Technical paper on Satellite Derived Bathymetry

Pilot project on the West Coast of Greenland

Author: *Philip Sigaard Christiansen*

Danish Geodata Agency – Hydrographic Office, Arctic

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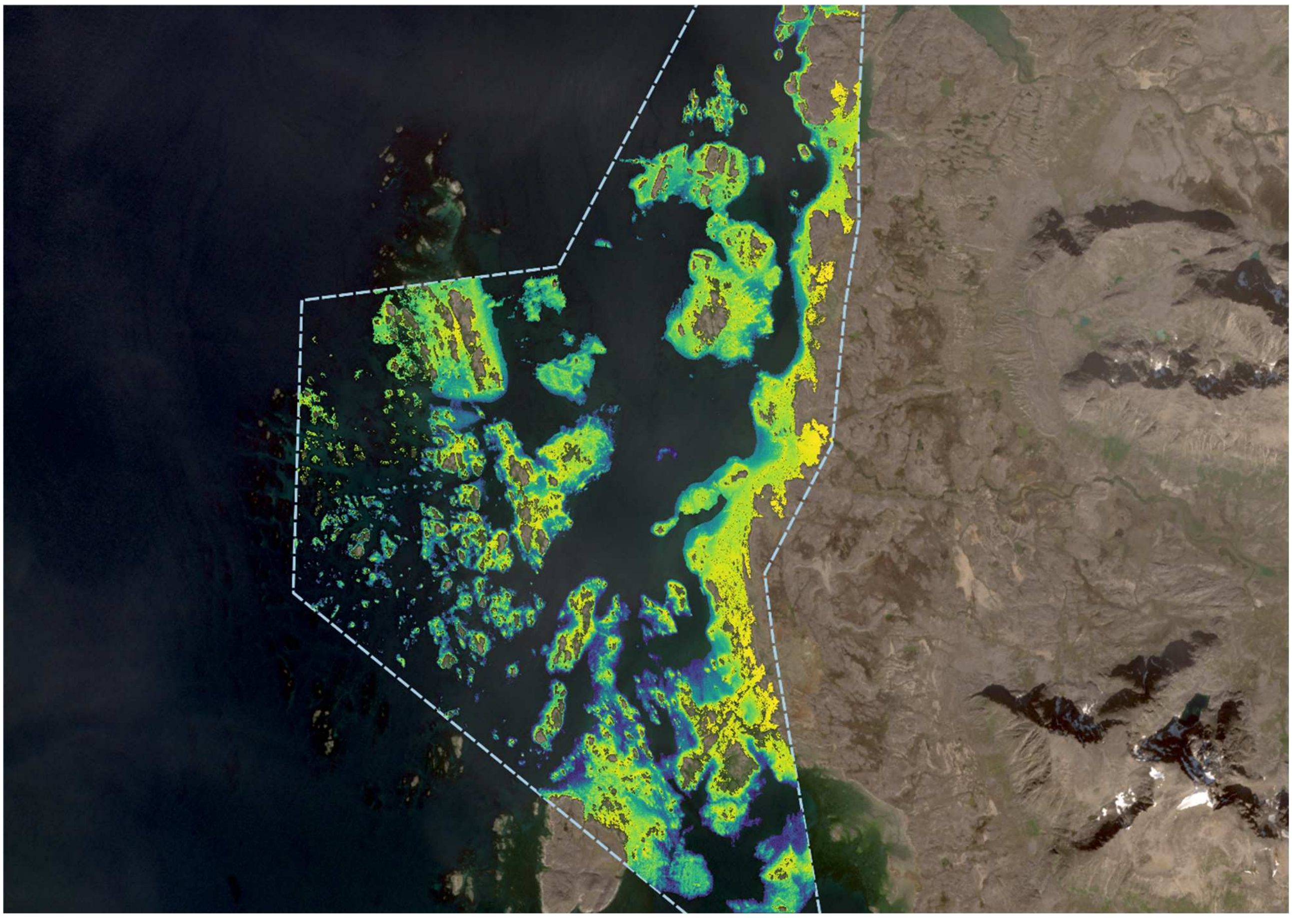

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Abstract
Satellite Derived Bathymetry (SDB) is a method for surveying shallow water depths based on satellite source data. In this project, we have received SDB data and raw satellite images on the West Coast of Greenland, which has been requested from two different data providers. The SDB data was received in two phases: First, an uncalibrated dataset, and second, a calibrated dataset where depth data acquired by multibeam echo sounder was provided beforehand. This provides us with a proper basis for analyzing and comparing the data with a good understanding of where SDB can be applied and where it can not.

It is found that SDB is highly dependent on satellite sensor, method adopted by the data provider and weather-, water-, and seabed conditions. It is concluded that for navigational and nautical charting purposes in Greenland, SDB should not be used as the main source of information, because it is not fully reliable in identifying all obstructions and hazards. That said, SDB does provide value in identifying changes that are potentially a risk for navigation and can help in prioritizing future surveys. In addition, SDB can be used in relation to environmental related studies. In the future as more satellite data becomes available and new approaches to SDB are developed, there is a potential for SDB being used for charting in Greenland.

1 Introduction

The purpose of this report is to provide the Danish Geodata Agency (DGA) with insights into the field of remote sensing, and specifically the method of SDB, and investigating new technologies related to surveying. The satellite technology is only expected to become more prevalent in the future, and the DGA will closely monitor any new developments within this field. Methods that can supplement traditional ways of surveying could provide benefits not just for navigation and charting but also other research areas such as environmental monitoring, hydrodynamic modelling and coastal protection.

Satellite Derived Bathymetry (SDB) is a passive remote sensing technique that started out in the 1970s using multispectral sensors. It mainly started out as R&D and commercial use began around the mid 2000s. A number of methods exist, of which the best known are empirical regression methods, photogrammetry and radiative transfer models. The methods are quite different in both their approaches, complexity and applications. They can be summarized as follows:

- Historically, empirical methods, that are based on a log-ratio relationship of reflectances, were mostly used and still are. It is easily applied as long as one has a minimum of two bands in the visible region and some well-known water depths. However, one has to assume that parameters derived from the empirical relationship are constant throughout the satellite image[1] and it only works for the given time of image capture.
- The photogrammetry approach is based on stereo image matching and therefore requires a minimum of two images, but it does require any prior known water depths. However, the method requires the presence of contrasting features like objects on the seafloor for the image matching to work.
- Lastly, the radiative transfer models, which is mainly addressed here in this project, utilize several bands from a single satellite image and without the strict need for any prior known water depths. This makes it an interesting tool for Greenland where well-known bathymetry and applicable satellite images are quite sparse. The method will be described in more details in the next section.

Greenland is chosen as the focus area of this study for a number of reasons:

1) Arctic waters are in general very remote with many hazardous rocks that make navigation difficult. This, together with the presently limited surveyed arctic waters, suggests that SDB with its wide coverage could be a promising method for measuring shallow water depths that usually are inaccessible or dangerous for navigation.

2) SDB might serve as a reconnaissance tool to identify potential routes or dangers for the surveyors.

[1] Optical properties of the water and bottom types are rarely constant, especially in coastal waters.

3) Not much attention has been given to SDB in Greenland where waters and seabed are markedly different from previous SDB studies in other places of the world. Therefore, it is also a new interesting area of study.

The report continues as follows: First, an introduction to the basic theory and the SDB method is given. This section requires some knowledge of basic physics and mathematical principles and may be skipped by the reader. Then the provided SDB data delivery is displayed together with the used satellite scenes and the reference multibeam dataset. Following this, an analysis of the provided SDB data is carried out, which includes a comparison between sensors, data deliveries, multibeam and calibration. Finally, a discussion, conclusion and reflection of the project are given.

2 Basic theory

The main principle of SDB is illustrated in Figure 1. Sunlight propagates through -and interacts with the atmosphere and water column after which it reflects off the bottom and propagates back again to be measured at a satellite sensor. The sunlight interacts with both the atmosphere and water column by absorption and scattering, and at the air-water interface, the light will be refracted[2]. The sum of all these processes results in a measured signal at the remote sensor, and if the physics is modelled correctly, one can obtain the water depth among other parameters from the signal by inversion methods.

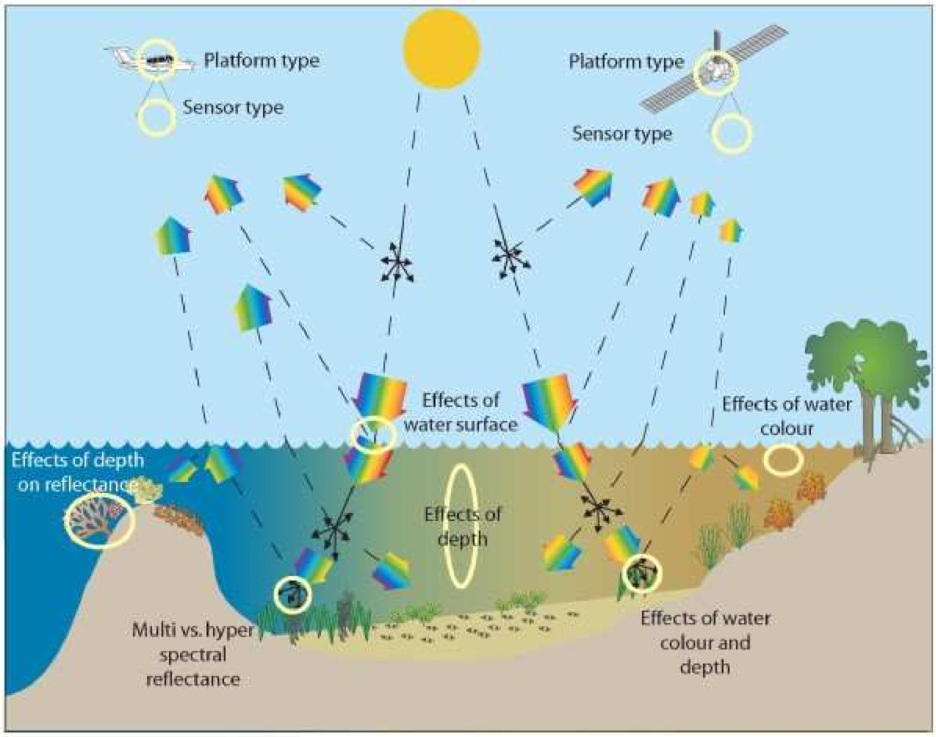


Figure 1: Illustration of the different interactions of the sunlight with atmosphere, water, air-water interface and seabed before being measured at the remote sensor (Centre for Spatial Environmental Research, University of Queensland).

[2] The light changes direction when passing from one medium to the other.

Radiative Transfer Theory

The propagation of light in seawater is governed by radiative transfer theory, which provides a way of quantifying the optical properties of water. Radiative transfer theory is quite comprehensive, and we will not be going in to details other than just give a brief summary of definitions used in the description of the method.

The most fundamental quantity in terms of received radiant energy at a sensor is denoted the spectral radiance $L(x, y, z, t, \theta, \phi, \lambda)$. It is a measure of the amount of radiant energy incident on an area ΔA in a time interval Δt from a solid angle $\Delta\Omega$ centered at angles (θ, ϕ) at a wavelength interval $\Delta\lambda$ in the infinitesimal limit [Mobley 2001]. See Figure 2.

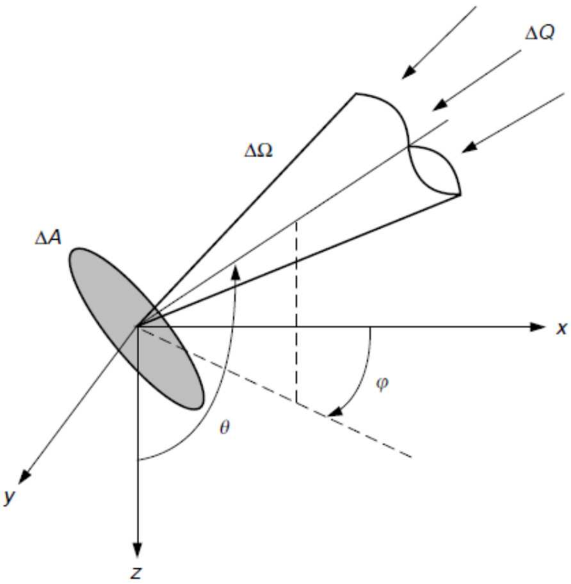


Figure 2: Geometry of a light source incident on a surface (Mobley, 2001).

Often the radiance is assumed horizontal homogenous and time independent, such that is it written as $L(z, \theta, \phi, \lambda)$ (Mobley, 2001). Integrating the radiance over a flat surface facing downwards with respect to horizontal gives the downwelling plane irradiance $E_d(z, \lambda)$. It is the sum of downwelling radiance weighted by the cosine of the light direction corresponding to a "flat sensor" at depth z:

$$E_d(z, \lambda) = \int_{2\pi} L(z, \theta, \phi, \lambda) |\cos\theta| d\Omega$$

If the surface is facing upwards instead, it is denoted the upwelling irradiance $E_u(z, \lambda)$. The difference $E_d(z, \lambda) - E_u(z, \lambda)$ is the net irradiance.

The optical properties of water are often grouped into two categories:

- **Inherent optical properties (IOP):** They depend only on the medium and are independent of the ambient light field, i.e. they are inherent to the medium. Examples are absorption coefficient and scattering coefficient.

- **Apparent optical properties (AOP):** They depend on both the medium and directional structure of the ambient light field. Examples are remote sensing reflectance and attenuation coefficients.

We will be referring to a certain AOP called the remote-sensing reflectance $R_{rs}(\theta, \phi, \lambda)$:

$$R_{rs}(\theta, \phi, \lambda) = \frac{L_w(\theta, \phi, \lambda)}{E_{d\_w}(\lambda)},$$

Where $L_w(\theta, \phi, \lambda)$ is the water-leaving radiance, i.e. not including sky and solar radiance reflected from the surface, and $E_{d\_w}(\lambda)$ is the downwelling irradiance as mentioned above. Both quantities are evaluated just above the water surface, which is denoted with the *w* subscript. The remote sensing reflectance is a measure of how much of the downwelling irradiance is eventually returned through the water surface in a solid angle $\Delta\Omega$ at angles (θ, ϕ); see Figure 3 for an illustration. $L_w(\theta, \phi, \lambda)$ is not measured directly, but is inferred from the total upwelling radiance measured either above the water surface or below the water surface and extrapolated upward through the surface.

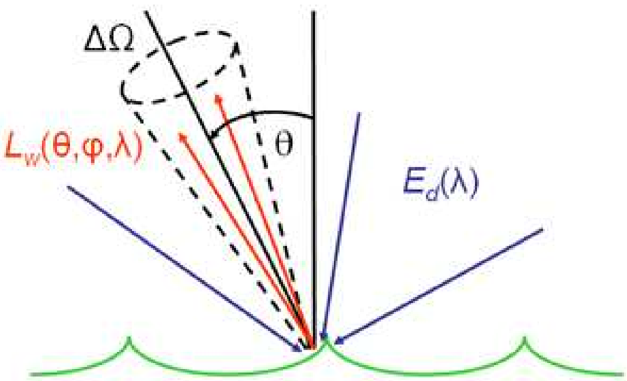


Figure 3: Illustration of the water-leaving radiance in relation to the downwelling irradiance. The ratio of the two is denoted the remote sensing reflectance (Mobley, 2018).

Method

In this section, we will describe the SDB method based on the semi-analytical model by (Lee, 1998) (Lee, 1999). The method is a remote-sensing reflectance model for shallow waters that does not require any in situ depth measurements, but by doing so may improve the quality of the results. It can be used to retrieve water depths in addition to optical properties of the water and seabed from above surface multispectral or hyperspectral satellite measurements[3].

[3] Multispectral typically refers to sensors with 3-10 wavelength bands. Hyperspectral typically refers to sensors with more than 100 very narrow wavelength bands.

For optically shallow waters assuming water homogeneity and single scattering, the remote-sensing reflectance can be written as (Lee, 1999):

$$R_{rs} \approx \frac{0.5 r_{rs}}{1 - 1.5 r_{rs}},$$

where r_{rs} is the subsurface remote-sensing reflectance evaluated just beneath the surface. According to single scattering theory, it can be represented as a sum of contributions: One from the water column (C) and one from the sea bottom (B):

$$r_{rs} \approx r_{rs}^{C} + r_{rs}^{B}$$

$$\approx r_{rs}^{deep}\left(1 - e^{-\left(\frac{1}{\cos\theta_w} + \frac{D_u^C}{\cos\theta}\right)\kappa H}\right) + \frac{1}{\pi}\rho e^{-\left(\frac{1}{\cos\theta_w} + \frac{D_u^B}{\cos\theta}\right)\kappa H}$$

Here $\kappa = a + b_b$ is the attenuation coefficient, which is the sum of the absorption coefficient a and backscattering coefficient b_b. D_u^C and D_u^B are distribution functions relating κ (an IOP) to the diffusive attunation coeficient K (an AOP). ρ is the bottom albedo, which depends on the wavelength. θ_w is the water solar zenith angle. θ is the subsurface viewing angle. H is the water depth. Finally, r_{rs}^{deep} is the remote-sensing reflectance for optically deep waters (Lee, 1998) (Lee, 1999) (Gordon, 1988) (Morel, 1993):

$$r_{rs}^{deep} \approx \left(g_0 + g_1\left(\frac{b_b}{a + b_b}\right)^{g_2}\right)\frac{b_b}{a + b_b}$$

In addition, the distribution functions for the water column and sea bottom are, respectively (Lee, 1998) (Lee, 1999) (Kirk, 1991):

$$D_u^C \approx D_0\left(1 + D_1\frac{b_b}{a + b_b}\right)^{0.5}, \qquad D_u^B \approx D_0{}'\left(1 + D_1{}'\frac{b_b}{a + b_b}\right)^{0.5}$$

Here $g_0, g_1, g_2, D_0, D_0', D_1, D_1{}'$ can be determined by numerical simulations with for example Hydrolight[4] giving the best fit for a given set of IOPs, depths, albedos and viewing angles. (Lee, 1998) provided best-fit values based on several simulations:

$$g_0 = 0.084, \qquad g_1 = 0.170, \qquad g_2 = 1$$

$$D_0 = 1.03, \qquad D_0' = 1.04, \qquad D_1 = 2.4, \qquad D_1' = 5.4$$

Now with the model formulated and the above mentioned assumptions and best-fit values, the problem can be summarized as follows. The problem is described by below function:

$$R_{rs} = f(a(\lambda), b_b(\lambda), \rho(\lambda), H, \theta_w, \theta, \phi),$$

where λ is the wavelength. For a given set of viewing and solar angles this reduces to:

[4] Hydrolight: http://www.oceanopticsbook.info/view/radiative_transfer_theory/level_2/hydrolight

$$R_{rs} = f(a(\lambda), b_b(\lambda), \rho(\lambda), H)$$

Given the above modelled spectrum R_{rs} and a measured spectrum R_{rs}^{meas} from the satellite, one can derive the water depth H along with the other parameters by inverse methods.

Each measured spectrum consist of three unknown spectra a, b_b, ρ and one unknown scalar H. This suggests that for a sensor with n bands, we have $2n + 1$ unknown variables to estimate, resulting in an underdetermined problem. To avoid this, the above equation for R_{rs} is often parameterized, so that the variables are not dependent on wavelength. An example of this is given in (Wettle, 2006).

We have now shortly reviewed the method that is used to estimate the water depths. For a more detailed explanation, the reader is referred to (Lee, 1998) (Lee, 1999) (Wettle, 2006).

3 Data

SDB data was delivered by two providers based on the method described in the previous section. Initially, no known water depths were given to the providers, but at a later stage some water depths were provided in order to see how well the model could be calibrated using existing acoustic multibeam echosounder data. The calibration was only applied to a subset of the data.

The data was received by the providers in 2018-2019 in two phases: First, a data delivery without any supplied multibeam, and second, a calibrated data delivery with multibeam data provided beforehand. Areas were chosen based on the following: Expected SDB coverage, expected overlap with multibeam data and areas containing both shallow and deep waters.

The first provider (denoted Provider 1 in the following) was requested to apply SDB for three different areas in Greenland, see Area 1-3 in Figure 4. The data was received as derived water depths including uncertainties.

The second provider (denoted Provider 2 in the following) was requested to apply SDB for a single area as a reference, see Area 3 in Figure 4. The data was received as derived water depths including uncertainties.

Thus, we have two different providers applying SDB for the same area using the same satellite source image, giving a good foundation for comparison.

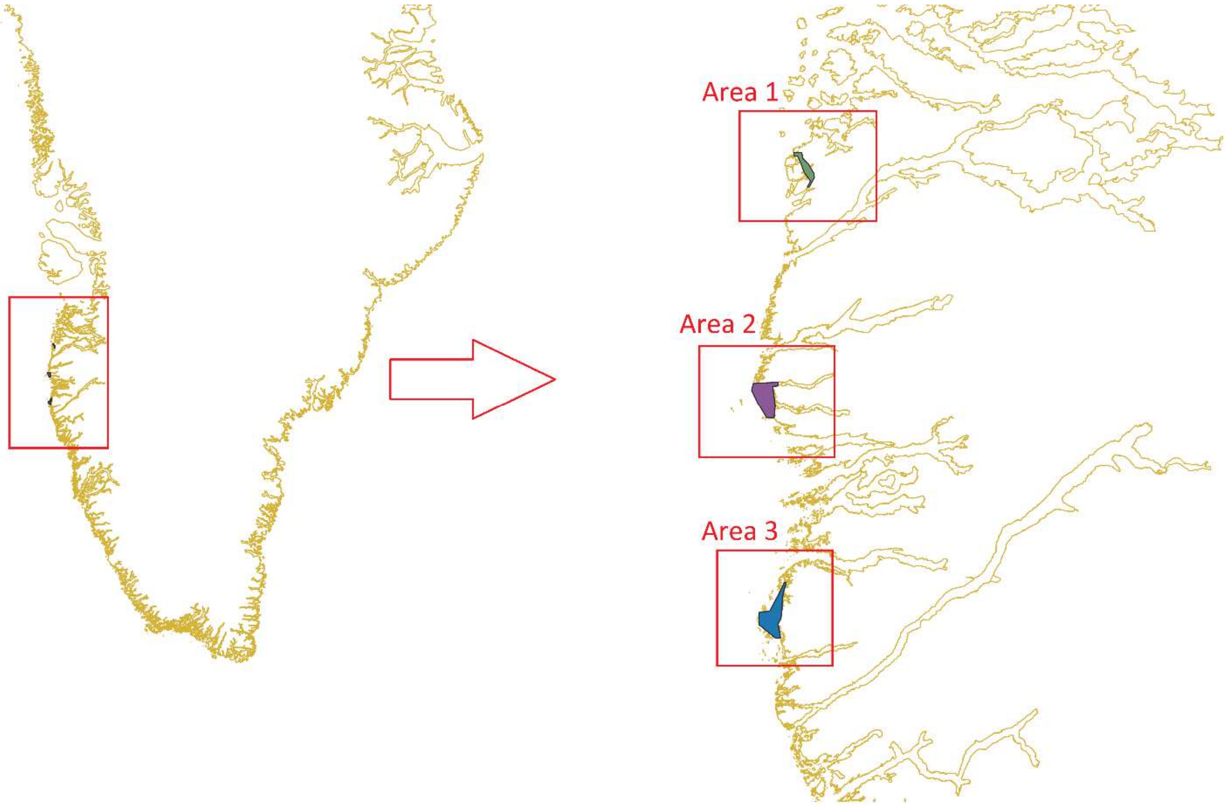


Figure 4: Areas on the West Coast of Greenland where SDB was provided. Provider 1 supplied SDB for Ares 1-3 and Provider 2 provided SDB for Area 3. Calibration was only performed on Area 3 by both providers.

The data delivery consists of the following:

- Satellite source imagery used for SDB.
- SDB consisting of tide corrected water depths in meters in reference to LAT.
- Estimated uncertainties (LE90) [5].
- A report on the delivery and results.

Satellite imagery

The delivered SDB is based on two sources of optical satellite data: ESA's Sentinel-2 sensors with a spatial resolution of 10m and DigitalGlobe's WorldView-2/3 sensor with a spatial resolution of 2m[6]. The spectral bands that are of most importance to aquatic remote sensing, and give information of the water column, are within the visible wavelength spectrum. Sentinel-2 has three bands and WorldView-2/3 has six bands in this range. See below Figure 5 and Figure 6.

[5] 90th percentile linear error.

[6] In addition, the WorldView dataset also includes a panchromatic band with a resolution of 50cm but it is not used for SDB.

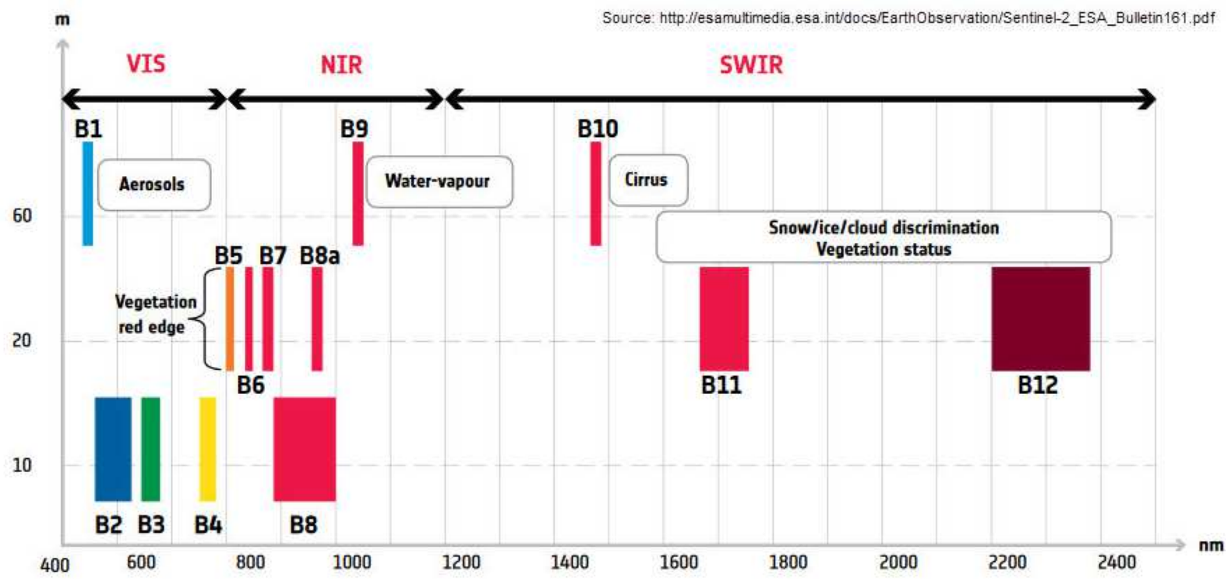


Figure 5: Sentinel-2 spectral bands of which B2, B3, and B4 are of most importance to SDB.

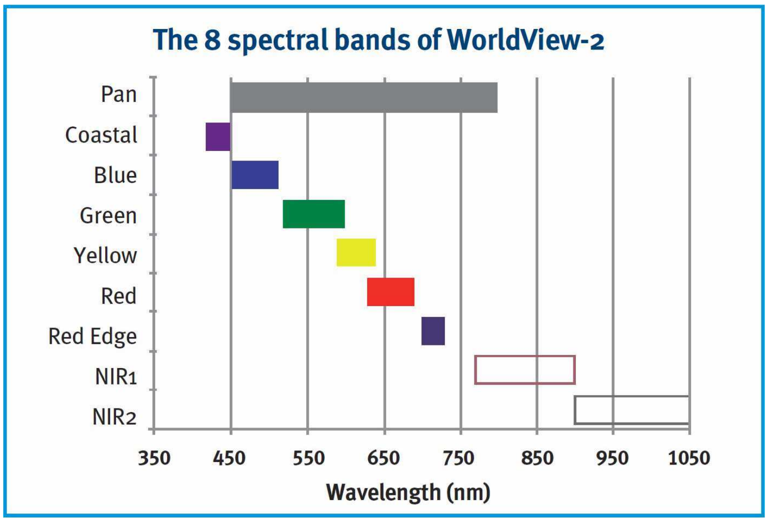


Figure 6: WorldView-2 spectral bands of which six of them are of most importance to SDB (https://www.satimagingcorp.com/satellite-sensors/worldview-2/)

Along with the SDB delivery, we also requested the raw satellite images from which the depths are derived. This is mainly for quality control but also to track back to the source in case of need. The years of which the satellite images were taken are in the range 2012-2018. See below Figure 7 for an overview of the true color RGB satellite images for the areas.

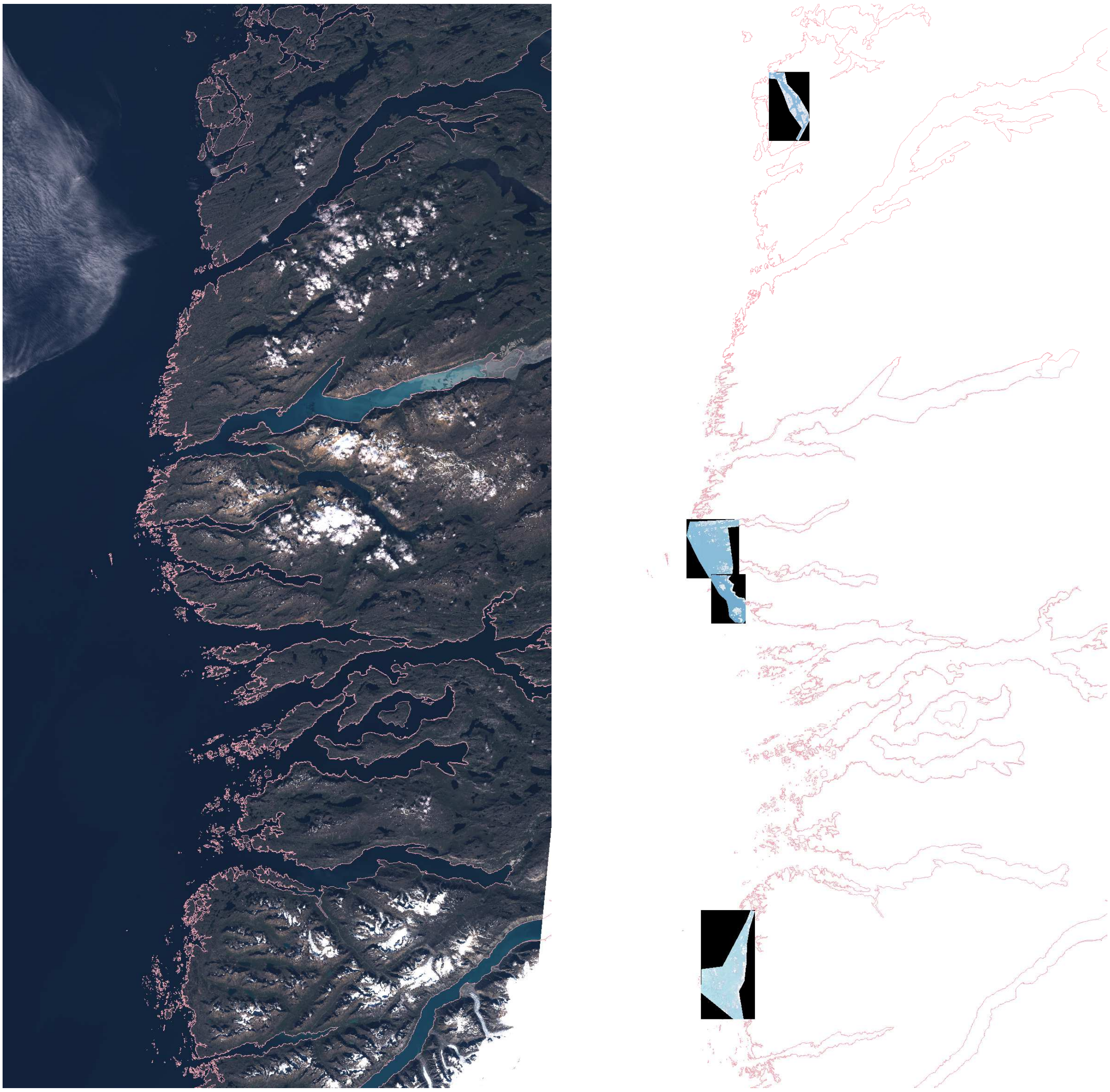


*Figure 7: **Left:** Sentinel-2 RGB satellite imagery stitched together (10m spatial resolution). **Right:** Combination of WorldView-2 and WorldView-3 RGB satellite imagery (2m spatial resolution).*

SDB delivery

In the following, we will present examples of the received SDB in the three different areas. In Areas 1-2 we have uncalibrated SDB data, and in Area 3 we have both uncalibrated and calibrated SDB from the two providers, giving a very good foundation for comparing and analyzing. For examples on the reported depth uncertainties, the reader is referred to Appendix A.

The workflow for deriving the SDB can in general be summarized as follows:

1) Satellite image selection:
   Satellite images are selected from an archive of available images and the most optimal image is selected based on the following requirements: Minimum of clouds and haze, ice-free conditions, good water clarity, minimum of water- and breaking waves and highest available sunlight (i.e. summer months).
2) Pre-processing including atmospheric and sun glint corrections.
3) Retrieval of water depths using an inversion model as described in the Method section.
4) Tidal correction to refer to reference LAT.
5) QA/QC including removal of potential artefacts and defining a "cut-off" depth[7].
6) Estimation of depth uncertainties.

[7] The cut-off depth is defined as the depth interface between optically shallow water and optically deep water, i.e. it is the maximum depth at which we can expect to retrieve SDB from. It is locally varying.

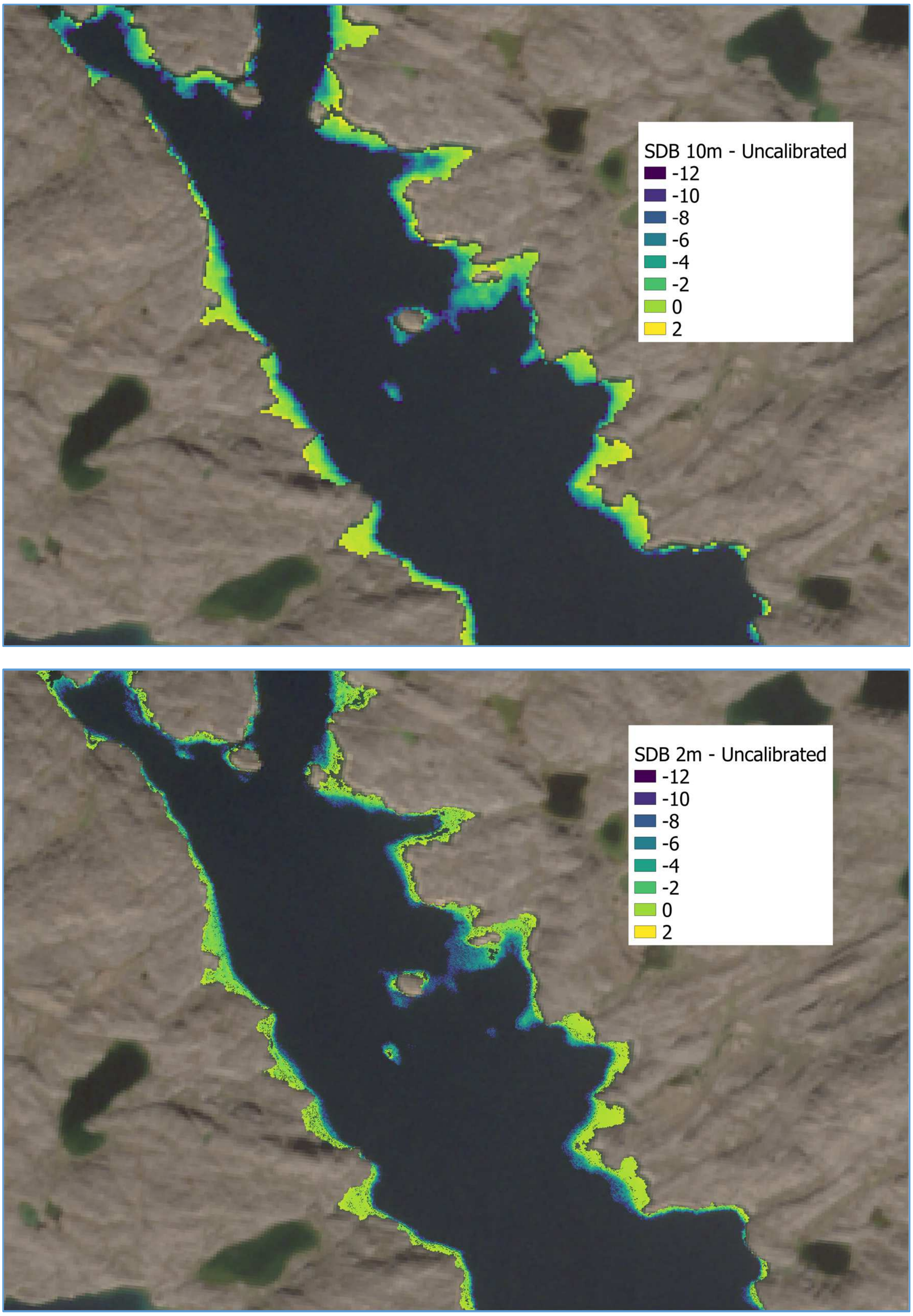


Figure 8: Færinge Nordhavn - Area 1.

***Top:** SDB 10m. **Bottom:** SDB 2m.*

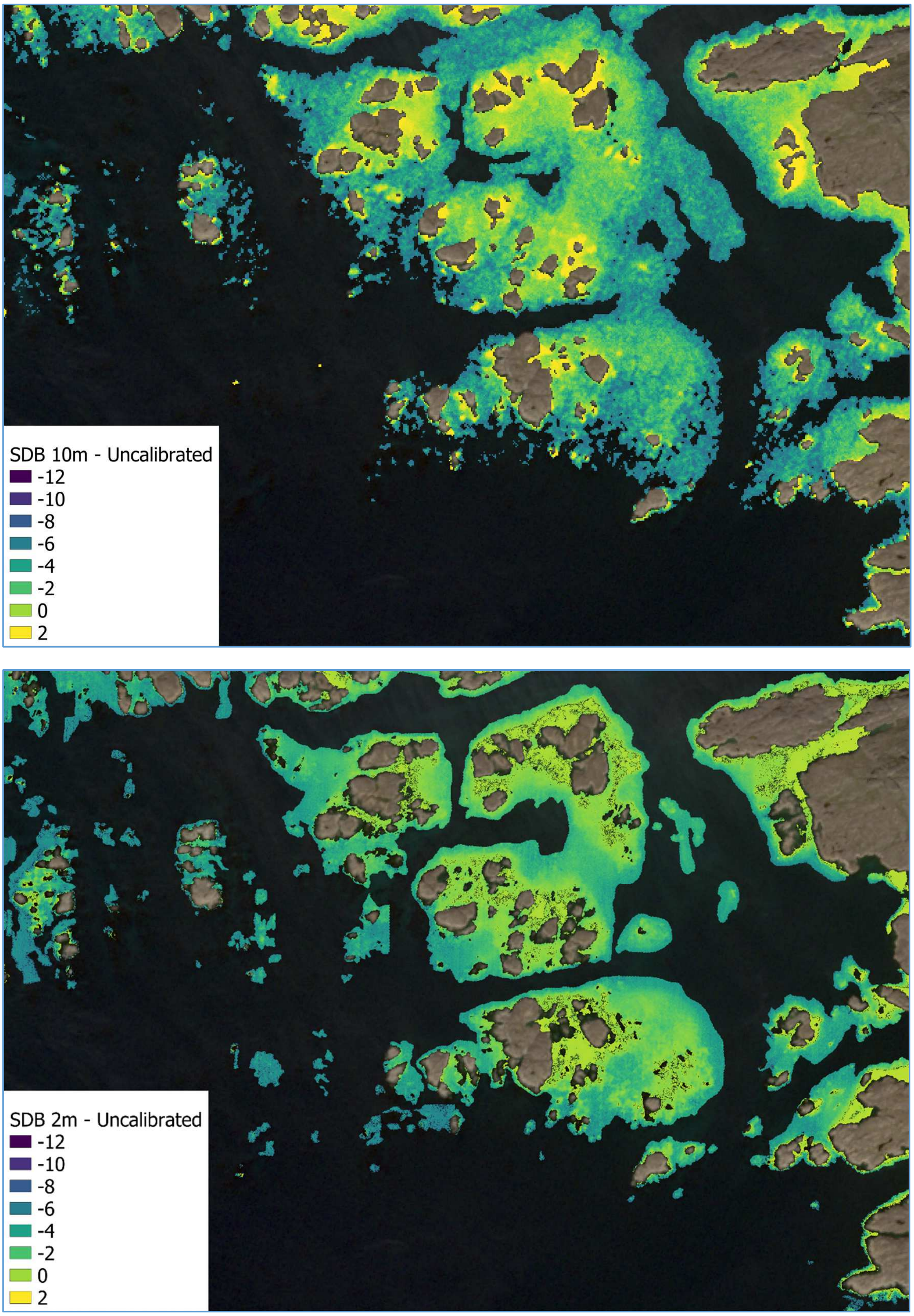
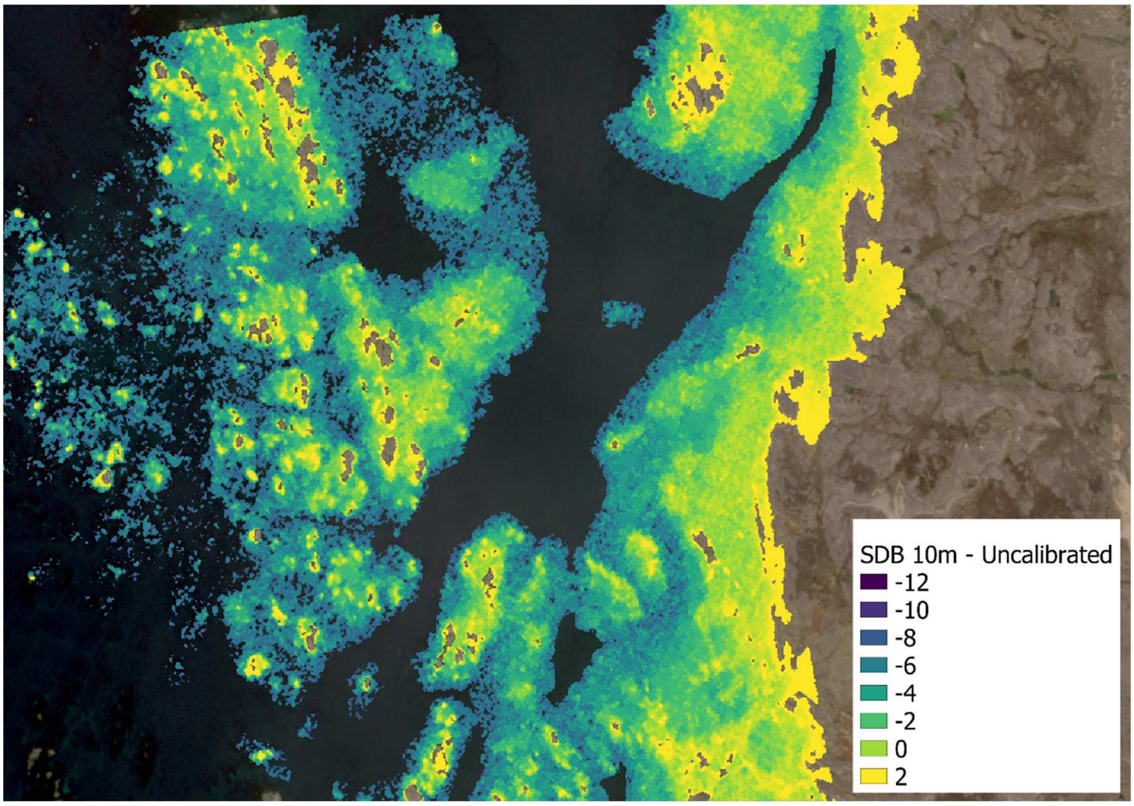


Figure 9: Sisimiut - Area2.

***Top:** SDB 10m. **Bottom:** SDB 2m.*



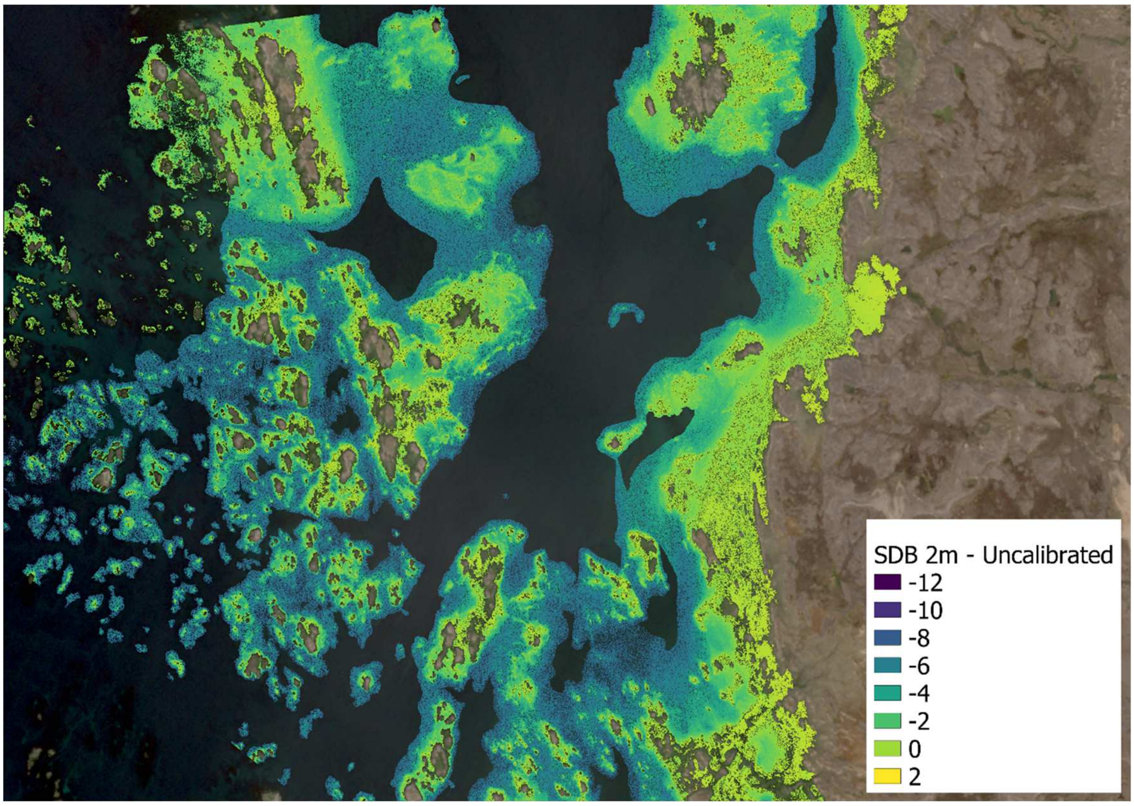


Figure 10: Anders Olsen Sund Syd - Area 3 - Provider 1 - Uncalibrated.

***Top:** SDB 10m. **Bottom:** SDB 2m.*

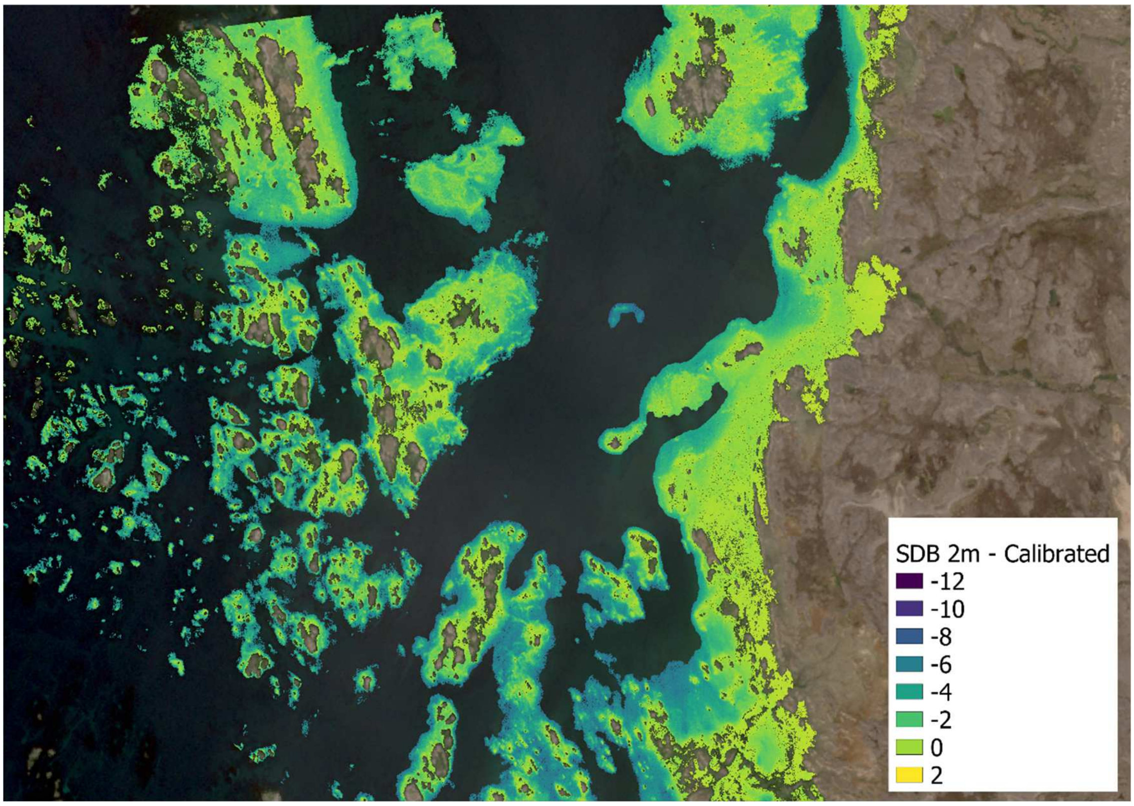
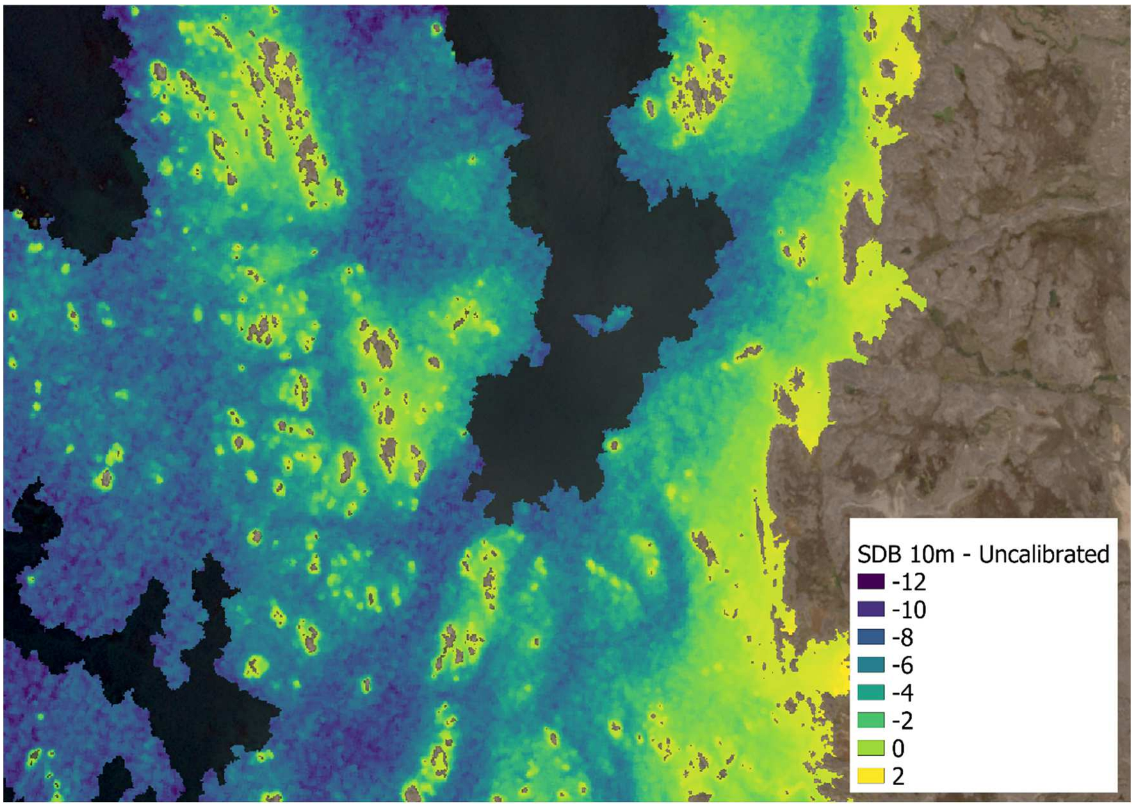


Figure 11: Anders Olsen Sund Syd - Area 3 - Provider 1 – Calibrated.

SDB 2m.



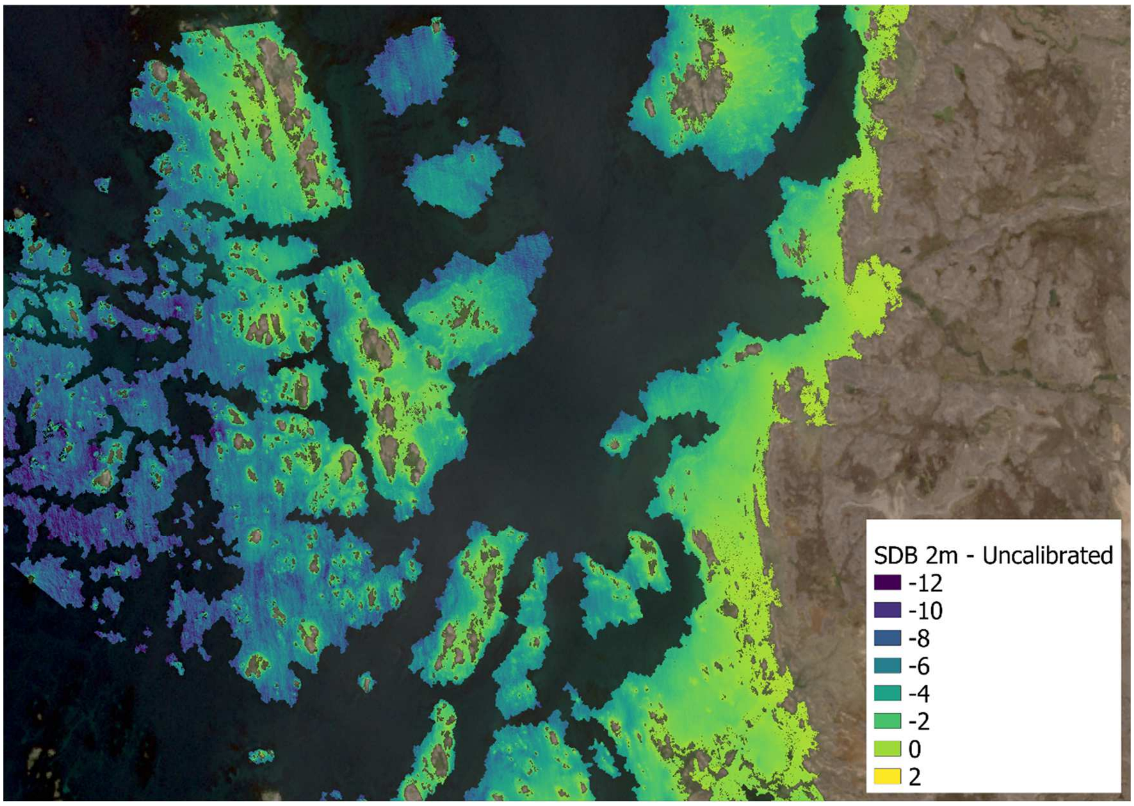


Figure 12: Area 3 - Anders Olsen Sund Syd - Area 3 - Provider 2 - Uncalibrated

***Top:** SDB 10m. **Bottom:** SDB 2m.*

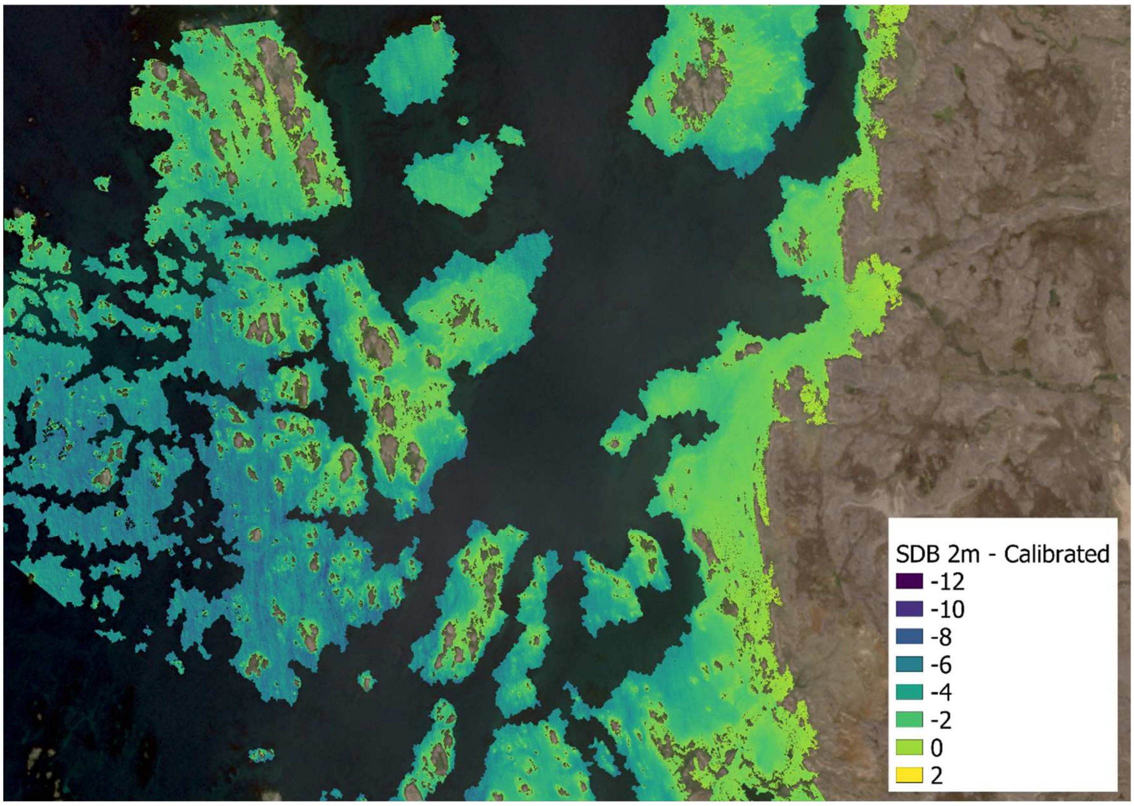


Figure 13: Anders Olsen Sund Syd - Area 3 - Provider 2 - Calibrated.

SDB 2m.

Multibeam reference data

The multibeam surveys, that are used as reference in this report, were collected by multibeam echo sounder and delivered by the surveyors from The Danish Defence (SOM) in cooperation with DGA. The multibeam data was collected in the years 2012-2018, more or less the same range as the satellite source images. The time of satellite image capture and the collected multibeam will be different and therefore temporal change may be present, however, such changes are expected to be small due to a predominantly rocky seabed in the areas of investigation.

Below is the multibeam coverage of the reference data with SDB coverage overlaid to see where there is overlap. The overlapping areas can be used in the analysis to compare and compute statistics. Only a small subset of the multibeam data was delivered to the data providers for calibration.

SDB only applies to shallow waters while the multibeam datasets used in this project mainly measure deeper areas, so the overlap is limited as seen in the figures below. The areas were selected to maximise this overlap as much as possible to limit a potential bias.

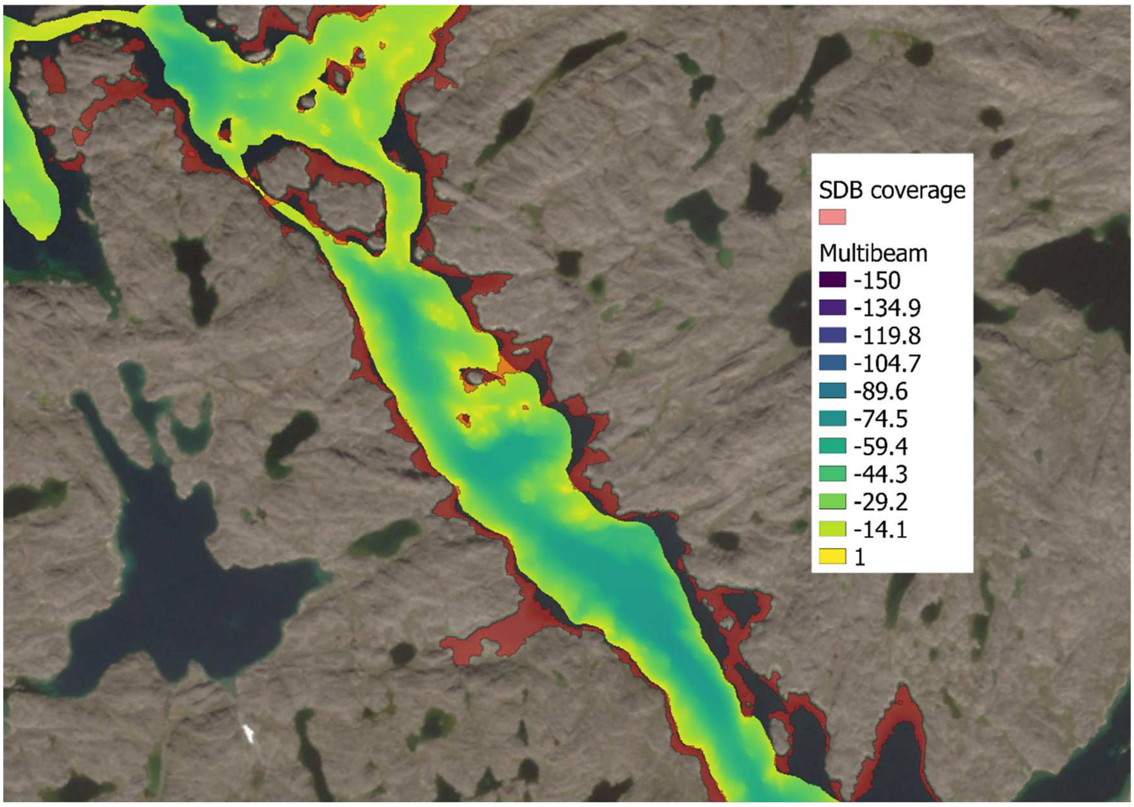


Figure 14: Færinge Nordhavn - Area 1. Multibeam coverage with transparent SDB overlay.

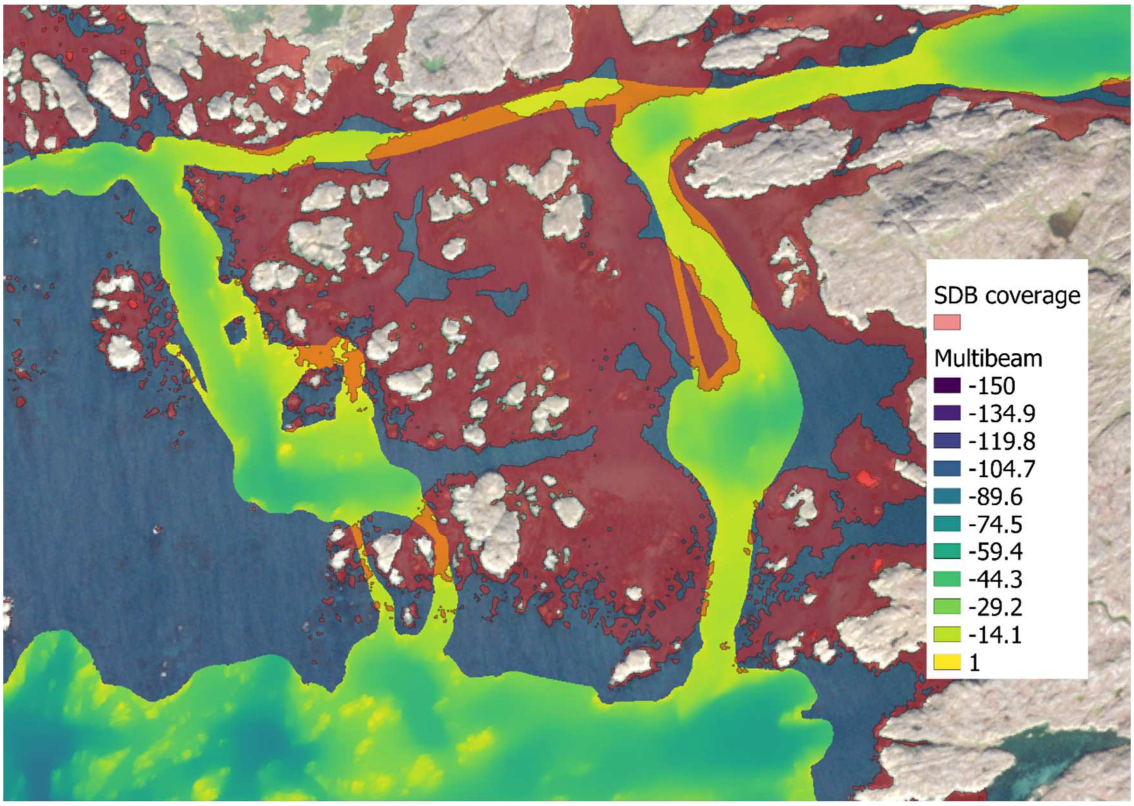


Figure 15: Sisimiut - Area 2. Multibeam coverage with transparent SDB overlay.

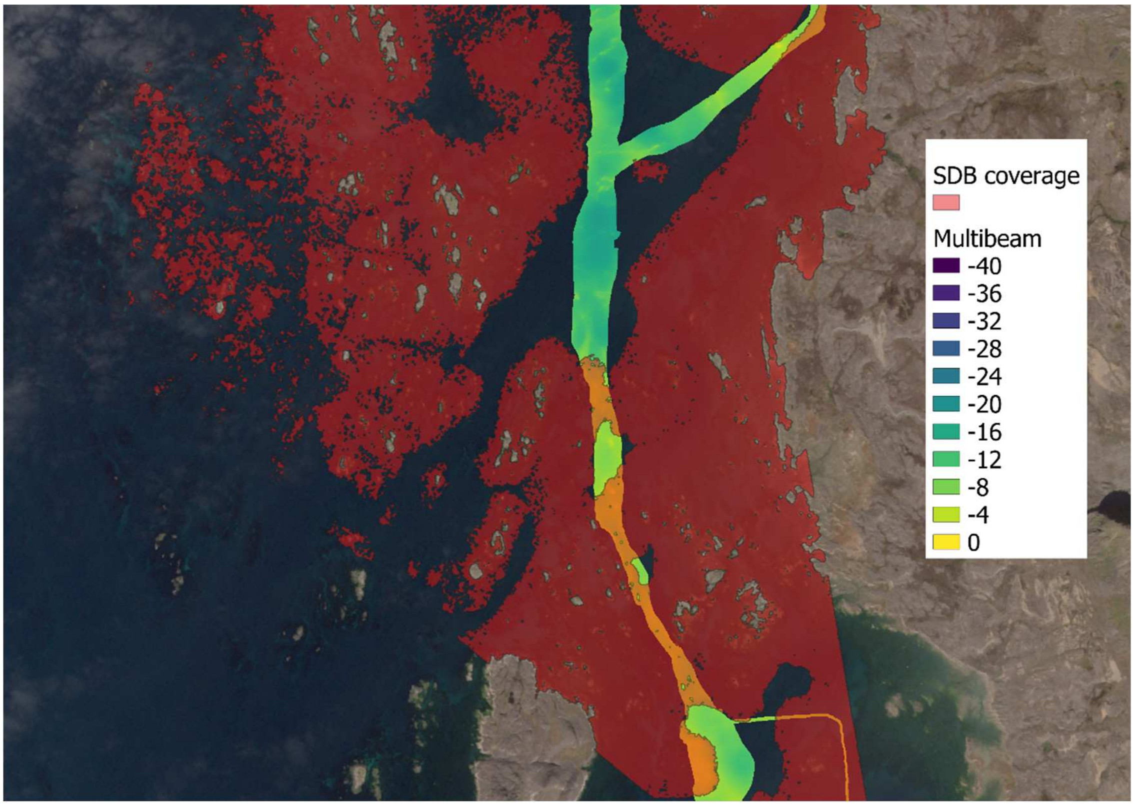


Figure 16: Anders Olsen Sund Syd - Area 3. Multibeam coverage with transparent SDB overlay.

4 Data analysis

In this section, we will look more into the SDB data. We will start off by computing some standard statistics. We then plot the differences between SDB and reference multibeam and compute the RMSE[8]. Lastly, we will look at some specific data examples of where SDB can be applied and where it can not be applied.

Statistics and histograms

The results are presented below with histograms of SDB 10m and 2m, respectively, showing the variability and the achieved depths as they are recorded by the providers. Below these are the histogram of differences between SDB and multibeam presented. These were calculated based on the differences between SDB and gridded multibeam. The histograms presented here are only for Area 3, and for Area 1-2 the reader is referred to Appendix B.

[8] RMSE = Root Mean Square Error.

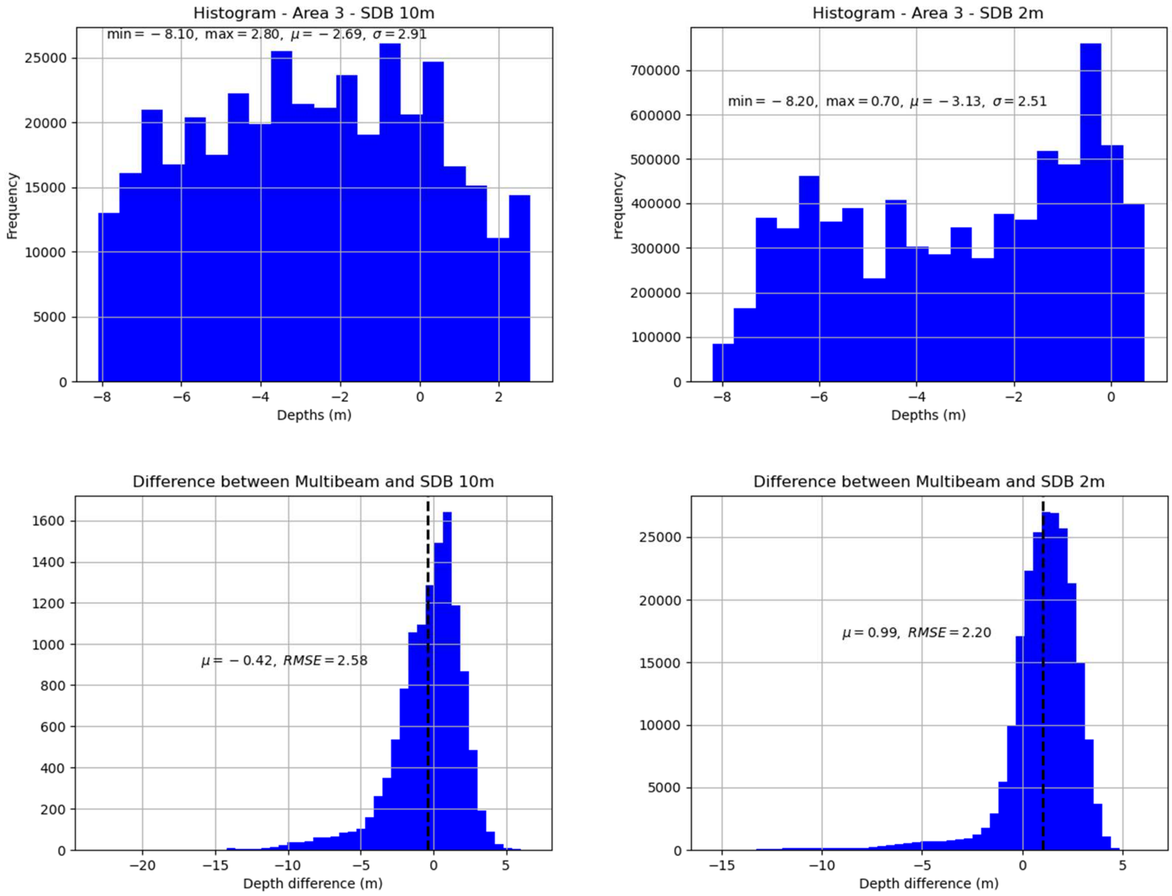
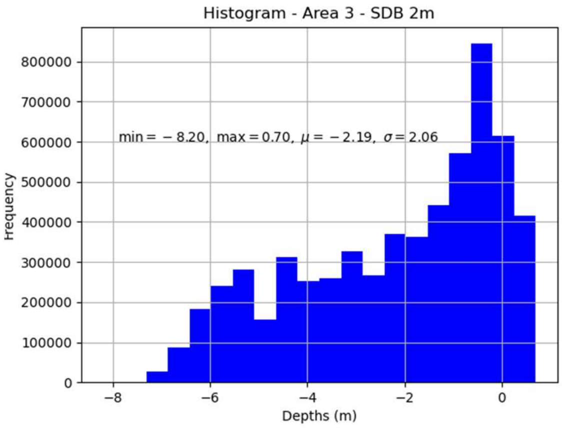


Figure 17: Anders Olsen Sund Syd - Area 3 - Uncalibrated - Provider 1.

***Top:** Histograms of depths. **Bottom:** Histogram of differences between SDB and multibeam.*

Looking at the uncalibrated dataset for Area 3 for Provider 1, depths are measured down to approximately 8m. Some differences between sensors are present.

Looking at the difference plots, there is a small offset (represented by the black vertical line, which is the mean) and it is not the same size or direction as was seen in Area 2. The RMSE is lower than for Area 1-2. Some high depth differences are present indicating either artifacts or non-seabed measurements.



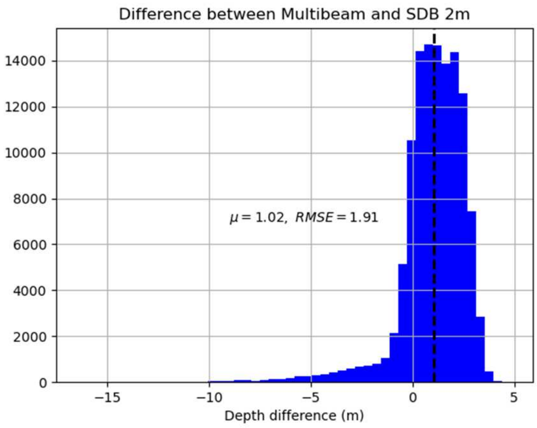


Figure 18: Anders Olsen Sund Syd - Area 3 - Calibrated - Provider 1.

***Top:** Histograms of depths. **Bottom:** Histogram of differences between SDB and multibeam.*

Now we will look at the effects of calibration. The calibration was only provided for the 2m dataset from Provider 1. According to Provider 1, the calibration dataset did not change anything in the model performance so the depths are more or less the same, but a new cut-off depth at approx. 7m and extra QC/QA were performed giving better results. This resulted in many of the deeper depths being removed, which is also apparent in above histogram.

The RMSE has decreased from 2.20m (uncalibrated) to 1.91m (calibrated), which is indeed a positive result. Some deeper non-seabed data points are still present but in a less degree. We will see more on the effects of calibration in the data examples.

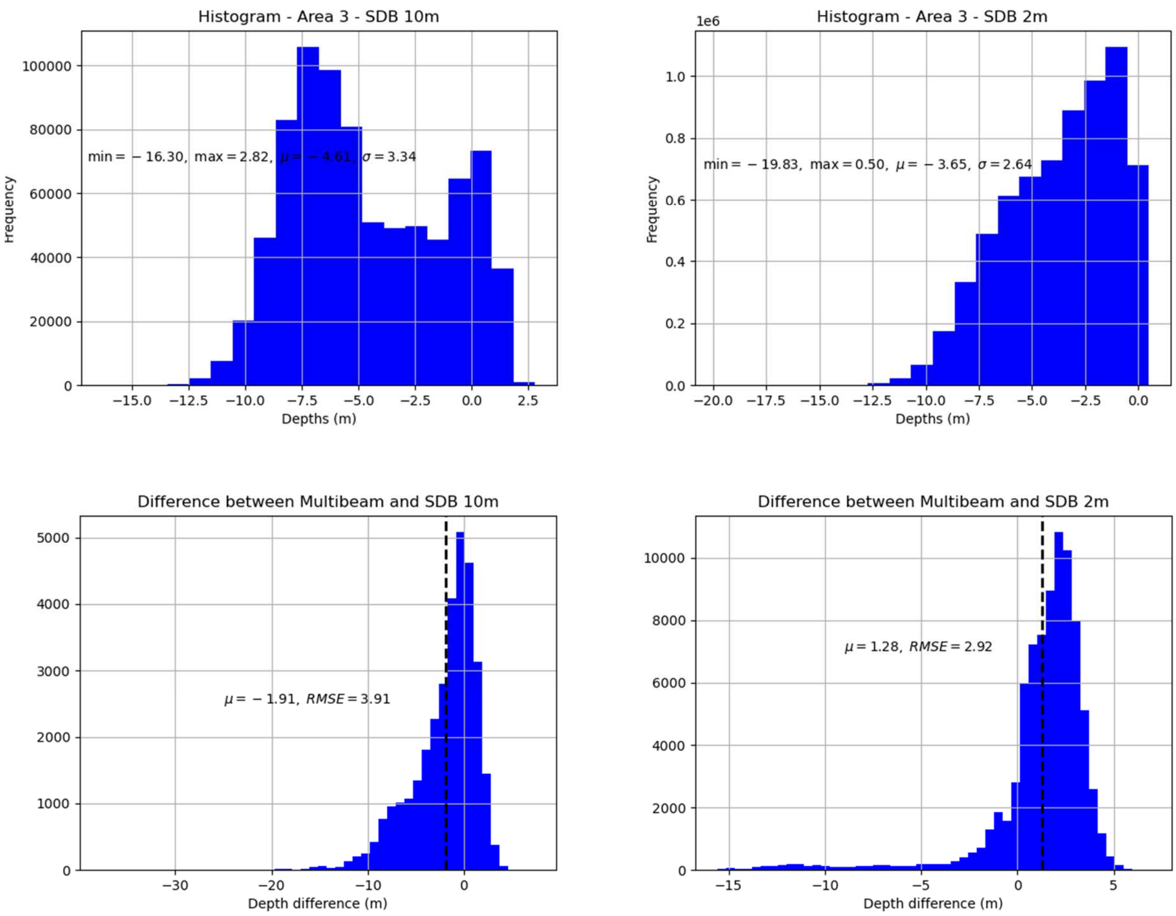
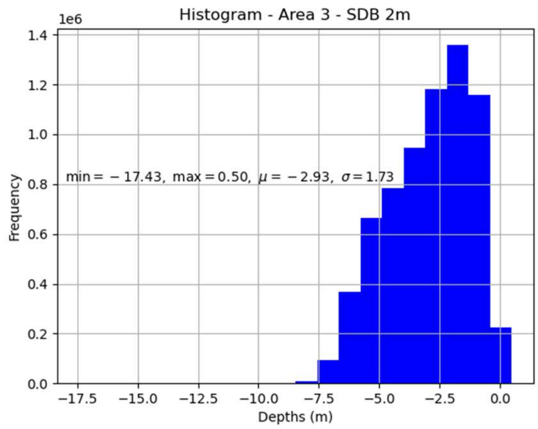


Figure 19: Anders Olsen Sund Syd - Area 3 - Uncalibrated - Provider 2.

***Top:** Histograms of depths. **Bottom:** Histogram of differences between SDB and multibeam.*

Now looking at the results from Provider 2. Depths are measured down to approximately -16m and -19m, respectively, but with the main part being above -10m. A peak at -7.5m in the 10m dataset is observed.

Here we also see an offset in the data and some large depth differences that most likely are not contributed to seabed. The offset suggests that there is a systematic error in the datasets. The RMSE for Provider 2 is significantly larger than Provider 1 for the same area.



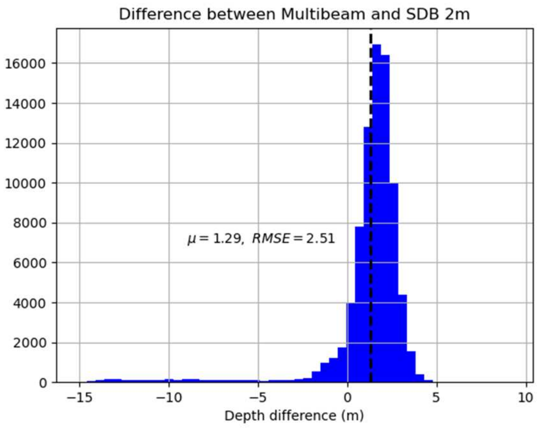


Figure 20: Anders Olsen Sund Syd - Area 3 - Calibrated - Provider 2.

Top: *Histograms of depths.* ***Bottom:*** *Histogram of differences between SDB and multibeam.*

Provider 2 used both the provided multibeam data and SDB 10m for calibrating the SDB 2m. It resulted in many deeper depths being adjusted. Provider 2 also delivered a calibrated 10m SDB dataset but because of some gridding issues it was excluded from the analysis.

The calibration resulted in a lower RMSE of 2.51m compared to the original value of 2.92m. Some deeper non-seabed data points are still present but in a lesser degree.

Data examples

The data can not be analyzed by histograms alone. One has to look at specific areas to get a good picture of what is happening in the data results. Therefore, examples of different cases of SDB are presented using horizontal profiles as shown in below figures. In the profiles, the X-axis is the profile length in meters and the Y-axis is depths in meters.

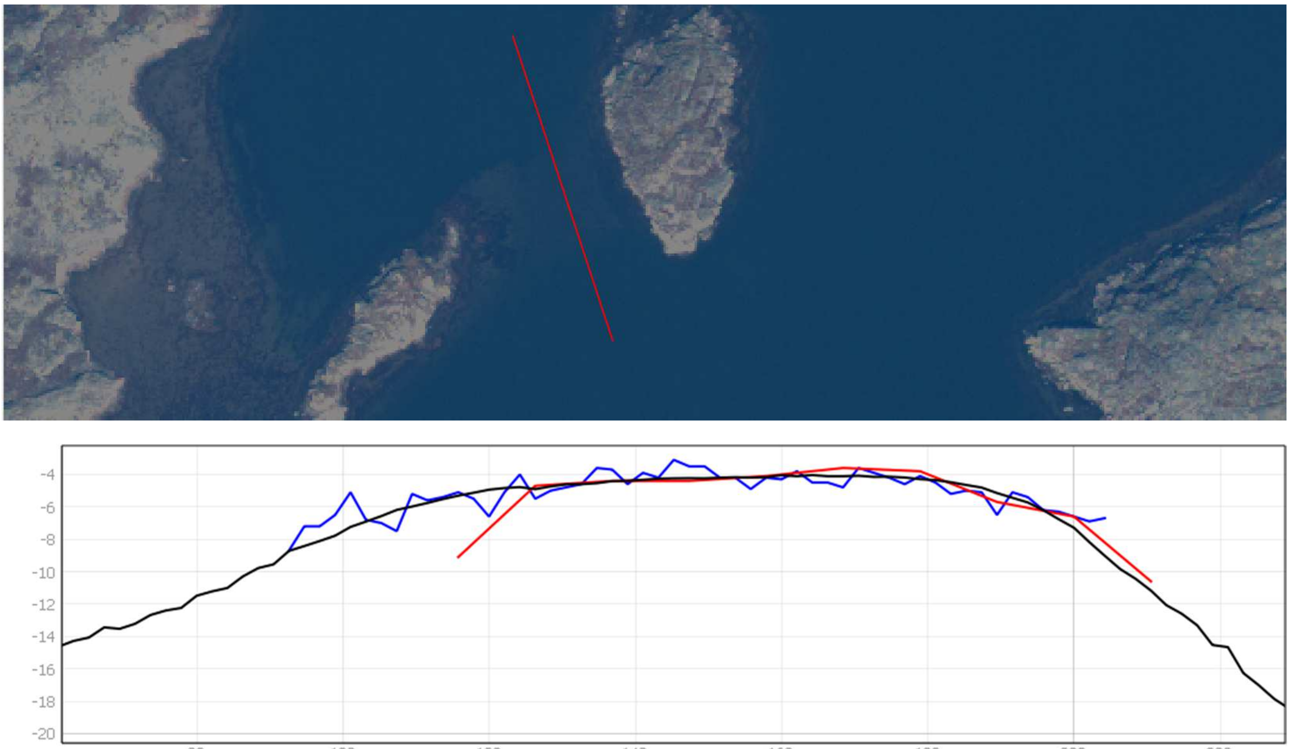


Figure 21: Example 1 - Profile in Area 1.

Blue line: *Uncalibrated SDB 2m based on WV-2/3.*

Red line: *Uncalibrated SDB 10m based on Sentinel-2.*

Black line: *Multibeam reference survey.*

Here we see that both SDB datasets capture the depth of the shallow area quite well down to approximately 8m. The Sentinel-2 dataset is however off in the start of the profile.

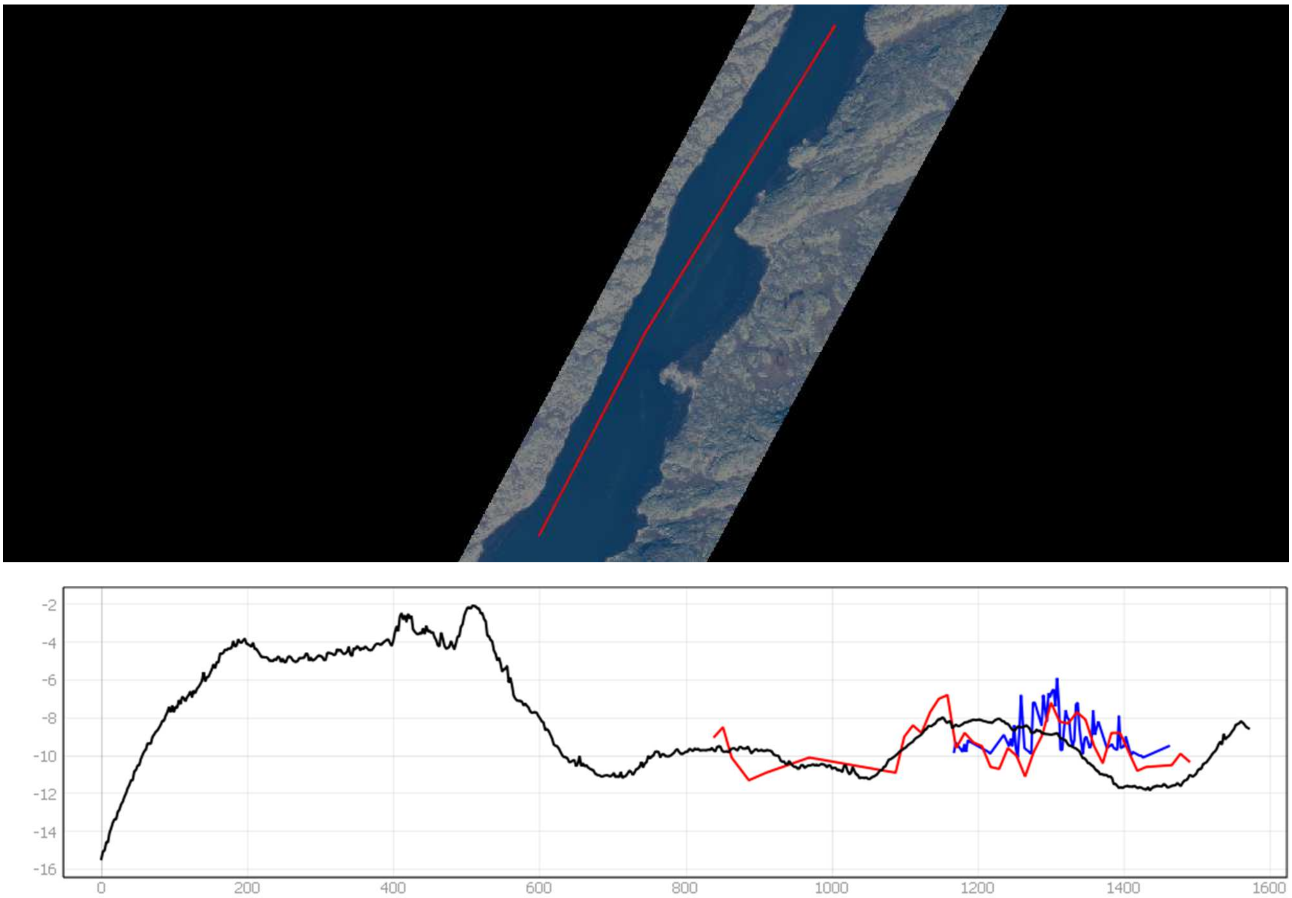


Figure 22: Example 2 - Profile in Area 1.

Blue line: *Uncalibrated SDB 2m based on WV-2/3.*

Red line: *Uncalibrated SDB 10m based on Sentinel-2.*

Black line: *Multibeam reference survey.*

In this example, the SDB method has some issues, especially the 2m dataset. This very narrow strait is known to have a lot of currents, which could give a high turbidity and explain why the depths are not measured even though the area is very shallow.

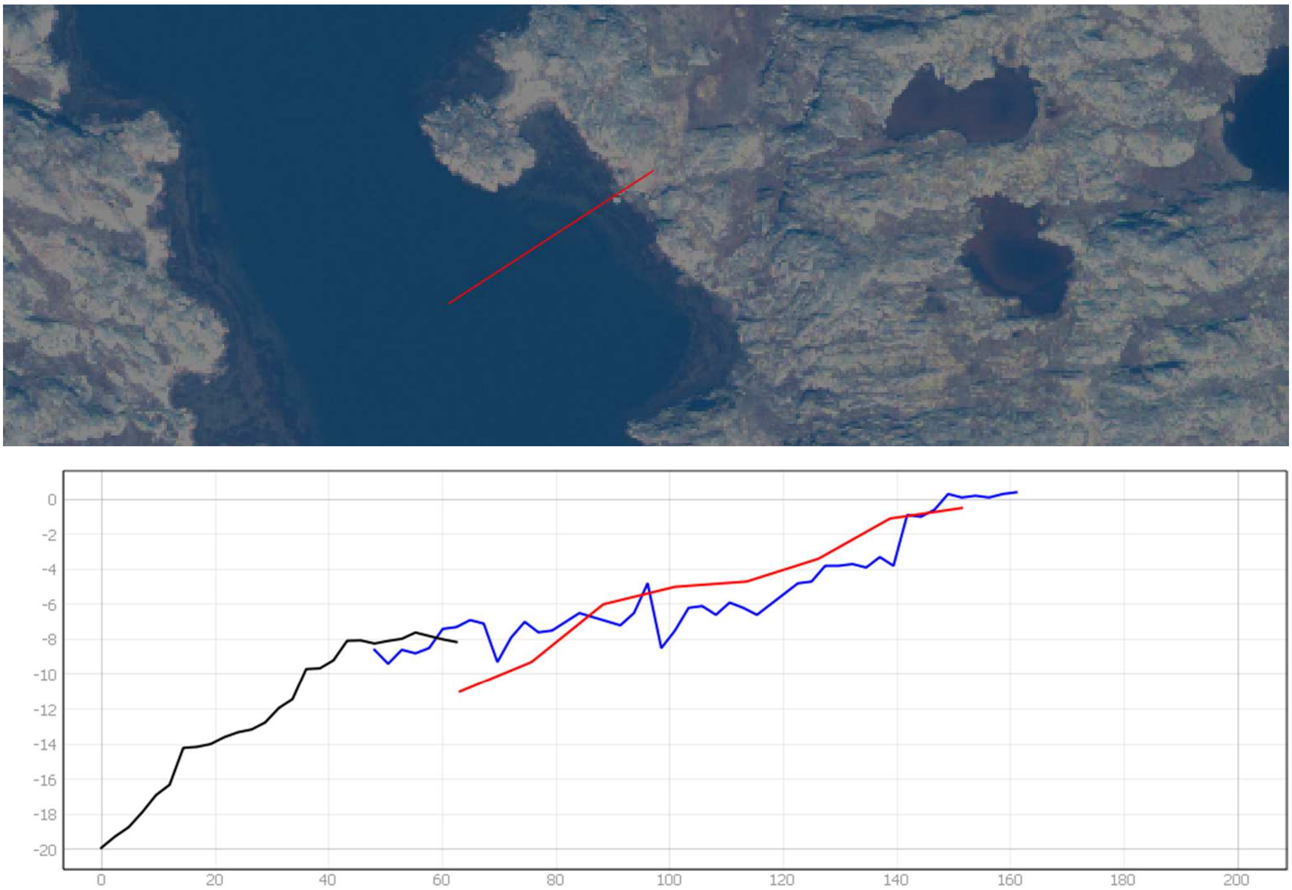


Figure 23: Example 3 - Profile in Area 1.

Blue line: *Uncalibrated SDB 2m based on WV-2/3.*

Red line: *Uncalibrated SDB 10m based on Sentinel-2.*

Black line: *Multibeam reference survey.*

This is a good example of where SDB could benefit; In the interface between land and the multibeam measurements (depth range 0-8m).

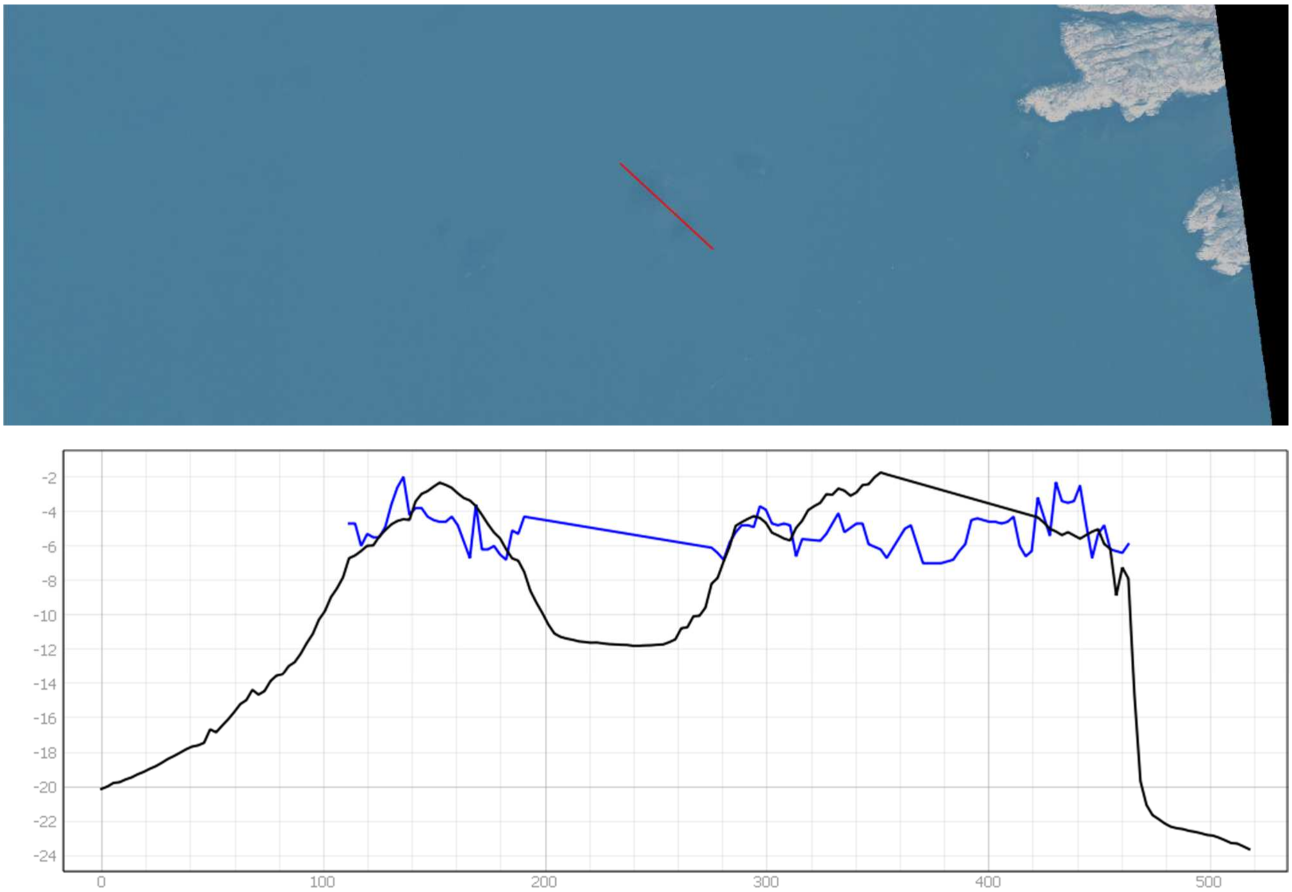


Figure 24: Example 4 - Profile in Area 2

Blue line: *Uncalibrated SDB 2m based on WV-2/3.*

Black line: *Multibeam reference survey.*

Now looking at Area 2. In this example, we are in deep waters but with some rocks showing up and potentially being a danger to navigation. Both peaks are captured somewhat by the WV-2 dataset, but in between, the depths are too deep and no SDB is measured (the blue straight line in the middle is interpolation). Unfortunately, the Sentinel-2 dataset does not capture any of the peaks.

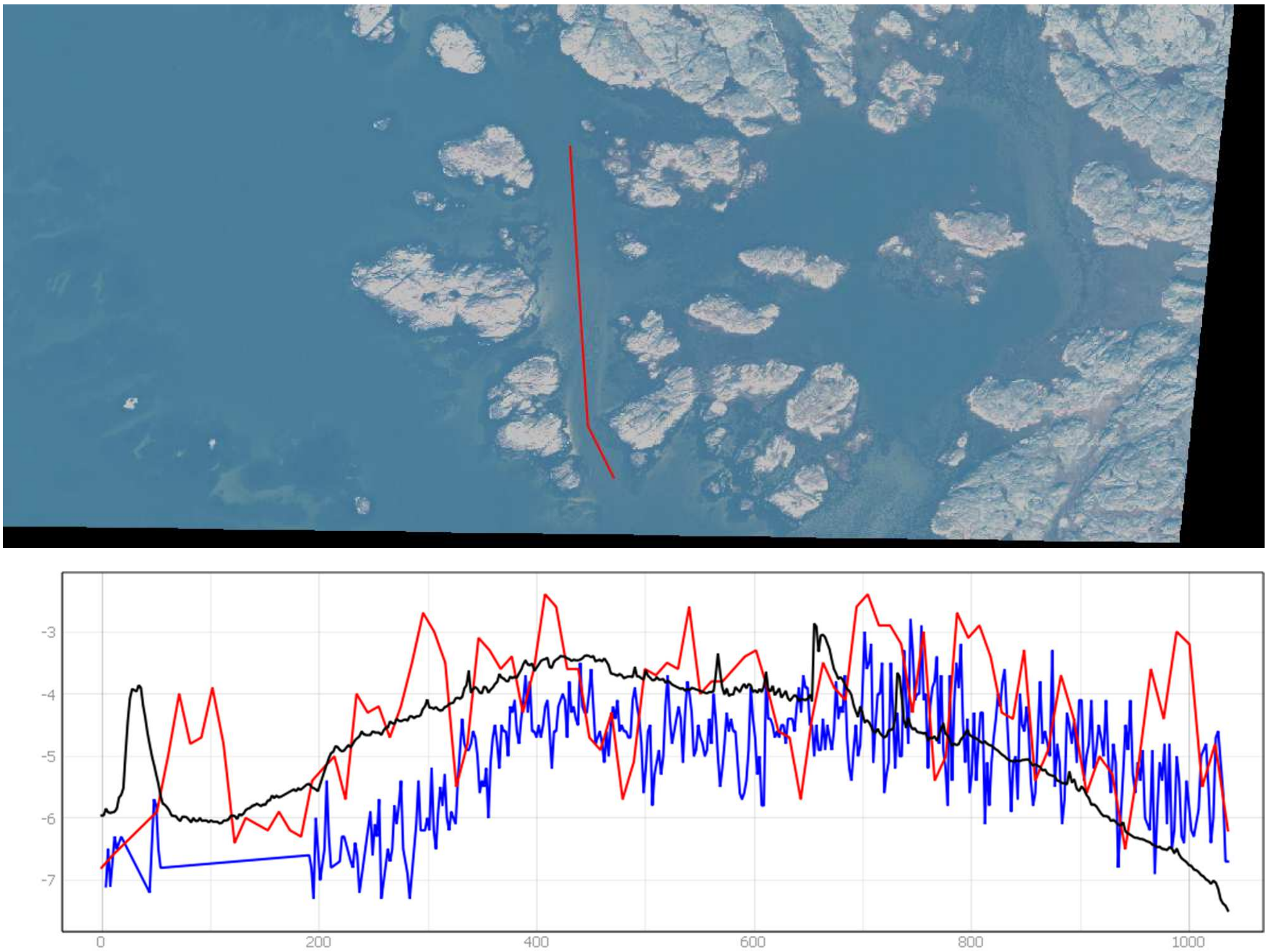


Figure 25: Example 5 - Profile in Area 2.

Blue line: *Uncalibrated SDB 2m based on WV-2/3.*

Red line: *Uncalibrated SDB 10m based on Sentinel-2.*

Black line: *Multibeam reference survey.*

In this example, the SDB 2m dataset has some issues and a lot of noise is present. Here the SDB 10m dataset actually performs better.

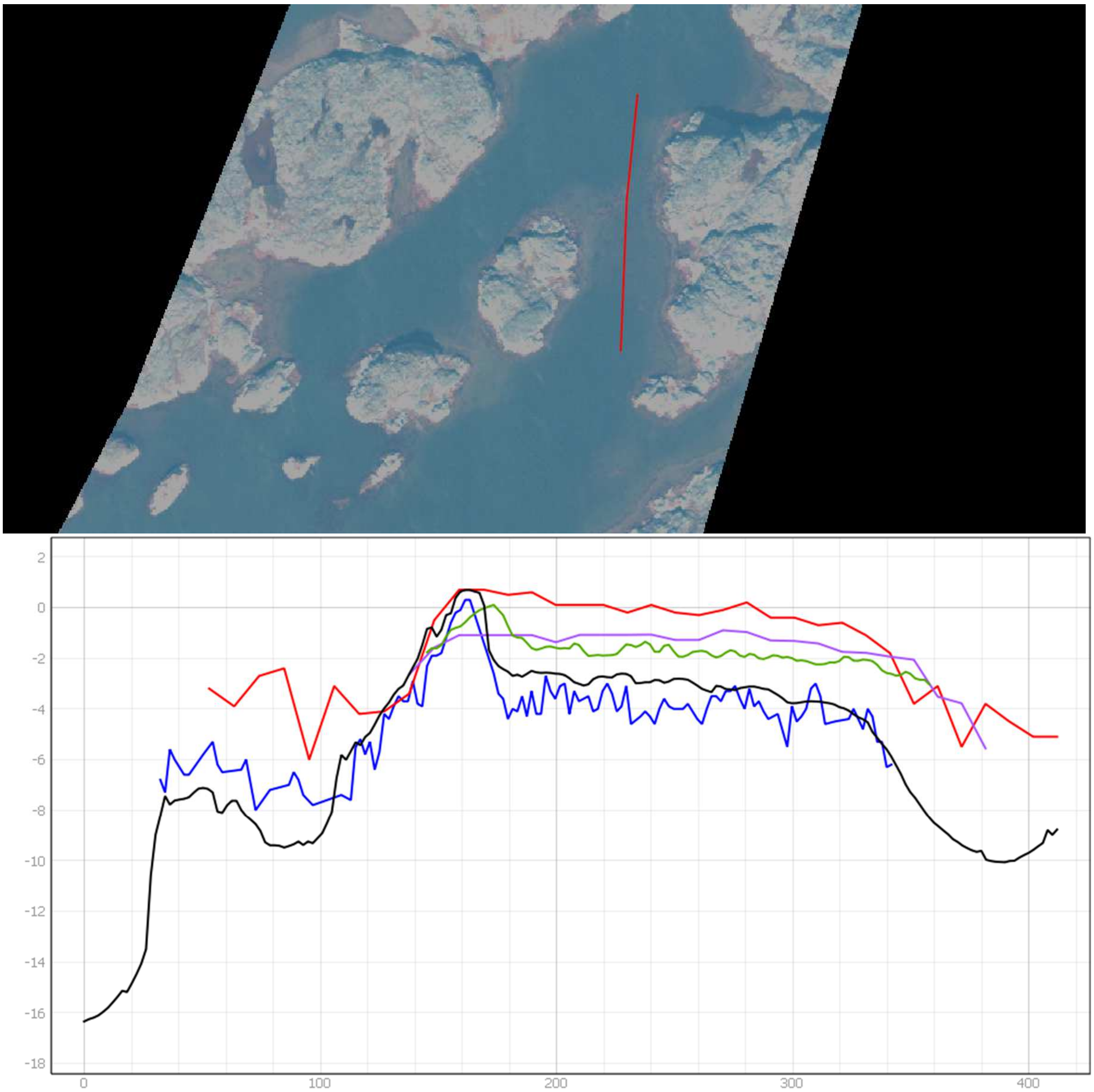


Figure 26: Example 6 - Profile in Area 3.

Blue line: *Provider 1 uncalibrated SDB 2m based on WV-2/3.*

Red line: *Provider 1 uncalibrated SDB 10m based on Sentinel-2.*

Green line: *Provider 2 uncalibrated SDB 2m based on WV-2/3.*

Purple line: *Provider 2 uncalibrated SDB 10m based on Sentinel-2.*

Black line: *Multibeam reference survey.*

In this example, we have three depth regimes: Very deep where no SDB is retrieved (8-16m), shallow where one of the datasets somewhat retrieves SDB and very shallow with a peak where all datasets retrieves SDB (+0-4m). The 2m and 10m datasets from Provider 2 are quite similar and does not capture the peak very well. The 2m dataset from Provider 1 captures both the depth and peak quite well.

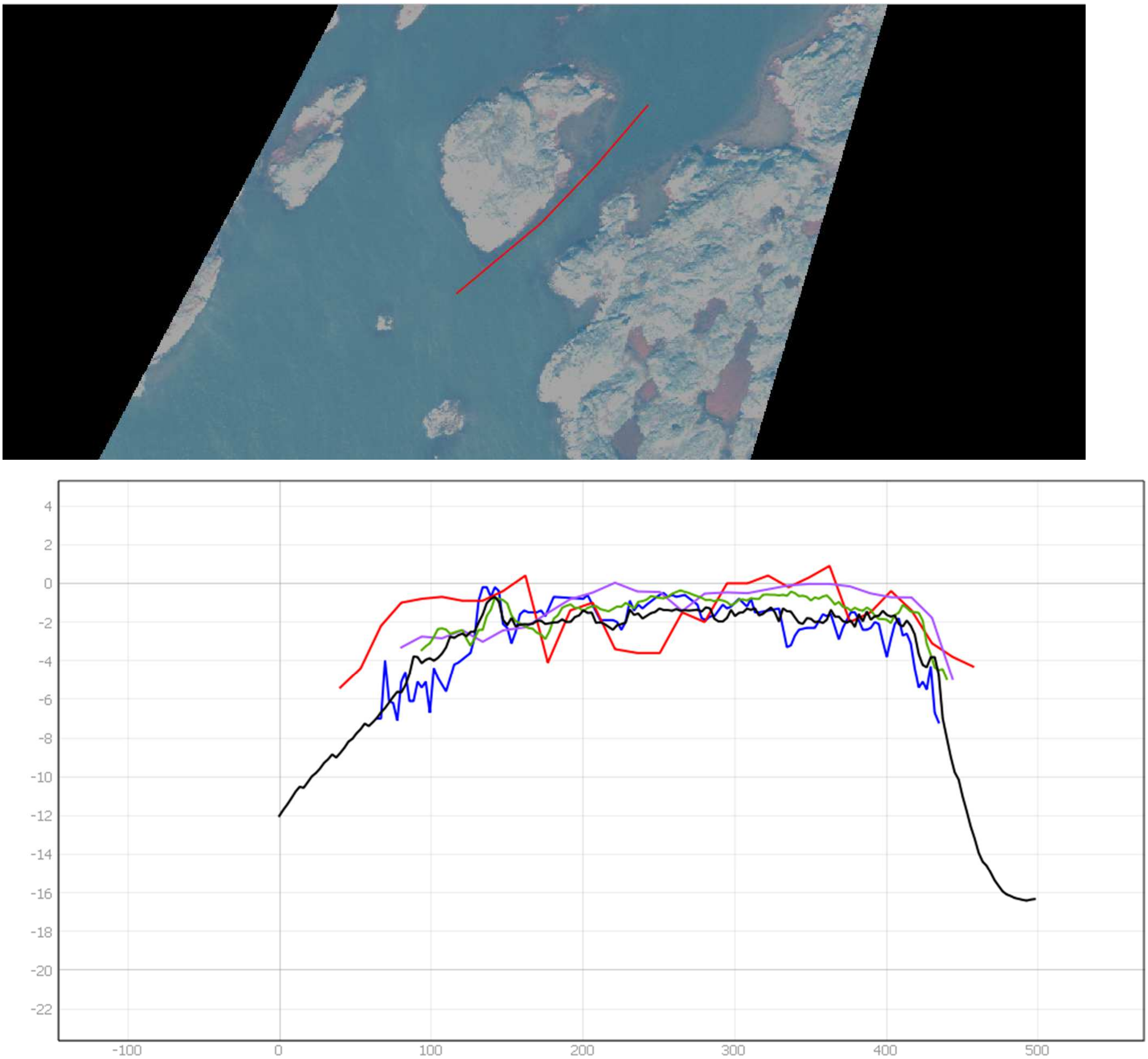


Figure 27: Example 7 - Profile in Area 3.

Blue line: *Provider 1 uncalibrated SDB 2m based on WV-2/3.*

Red line: *Provider 1 uncalibrated SDB 10m based on Sentinel-2.*

Green line: *Provider 2 uncalibrated SDB 2m based on WV-2/3.*

Purple line: *Provider 2 uncalibrated SDB 10m based on Sentinel-2.*

Black line: *Multibeam reference survey.*

In this example all datasets captures the depths quite well. Depths can be retrieved down to 4-7m.

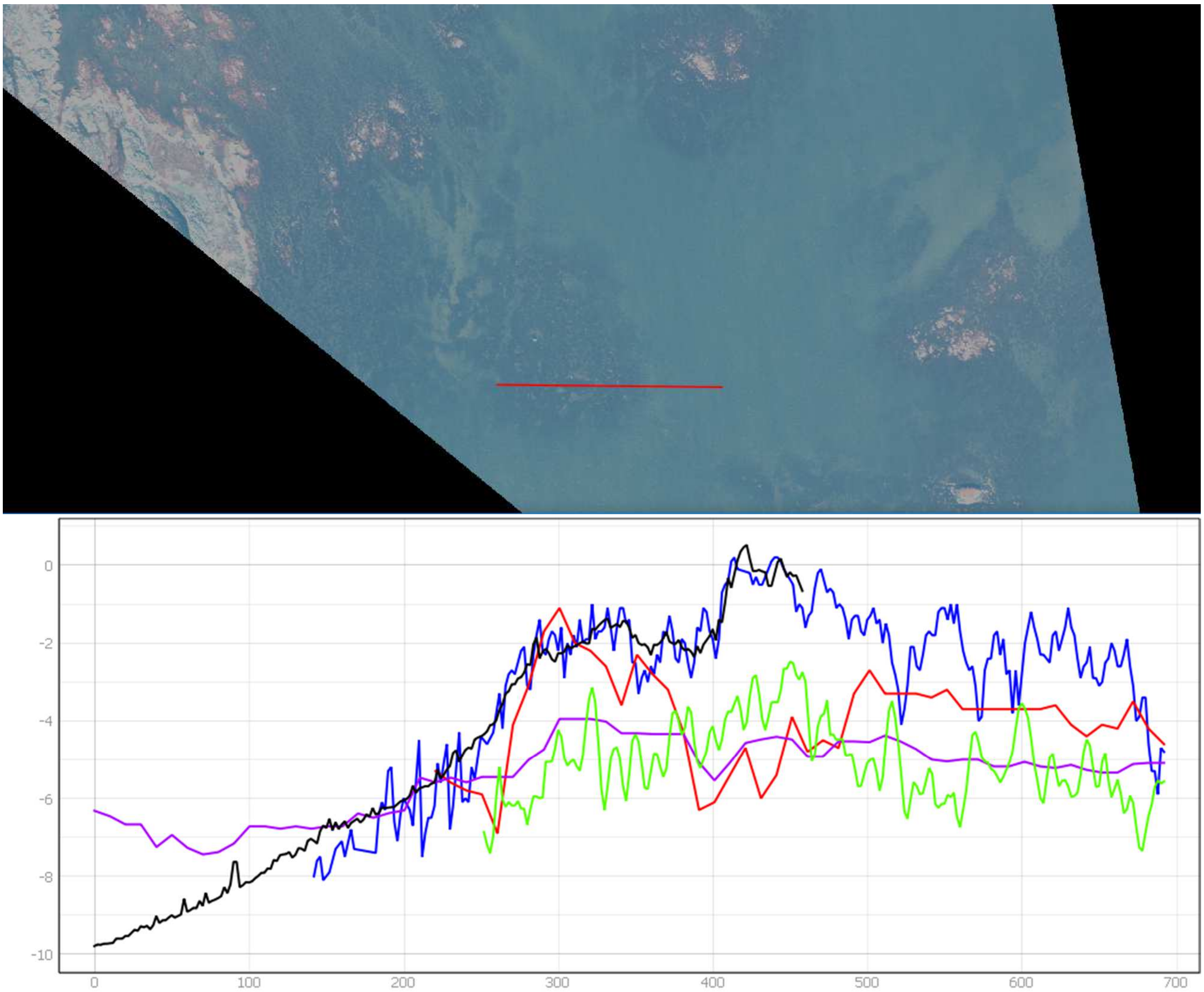


Figure 28: Example 8 - Profile in Area 3.

Blue line: *Provider 1 uncalibrated SDB 2m based on WV-2/3.*

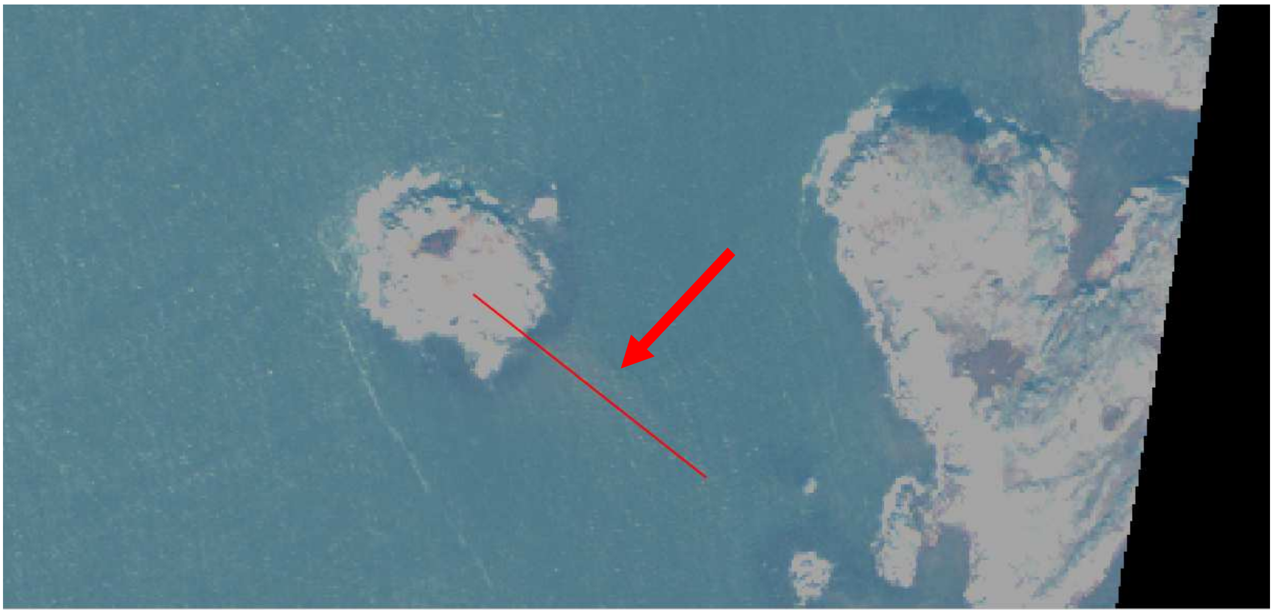
Red line: *Provider 1 uncalibrated SDB 10m based on Sentinel-2.*

Green line: *Provider 2 uncalibrated SDB 2m based on WV-2/3.*

Purple line: *Provider 2 uncalibrated SDB 10m based on Sentinel-2.*

Black line: *Multibeam reference survey.*

This area is a good example of where we have multibeam reference all the way from deep to very shallow. In addition, a lot of hard seabed and kelp is present in the area so that is a good test of the performance. We see that the 10m dataset from both providers is quite off and does not capture the depths very well. The 2m dataset from Provider 1 is quite accurate but still noisy which is due to the kelp/hard seabed. The 2m dataset from Provider 2 has a big offset but does follow the seabed topography to some degree.



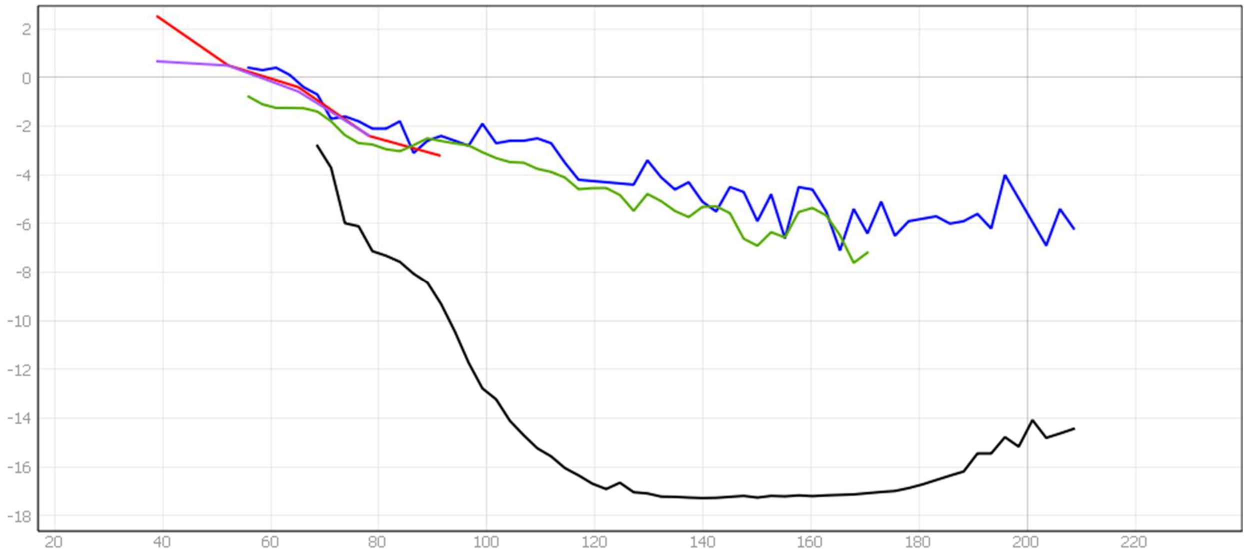


Figure 29: Example 9 - Profile in Area 3 - Effect of suspended sediments in the water.

Blue line: *Provider 1 uncalibrated SDB 2m based on WV-2/3.*

Red line: *Provider 1 uncalibrated SDB 10m based on Sentinel-2.*

Green line: *Provider 2 uncalibrated SDB 2m based on WV-2/3.*

Purple line: *Provider 2 uncalibrated SDB 10m based on Sentinel-2.*

Black line: *Multibeam reference survey.*

This is an example of why it is important to QC and validate SDB data. In the WV-2/3 satellite image there is water waves and current that caused suspended sediments in the water column, increasing the turbidity (see above red arrow in the image). This resulted in depths being completely off because it was interpreted as shallow depths as is seen by the blue and green lines. Only the 2m datasets were affected due to the satellite source image.

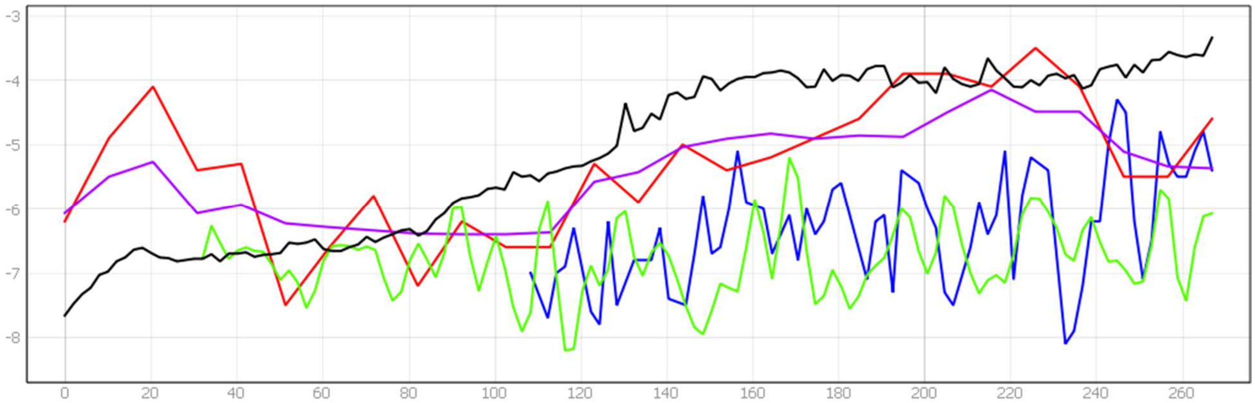


Figure 30: Example 10 - Profile in Area 3 - Effect of water waves.

Blue line: *Provider 1 uncalibrated SDB 2m based on WV-2/3.*

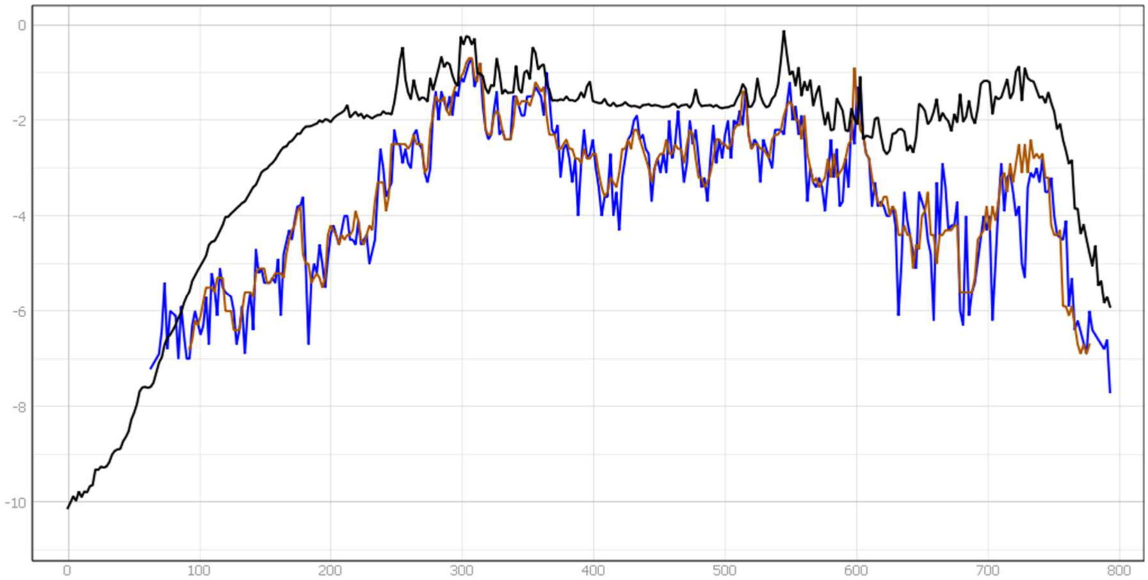
Red line: *Provider 1 uncalibrated SDB 10m based on Sentinel-2.*

Green line: *Provider 2 uncalibrated SDB 2m based on WV-2/3.*

Purple line: *Provider 2 uncalibrated SDB 10 based on Sentinel-2.*

Black line: *Multibeam reference survey.*

Here we see the effect of water waves which was present in the WV-2/3 satellite source image. This resulted in the 2m dataset being quite off and looks just to be noise. The 10m dataset did not perform that well either but it is most likely not due to surface waves.



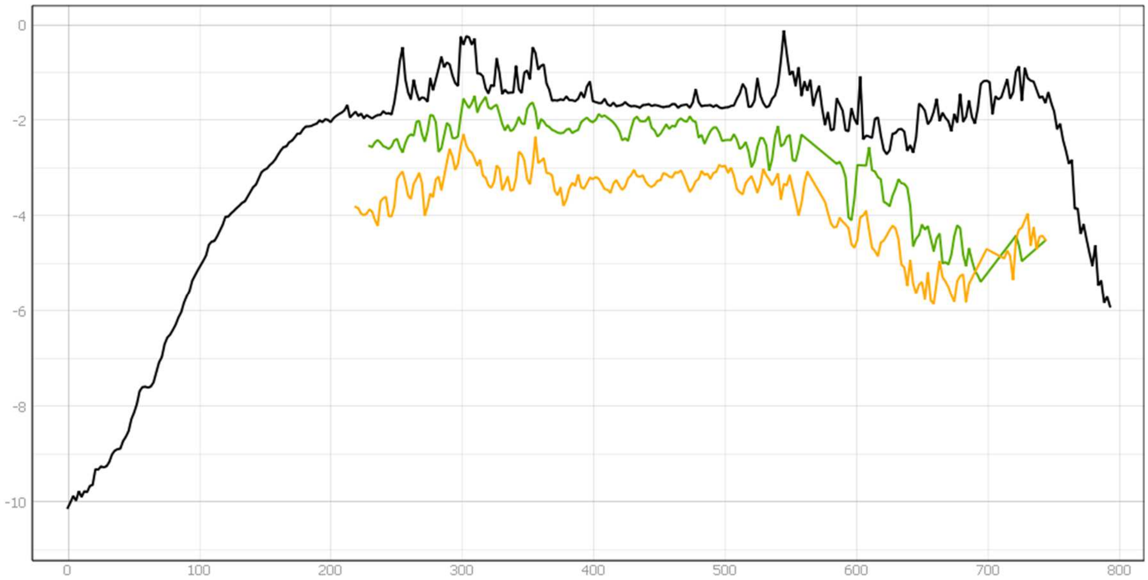


Figure 31: Example 11 – Profile in Area 3 – Effect of calibration.

Blue line: *Provider 1 uncalibrated SDB 2m based on WV-2/3.*

Brown line: *Provider 1 calibrated SDB 10m based on Sentinel-2.*

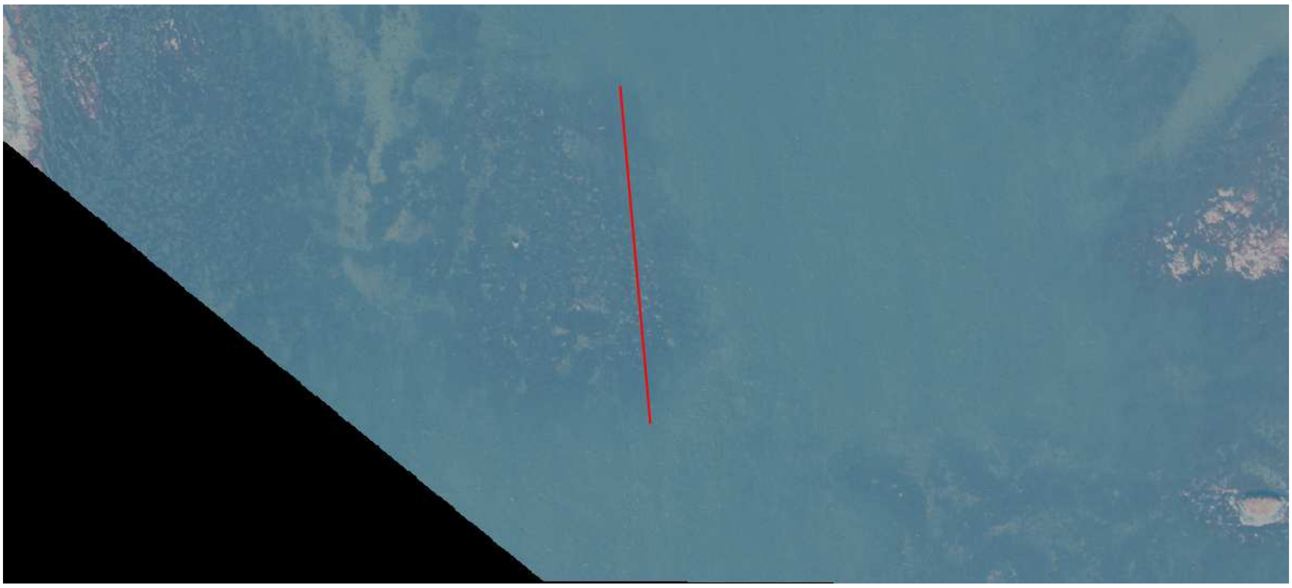
Green line: *Provider 2 uncalibrated SDB 2m based on WV-2/3.*

Orange line: *Provider 2 calibrated SDB 10m based on Sentinel-2.*

Black line: *Multibeam reference survey.*

Here we see the effects of calibration for Provider 1. The calibration did not change much in the modelled depths, but the cut-off depth has changed and the noise has been greatly reduced.

Now looking at calibration from Provider 2, not much improvement is seen for this area, rather the opposite has occured. All the profiles for both Provider 1 and Provider 2 have some problems at the start and end of the profile due to kelp and hard seabed.



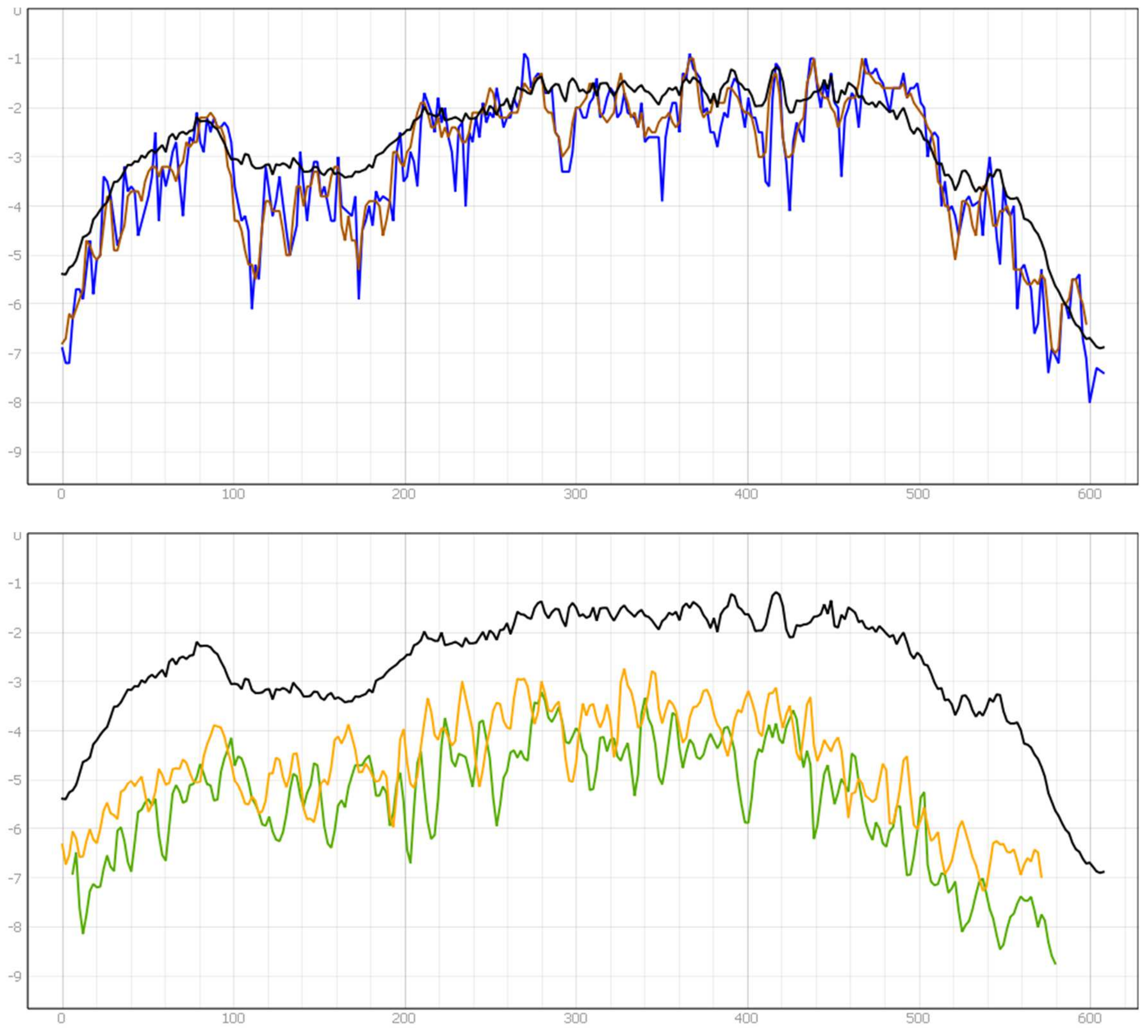


Figure 32: Example 12 - Profile in Area 3 - Effect of calibration.

Blue line: *Provider 1 uncalibrated SDB 2m based on WV-2/3.*

Brown line: *Provider 1 calibrated SDB 10m based on Sentinel-2.*

Green line: *Provider 2 uncalibrated SDB 2m based on WV-2/3.*

Orange line: *Provider 2 calibrated SDB 10m based on Sentinel-2.*

Black line: *Multibeam reference survey.*

For Provider 1, again the modelled depths are more or less the same and the noise level has been reduced.

For Provider 2, we see a small improvement in the modelled depths.

Summary of analysis

The analysis can be summarized as follows:

1) SDB in these specific areas (Area 1-3) can measure shallow waters down to approximately 7m. This highly depends on the local water and seabed conditions and satellite sensor, which can give greater, shallower or no depths measured at all.

2) Important environmental factors observed in this project are: Wind and current, suspended sediments in the water column, kelp and hard seabed.

3) In general, the SDB based on WV-2/3 performs better than Sentinel-2, mainly because of the higher spatial resolution. Unfortunately, the satellite source image from WV-2/3 that was used for Area 3 contained a lot of waves and suspended sediments in the water column causing a poorer result. An increasing number of available satellite images in the future might mitigate this problem.

4) A systematic error is observed in the datasets for Area 2 -3. The origin of this error is uncertain but sources could be waves, non-seabed measurements or tidal correction.

5) Calibration had different effects depending on the provider:
   The calibration from Provider 1 resulted in less noise and a different cut-off depth that improved the data and decreased the RMSE from 2.20m to 1.91m. In addition, extra QC was performed removing some non-seabed measurements.
   The calibration from Provider 2 resulted in new modelled depths that in some cases improved the data but in other cases it did not. The RMSE decreased from 2.92m to 2.51m, which means that the calibration in general had a positive effect.
   If more multibeam data is provided beforehand to the providers, it might improve the calibration even more.

6) If more near coastal multibeam were available, the RMSE is expected to be lower because SDB only applies to very shallow waters. It should be noted that the available multibeam reference datasets in general measures deeper waters, and it is often on the border of what SDB is capable of measuring, so that will bias the analysis to some degree. That said, it highly depends on the uncertainty as a function of depth, and that can be more complex than just assuming it increases with depth.

5 Discussion

We will now be discussing the data delivery and analysis.

The data was delivered by the providers as requested and it was indeed a good decision to also obtain the raw satellite images, so one can inspect the corresponding satellite image, as is shown in the data examples. In addition, the fact that we requested SDB for several areas, from different providers and both uncalibrated and calibrated versions gave us a very good basis for comparing and analyzing the data.

The coverage of Area 1 is less than anticipated but given the high slopes and deep waters it is to be expected. The coverage of Areas 2 and 3 are very good but also had some challenges like waves and suspended sediments in the water column that affected the measurements. It is interesting to see how big a difference there is given the different satellite sources, both in coverage and depth penetration.

In general, it is difficult to find satellite images that have the perfect conditions for SDB in Greenland, i.e. cloud and haze free, no ice, little or no waves, clear waters and highest sunlight energy. Increased mapping frequency and bigger image archives will definitely improve this in the future.

In the analysis we see depth differences of >5m and RMSE values up to 3.91m which is quite high when considering applications for shallow waters. That said, often there is a reason for such high depth differences (i.e. systematic errors) which can be avoided by interpretation by data experts. In the best case scenario, the RMSE was observed to be 1.91.

We see a big difference between satellite sensors. In general, the SDB 2m dataset based on WV-2/3 is more accurate than the SDB 10m dataset based on Sentinel-2, but cases of the opposite can also be observed, as is shown in the data examples. WV-2/3 provides higher spatial details making it better for detecting rocks and obstructions, and it often detects subsurface rocks that can not be seen in the dataset based on Sentinel-2. The advantage of Sentinel-2 is that it has a bigger image archive giving an advantage in the image selection process, and it is also freely available. In the future, satellite sensors with better spatial resolution, spectral information and more frequent measurements in the Arctic will improve SDB. Regarding the SDB method itself, one can imagine that using multiple satellite images can improve the output.

Regarding providers, we see a very big difference even though the basic method is the same. This emphasizes how different the approaches can be to the SDB method including the interpretation of the data.

Considering calibration with multibeam data, we see that for Provider 1 that the modelled depths did not change much but it decreased the noise level to a high degree. For Provider 2 we see that the modelled depths changed and generally improved the data but cases of the opposite happening were also found. Calibration overall is an improvement.

6 Conclusion

The purpose of this project is to get insight into the method of SDB and give recommendations on what it can be used for. We conclude that SDB can be used to map depths down to approximately 7m in Greenlandic waters given optimal conditions for SDB that include sufficient water clarity, a minimum of hard seabed and kelp, a minimum of surface waves and current and high resolution satellite imagery. It is observed during the project that SDB is highly location-, sensor-, method- and interpretation dependent.

Regarding calibration, we see an increase in performance when calibrating SDB with existing multibeam surveys. It is recommended to calibrate SDB if possible.

For navigational and nautical charting purposes in Greenland, SDB should not be used as the main source of information, because it is not fully reliable in identifying all obstructions and hazards. That said, SDB does provide value in identifying changes that potentially are a risk for navigation and can help prioritizing future surveys (e.g. as a survey reconnaissance tool).

For environmental studies that do not require full seafloor coverage and obstruction detection in the same manner as is required for navigational purposes, SDB is expected to have applications.

In the future, it is expected that SDB and remote sensing in general will become more prevalent in the marine sector with new sensors and missions such as ICESat-2 (active laser based), new generation of WorldView, micro satellites and drones. As more satellite data becomes available and new approaches to SDB are found (like multi-temporal image analysis), there is a potential for SDB being used for charting in Greenland. However, the challenges of Greenlandic waters will remain.

7 Reflections

During this project, we learned how SDB and the implemented method works and where it can be applied in Greenlandic waters. Most of all, we learned how important validation and interpretation are in order to get the proper value from SDB. It is a very interesting field to follow and there exist many different approaches to satellite data.

8 Acknowledgements

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10 Appendix A – Example of uncertainties

Below are the reported uncertainties by the providers for the SDB 2m datasets (calibrated version).

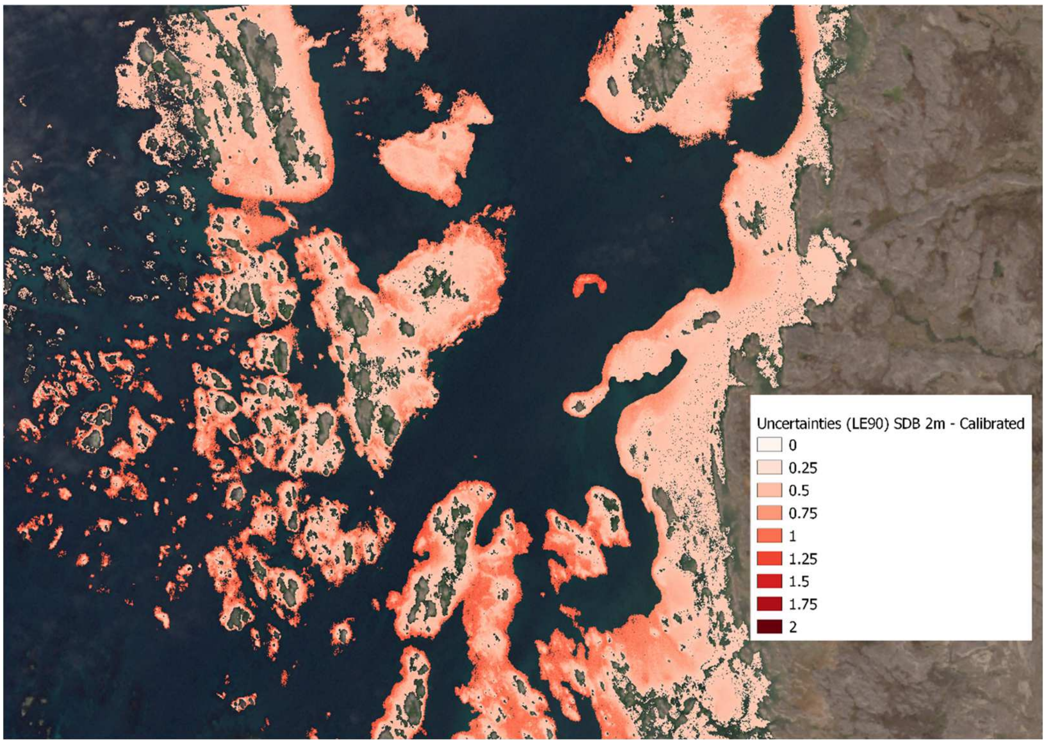

Figure 33: Depth uncertainties - Area 3 - Provider 1 - Calibrated.

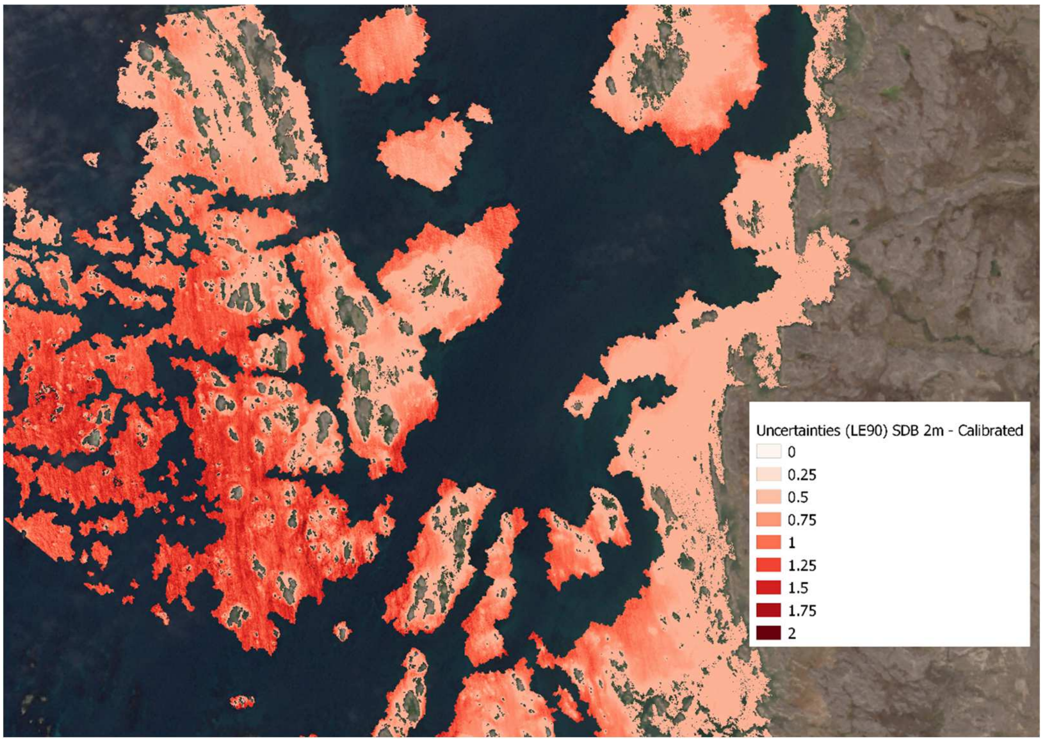

Figure 34: Depth uncertainties - Area 3 - Provider 2 - Calibrated.

11 Appendix B – Analysis of Area 1 and 2

Below are histograms of recorded SDB depths and histogram of differences between SDB and reference multibeam for Area 1-2. The histograms of differences were calculated based on the differences between SDB and gridded multibeam.

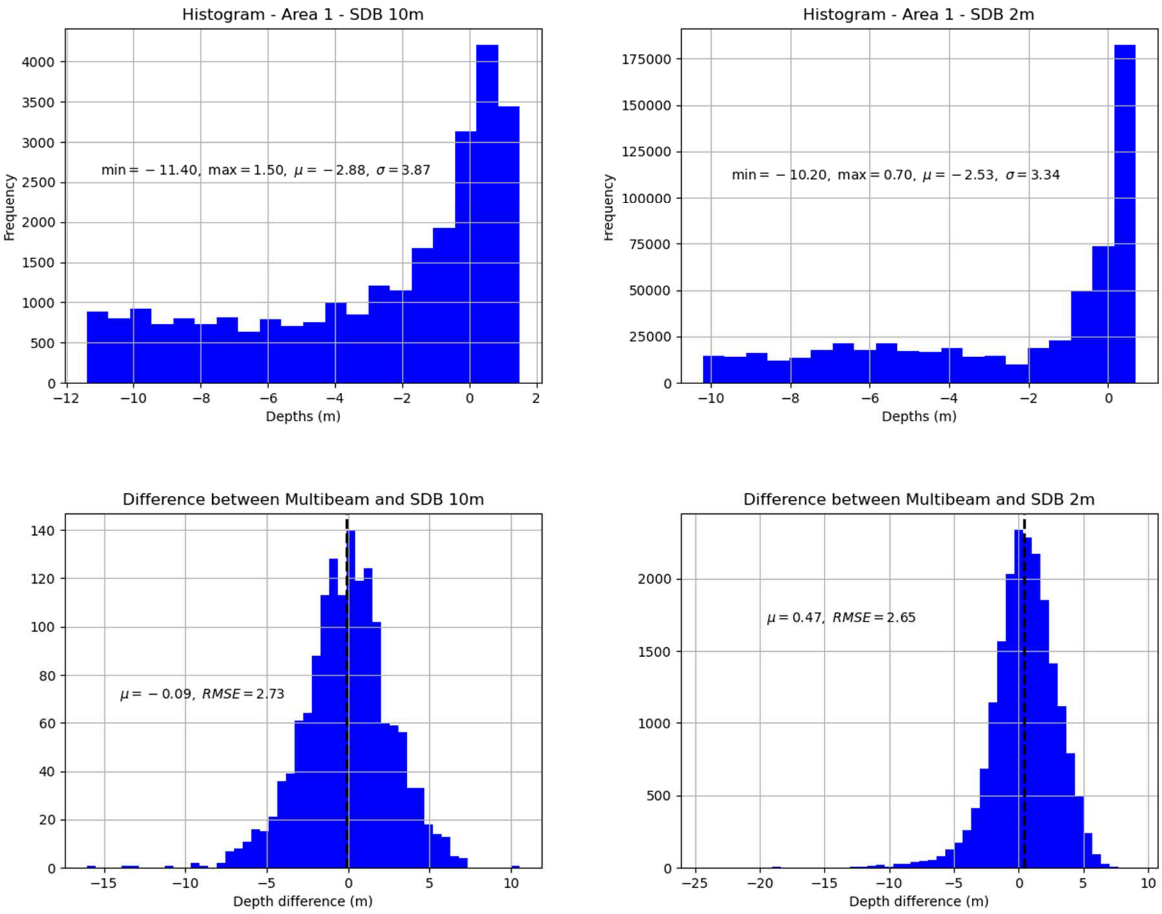

Figure 35: Færinge Nordhavn - Area 1.

***Top:** Histograms of depths. **Bottom:** Histogram of differences between SDB and multibeam.*

For Area 1 depths are measured down to approximately 11m with a majority of depths in the shallow end. There is a clear tail on both 10m and 2m histograms.

Looking at the histogram of differences, it is more or less centered on zero, which is expected (the black vertical line is the mean). The RMSE is almost similar for the two sensors, which is interesting. Some high differences are present indicating either artifacts or non-seabed measurements.

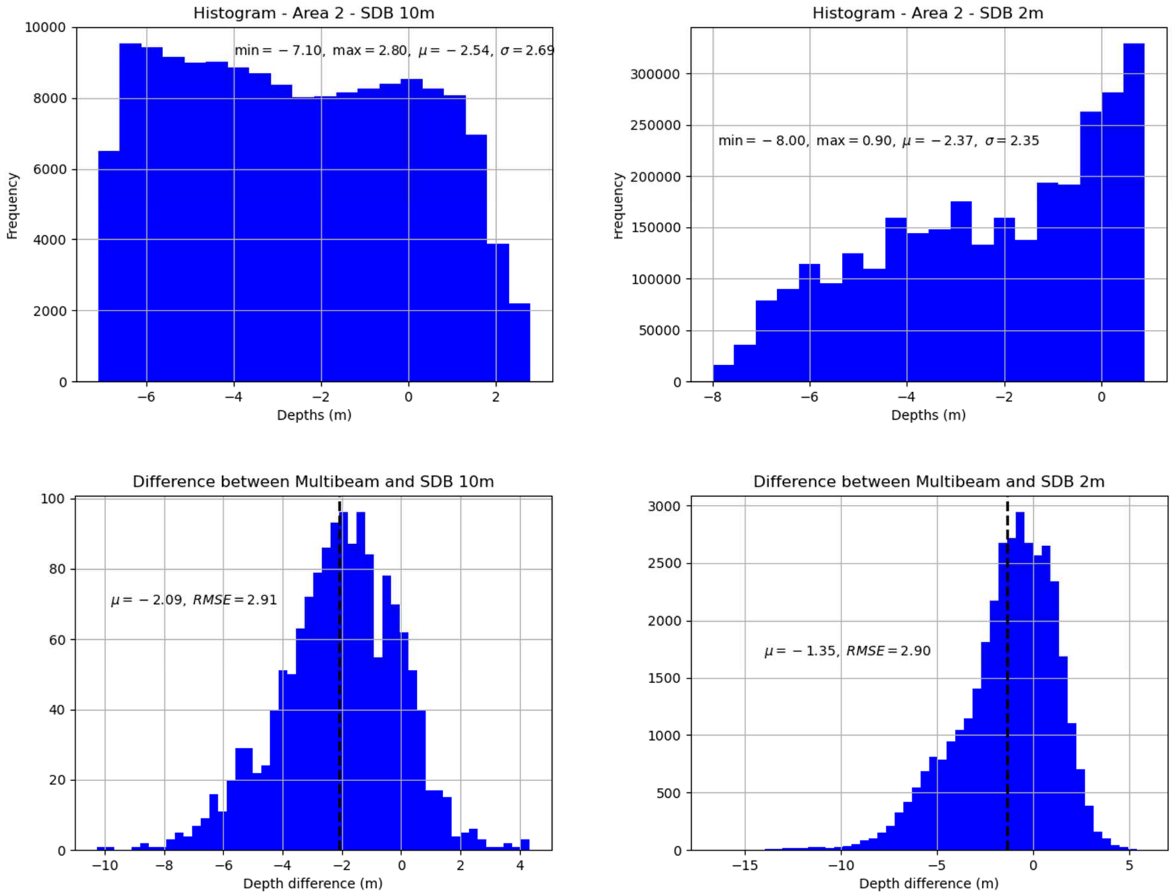

Figure 36: Sisimiut - Area 2.

***Top:** Histograms of depths. **Bottom:** Histogram of differences between SDB and multibeam.*

In Area 2 there seem to be a bigger difference between the two sensors. For the 10m dataset, the histogram is more uniform with many depths in the range 3-7m, while the 2m dataset peaks in the very shallow range. Looking at the data, this could indicate some of the measured depths in the 10m dataset are noise and not actual seabed measurements. Depths are measured down to approximately 7-8m.

Looking at the difference histograms, the RMSE is higher than for Area 1 and there is an offset in the data represented by the black vertical line suggesting that there is a systematic error in the datasets. This is particularly clear in the 10m dataset. Again, some high differences are present indicating artefacts or non-seabed measurements.