# Internal Reflector Slope Fields as a Proxy for Ice Sheet Velocity Structure

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## Internal Structures as a Record of Ice Flow Conditions

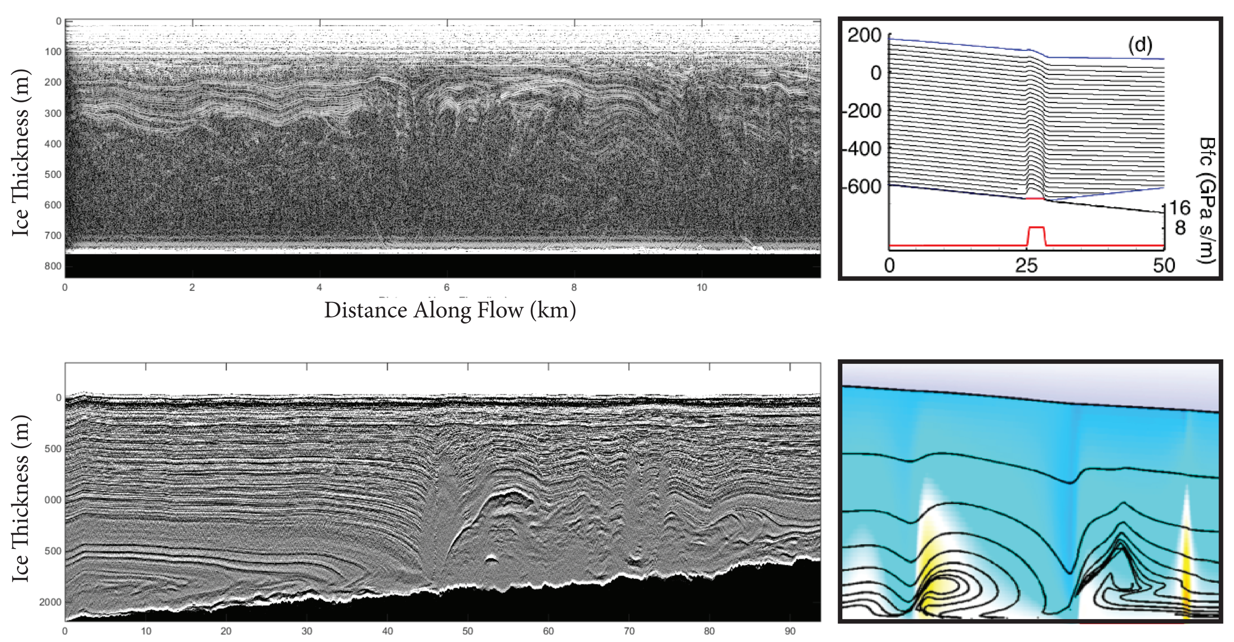
Observations of the ice sheet system provide a shapshot of modern conditions, but we have very few methods for determining the historic flow field of the system. In areas historically occupied by the ice sheet, we can use glacial geology to diagnose past ice sheet behavior, but we have few data that describe past behavior in currently ice covered regions. This type of data would be incredibly valuable, as it would allow us to diagnose both transient and stable behavior of the system.

**We believe that ice structures, imaged using ice penetrating radar, have the potential to provide ground truth for our assumptions about the current boundary conditions of the ice sheet system, as well as indicate the temporal and spatial stability of those assumed characteristics.**

Variability in the frictional characteristics of the bed found along a flow line will cause compression or extension within the ice column. This will tend to drop down or push up particles, and deform the originally flat laying isochrones in a way that is controlled by the magnitude of the change in in the boundary condition. *In regions where there is expected variability in the friction at the bed, there must be an accompanying internal structure.* Searching for these structures will either validate or force us to change our current assumptions about the boundary conditions of the system.

## Moving Toward a More Quantitative Interpretation

Several studies have used internal structures to interpret properties of the subglacial system. Figures from two of those studies are presented here, which show the original imaged structure (left) and the final numerical model (right) explaining the structures' formations. In both cases, the authors were only capable of qualitative comparison between the data and models. ***In order to move toward a more quantitative, automatable interpretation scheme for these structures, we must defining a numerical metric that can describe their important features. For steady state structures, we argue this metric is the reflector slope.***

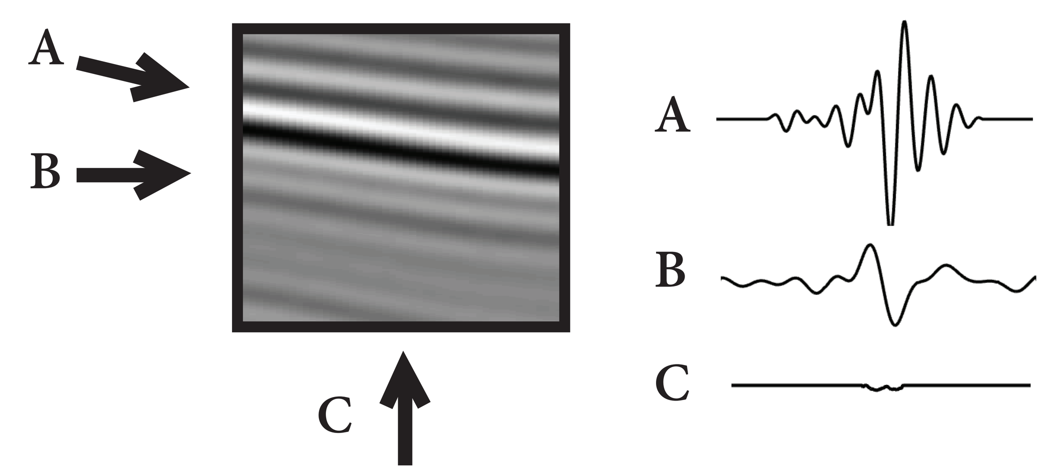



*Figures from Christianson et al. (2013) and Wolovick et al. (2014)*

## Automatic Slope Extraction

To explore the large radar data sets being collected through programs like Operation IceBridge, the first step is to develop an automated algorithm for extracting slope information from the radar image. We have developed a numerically efficient method which uses the Radon Transform and a rolling analysis window to compute the local slope field in the data.

The Radon transform acts as a slant stack, computing the power for all possible angular orientations of the data. The following example illustrates how the algorithm works:




The radon transform is computed for the window presented on the left, and three different angle stacks are presented to the right. The stacks with the most energy can be interpreted as the dominant slope for that window. This algorithm has several advantages:

1) It does not require layer continuity across the data set to function. This means it works well in data sets where gaps make layer tracing impossible.

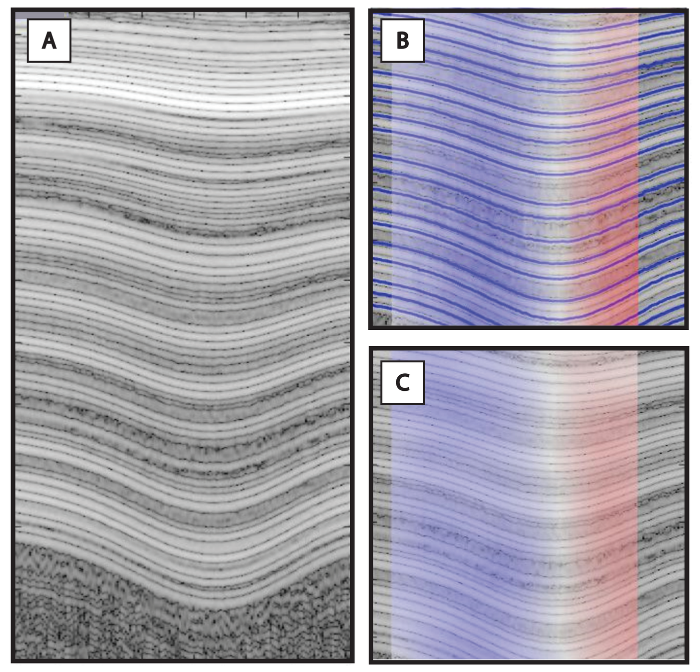
2) It is numerically efficient. The Radon Transform can be computed using an FFT, which means slope fields can be computed quickly over large data sets.

3) In the steady state, reflector slope directly maps to the ratio between the horizontal and vertical velocity of individual particles in the ice column, making the data set directly comparable to model output.

## Algorithm Performance

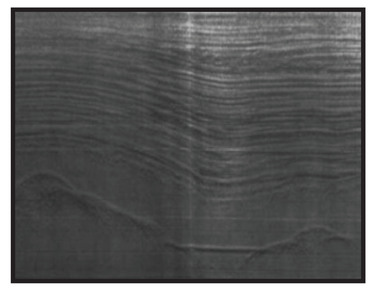
To the right we present the results of the algorithm for a ground based radar survey collected over the North East Greenland Ice Stream. Panel A shows the raw data, panel B presents the slope field computed through layer picking, computing the slope, and interpolating over the domain, while panel C shows the direct output of the rolling Radon Transform calculations. As you can see, panel C compares favorably for these low frequency, un-aliased data.

Continued testing must be done to optimize performance for higher frequency data, where the internal layers are more prone to aliasing and power loss in regions of steep dip. Preliminary results are positive for new Operation IceBridge data, however older surveys (pre 2012) may need to be reprocessed to enhance the internal layers before slope analysis can be done.




## Current and Future Science Objectives

Our first targets for this analysis is the shear margins of the North East Greenland Ice Stream. Extremely steep slopes are seen in the across flow direction despite no topography upstream to control their formation. These must therefore be a function of the frictional properties of the margins, providing valuable constraints on the material properties of the substrate in streaming flow.



We would also like to target known subglacial lakes (like the one pictured here from Siegert et al., 1996) to investigate their long term impact on the flow field of the overriding ice.

**Presented below are a set of some of the experiments we are conducting to characterize the suite of reasonable, expected internal structures for steady-state boundary conditions. These will provide a baseline for comparison with the subglacial lake, shear margin, interior data sets we are pursuing**

## Acknowledgements

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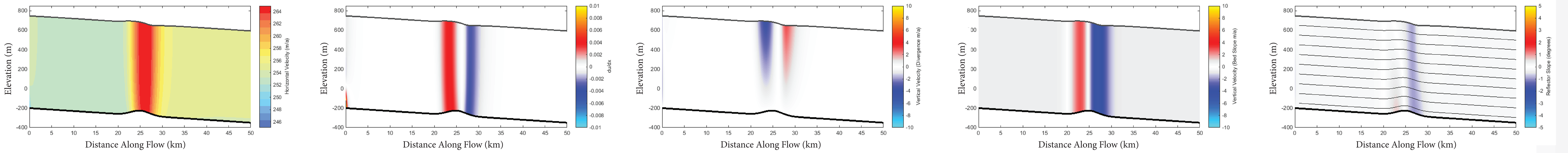
## Numerical Experiments

Horizontal Velocity | Ice Divergence -> Vertical Velocity | Bed Slope | Total Slope Field

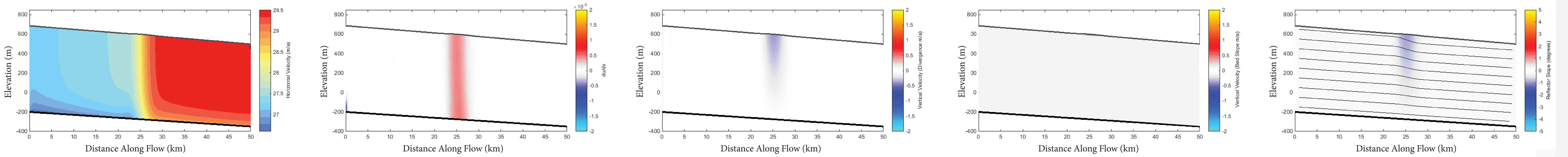
### Exp. 1 - Bed Bump

In this experiment we tested the effects of a 50m topographic feature in the bed. When run to steady state, the flow field closely resembled plug flow, leading to relatively simple structure geometry. The largest features are seen at depth, which are dampened near the surface due to dynamic effects.




### Exp. 2 - Accumulation Anomaly

In this experiment, we tested the effects of a 5x accumulation anomaly on the internal structure. Again, we find near plug flow behavior, but the dynamic effects of additional accumulation can only be seen when the background conditions are similar to those outside of streaming flow.




### Exp. 3 - Frictional Anomaly

The final experiment we have run examines the effects of an increase in the basal friction coefficient of 10x. Longitudinal stresses cause significant deviation from plug flow, resulting in structures that are assymetric over the anomaly. These results match previous analysis of the Whillans grounding line.