Proof of concept:

Satellite derived bathymetry (SDB) in Norway

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Introduction

Bathymetry is about the measurements of depth in seas and oceans. This can be done using various instruments such as sonar, USV or green laser, but also through optical satellite images. There are several approaches based on different models, algorithms or machine learning, but central for most approaches are the measurements of reflection in the water surface and through the water column. Especially in the coastal zone, this technique has proven effective through many documented results, where under very ideal conditions it has been shown to have a good effect down to a depth of 40 meters. This provides good opportunities to survey shallow areas of the seafloor along the coastal zone, which are currently covered by neither sonar nor LIDAR.

Project details

Description: This document is the result from a short sprint carried out in October and November 2023. The purpose for this sprint was a proof of concept regarding SDB in Norway, and the aim was to explore if there were a potential in SDB for further research.

Study area: The area of interest is the coast around Fjøløy and Klosterøy in Stavanger municipality. The area was chosen based on existing bathymetric survey which was conducted there.

Data sources: The bathymetry layer was created from a Sentinel-2 optical imagery. Sentinel-2 is a part of the Copernicus program from ESA and is currently a constellation of two satellites. The satellites collect multi-spectral data divided in 13 bands and have a spatial resolution of 10 to 60 meters. The bathymetry layer was compared with a LIDAR-dataset which acted as a ground truth. The ground truth was collected in 2021 using green laser technology.

Computing: The code was computed using the online platform Google Earth Engine (GEE), which enable an easy access to the freely available satellite data and a very limited computing time. Several studies have already been conducted on this topic and we choose to adapt the open-source GEE code of Li Jiwei et al. (2021).

Link to original Li Jiwi et al. code:
https://github.com/CoralMapping/GEE_Sentinel2_Bathymetry_Paper/tree/main

Link to our modified code:
https://github.com/mwaymel/GEE_Sentinel2_Bathymetry_Fjoloy

Method of procedure

The main steps of our code are:

- Collecting images: the time step on our study is the whole year 2021, to be in coherence with the lidar ground truth data
- Masking of bad quality pixels: removing pixels with cloud, cloud shadow, snow and saturation effect
- Land masking: removing non water pixels with a NDWI filter in addition of a classification test
- Computing the bathymetric map: applying formula detailed in the article of Li Jiwei et al. (2019) using green and blue bands (having both a 10m resolution)
- Converting the result from middle water to NN2000 based on a separation model (https://kartkatalog.geonorge.no/metadata/middelvann-over-nn2000/30a0fb0a-1d7d-4c62-9f28-8769a7ec9dcd)
- Smoothing: using a convolution with a normalised gaussian kernel (radius of 7 pixels and sigma value of 3)
- Exporting results: raster and vector maps up to 50 meters to the coast
- Quality testing (GEE and python): comparison with ground truth (map of error and histogram), statistic parameters computing (parameters of fitting gaussian, Mean Bias Error, Root Mean Square Error)

Results

The following images are the key results conceived under this sprint. Figure 1 – 3 displays a similar arrangement of depth between the predicted values and the field data. Even though there's not a perfect match between the two images, they clearly display a lot of the same tendencies for shallow and deeper areas. This is confirmed by our statistical measurements from the histogram in Figure 4, where we had a Root Mean Square Error (RMSE) of 2,826 meters and a Mean Bias Error (MBE) of -0,192 meters. Here the RMSE refers to the average distance between the ground truth and the predicted values. The MBE is an evaluation of the prediction model and displays the average difference between the prediction and ground truth without any consideration to direction. A negative result as here, indicates that the prediction in average is smaller/shallower than the actual value/depth. As a comparison, in the article of Li Jiwei et al. (2021), they found a RMSE value ranging from 1,2 to 1,9 meters, and an MBE ranging from -0,15 to 0,13. Figure 5 underpins the accuracy of the result by illustrating that as much as 70% of the predicted values where within +/- 2 meters of the field data, whereas 17% of the values were identical.

Figure 1: Bathymetry result constructed from satellite data. The label illustrates depth in meters.

Figure 2: Visualisation of the ground truth used to evaluate the result. The label illustrates depth in meters.

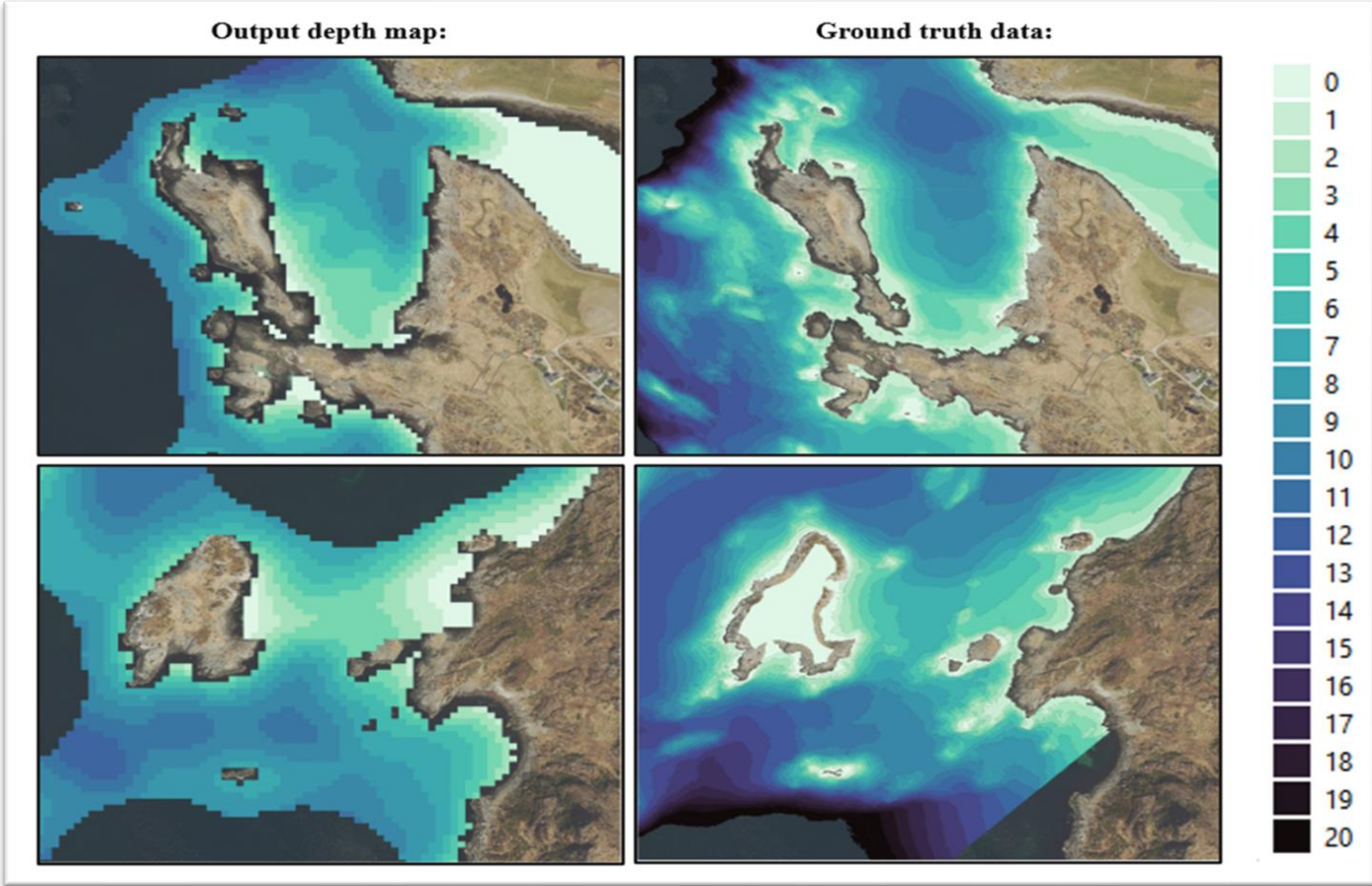


Figure 3: A detailed comparison the predicted map and ground truth of two selected areas. The label illustrates depth in meters.

Figure 4: Differences between the predicted values and ground truth (in meters)

Kartverket

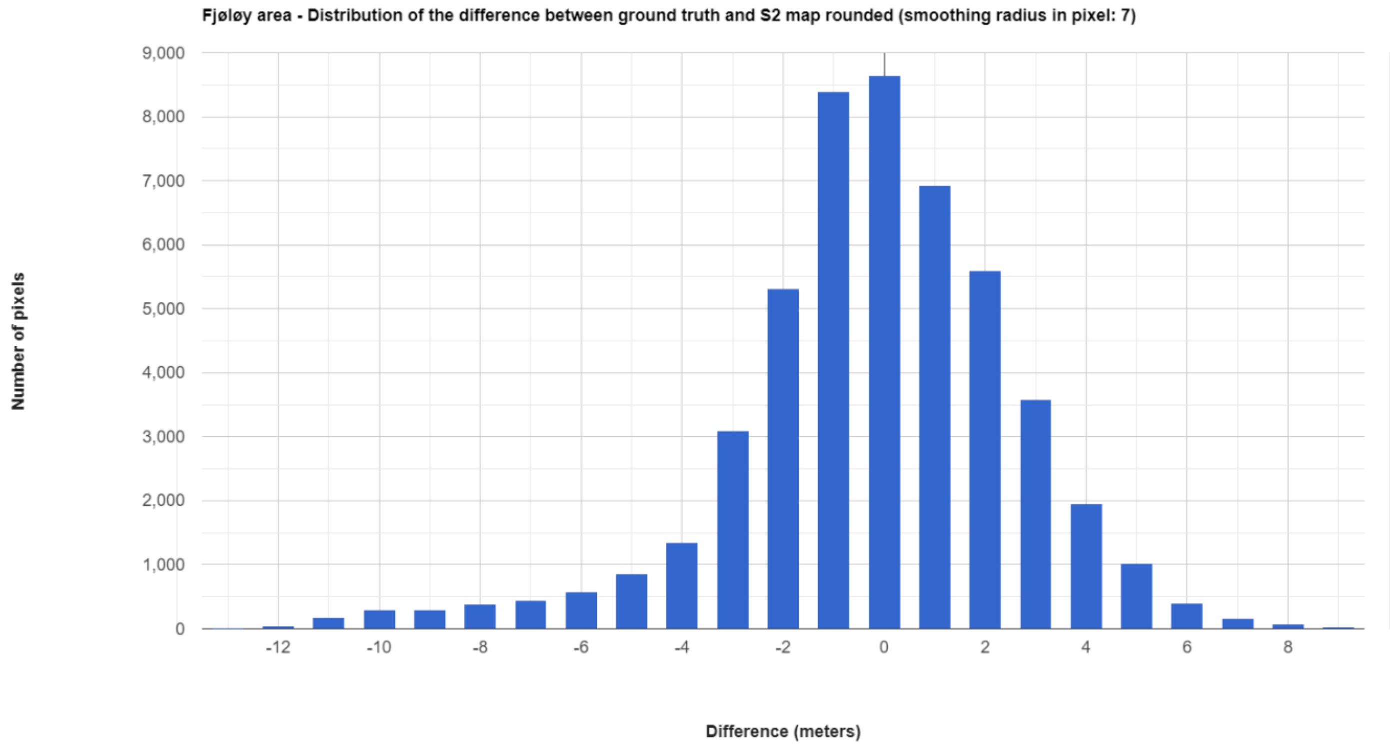


Figure 5: Histogram showing the distribution of pixels and their deviation from the ground truth.

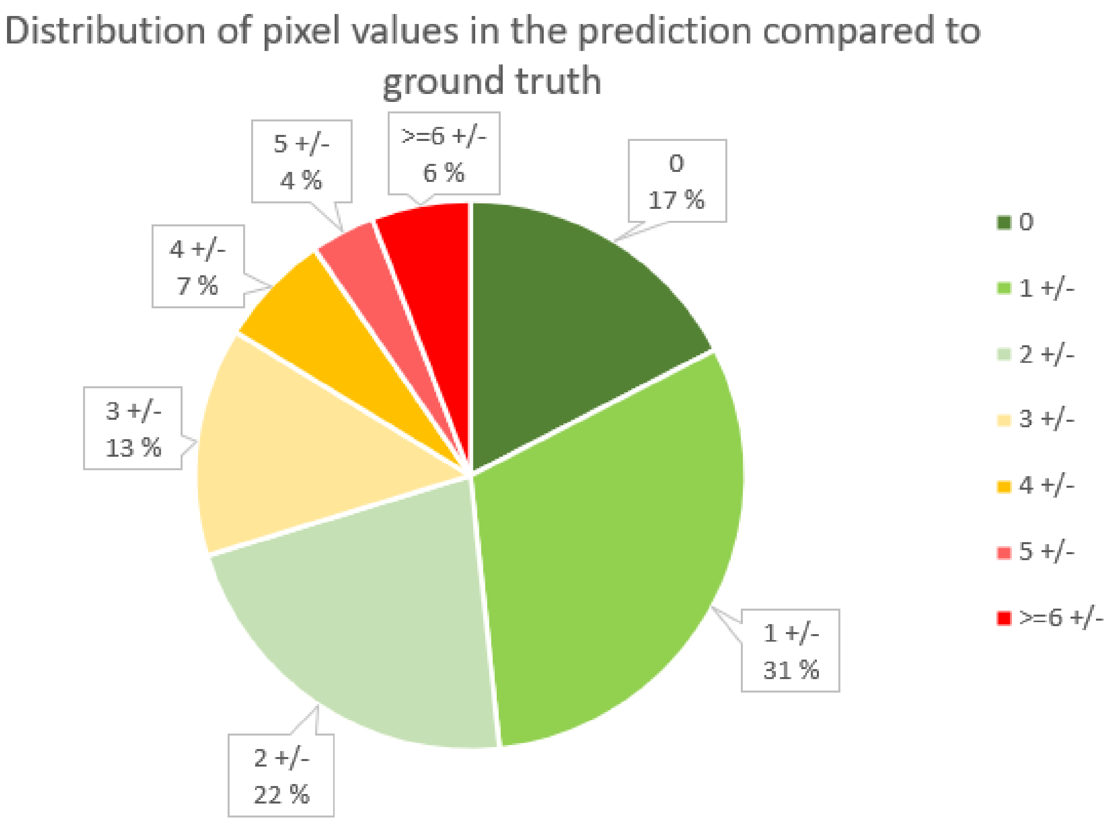


Figure 5: Diagram showing the percentage of pixel that deviate for the ground truth in either direction.

Experiences and recommendations

Adaptations of the original code

A lot of smaller adjustments were made to the original code to archive a satisfying result. We also added a comparison to the ground truth. Following is a description of the difficulties we met and the choices we made to improve the results.

Time period:

The longer period the better results, as detailed in the article of Li Jiwei et al. (2021). Since the field data on Fjøløy area are from 2021, we arbitrarily decided to consider the whole 2021 year.

Calibrating the Chl-a value:

The depth of water is obtained using Blue and Green channel by this formula (Li Jiwei et al., 2019): $Depth = m0 \frac{ln(1000*rrsblue)}{ln(1000*rrsgreen)} - m1$ where $m0$=52.073$*e$(0.957$*Chla$) and $m1$=50.156$*e$(0.957$*Chla$).

Chla is the Chlorophyll-a concentration obtained by the formula *Chla = 10^(-0.4909+191.659*w)* where *w = Rrs(Green) – 0.46*Rrs(Red) – 0.54*Rrs(Blue)*.

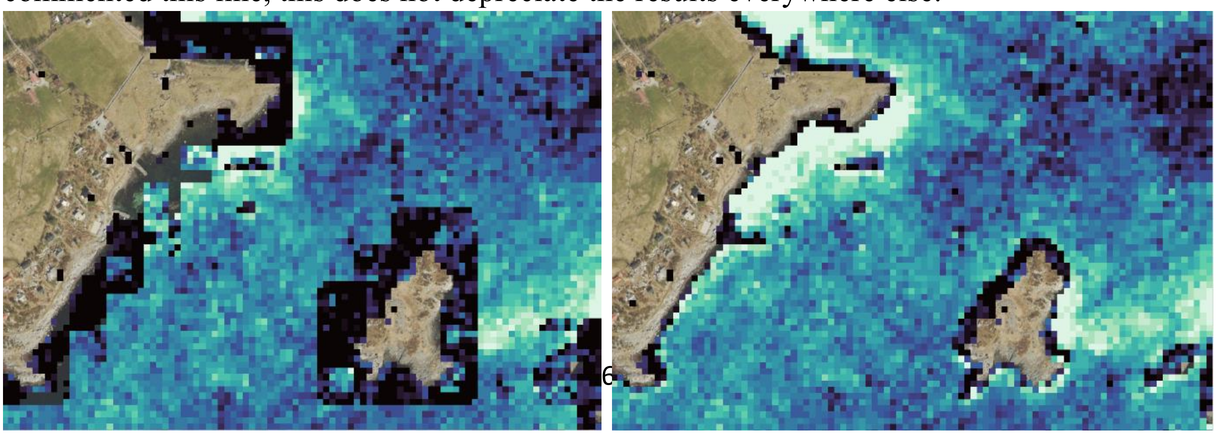
This chlorophyll-a value depends on the area of the world. The study by Li Jiwei et al. (2019) were conducted in warm waters in southern hemisphere. Therefore, we needed to adapt the *m0* and *m1* coefficients for Norway. Based on the formula, we obtained a Chl-a value of 0.3 in our area of Fjøløy.

Solving two strange border effects

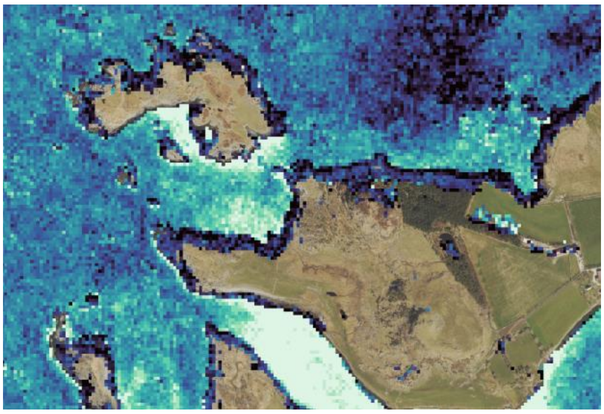
When we ran the code at first, we obtained some strange 6-pixels effect near to the shore. After some inquiry, it appeared that this effect was caused by the line 32 of original code (approximately line 37 in our) in the masking part:

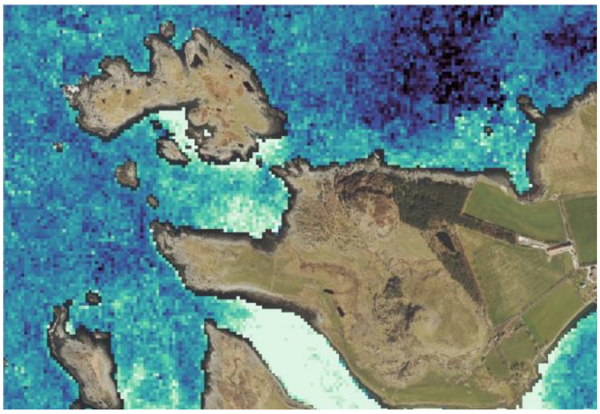
ma = ma.and(img.select(['B9']).lt(300));

B9 correspond to the band called *water vapor,* which is primarily used for atmospheric correction and has a resolution of 60m (6 pixels). We solved this problem simply by commented this line, this does not depreciate the results everywhere else.



Then, we realized that we had another strange coastal effect, where some inland pixels were not masked by the NDWI<0 test:



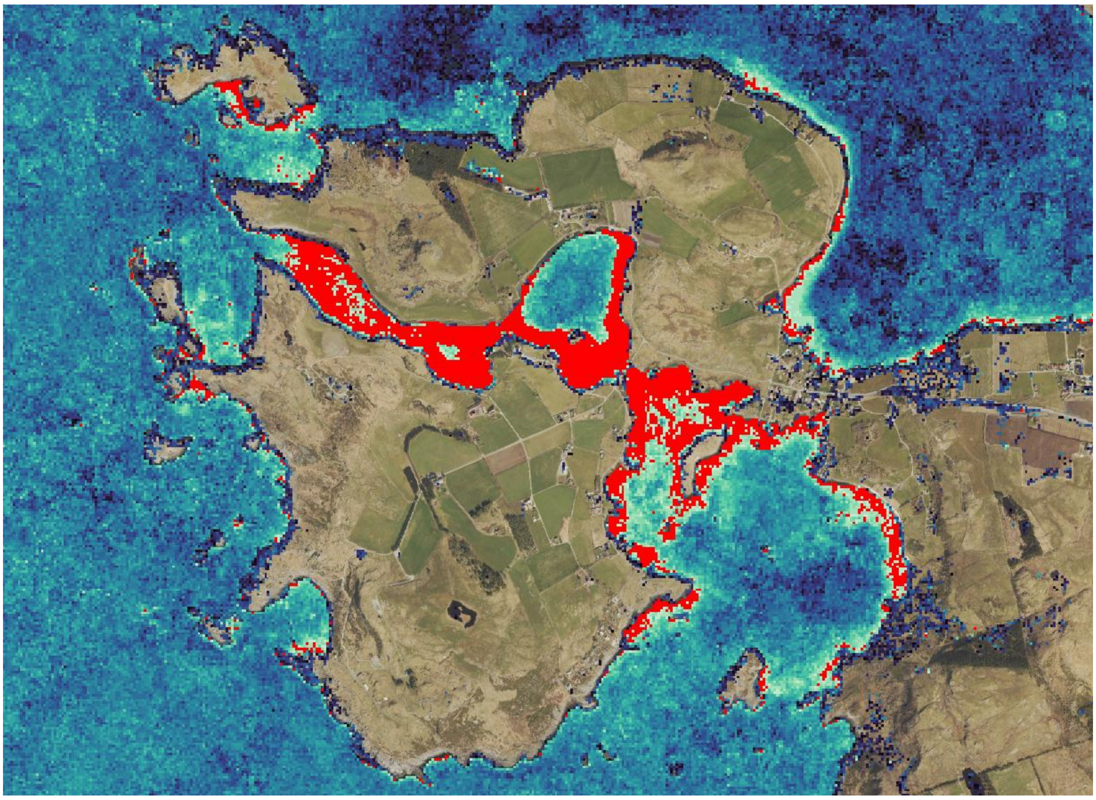


The NDWI map used for masking is made of, for each pixel, the median of the NDWI value in all images of the time series. We think that the problem might be caused by the fact that the times series is already masked (cleaned from clouds etc) when median NDWI map is built, and this might change the balance of extreme pixel values when taking the median, and then provoke a "false" median choice and create artefacts. We found a solution in building a second NDWI map from raw time series (unmasked) and applying it after the first masking.

Handling positive depth areas

The formula to compute depth is linear and causes some areas with a "positive depth", that is above water level, especially in the corridor between Fjøløy and Klosterøy.

In red, the positive values:

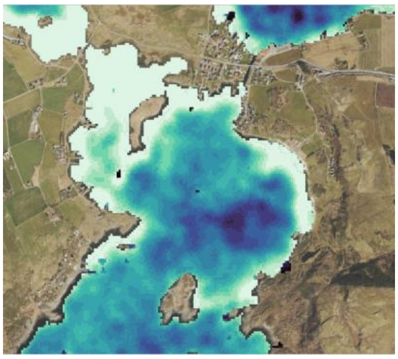


The code from Li Jiwei et al. put a threshold at 0m and set all values above to 0m. It also does the same with values above 20m depth set to 20m, but this only affects a few artefacts because the output does not contain areas (bigger than 1 or 2 pixels) deeper than 13m approximately. Setting values above 0m to 0m seems very reasonable from a physical point of view because the bottom of the sea can't be above sea level. But it is also a loss of information because the algorithm detects a difference between +1m and +4m. And even if these values are obviously false, the area with +1m is probably deeper than the area with +4m, so we lose some information by setting both to 0m. We didn't have time to focus deeper on this problem, but we think that if this code is to be used, this point should be inquired.

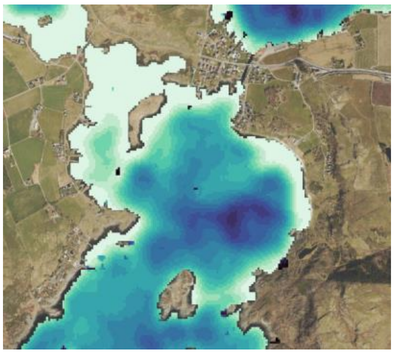
Adjusting the smoothing method

The depth image we got in output of Li Jiwei code needed to be smoothed to be compared to the field data. The reasons are raw data contains a lot of noise and aims to indicate a trend more than a precise measurement (as we know it is not exact), and the field data itself results of an interpolation and a smoothing. Therefore, we added a smoothing part to the code, using a convolution. We first tried with a uniform circle kernel. We made test with a kernel radius from 2 to 10 pixels. A radius of 7 appeared to be a good compromise.

Uniform kernel, radius 3 px:



5 px:



7 px:

After that, we tested a gaussian kernel instead of uniform. A gaussian kernel with radius of 7 pixels and sigma value of 3 gives slightly better results than the uniform 7px radius kernel (based on statistics parameters).

Building the area of interest with a 50m buffer and closing holes

The method based on satellite data we used only proposes depth up to approximately 15 meters. Then, it is relevant for shallow areas only. We can't guess which areas are shallow but in general, shallow waters are closer to the coastline. We decided to keep areas up to 50 meters from the coast. This gives better results than using 100 meters (based on statistical parameters of the comparison with field data). To build our area we first built a vector land mask by keeping negative NDWI values and deleting land pieces smaller than 100m2 because this corresponds to 1 pixel and corresponds in general to an artefact. Then, we applied 2 buffers to the land polygon to build our study area: a 200m buffer and a -150m buffer. This technique results in a 50m buffer but avoiding holes and notched border, filling bays and rivers up to 400m wide.

With a 50m buffer only:

With a 200m and a -150m buffer:

Putting the result into a vertical coordinate system

Since we compare our depth map to field data, we need to put the result into the same vertical coordinate system. This was done by assuming that the water level in the depth map mosaic is coherent for the whole extent, since the mosaic is generated from images throughout a year. Therefore, the result should represent the middle water level in this area. This can easily be translated into NN2000 using the separation model mention earlier, taking into account that our algorithm gives as output a depth (positive values) and not an altitude (negative values for sea bottom). This means we have to subtract the correction instead of adding it.

This is a very convenient solution for converting the result to NN2000 and can cause small errors since we must assume that the image displays a middle water level. In reality, we cannot be certain that this hypothesis is acceptable. Another small error can come from the fact that the middle water in the separation model is based on the mean value between 1996 – 2014. This is not necessarily the same as the mean value for a given year, such as in 2021.

Perspectives of improvements

- Using the same technique than Li Jiwei et al. (2021), a special attention should be given to the coefficients *m0* and *m1* (as detailed in *Handling positive depth areas* part). A proper calibration based on field data and using statistics indicators should be conducted.
- Overall, the algorithm used can definitely be improved by conducting proper calculation of optimal values for every parameter. Some corrections could also be added. For example, implementing *Snell's law* could improve refractions correction.
- It seems that another method of computing depth from satellite images has proven effective, using a spectral band with a wavelength between 0,4 - 0,45µm, often

referred to as “*coastal aerosol*” or “*deep blue*”. This spectral band is not available on Sentinel 2. Moreover, as it is a more recent technology, less articles deal with this technique. We haven’t inquired about it, but it should be tested (using another satellite, like Landsat 8 for example) to see if it can improve the accuracy of the results. Landsat 8 only has a resolution of 30 meters but as the result is smoothed, a resampling could still bring some very good results.

- It could also be interesting to test the use of a satellite with a higher resolution such as Worldview (0.5m) or Pléiades Néo (0.3m) (both not freely available). However, it is not at all sure that this could bring an improvement, as our results are not very accurate (limited by the spectral resolution anyway), and as we smooth the output.
- Combining different satellites could also be tried.
- If the project is scaled upwards, the method for converting the result to NN2000 might need some testing, to establish if the hypothesis of a coherent middle water level in the mosaic is acceptable or not.

Conclusion and further development

As a proof of concept, this report displays that there is a high potential in SDB in Norway. Based on the limited time used on this assignment, the result clearly shows good similarities with the field data, and there are several leads for improvements. Especially the method to transform to land reference level, and the calibration of *m0* and *m1* coefficients need careful consideration. Besides the capabilities to map the shallow parts of the sea bottom along the coast, depth computation based on satellite data can also be applied to rivers and lakes. We therefor advice that there should be done more research on this subject on a larger scale to determinate the capabilities in SDB.

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