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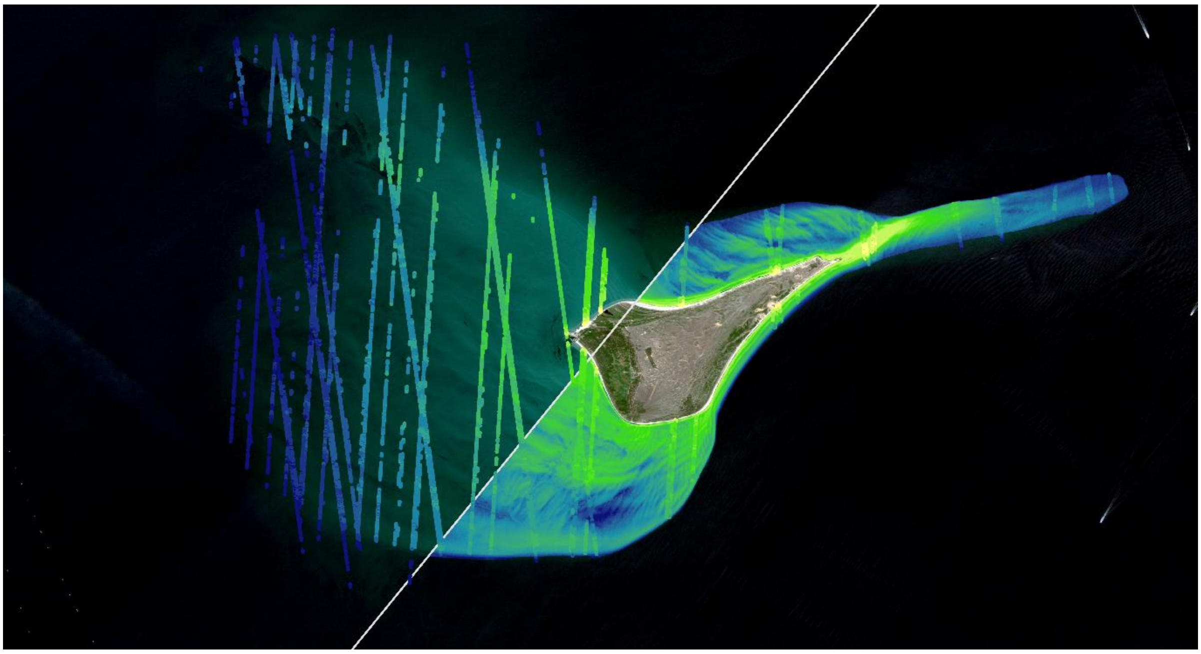

Novel estimation of shallow water bathymetry using ICESat-2 laser altimetry, signal processing and machine learning and Sentinel-2 optical data in a highly automated approach

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Executive Summary

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Executive Summary

Access to high-resolution and timely bathymetry of the highly dynamic shallow coastal zones is of great importance for a wide range of applications, covering societal, ecological, political, and economic purposes. The coastal zone is both a huge economic driver and living place for about 10% of the world's population. At the same time, exacerbation of natural hazards by climate change is increasingly putting vulnerable coasts under pressure. Also, key user needs recently published point to easier access to more detailed and up-to-date water depth grids at lower costs (Cesbron et al. 2021).

Currently, operational high-resolution Satellite Derived Bathymetry (SDB) is impaired by the limited availability and timeliness of ground truth data for calibration and validation purposes, the many manual interactions in the workflow, and the moderate speed of processing, which make production slow and expensive. In this project we addressed these issues by building a highly automated bathymetry production workflow with the goal to support data driven planning, monitoring, management, and protection for all stakeholders and communities concerned with applications in the coastal zones. The integrated approach implemented in this project is a big step towards detailed assessment of the dynamics in the coastal zone, which is a core element of the Copernicus Marine Environment Monitoring Service (CMEMS) future evolution, but also central to Blue Economy, marine spatial planning as well as maritime safety, especially in data-poor regions like the Arctic, and fully meets key user needs.

The project "Novel estimation of shallow water bathymetry using ICESat-2 laser altimetry, signal processing and machine learning and Sentinel-2 optical data in a highly automated approach" was funded under the European Space Agencies' Open Space Innovation Platform (OSIP). The overall objective was to build a self-calibrating and efficient bathymetry mapping system by leveraging accurate and consistent ICESat-2 laser altimeter data as a calibration source for high-resolution Copernicus Sentinel-2 based water depth retrievals. The combination of these two free and open satellite data sources with advanced machine learning and Bayesian optimisation enables a more accurate and efficient mapping of the world's shallow waters.

The activity was implemented in two phases, Phase A – Proof of Concept and Phase B – Demonstration of Feasibility and ran over 18 months.

During **Phase A**, we successfully prototyped a semi-automatic workflow consisting of signal processing routines for the extraction of bathymetry from ICESat-2 ATL03 laser photon clouds. This workflow substantially contributes to the goal of the project to create a novel self-calibrating data-fusion and machine learning approach where ICESat-2 data is used as reference for Sentinel-2 bathymetry retrievals. Overall, the comparison of the ICESat-2 bathymetry estimates with independent validation data showed that the processing chain successfully identifies the sea floor signal in the ICESat-2 ATL03 product for depths down to 25-30m. All results showed a very high correlation between measured depths and the ICESat-2 signals and confirmed that ICESat-2 is capable of capturing sea floor changes in dynamic areas.

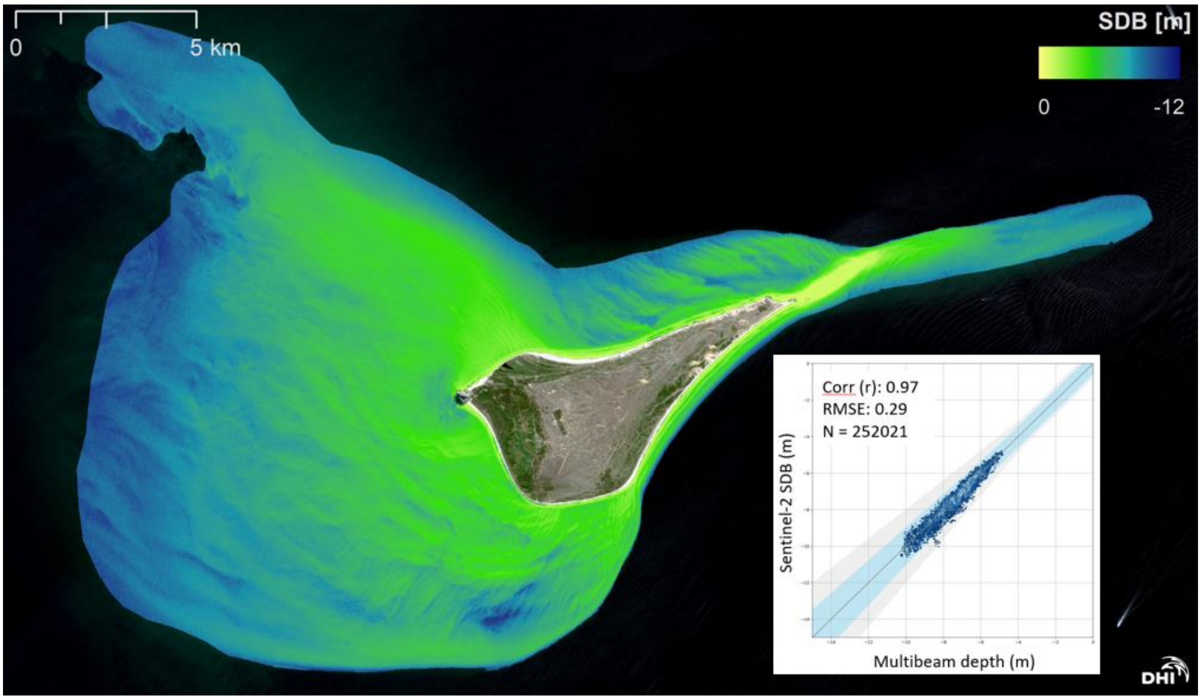
In terms of **increasing processing efficiency**, during Phase A we have initiated the optimization of our existing Sentinel-2 SDB radiative transfer models for GPU processing in an elastically scaling cloud environment. The optimisation of the workflow resulted in a reduction of processing time from roughly 12 hours to 15 minutes.

During **Phase B** of the project, we have successfully integrated the automated ICESat-2 processing chain into the SDB workflow, which now runs in the same environment as the bathymetry code and relies on a shared file structure. Moreover, the ICESat-2 data processing speed was increased by making the code more efficient, while the processing of 12 million points previously took one week, now it can be done in half a day. We adjusted the refractive index of seawater in the processing to match the wavelength of the ICESat-2 laser. The efficiency of the atmospheric correction was further improved which has increased the speed of processing with a minimal loss of accuracy.

Finally, the entire workflow was tested and quantitatively assessed at five different test sites: Brisbane-Australia, Anholt-Denmark, Aasiaat-Greenland, US Virgin Islands, and Barcelona-Spain. From the tests performed we can conclude that semi-automatic scheme consistently found better solutions, in line with or better than those found by an operator, thus significantly reducing the need for manual input in the processing chain.

The high correlation (r>0.99) and relatively small RMSE (<0.6m) found when validating ICESat-2 bathymetry against survey data at various locations supports the use of this data source as calibration data for SDB in areas of limited, missing, or outdated survey data for calibration. The spatial coverage and high revisit frequency of ICESat-2 further had several advantages in some of the investigated areas, being able to capture very recent and rapid changes and covering the full observed depth range, resulting in more robust calibration of SDB data.

The Sentinel-2 derived SDB showed high correlations compared to independent survey data (r = 0.96-0.98) and with a RMSE in the range of 0.3-1.5m. These results are in line or slightly better compared to other studies (e.g., Ma et al. 2020; Gleason et al. 2021; Ranndal et al. 2021; Thomas et al. 2021).



Satellite Derived Bathymetry (SDB) from Sentinel-2 acquired on 28 June 2021 around the island of Anholt, Denmark. The island is surrounded by large sandbank which is accurately mapped by combining ICESat-2 (calibration) and Sentinel-2 data. Comparison between independent multibeam depths and SDB is shown in the scatterplot. The shaded areas represent our standard uncertainty levels, with the blue and grey shading representing ±10% and ±20% SDB, respectively.

The achievements of this project make it now possible to derive an accurate bathymetry for a Sentinel-2 tile in a few hours compared to 1-2 days for the previous approach, which was heavy in operator interventions. In particular, the automatic integration of ICESat-2-depths as a calibration and validation source is a game changer for SDB production as accurate and timely data is now available in bulk almost automatically without the requirement of *in situ* data. With such an abundant source of calibration data, the accuracy of the SDB can be improved as many different water conditions and bottom types are represented and the SDB production can be quantitatively assessed. Moreover, in highly dynamic areas, representative and timely calibration data is key for better accuracies in SDB mapping. All in all, this reduced the production costs, the dependency on highly trained operators and consequently allows us to deliver faster to our users at reduced costs.

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