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Satellite Image Analysis (GEOG 581)
FINAL PROJECT PROPOSAL

1. STUDY TOPIC / PROBLEM

Mass loss from ice shelves has a profound effect on global climate, sea level rise, and ocean circulation patterns. Ice shelves lose mass primarily through two mechanisms—ocean-driven melting and iceberg calving—the primary driver of which is basal melting, or the notching of ice shelves by warm, high-salinity ocean water. This process creates a high-pressure environment dominated by various turbulent hydrodynamic processes, which in turn result in higher melt rates. Progress toward understanding these processes and their effect on ice-shelf melt rates is impeded by the difficulty of obtaining observational data in these environments, which motivates the development of new observational approaches.

A process of particular note induced by basal melting is the formation of subglacial discharge plumes that move upward along the ice face from the base to the ice-calving front, energizing and transporting sediments and accelerating melt. Hydrodynamic processes driving melt dictate glacier morphology, and glacier morphology, in turn, influences hydrodynamics, giving rise to feedback loops that generate strong patterns in ice morphology. Researchers have observed patterns of vertical linear grooves on freshly calved icebergs that offer insight into these coupled hydro- and morphodynamic processes. The ephemerality of calving events makes observing them difficult, and further information—such as the spatial distribution of such calving events relative to the glacier terminus and globally, their frequency, and the ratio of grooved icebergs to those without—is needed to ascertain which submesoscale environmental conditions and microscale processes support their formation.

2. GEOGRAPHIC REGION / EXTENT

A known site where groove morphology has been observed *in situ* is Xeitl S´ít’, also referred to as LeConte Glacier, the southernmost active tidewater glacier, located in Alaska (56.8382° N, 132.3515° W). The LeConte Bay tidal inlet will serve as the primary site from which imagery will be used for training *(Fig. 1, left)*. Additionally, icebergs exhibiting groove morphologies have been tentatively observed through satellite imagery in tidewater glacier inlets spanning the southeastern margin of the Greenland Ice Sheet *(Fig. 1, right)*. These inlets may serve as possible locations for testing.

3. TIME PERIOD

In situ and proximal observations—including direct measurements, photogrammetric Structure-from-Motion models derived from unmanned aerial vehicle–captured optical imagery, and point clouds generated from multibeam echosounder data—were made of icebergs exhibiting these groove morphologies in July 2024. Imagery used for training will be constrained to a three-month span centered on that month and widened if necessary.

Fig. 1. Google Earth imagery of the study areas. Left: Xeitl S'ít', also known as LeConte Glacier, and the adjoining LeConte Bay, located in Alaska (56.8382° N, 132.3515° W). Right: Tidal inlets at the southeasternmost tip of the Greenland Ice Sheet.

4. PROJECT GOALS

Our contribution to this line of inquiry is to develop a system for the automatic detection and statistical analysis of icebergs that exhibit groove morphology using optical satellite imagery. The first step toward this overarching goal, and the specific goal of this project, is to develop a binary classifier that, when applied to a given image collection, automatically filters for images containing icebergs that exhibit groove morphology, along with associated statistical metadata. For the first iteration of this algorithm, we aim to identify and isolate icebergs that satisfy a minimum area threshold of 400 square meters, analyze each for groove morphology, and retain only images in which groove morphology is present.

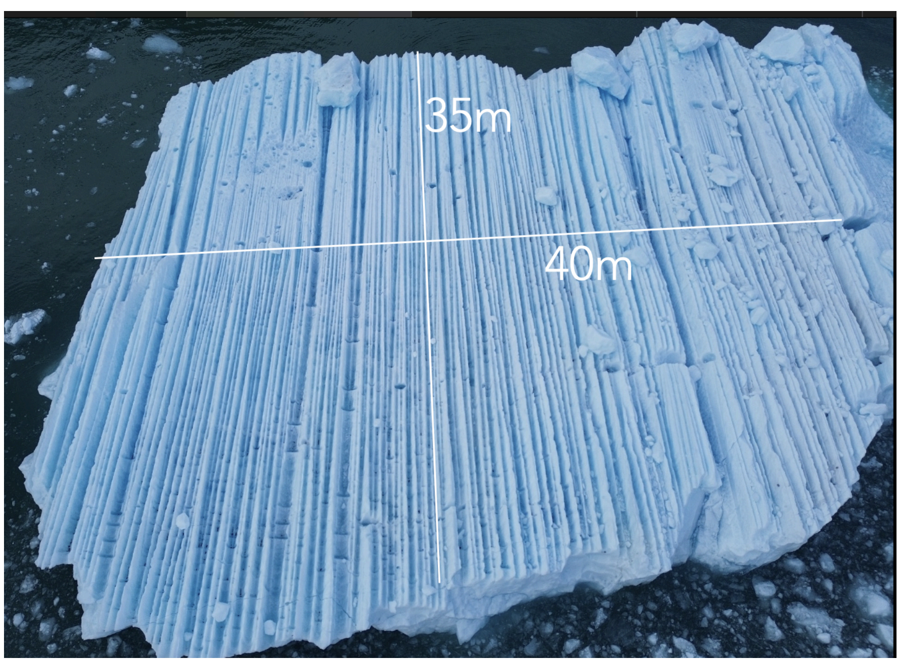

Fig. 2. Imagery of an iceberg exhibiting groove morphology, measured using Structure-from-Motion photogrammetric modeling and captured from an unmanned aerial vehicle (UAV).

5. REMOTE SENSING-DERIVED METRICS OR VARIABLES OF INTEREST

The two main problems we seek to address using bespoke methods are iceberg identification and the recognition of groove morphology. Both problems are contingent on the interaction between electromagnetic radiation and glacial ice, and iceberg identification relies on spectral discrimination between glacier ice and the surrounding water. Glacier ice is highly reflective across the visible and near-infrared portions of the electromagnetic spectrum, whereas water is absorptive and transmissive. This contrast simplifies the problem of discriminating between ice and water surfaces for iceberg identification.

We also anticipate challenges in differentiating between icebergs and clouds, which can share similar spectral characteristics in the visible and thermal wavelengths. We expect to obtain a robust image collection after filtering for cloud coverage, but if the number of images proves limited—and for future iterations that perform statistical analyses requiring stricter temporal constraints—cloud masking will be necessary. The high reflectivity of glacier ice often leads to pixel oversaturation over ice surfaces in optical satellite imagery. Glacier ice is less reflective in the red and near-infrared bands than in the blue and green bands, so these bands may be preferred for visualizing reflectance variation between groove peaks and occluded groove troughs. Imagery from the panchromatic band, for platforms that support it, can also be used to emphasize shadows.

6. APPROXIMATE SPATIAL AND TEMPORAL RESOLUTION NEEDED

The grooves themselves vary in size—they are highly linear in the along-face “vertical” mean flow direction of the subglacial discharge plume and have been observed to be uniform and parallel along the entire face of icebergs tens of meters in length, perpendicular to, and sometimes interrupted by, the layering of the glacial ice *(Fig. 2)*. The across-face “horizontal” direction is dominated by repetitive U- and V-shaped troughs of smaller grooves, thought to be recently developed, that span 0.3 to 0.4 meters in width on average. These smaller features are nested within larger, well-developed grooves that are between 5 and 20 meters wide on average, which will be the focus of this study.

Although temporal resolution is less of a concern, as our primary inquiry at this juncture focuses on spatial phenomena, there are still relevant temporal factors for effectively imaging groove morphology. We therefore note the following observations for consideration:

- Icebergs with groove morphology were directly observed to calve twice daily throughout July 2024.

- When gathering imagery for Structure-from-Motion modeling, the most effective imagery was captured approximately 16 hours after calving, allowing for surface whitening due to solar melting along crystal boundaries.

- Melting slows when ice surfaces are exposed to air; calved icebergs retain their morphology for approximately one to two days after exposure to sunlight.

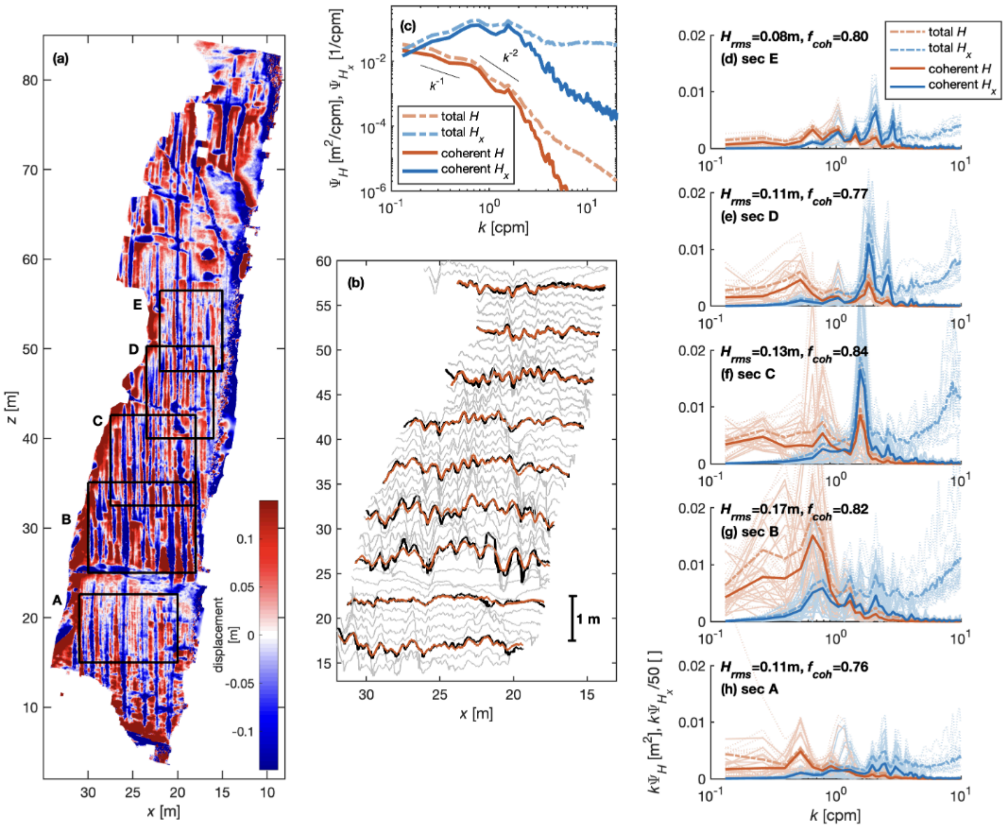

Fig. 3. Statistics derived from a Structure-from-Motion 3D reconstruction of an iceberg exhibiting groove morphology, imaged in the LeConte Bay tidal inlet in July 2024.

7. PLATFORM SENSOR OF CHOICE

Constraints imposed by the size of the large, well-developed grooves necessitate the use of Very High Resolution (VHR) optical sensors, such as those on PlanetScope and WorldView satellites, to distinguish groove morphology. Partner institutions within the broader GIANT (Greenland Ice sheet to AtlaNtic Tipping points from ice loss) project, of which this groove morphology study is a part, have existing access to VHR imagery for our region and timespan of interest, and we have reached out to have this access extended to us. Hypothetically, VHR satellites such as PlanetScope and WorldView should also offer revisit periods more than sufficient to acquire multiple images of groove morphology for training and testing within the given timespan.

8. OUTLINE OF PREPROCESSING STEPS

The workflow of our algorithm can be broken into three steps—filtering, masking, and processing *(Fig. 4)*. We propose the following architecture for training and image classification: images from the dataset will be filtered spatially and temporally, and for cloud coverage, based on dataset metadata. Each image will then be subjected to a series of masking processes, resulting in a collection of image subsets that contain only discrete iceberg surfaces, including the masking of land, clouds, and aquatic surfaces. These masking operations are expected to present the most challenging design problem and will likely evolve through experimentation and optimization if the initially conceived methods prove insufficient.

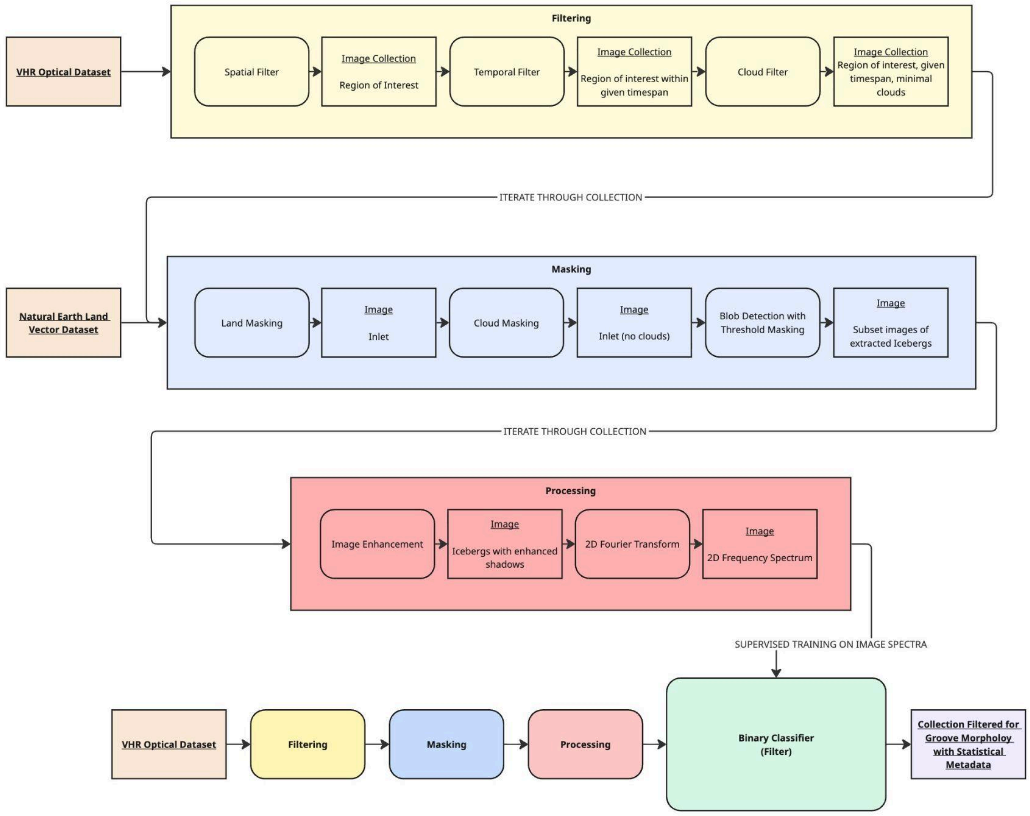

Fig. 4. Proposed system architecture for training and classification.

Lastly, each subset image containing only the extent of an individual iceberg will be subjected to image enhancement to emphasize variance between groove peaks and troughs, before a two-dimensional image spectrum is extracted using a Fourier transform. The resulting 2D image spectrum for each iceberg will be used to train the binary classifier through a supervised learning approach. Once the classifier is trained, input image collections will be subjected to the same preprocessing pipeline, enabling them to be filtered to retain only those images that contain groove morphology, along with limited statistical metadata that will be expanded upon in future work.

9. ACCURACY / VALIDATION

To validate the classifier, we will apply it to image collections filtered across multiple areas of interest and a range of temporal windows, using the LeConte Bay region as a benchmark. Model performance will be evaluated through manual review, from which we will construct a confusion matrix enumerating true positives, false positives, true negatives, and false negatives. Overall accuracy will be computed as the proportion of correct classifications relative to the total number of predictions. In addition to these quantitative metrics, we will qualitatively assess the conditions under which the model performs well or poorly, using these observations to inform conclusions about the factors driving model performance.

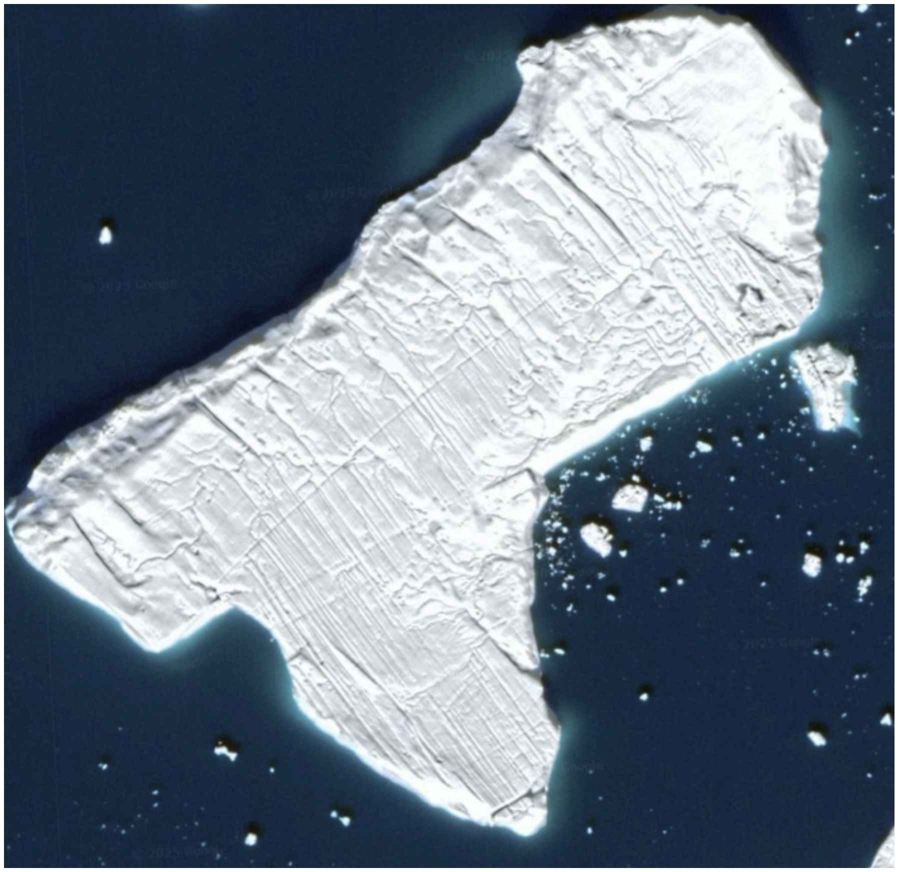

Fig. 5. An example of an iceberg in LeConte Bay, tentatively identified as exhibiting the groove morphology, from Google Earth Engine.

10. EXPECTED OUTPUTS

We expect the final output to consist of image collections filtered to retain only those images containing icebergs that exhibit groove morphology, accompanied by statistical metadata describing metrics of interest. These metrics will include the total number of icebergs identified and analyzed, as well as the range, mean, median, and mode of iceberg sizes. For the final presentation, we plan to display a map highlighting detected icebergs, with distinct symbology indicating the presence or absence of groove morphology. We will also present plots of the two-dimensional Fourier transform spectra to emphasize patterns associated with groove morphology, along with graphs of relevant statistics to support a qualitative analysis of the model’s success and failure modes.