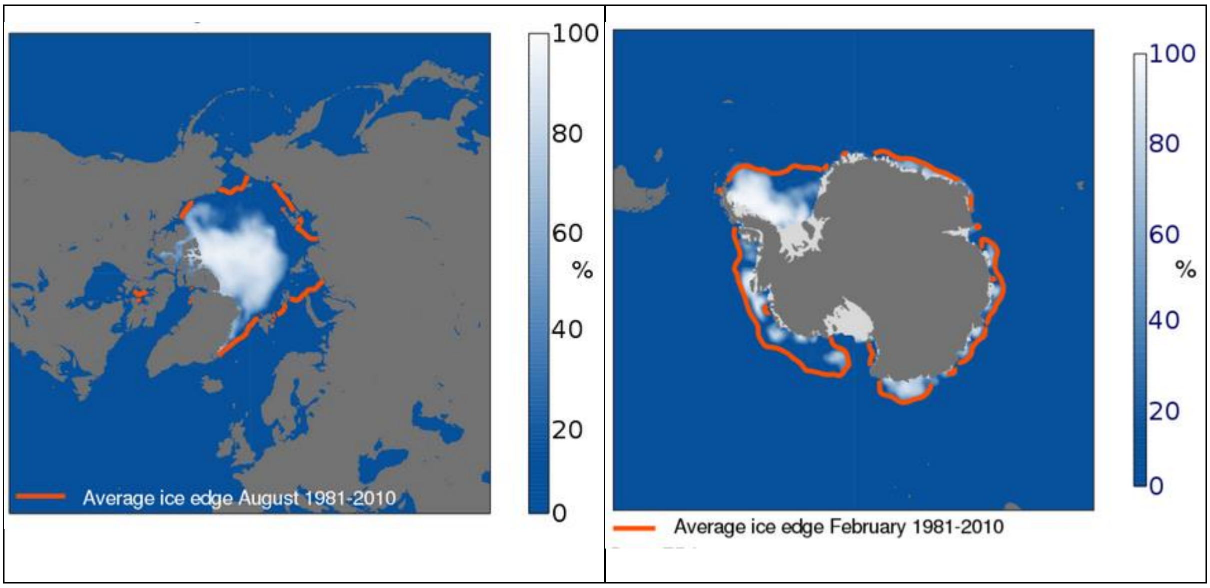

Figure 19: Average ice edges (red line) of the peak summer months for the Arctic (left) and Antarctic (right). The white zones represent the ice cover of August (left) and February (right) which were amongst the years with little ice cover. Image courtesy: Copernicus[32]

The sun elevation is of importance for SDB methods which rely on the reflectance of sunlight from the seafloor (RTE, empirical, ML and photogrammetric methods). Ideally, sun (and sensor) elevation should be greater than 30 to 55 degrees which, especially in higher latitudes can be seldom met.

32 https://climate.copernicus.eu/sea-ice

CHAPTER 6 APPLICATIONS OF SDB

6.1 Environmental characterisation

Shallow-water habitats are among the most valuable and productive ecosystems in the world. These ecosystems include coral and oyster reefs, seagrass, macrophyte beds and are a valuable niche of biodiversity hotspots. With high anthropogenic pressure (e.g., water level regulation, offshore exploration and water resources management) and the effects of climate change (e.g. water warming, sea level rise, tsunami, beach erosion, loss of biodiversity, presence of alien species) there is a greater need for accurate and up-to-date information on bathymetric data of shallow coastal regions. Changes in substrate topography due to human activity and climate variability can in fact lead to disruptions of natural physiologic processes in aquatic habitats with negative consequences on ecosystem functions.

Bathymetric data are often the primary dataset included in habitat mapping and submarine geomorphology mapping efforts. Shallow water bathymetry, accessible from SDB methods, is therefore critical as it provides a foundation for measuring underwater light density, mapping and monitoring benthic habitats to assist in their conservation and monitoring.

A variety of environmental studies and applications have been consequently developed based on SDB data. Scientists use bathymetry to study the habitats of benthic (bottom-dwelling) organisms, to determine where fish and other water life feed, live, and breed as well as to discover macrophytes growth and status at variable water depth ranges (Kutser et al., 2020[33]). Temporal monitoring of SDB at local to global scale reveals geomorphological changes, sedimentation and erosion processes, and underwater formations. Sediment transport mechanisms are also revealed by quantitative analyses of bottom morphology such as those conducted using methods from geomorphometry (Lecours et al., 2016[34]; Lucieer et al., 2019[35]), while the detection of subaqueous bedforms would allow the discovery of new marine habitats.

If SDB mapping forms the basis of understanding physical, and ecological processes in a variety of aquatic systems, the combination of SDB to digital surface model of adjacent lands supports the comprehensive understanding of coastal and intertidal habitats and coastal zones processes. Further applications (e.g. monitoring of full coastal evolution, including interlinked morphological behaviour between bottom substrates and beach developments) on environmental characterisation are hence developed.

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[33] Kutser, Tiit & Hedley, John & Giardino, Claudia & Roelfsema, Chris & Brando, Vittorio. (2020). Remote sensing of shallow waters – A 50 year retrospective and future directions. Remote Sensing of Environment. 240.

[34] Lecours, V., M. F. J. Dolan, A. Micallef, and V. L. Lucieer. 2016a. A review of marine geomorphometry, the quantitative study of the seafloor. Hydrol. Earth System Sci. 20, 3207–3244.

[35] Lucieer, V., Barrett, N., Butler, C. et al. A seafloor habitat map for the Australian continental shelf. Sci Data **6**, 120 (2019). https://doi.org/10.1038/s41597-019-0126-2

6.2 Combined bathymetric survey

A combined survey describes the combination of multiple survey concepts and systems to take advantage of the synergies of the used methods. A common example is the combination of SDB with acoustic surveys. MBES surveys typically do not survey water depths shallower than 5 to 10m or are high labour and cost intensive when they do, whereas SDB methods can provide this depth zone and its uncertainties can be quantified in the overlapping regions.

Single beam surveys can be combined with SDB data to refine the SDB model and result in a spatial bathymetric grid which otherwise would need to be done by interpolation. Combining SDB with airborne lidar bathymetry surveys can improve planning for lidar campaigns, fill data gaps in coverage, and extend coverage to areas where lidar data is not available. An example of an integrated survey approach is the bathymetric survey of Tonga. The Land Information New Zealand (LINZ) designed the surveys to take advantage of innovative technologies using SDB, planes, airborne lidar and autonomous technology to measure Tonga's waters.[36]

6.3 Charting

SDB methods which do not require training data are useful information in carrying out pre-survey plans (reconnaissance) particularly in the areas where no prior survey has been carried out or in the case that the existing charts are doubtful or inaccessible. DB data enhances planning accuracy and reduces surveying risks in sites that are otherwise not well-known. In addition, SDB data can be used to complement information for the production nautical charts, particularly for the detection of non-navigable shallow areas. However, the presentation of depth data on charts obtained by means of SDB must be well identified, i.e. masked, annotated, so that the users are aware that the area in question is not surveyed using the standard hydrographic technique. The use of SDB data for the identification of non-navigable shallow areas has been used by many hydrographic offices worldwide.

See also the section 6.7 on feature detection.

From a practical perspective, it may be worthwhile to classify the SDB depths into the following classes :

Table 4. Depth intervals and their general description

Depth intervals	**General Description**
0m - 3m	Extremely shallow waters found near landfall points and coasts outlined with reefs. These areas typically contain dangerous underwater obstructions in the case of natural coasts. Abruptly reducing water depths near artificial islands at the water-revetment interface is a case when man-made offshore facilities are being

36 https://www.linz.govt.nz/news/2019-10/kingdom-tonga-receives-high-tech-data-new-zealand

	considered. These areas are potentially dangerous for manoeuvring small boats and crafts and pose significant safety hazards for connecting up from land to sea using a sounding pole. However, these areas are critical for engineering and construction requirements where pipelines, cables etc are required to be laid and the slope of the shore needs to be determined with regards to the high-water line. In most cases it is almost impossible to carry out a conventional survey and is one of the most important areas where SDB becomes an ideal tool to fill the gaps.
3m - 5m	Areas similar to (a) above but provide manoeuvring space for shallow draught, lightweight boats. These are areas where specific types of acoustic systems, such as interferometric, can provide useful quality bathymetric data.
5m - 10m	Areas where shallow draught boats may approach and manoeuvre safely. The 7m to 10m depth band also forms the cusp of operations between a bigger offshore vessel and a small boat.
10m - 15m	Areas of operation of bigger offshore vessels with loaded draughts of about 3.5m.
15m - 25m	Areas that are generally safe for general navigation for most types of seagoing ships when adequately surveyed.
≥ 25m	Areas that are safe for general navigation for all types of seagoing ships, when adequately surveyed.

6.4 Hydrodynamic modelling

Bathymetry overall influences water circulation in several ways, by e.g. separating adjacent basins, inducing gravity currents, enhancing internal waves and vertical mixing. Along coastlines, bathymetry directly shapes the propagation of surface wind waves, generates near-surface currents and affects sediment transportation and resuspension (Gallerano et al. 2019[37]). SDB can provide essential information for modelling ocean, marine and inland coastal areas (e.g. lakes and rivers). Most existing hydrodynamic models indeed require bathymetric base information with a degree of detail which increases as the model increases in complexity. The simplest one-dimensional models require the average depth of the water body (or portion) to be modelled, or a hypsometric curve which provides estimates of the horizontal area associated to each depth. Contrarily, two to three-dimensional models need updated and highly detailed bathymetries for resolving large to small scale hydrodynamic phenomena. The latter models in fact numerically solve the equations of water motion by discretizing the water body in a computational grid composed by several cells of a given water depth. It is important for these models to have bathymetric information at a minimum resolution of the computational

[37] Gallerano, F., Cannata, G., & Palleschi, F. (2019). Nonlinear waves and nearshore currents over variable bathymetry in curve-shaped coastal areas. Journal of Ocean Engineering and Marine Energy, 5(4), 419–431. https://doi.org/10.1007/s40722-019-00153-8

grid or higher, in order not to smooth those bathymetric features that are relevant for the hydrodynamics, such as canyons, ridges, bars and others (Murrey and Gallego, 2017[38]).

Despite the fact that SDB only provides information for the shallow areas, it is also well known that hydrodynamic processes at coastal scales are typically modelled with higher horizontal resolution, such that nesting models at different spatial resolutions is a standard practice in hydrodynamic modelling (Debreu and Blayo 2008[39]). In fact, coastlines, estuaries and even shallow lakes are often highly dynamic areas, where large scale atmospheric forcing (e.g. storms, extreme floods), tides, wind waves and riverine inflows interact and heavily affect water circulation and underwater topography. Thus, for such regions, not only higher resolution is generally required, but also bathymetry is often not static, as it changes in time (Jacob and Stanev, 2021[40]). In this regard, SDB represents a valuable alternative for high resolution and time-referenced bathymetry data, as most circulation models use fixed bathymetries due to the costs and the time required for high resolution bathymetric surveys.

6.5 Coastal and offshore engineering

Coastal and offshore engineering includes the design, installation and asset integrity monitoring of marine and coastal structures. SDB and related information on seabed characterisation can be used to support the pre-installation and post-installation of nearshore marine assets such as pipeline and cable landings, and coastal structures.

During the pre-installation phase, SDB can provide reconnaissance bathymetry data as valuable input for the desktop studies of the planned construction site. Archived satellite imagery data enable engineers or coastal planner temporal and historic bathymetry analysis at regular interval to understand the seafloor and shoreline dynamics. The temporal analysis also offers advantages for coastal engineering applications and post-installation monitoring, for example contributing to overtime environmental impact, coastal resilience or beach replenishment studies, seabed mobility that might impact the assets.

SDB provides reconnaissance information for optimizing on-site surveys (vessel based MBES or airborne lidar bathymetry ALB). The bathymetric information can be input to optimize survey line planning; the SDB related information on seafloor dynamics and environmental conditions (see chapter 6) provide intelligence for the survey scheduling.

SDB information on seabed characterization can be considered to help in planning and optimising higher resolution or validation surveys for environmental surveys. For example, if the mission is to map high resolution of seagrasses in a large area, with satellite seafloor benthic classes, it can help identify the focus are to be map using Airborne Lidar Bathymetry (ALB) or MBES or mission planning of ground truth sampling using underwater videos or images.

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[38] Murray, R. B. H., & Gallego, A. (2017). Data review and the development of realistic tidal and wave energy scenarios for numerical modelling of Orkney Islands waters, Scotland. Ocean & Coastal Management, 147, 6-20.
[39] Debreu, L., & Blayo, E. (2008). Two-way embedding algorithms: a review. Ocean Dynamics, 58(5), 415-428.
[40] Jacob, B., & Stanev, E. V. (2021). Understanding the impact of bathymetric changes in the German Bight on coastal hydrodynamics: One step toward realistic morphodynamic modeling. Frontiers in Marine Science, 8, 576.

In terms of practicality, SDB enables the mapping of large remote areas at reduced cost and without data collection on the ground. This is a key benefit in challenging locations due to safety and environmental factors.

6.6 Coastal archaeology

Seafloor data can assist with the identification of sites of cultural heritage. Coastlines around the world were not always where they are located today. On the Gulf of Mexico coast of Florida, for example, the coastline was roughly 200 kilometres seaward from today's coastline when it is thought that humans first made it to Florida, about 14,550 years BP (Halligan et al., 2016[41]). In archaeology, the presence of waterways increases the suitability of finding sites of cultural heritage as people have always used waterways as conduits for travel, provision of navigational waypoints, and provision of habitats for game resources. In many areas around the globe, such waterways are not submerged; during the process of sea level rising, what was once an inland site could have become a coastal site before leaving the terrestrial domain altogether (Erlandson, 2001[42]). The probability of finding offshore sites of cultural heritage is thought to be driven by proximity to former freshwater sources (Thulman, 2009[43]). Satellite-derived bathymetry provides an opportunity to capture former river channels, tidal deltas, and springs that are now underwater in the marine environment. Like what has been done in terrestrial environment using lidar data (e.g. Chase et al., 2012[44]), topographic signatures of sites of cultural heritage derived from satellite-derived bathymetry may serve as a proxy to detect potential sites or predict the suitability of finding other sites in different areas of interest.

6.7 Feature detection

SDB data represent gridded bathymetric surfaces with the smallest cell size (pixel) of a certain areal size as the smallest unit. For each pixel, only one depth value is given, which can be assumed to represent the average depth of the entire topography within the cell. This means that underwater obstructions that have a smaller diameter than the pixel size cannot be detected.

It is also important to note that the pixel size of the satellite image is not equal to the smallest obstruction that can be measured in an SDB grid, as satellite pixels are "mixed pixels" and effects on the water surface and scattering in the water column (and atmosphere) can lead to a mixing of spectral information from adjacent locations. Finally, it also depends on post-processing, namely the filtering methods - if any are applied - that determine the ability to identify individual obstacles within an SDB grid. Therefore, undetected objects larger than the

[41] Halligan JJ, Waters MR, Perrotti A, Owens IJ, Feinberg JM, Bourne MD, Finnerty B, Winsborough B, Carlson D, Fisher DC, Stafford TW & Dunbar JS (2016). Pre-Clovis occupation 14,550 years ago at the Page-Ladson site, Florida, and the peopling of the Americas. Science Advances, 2(5), 1-8.

[42] Erlandson (2001). The archaeology of aquatic adaptations: Paradigms for a new millennium. Journal of Archaeological Research, 9(4), 287-350.

[43] Thulman DK (2009). Freshwater availability as the constraining factor in the Middle Paleoindian occupation of North-Central Florida. Geoarchaeology, 24(3), 243–276.

[44] Chase AF, Chase DZ, Fisher CT, Leisz SJ & Weishampel JF (2012). Geospatial revolution and remote sensing lidar in Mesoamerican archaeology. Proceedings of the National Academy of Sciences of the United States of America, 109(32), 12916-12921.

image pixel size are possible. Figure 20 provides a modelled example of how a shallow water obstruction will be seen at different spatial resolutions.

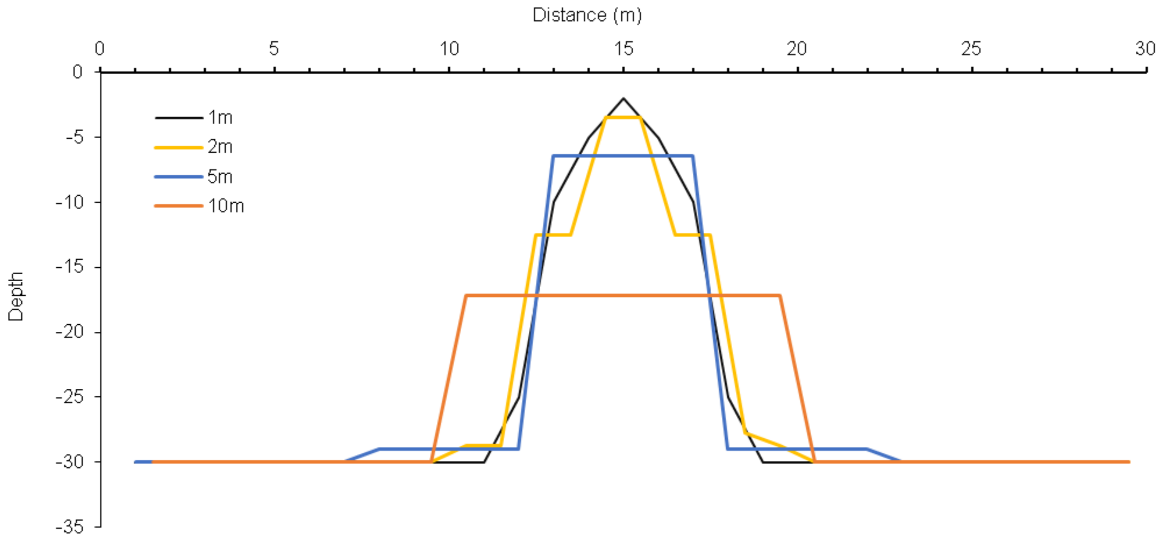

Figure 20: Theoretical example of an object detection with different spatial resolutions (pixel sizes). The 1m curve illustrates a modelled small diameter obstruction. The 2m, 5m and 10m curves illustrate the bathymetry for the different pixel sizes.

ANNEX

The following table provides a list of satellite sensors which have the potential to be used for SBD analysis.

Table 5: List of common satellite sensors for SDB analysis

Satellite name	Satellite owner	spatial resolution	Spectral resolution	Temporal resolution	Bit depth	Recording period	Geo-location accuracy
WorldView-2	Maxar	2.0 m , multispectral (raw data have 1.85 m at nadir and 2.07 m at 20° viewing angle)	Coastal: 400-450 nm Blue: 450-510 nm Green: 510-580 nm Yellow: 585-625 nm Red: 630-690 nm Red Edge: 705-745 nm Near-IR1: 770-895 nm Near-IR2: 860-1040 nm	Revisit Time up to 1.1 days	11 bit	8 October 2009-ongoing	5m CE90
WorldView-1	Maxar	Panchromatic 0.50 meters GSD at nadir	Panchromatic	Revisit Time up to 1.7 days	11 bit	18 September 2007-ongoing	5m CE90
WorldView-3	Maxar	1.3 m, multispectral (raw data have approx. 1.1-1.5m from nadir to 45° viewing angle)	Coastal: 400-450 nm Blue: 450-510 nm Green: 510-580 nm Yellow: 585-625 nm Red: 630-690 nm Red Edge: 705-745 nm Near-IR1: 770-895 nm Near-IR2: 860-1040 nm	Revisit Time up to 1 day	11 bit	13 August 2014-ongoing	5m CE90
WorldView-4	Maxar	1.3 m, multispectral (raw data have approx. 1.1-1.5m from nadir to 45° viewing angle)	Panchromatic: 450-800 nm Blue: 450-510 nm Green: 510-580 nm Red: 655-690 nm Near infrared: 780-920 nm	Revisit Time <1 day	11 bit	11 November 2016-September 2019	4m CE90
GeoEye 1	Maxar	2.0 m , multispectral (raw data have 1.65 m at nadir and approx. 2.3 m at 45° viewing angle)	450-520 nm (blue) 520-600 nm (green) 625-695 nm (red) 760-900 nm (near IR)	Revisit Time up to 1.5 days	11 bit	6 September 2008-ongoing	5m CE90
Pleiades	Airbus	2.0, multispectral	Panchromatic: 480-830 nm Blue: 430-550 nm Green: 490-610 nm Red: 600-720 nm Near Infrared: 750-950 nm	Revisit Time up to 1 day	12 bit	17 December 2011-ongoing	3m CE90

Satellite name	Satellite owner	spatial resolution	Spectral resolution	Temporal resolution	Bit depth	Recording period	Geo-location accuracy
Pleiades Neo	Airbus	1.3 m, multispectral	Deep Blue 400-450 nm and Blue 450-520 nm Green 530-590 nm Red 620-690 nm Red Edge 700-750 nm Near-infrared 770-880 nm Panchromatic 450-800 nm	Revisit Time up-twice a day	12 bit	Starting from 2021-ongoing	5 m CE90
SkySat*	Planet	1m, multispectral	Blue: 450-515 nm Green: 515-595 nm Red: 605-695 nm NIR: 740-900 nm Pan: 450-900 nm	Revisit Time up-12 times per day	8 bit	21 November 2013-ongoing	10m RMSE
Sentinel 2	European Space Agency	10m/20m/60m	Coastal: 433-453 nm Blue: 458-523 nm Green: 543-578 nm Red: 650-680 nm Red-Edge 1:698-713 nm Red-Edge 2: 733-748 nm NIR: 785-900 nm NIRn: 855-875 nm Water Vapor: 935-955 nm Cirrus: 1360-1390 nm SWIR1: 1565-1655 nm SWIR2: 2100-2280 nm	3-5 days	12 bit	23 June 2015 - ongoing	10m RMSE
Landsat 7	NASA/USGS	15m/30m	Blue: 450-520 nm Green: 520-600 nm Red 630-690 nm NIR 770-900 nm SWIR 1 1550-1750 nm Thermal 1040-1250 nm SWIR 2 2090-2350 nm Panchromatic 520-900 nm	16 days	8 bit	15 April 1999 - ongoing	30m RMSE
Landsat 8	NASA/USGS	15m/30m	Coastal aerosol 430-450 nm Blue 450-510 nm Green 530-590 nm Red 640-670 nm Near Infrared (NIR) 850-880 nm SWIR 1 1570-1650 nm SWIR 2 2110-2290 nm Panchromatic 500-680 nm Cirrus 1360-1380 nm Thermal Infrared (TIRS) 1 1060-1119 nm Thermal Infrared (TIRS) 2 1150-1251 nm	16 days	12 bit	11 February 2013 - ongoing	30m RMSE

Satellite name	Satellite owner	spatial resolution	Spectral resolution	Temporal resolution	Bit depth	Recording period	Geo-location accuracy
Landsat 9	NASA/USGS	15m/30m/100m	Coastal aerosol 430-450 nm Blue 450-510 nm Green 530-590 nm Red 640-670 nm Near Infrared (NIR) 850-880 nm SWIR 1 1570-1650 nm SWIR 2 2110-2290 nm Panchromatic 500-680 nm Cirrus 1360-1380 nm Thermal Infrared (TIRS) 1 1060-1119 nm Thermal Infrared (TIRS) 2 1150-1251 nm	16 days	14 bit	27 September 2021 - ongoing	30m RMSE
SPOT 5	Airbus	5m/10m/20m	Panchromatic: 480-710 nm Green: 500-590 nm Red: 610-680 nm Near IR: 780-890 nm SWIR: 1580-1750 nm	Revisit time 2-3 days	8 bit	30 may 2002 - 31 March 2015	
SPOT 6	Airbus	1.5m/6m	Blue 455–525 nm Green 530–590 nm Red 625–695 nm Near-Infrared 760–890 nm	Revisit time 1-3 days	12 bit	9 September 2012 - ongoing	10m
SPOT 7	Airbus		Blue 455-525 nm Green 530–590 nm Red 625–695 nm NIR 760–890 nm	Revisit time 1-3 days	12 bit	30 June 2014 - ongoing	10m
IKONOS	Maxar	1m/4m	Panchromatic: 450 - 900 nm Blue: 450 - 530 nm Green: 520 - 610 nm Red: 640 - 720 nm NIR: 760 - 860 nm	Revisit time 3 days	11 bit	24 September 1999 -31 March 2015	
QUICKBIRD	Maxar	0.65m/2.62m	Panchromatic: 450-900 nm Blue: 450-520 nm Green: 520-600 nm Red: 630-690 nm NIR: 760-900 nm	Revisit time 1-3.5 days	11 bit	18 October 2000 one - 27 January 2015	15m

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