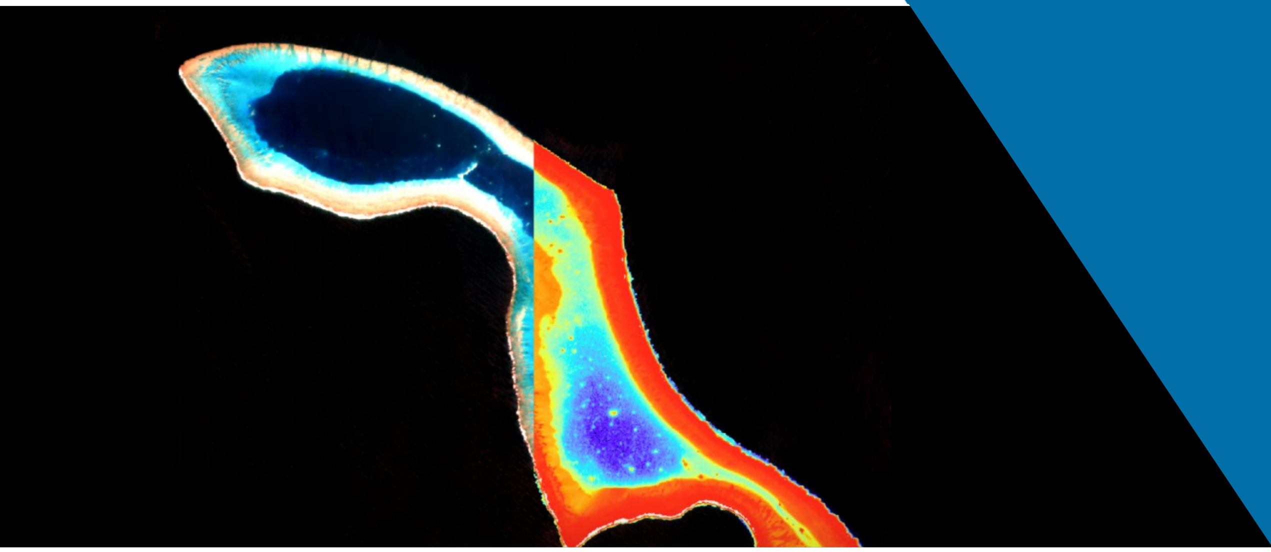

Satellite Derived Bathymetry

AusSeabed Community Guidelines

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Image credit: Front Cover

Satellite Derived Bathymetry of Indispensable Reef, Solomon Islands by Matthew Ellis

This document has been published with the endorsement of the AusSeabed Steering Committee and Executive Board.

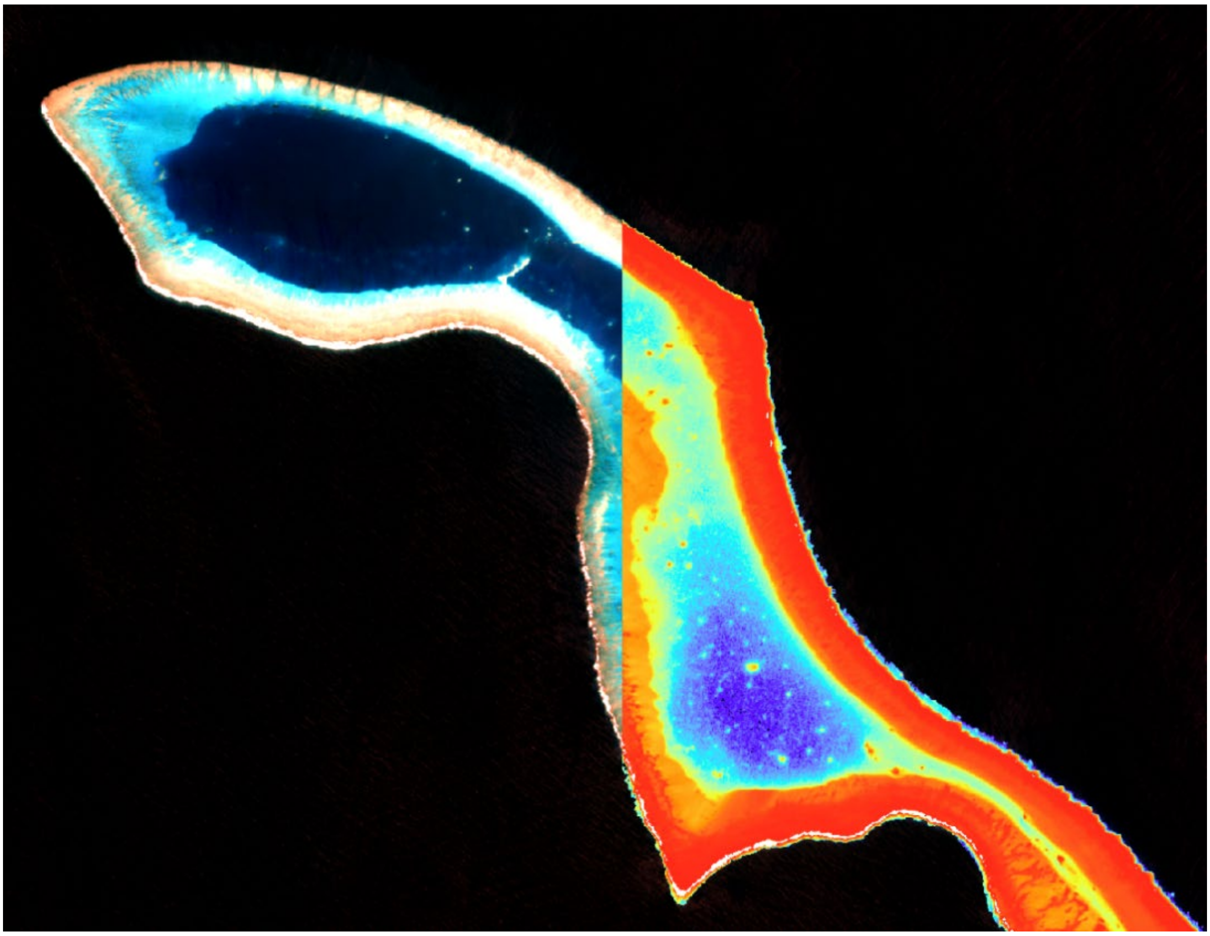
Suggested reference: Ellis, M., Formanek, R., and Townsend, N. 2022. *AusSeabed Community Guidelines: Satellite Derived Bathymetry.* Ocean Best Practices Repository, Belgium.

AusSeabed acknowledge the Traditional Owners of the land and sea country in Australia on which this work was conducted, The Aboriginal and Torres Strait Islander People. They were the first scientists, explorers, resource experts, and environmental managers. Their custodianship sets the benchmark for true sustainability.

Purpose and use of the guidelines

The Satellite Derived Bathymetry (SDB) guidelines are intended to provide users of SDB sourced from the AusSeabed Data Portal with the required knowledge to appropriately use SDB datasets. This is not a guide on how to produce SDB, rather a summary of the reliability and risks involved when using SDB for individual use cases.

The Hydrographic Standards Working Group (HSWG) of the International Hydrographic Organisation (IHO) is currently (2022) developing a set of best practice SDB Guidelines. This guideline should be referend to in conjunction with these guidelines once available.



Satellite Derived Bathymetry of Indispensable Reef, Solomon Islands

Acknowledgements

The authors would like to thank the reviewers involved in this work; technical staff from IIC Technologies, Ralph-Talbot-Smith from the Western Australian Department of Transport and Steven Sagar from Geoscience Australia.

Contents

1. What is Satellite Derived Bathymetry

Satellite Derived Bathymetry (SDB) can be broadly defined as any measurement of seafloor depth using a spacebourne sensor. The most common form of SDB is produced from optical sensors and imagery, which can be multispectral or hyperspectral, leveraging the relationship between light attenuation, bottom type/reflectance and water depth to model bathymetry. SDB measurements are described as either water column depths or seafloor depths depending on user preference and background.

1.1 Types

The types of SDB can be described by the type of input imagery used as the input, as well as the type of model used to relate observations to seafloor depth. The most common type of SDB is produced using optical Multispectral Imagery (MSI), however for completeness other possible methods are listed in Table 1.

Name	Description	Sensor Type	Active/ Passive	Example Source Imagery
Altimetry/ Satellite Derived LiDAR	Uses laser to measure depth by collecting returned photons and recording the travel time	Spaceborne Laser	Active	Icesat 2 (Advanced Topographic Laser Altimeter System)
Intertidal Elevation Modelling	A representation of the intertidal zone by extracting waterline contours at various tidal heights.	SAR/MSI	Active/ Passive	Sentinel 1, Sentinel 2
Optical SDB	Use of satellites with multispectral or hyperspectral sensors on board to derive water column depth by measuring spectral radiance.	MSI	Passive	Landsat 8, Pleides
Photogrammetric SDB	Uses geometric processing techniques on a stereo pair of images to determine depth.	Stereo MSI Pair	Passive	Worldview 2
SAR SDB	Derives depth from the relationship between hydrodynamic surfaces and seafloor topography.	SAR	Active	Sentinel 1, TerraSAR
Wave Kinematic SDB	Derives bathymetry from the propagation and dispersion of surface waves.	MSI	Passive	Worldview 2

Table 1: Limited examples of types of SDB methods and required input datatypes.

1.2 Advantages and disadvantages

It is important to note that although there are some compelling advantages to using SDB to map optically shallow coastal areas, it is not a replacement for traditional survey methods. SDB should be seen as a complementary surveying method to traditional Echosounder and Lidar based approaches. You should consider the accuracies, extent, and temporal coverage of your use case before deciding if SDB is the right hydrographic data source for you.

Advantages:

- Low cost
- Possible to map large areas relatively quickly
- Ability to map changes over time
- Un-intrusive
- Ability to map remote and challenging environments (e.g. Remote islands, reef crests etc.)

Disadvantages:

- Poor vertical uncertainty compared to traditional echosounder or LiDAR based surveying
- Less certainty in feature detection capabilities
- Requirement for either in-situ data or repeated analytical measurements to reduce error
- Requirement for high quality in-situ data to quantify error.
- Not suitable for some locations or benthic types

1.3 Note on Uncertainty and Hydrographic Surveying

Accuracy and precision are widely used measures of observational error. In the field of hydrographic surveying, Total Propagated Uncertainty (TPU) is used to quantify "all measurement errors, both systematic and random, derived from several sources" consisting of both a horizontal and a vertical component (Mavraeidopoulos et al., 2017). This vertical component is known as the Total Vertical Uncertainty (TVU). Considering this, it is important to note the difference between the term's accuracy and uncertainty within these guidelines. An increase in accuracy means the depth measurement is closer to the actual value, while an increase in uncertainty means that there is more error, both random and systematic, in the depth measurement.

2. How is optical SDB produced

There are several methods that can be used to produce SDB from optical imagery. These methods can broadly be grouped into two categories:

1. Empirical/Statistical Methods:

   In its most basic form, a regression between known depth values and band reflectance. Stumpf et al. (2003) popularised the use of log band ratios as the independent variable, minimising the influence of benthic albedo. Contemporary implementations utilise Machine Learning and Artificial Intelligence based approaches to increase the robustness of the model.

   - Examples: Linear Regression, Statistical models, Machine Learning/Artificial Intelligence approaches etc.

   - Requires: In-situ data

2. Analytical/Physical Methods:

   Radiative Transfer Models of sunlight interaction with the atmosphere, water surface, water column and bio-optical water parameters.

   - Examples: Bio-optical or Physical Inversion models with varying levels of complexity

   - Requires: Accurate imagery pre-processing, large computing power, knowledge of or modelled characterisation of environmental parameters

Further classification of optical SDB model approaches can be seen in Figure 1. For more detailed information, refer to Ashphaq et al. (2021).

These methods all have different pros and cons when considering processing time, accuracy and consistency over different bottom types. Whether the method of SDB production is suitable for your use case needs will likely be decided by its suitability of use for the local environmental conditions at your area of interest, as well as your vertical uncertainty and feature detection requirements. Note that not all environments are suitable for some forms of SDB Production, but another method may be suitable. For example, Optical SDB approaches are not suitable for consistently turbid waters, but non-optical approaches may still be able to produce SDB for your projects requirements.

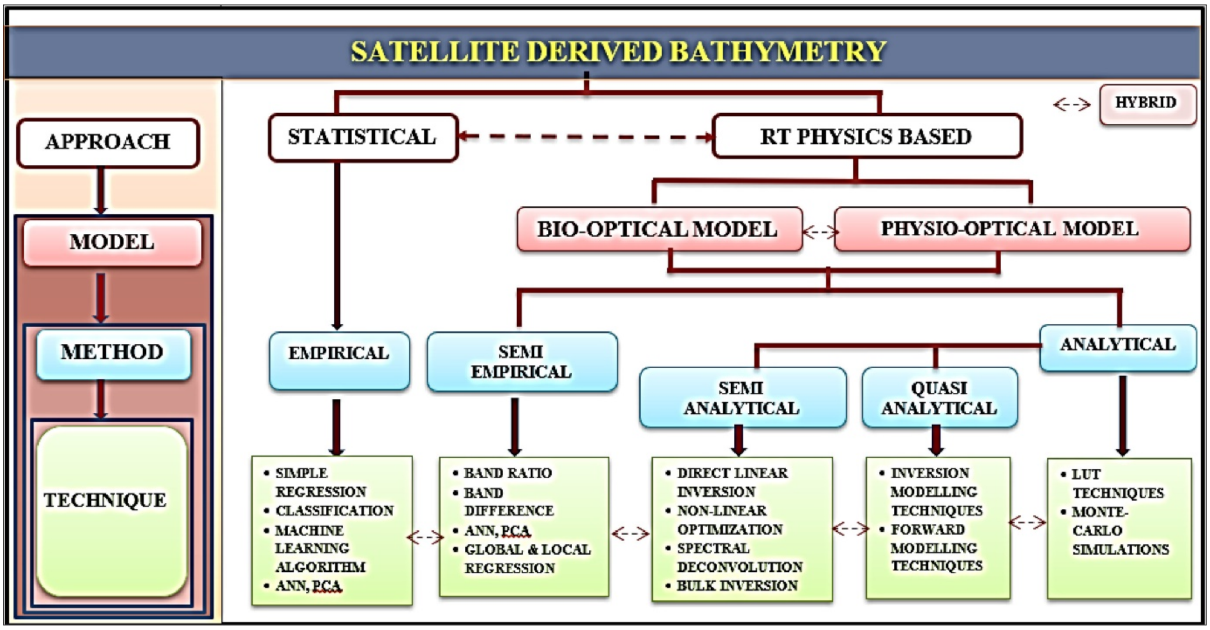


Figure 1: Conceptual Framework of Optical SDB Methodologies created by Ashphaq et. al. (2021).

2.1 Does the source satellite imagery matter?

When it comes to the input MSI SDB is produced from, it is not always a case that higher imagery resolution results in better SDB. Optical sensors have a tendency to produce a lower signal to noise ratio as the spatial resolution increases. Poor SDB uncertainty due to sensor noise is an important consideration as marine remote sensing has a significantly smaller signal to noise ratio compared to their terrestrial counterparts.

A study by the Canadian Hydrographic Office compared the suitability of 6 Multispectral/Optical imagery sources for SDB production, chosen to include high, medium-high and medium spatial resolutions; WorldView-2, Pléiades, PlanetScope, SPOT, Sentinel-2, and Landsat-8. They found that all 6 sensors were capable of deriving depths within Zone of Confidence C vertical uncertainty requirements. The Zone of Confidence C is a measurement of accuracy used in nautical charting, which has a vertical requirement of measurements being within ± 2m + 5% water depth of actual depth. They also concluded that outside of observing an increase in vertical accuracy with higher resolution imagery, “The choice of sensor is less critical than overall image quality” (Ahola et al., 2020).

Even though the quality of the input imagery is the most important factor when considering the suitability of SDB, different sensors do offer unique advantages. For example, Worldview 2 has a yellow band not present in many other Multispectral sensors that can be very useful in SDB production in certain environments. Some examples of factors that differ among sensors that may make them more or less suitable for producing SDB for a given location include:

- Positional accuracy
- Radiometric quality
- Acquisition parameters (Nadir Angle, solar viewing angle, etc.)
- Spatial Resolution

- Signal to Noise Ratio

Although the environmental conditions of the processed imagery are likely the most significant factors that affect SDB quality, users should also consider if the optical sensor used meets their requirements.

2.2 Imagery pre-processing

Before models are applied to imagery to produce SDB, there are several pre-processing steps required to make the input imagery suitable for modelling purposes. These pre-processing steps all aim to isolate pixel signal resulting from seafloor depth by removing unwanted noise from the source imagery (Hartmann et al., 2017). Some of these pre-processing steps include but are not limited to:

- Radiometric Calibration: Conversion of raw digital numbers into reflectance values
- Atmospheric Correction: Removing the reflectance captured by the sensor that results from photons reflecting from interactions with the atmosphere.
- Masking: Removal of land, cloud, cloud shadow, haze, and other undesirable objects from the scene. This can be performed in many different ways, but normally relies on a Near Infrared (NIR) band.
- Sun Glint Correction: An optical correction that can reduce the reflection caused by light reflecting at the air/water interface (water surface) into the direction of the sensor.
- Adjacency Correction: An optional correction to remove photons that were reflected by adjacent bright objects (i.e., sandy beach, ice) and have been incorrectly captured by the sensor as originating in pixels near their actual source.

3. Uncertainties and feature detection capabilities

3.1 Vertical Uncertainty

The Vertical uncertainty and uncertainty of SDB varies between method used, quality of input imagery, availability and uncertainty of in-situ calibration data and the spatial and temporal resolution of the input imagery. Although it has been shown that vertical accuracies of 1m or better are achievable, in general the vertical uncertainty of SDB should be treated with caution.

As the depth of the water column increases, the amount of sunlight penetrating to the seafloor and returning out of the water column decreases. Therefore, the signal to noise ratio worsens the deeper the area you are trying to map. In general, the vertical uncertainty of SDB is higher for deeper depths compared to shallow depths.

Some SDB datasets may have a vertical uncertainty given, using a subset of the in-situ data to validate the SDB model. It is important to note that often in-situ data may be over-representative of a certain location, depth range or benthic type. Therefore, the reported uncertainty may not be uniform across the entire dataset and caution should be used.

Spatial resolution of the input imagery can impact the vertical uncertainty of the resulting SDB. The reflectance measured by the sensor is the average reflectance across the pixel, and therefore the resulting depth could be seen as the 'weighted' average for that area. Even when an accurate depth return is achieved for a single pixel, there can be wide variations in depth when compared to traditional bathymetry of a higher spatial resolution.

SDB can be calibrated using in-situ data collected using more accurate sensors to increase the vertical accuracy. Empirical-based models normally require in-situ data as a model input, and the quality of this input data and the specifics of the modelling techniques used both have large impacts on the resultant SDB vertical uncertainty. Bio-physical inversion based models do not always require in-situ depths as a model input, but can similarly benefit from calibration with in-situ data. The important point to note is that any increase in vertical accuracy is dependent on the vertical accuracy of the calibration dataset. Icesat-2 Satellite Lidar Bathymetry (SLB) depth measurements are increasingly being used as a SDB calibration source for areas where SDB producers do not have access to appropriate in-situ data (Babbel et al., 2021), but it is important to remember that the vertical uncertainty of Icesat-2 is still not as accurate as those achieved by properly performed and calibrated echosounder surveys.

A study comparing the vertical uncertainty of 2m Worldview 2/3 SDB vs a combined multibeam-echosounder/airborne lidar bathymetry (MBES/ALB) shoal-biased 2m grid surface in The Kingdom of Tonga shows that the mean differences of less than a metre is possible, but not guaranteed (Cooper, 2021). Figure 2 shows there is a clear worsening of vertical uncertainty and consistency as depth increases.

Nomuka Area MBES/ALB to SDB Comparisons - 2m increments							
All Data							
Depth band	Mean Diff (m)	St Dev (m)	Mean+2SD (m)	Min (m)	Max (m)	Range (m)	Count
<2m	0.14	0.61	1.34	-12.19	2.03	14.22	1434656
2-4m	0.22	0.89	1.96	-6.49	3.40	9.89	517057
4-6m	0.43	0.91	2.21	-6.13	5.01	11.14	365271
6-8m	0.50	1.08	2.62	-5.96	6.40	12.36	285653
8-10m	0.69	1.27	3.18	-5.55	8.03	13.58	247755

Figure 2: Comparison of vertical uncertainty of 2m Worldview 2/3 SDB vs a combined MBES/ALB surface conducted by Toitū Te Whenua Land Information New Zealand (Cooper, 2021)

3.2 Horizontal Uncertainty

The horizontal uncertainty of SDB is a function of the input satellite imagery used to produce the SDB. This is different than the spatial resolution of the input imagery and refers to the horizontal uncertainty of the pixels. For example, the Sentinel 2 MSI sensor has a spatial resolution of 10m and a quoted horizontal uncertainty of ±11m.

The horizontal uncertainty of the input imagery is controlled by the satellite imagery supplier and is often improved upon using Ground Control Points (GCP) prior to being made available to consumers. The quoted uncertainty will normally be specified with a given confidence interval (i.e., 95%).

As the horizontal uncertainty of SDB is a function of the input imagery's uncertainty, SDB typically has a high horizontal accuracy. This means that SDB is often an effective tool for improving the geolocation of seafloor features that have previously been mapped before the introduction of GPS and other technologies (i.e. Coral Reefs that have been 'sketched in' on historical fairsheets).

Not all SDB is produced using an adjacency correction, which as previously discussed attempts to correct for photons from bright substrates that have 'bled' into surrounding pixels when measured by the sensor. This can lead to steep areas of seafloor (i.e. coral reef drop offs) appearing to be wider with a less intense gradient. SDB post-processing QC procedures should remove returns where this occurs, however this is not always the case and is something users of SDB should be aware of.

Satellite imagery providers often perform orthorectification on their 'analysis ready' processing level. This corrects for the optical distortion that elevation and senor acquisition angle have on the geolocation of pixels. Some methods used to orthorectify imagery are unsuitable for SDB processing as they can lead to horizontal distortions of submerged pixels.

3.3 Feature Detection Capabilities

It should be noted that the feature detection capability of SDB is fundamentally different to acoustic and LiDAR based sensors. Traditional Hydrographic Surveys can be characterised by their ability to achieve:

- Bathymetric Coverage: “Extent to which an area has been surveyed using a systematic method of measuring the depth and is based on the combination of the survey pattern and the theoretical area of detection of the survey instrumentation” (IHO Standards for hydrographic surveys).
- Feature Detection/Search: “Extent to which an area has been surveyed using a systematic method of identifying features” (IHO Standards for hydrographic surveys).

SDB is unable to achieve either full bathymetric coverage or full feature detection as the technology currently does not meet the minimum requirements of ‘returns per area of detection’ or the definition of a systematic method of survey. Single scene SDB can be considered to achieve a single return for each processed pixel of the input imagery.

Considering the above definition of Bathymetric coverage, it is important to note that when SDB is described as having ‘full coverage’, it does not refer to meeting survey specifications for full bathymetric coverage, but that SDB is continuous and can be free of gaps.

SDB is capable of identifying features, however it is not possible to guarantee a minimum level of detection as described in S-44 IHO surveying standards. SDB data should only be used in applications where the existence of undetected features is not prohibitive. When considering the likelihood of SDB in identifying seafloor features, the following factors should help form SDB users’ judgement:

- The pixel size of the feature vs the input satellite imagery (i.e. SDB can only identify features larger then several pixels of input imagery).
- The depth of the feature (shallower features are more likely to be detected compared to deeper features as they have a stronger signal to noise ratio.)
- The benthic colour of the feature, and the contrast between the feature and surrounding benthos.

4. Other Considerations of using Satellite Derived Bathymetry

4.1 Dark Substrates

One of the largest barriers to accurate depth measurement using SDB is the presence of dark benthic types. Dark areas, such as those colonised by vegetation, often result in the overestimation of depth and larger amounts of uncertainty. Most SDB models struggle to differentiate changes in reflectance due to an increase in depth versus substrate colour, even those that are specifically designed to work over multiple substrate types.

If your area of interest has significant amounts of dark substrates, you should be wary of ‘false/overestimated depths’ over these areas.

4.2 Suitable SDB Locations

SDB is not a suitable mapping method for some locations due to a variety of local environmental and climatic conditions. Additionally, some locations are unsuitable for SDB due to a lack of suitable imagery existing for that area. Some considerations as to whether a site is suitable for SDB are mentioned below:

- Depth: The potential depths SDB is able to map down to vary depending on the optical complexity of water, the benthic substrate of the seafloor, and the quality of available imagery sources. As a general guide based on current capability, maximum achievable depths range from up to ~30-40m in extremely favourable clear tropical waters to ~5m in challenging optically complex polar environments (Mavraeidopoulos et al. 2017).
- Turbidity: Both inorganic and organic turbidity can make a site unsuitable for SDB. Inorganic SDB results in an underestimation of depth as sunlight reflects off suspended particles in the water column. Organic turbidity results in an overestimation of depth as organisms in the water column absorb sunlight. Areas such as tropical river mouths are very difficult to map due to the lack of images where turbidity is not present.
- Cloud cover: Some parts of the planet are more prone to persistent cloud cover then others.
- Benthic Type: SDB is generally less accurate over dark vegetated areas.

5. Case Study: IX Blue Niue Bathymetric Survey

In 2017 Toitū Te Whenua Land Information New Zealand required a large area to be surveyed for charting purposes. iXblue, EOMAP and Geomatics Data Solutions undertook the project using three different sensor types; SDB, ALB and vessel mounted MBES. Multiple methods were used due to the extent of the survey area to ensure survey grade precision. These surveys were focused on improving Tonga's nautical charts and navigational safety to assist in expanding shipping and tourism for the country (Toitū Te Whenua Land Information New Zealand 2019).

The waters in the Pacific are clear and pristine, optimal conditions for the optical sensors in SDB (iXBlue Australia, 2019a). The project required several thousands of square miles over Tonga, Niue, the Cook Islands and Tokelau to survey. The capabilities of SDB allowed accurate positioning of all the islands, drying shoals, reefs and atolls as well as charting the waters surrounding them up to 15 metres in a fast and cost-effective time frame. The results from the SDB survey allowed identification of shallow areas to plan the next phase using ALB surveys. In many cases, the ALB system was able to survey depths in excess of 20 metres as well as identify small features in the right environmental conditions, potentially hazardous to navigation (iXBlue Australia, 2019b). Surveying the shallow and potentially hazardous areas using ALB made the final phase of MBES surveys faster and more effective. The MBES surveys concentrated on filling the areas not adequately covered with ALB surveys and all areas deeper than 20 metres (iXBlue Australia, 2019b).

The project saw 6 months of field work resulting in over 30, 000 GB of data, disclosing previously uncharted features such as wrecks, atolls and volcanos. The initial use of SDB provided a baseline dataset to not only map drying areas and waters to 15 m but also allowed strategical planning for expensive MBES and ALB surveys on navigationally hazardous areas. This seafloor imagery revealed new characteristics of the marine habitat and the biodiversity of its flora and fauna. This information may go on to assist governments and scientists with coastal zone and marine habitat management. This merged method in data collection and collaboration from experts in their field has provided much needed improvements in navigational safety in an area where preceding charts were measured in fathoms.

6. Conclusions

Satellite Derived Bathymetry should be seen as a complementary survey technique that can provide cost effective seabed data coverage for areas not already surveyed by higher uncertainty acoustic or LiDAR sensors with suitable environmental conditions. It's economic, spatial and temporal advantages make it a powerful mapping technique for a wide range of hydrospatial applications such as remote area reconnaissance survey, survey of very shallow navigationally dangerous areas, and regular monitoring of very shallow seafloor change detection (Herrmann et al., 2022). The vertical uncertainty of SDB is not comparable to high quality traditional hydrographic surveying techniques. However its horizontal accuracy and ability to be utilised in remote and unsurveyed locations make it a suitable data source for a range of applications in very shallow coastal and reef waters where existing bathymetric data does not satisfy a user's requirements.

7 Glossary

ALB	Airborne Lidar Bathymetry
GCP	Ground Control Points
HSWG	Hydrographic Standards Working Group
IHO	International Hydrographic Organisation
MBES	Multibeam Echosounder
MSI	Multispectral Imagery
NIR	Near Infrared
SAR	Synthetic Aperture Radar
SLB	Satellite Lidar Bathymetry
SDB	Satellite Derived Bathymetry
TPU	Total Propagated Uncertainty
TVU	Total Vertical Uncertainty

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