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Comparison of complementary methods of melt pond depth retrieval on different spatial scales

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Abstract

Pond bathymetry and average pond depth are important to describe the distribution of meltwater volume from snow and sea ice. Melt pond models that take depth into account are typically based on manual in situ measurements, whereas the possibilities for measuring depth have recently increased substantially.

Our contribution gives an overview of melt pond depth retrieval methods applied during the MOSAiC expedition, their resolutions, accuracies and limitations. We use data from the MOSAiC campaign to showcase different methods and give an outlook towards a satellite based pond depth retrieval.

Melt pond depth retrieval methods

In-situ measurements

During the MOSAiC campaign several methods for in-situ depth sampling have been applied.

The classical ruler based measurement delivers high accuracies, especially for smaller depths, but there is a trade-off between sampling density and spatial coverage. The resulting measurement density is mostly in the range of 1-3 points per meter. As a partly automatized evolution to this, a *Magnaprobe* snow depth probe was modified with a buoyant snow basket which also allows for efficient water depth sampling [1]. Both approaches are problematic for melt pond depths beyond 1m.

Developed specifically for connecting different approaches of bathymetry retrieval, the *Böötle* is a remotely controlled swimming platform equipped with a point echo sounder and three spectroradiometers. Two of its main advantages are the ability to measure spectra without an operator close to the sensor, as well as its accurate depth measurements in ponds, including those up to several meters deep. On the contrary, its size and draft limits measurements to water depths > 15cm.

Airborne measurements

Measurements from drone and helicopter platforms allow for a greater spatial coverage combined with a larger spatial resolution. Routinely, hyperspectral data and RGB photos are acquired from which the pond bathymetry can be estimated by spectral attenuation in the pond water column [3] or photogrammetry [2]. Both methods have a resolution in the 1-3 centimeter range. The nature of these remote sensing approaches makes it hard to achieve similar accuracies to direct in-situ sampling.

Spaceborne measurements

Up to now, there is no readily available satellite-derived melt pond depth product. Given the spatial resolutions of the satellites in ESA's Copernicus Programme, as well as the Copernicus Contributing Missions, a spatial resolution in the 1-10m range is assumed.

For a multispectral approach, accuracies are estimated to be lower than their airborne counterparts, because of the currently coarser spectral resolution. Of major influence for melt pond depth accuracy is also the applied atmospheric correction [6].

A different space-based approach is IceSat-2's time-of-flight measurement [4]. It is independent of spectral atmospheric corrections, but provides coarse spatial resolution and the line-based measurement pattern does not allow for observation of a melt pond's time-wise evolution.

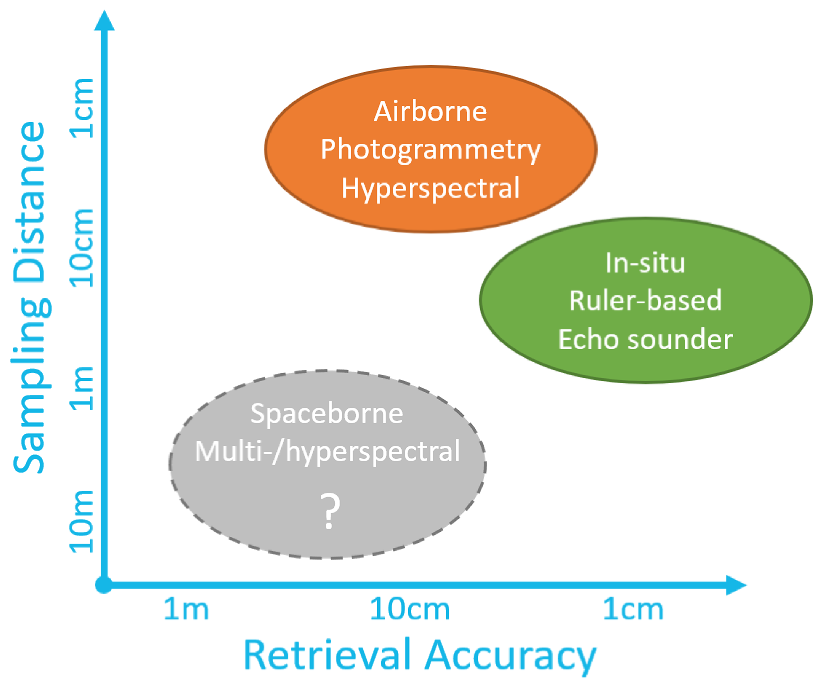

Figure 1 (top). The *Böötle* measurement platform during the MOSAiC campaign (photo: Hannes Spitz)
Figure 2 (right). Approximate classification of melt pond depth retrieval methods

Comparison based on MOSAiC data

In-situ hyperspectral data

We used the König (2020) [3] hyperspectral melt pond depth model on data of *Mystery Lake* retrieved by *Böötle* (Figure 3). The hyperspectral model exhibited a high correlation with the echo sounder data within its designed range of up to 1m depth. The model was developed for a slightly different viewing geometry as well as complete clear sky, which together might account for the 20% under estimation. The drop in performance beyond 1.15m may be attributed to absorption in the 710nm wavelength region utilized by the model. Using parts of the methodology of [3], we were able choose 593nm as a wavelength of good performance for the larger depths in our test case (Figure 3).

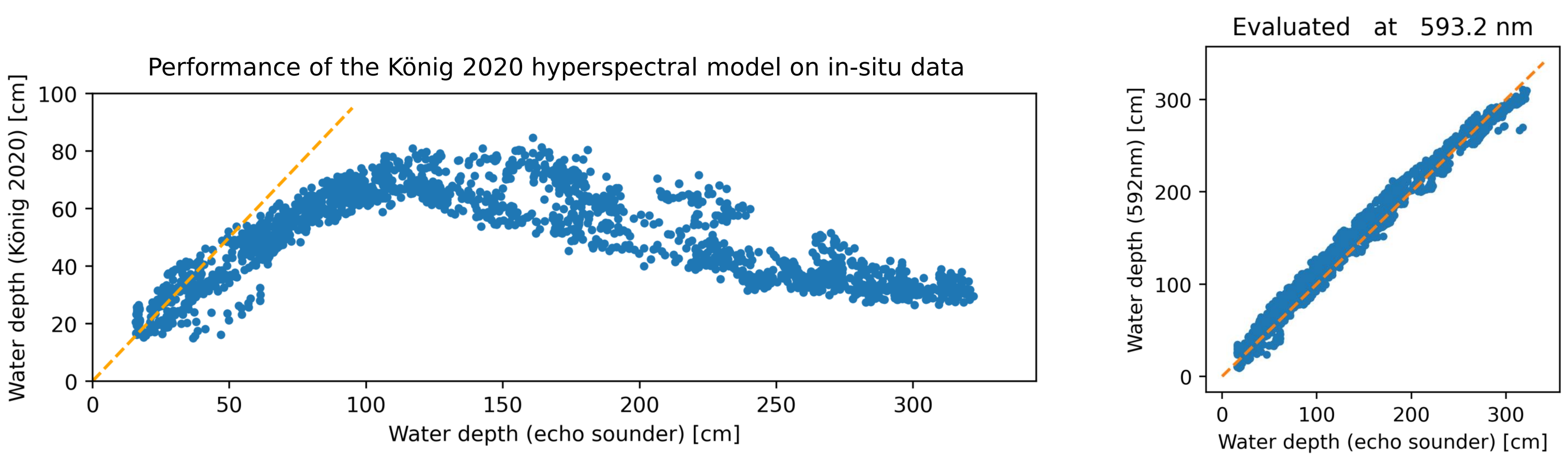

Figure 3. Left panel: König et al. (2020) hyperspectral model vs. echo sounder depth, both measured in-situ by *Böötle* on 9th July 2020. Right panel: model re-fitted and evaluated at 593nm instead of the original 710nm, but without the generalization for different solar zenith angles.

Airborne data

We used a different area with mostly shallow melt ponds (<0.5m) to compare results from airborne hyperspectral data (model see above) and photogrammetry [2]. To limit the results to photogrammetrically reconstructable ponds, we restricted our test to ponds of at least 1m diameter. The results show some correlation (Pearson's $r \approx 0.51$, Figure 4), but also in this instance, conditions were not clear sky as needed for the hyperspectral model.

Another comparison on *Mystery Lake* between helicopter-based photogrammetry and *Böötle's* echo sounder yields a higher correlation value (Pearson's $r \approx 0.92$, Figure 5) but in deeper parts of the melt pond, the photogrammetric approach yielded lower depth values of up to 20% difference. It has to be noted, that these two datasets differ in recording time by two days (July 7th and 9th), the earlier one showing shallower depths. Given the fact that *Mystery Lake* had a large catchment area and drained to the ocean two days later, these differences in depth should be further investigated as being possible signals.

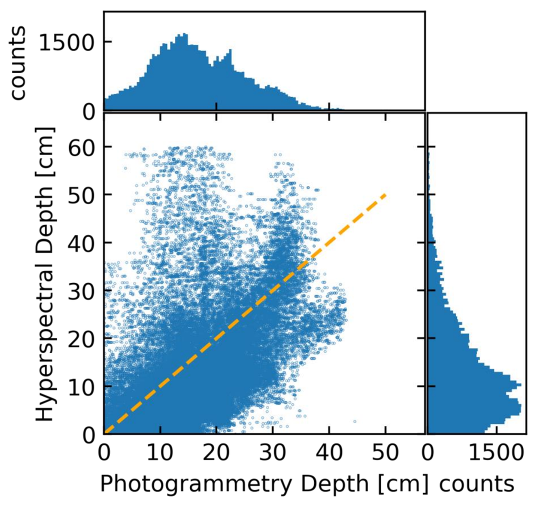

Figure 4. Comparison of two airborne pond depth retrievals

Spaceborne data

Data from satellites has not yet been evaluated, but over the course of the MOSAiC campaign several datasets of the areas around the ice floe's positions have been acquired, in at least two cases also coinciding with the times other in-situ measurements have been performed.

Despite the regularly high cloud coverage in the Arctic, the high revisit frequency of Sentinel-2 in high latitudes allowed for a spaceborne optical observation of *Mystery Lake*.

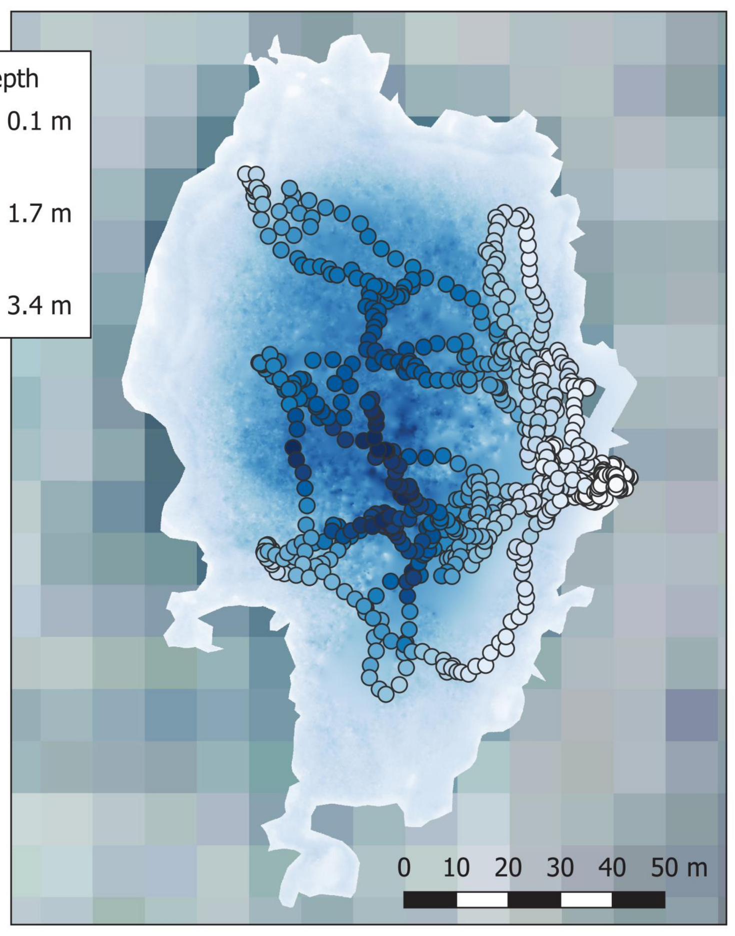

Figure 5. Plot of *Böötle* echo sounder data (9th July 2020) on a bathymetry chart of *Mystery Lake* retrieved by photogrammetry (7th July). Localization of Böötle data in this image is done via GPS, drift correction based on data from the FloeNavi system [5].
Background: Sentinel-2B scene from 7th July 2020.

Outlook

Hyper- and multispectral upscaling

The MOSAiC expedition created a wealth of in-situ and airborne hyperspectral datasets, many of which are associated with corresponding manual or echo sounder depth measurements. This will be a key component for scaling up melt pond depth retrievals to satellite products.

The quality and quantity of satelite data is also expected to rise in near future, with the upcoming EnMap satellite delivering hyperspectral data.

Positional accuracy

A key problem for referencing in-situ depth measurements with remotely sensed data is accurately locating the measurements. Due to the high resolution of airborne data, GPS alone is not sufficient to co-locate the in-situ data points. This gets compounded by the fact that on Arctic ice a drift correction is necessary.

Böötle carries a camera based system which allows for determining its position in a frame of reference local to the ice floe. These datasets have yet to be analysed.

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