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Transfer learning for Antarctic bed topography super-resolution

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High-fidelity maps of Antarctica's subglacial bed topography constitute a critical input into a range of cryospheric models. For instance, ice flow models, which inform high-stakes sea level rise projections, rely on truthful and sufficiently detailed Digital Elevation Models (DEMs) of the ice-bedrock interface. Adversely, data collection of bed elevation profiles is extremely challenging, requiring airborne geophysical surveys of the vast landscape. Subsequent processing, as well as interpolation of the limited measurements onto a regular grid, introduce additional layers of uncertainty.

While the prevalent continent-wide gridded data products for Antarctica's bed topography, like BedMachine or upcoming Bedmap3, which arise from laborious ongoing international collaborations, are limited to a spatial resolution of 500 meters, machine learning methods present new opportunities to go beyond existing resolutions. Super-resolution, a class of computer vision techniques, aims to increase the resolution of a given low-resolution image and thereby generate a high-resolution version of that image. With a grid of elevation values interpreted as a special case of a grid of pixel values (i.e. an image), super-resolution approaches can hence be applied to topography grids.

While existing bed topography super-resolution approaches for Antarctica have been challenged by the lack of available gridded data at dense target resolutions, which are needed to train deep learning architectures, we propose a probabilistic approach based on Gaussian Processes (GPs), that generates more robust and uncertainty-aware high-resolution topographies without the need for gridded target resolution training data. In addition, our proposed method leverages abundant high-resolution ice surface data from satellites by transferring covariance patterns from the ice surface to the bed via a purpose-designed covariance function.

We evaluate our multimodal Bayesian fusion model in a controlled topography reconstruction experiment over mountainous regions of East Antarctica, where we assess various models' skills to reconstruct original 500 m BedMachine topography, given the respective artificially degraded 1000 m, 1500 m, 2000 m, 2500 m, and 3000 m low-resolution input grids. As metrics we use root mean square error (RMSE), peak signal-to-noise ratio (PSNR), and the structural similarity index measure (SSIM) between reconstructions and withheld ground truth topographies. We compare our model against bilinear and bicubic interpolation baselines, DeepBedMap DEM and its multi-branch extension, MB_DeepBedMap DEM, as well as the Hybrid Attention Transformer (HAT), a pretrained state-of-the-art single image super-resolution model, for which we explore various fine-tuning strategies. Our results highlight the utility of our proposed uncertainty-aware and interpretable fusion model for the data-constrained endeavour of mapping Antarctica's subglacial bed topography at high resolutions.