C13C-0846: 3D Imaging and Automated Ice Bottom Tracking of Canadian Arctic Archipelago Ice Sounding Data

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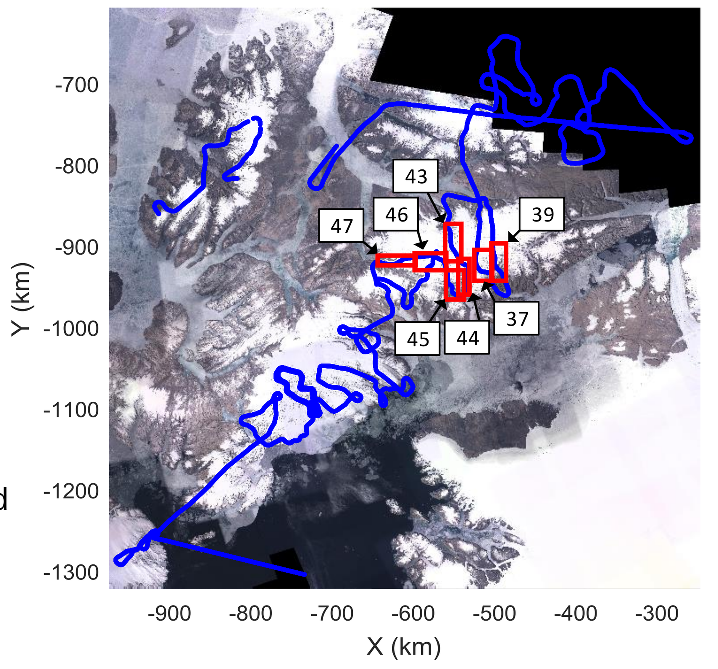
Abstract

The basal topography of the Canadian Arctic Archipelago ice caps is unknown for a number of the glaciers which drain the ice caps. The basal topography is needed for calculating present sea level contribution using the surface mass balance and discharge method and to understand future sea level contributions using ice flow model studies. During the NASA Operation IceBridge (OIB) 2014 arctic campaign, the Multichannel Coherent Radar Depth Sounder (MCoRDS) used a three transmit beam setting (left beam, nadir beam, right beam) to illuminate a wide swath across the ice glacier in a single pass during three flights over the archipelago. In post processing we have used a combination of 3D imaging methods to produce images for each of the three beams which are then merged to produce a single digitally formed wide swath beam. Because of the high volume of data produced by 3D imaging, manual tracking of the ice bottom is impractical on a large scale. To solve this problem, we propose an automated technique for extracting ice bottom surfaces by viewing the task as an inference problem on a probabilistic graphical model. We first estimate layer boundaries to generate a seed surface, and then incorporate additional sources of evidence, such as ice masks, surface digital elevation models, and feedback from human users, to refine the surface in a discrete energy minimization formulation. We investigate the performance of the imaging and tracking algorithms using flight crossovers since crossing lines should produce consistent maps of the terrain beneath the ice surface and compare manually tracked "ground truth" to the automated tracking algorithms. We found the swath width at the nominal flight altitude of 1000 m to be approximately 3 km. Since many of the glaciers in the archipelago are narrower than this, the radar imaging, in these instances, was able to measure the full glacier cavity in a single pass.

Data Set

NASA OIB flew three flights for the Canadian Space Agency (CSA) to collect 3D glacier imaging data over the Canadian Arctic Archipelagos (Ellesmere, Axel Heiberg, and Devon Islands). The data segments from these missions are shown in the table below and in the figure to the right over a Landsat-7 mosaic. Data frame locations with corresponding frame IDs are shown for the ice bottom images shown along the bottom of the poster.

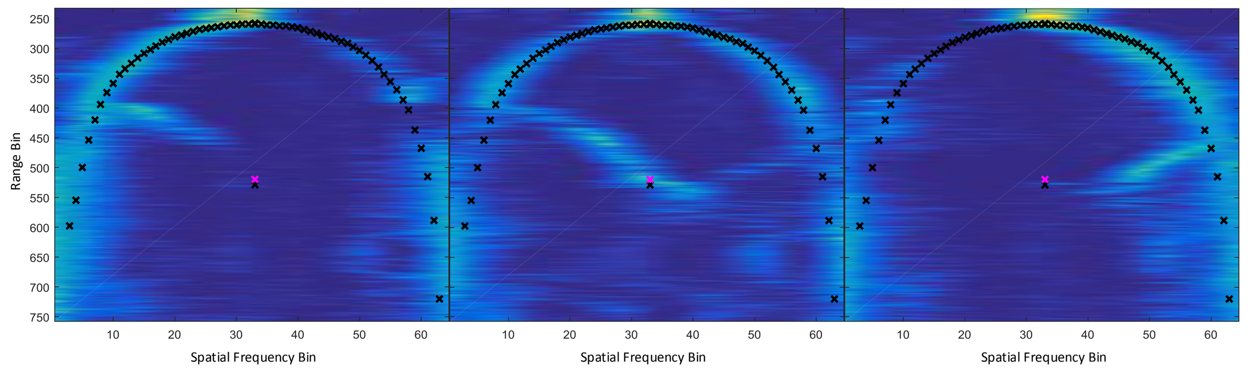
To maximize coverage, MCoRDS (Fernando et al. 2014) was configured to transmit 3 beams. The beams were time multiplexed so that data were recorded from the left beam, then the nadir beam, then the right beam. The tables and plots below show the waveform-beam configuration, radar parameters, and the geometry of the imaged swath using the three beams.



Segment	Mission Name	Frames
20140325_05	CSA: Axel Heiberg-Eureka/Thule	2
20140325_06	CSA: Axel Heiberg-Eureka/Thule	1
20140325_07	CSA: Axel Heiberg-Eureka/Thule	5
20140401_03	CSA: North Canada Glaciers	48
20140506_01	CSA: South Canada Glaciers	35

Waveform	Look Angle	Attenuation	Weights	Direction
1	Left	15 dB	Hanning	30 deg
2	Nadir	20 dB	Hanning	0 deg
3	Right	15 dB	Hanning	-30 deg

Parameter	Value
Radar carrier-frequency	195 MHz
Signal bandwidth	180 MHz to 210 MHz
Transmit pulse duration	3 μs
Number of transmit antennas	7
Number of receive antennas	15
Antenna type	Loaded Dipole (Byers et al. 2012)
PRF	12 KHz
Effective PRF (TDM, stacking)	307 Hz



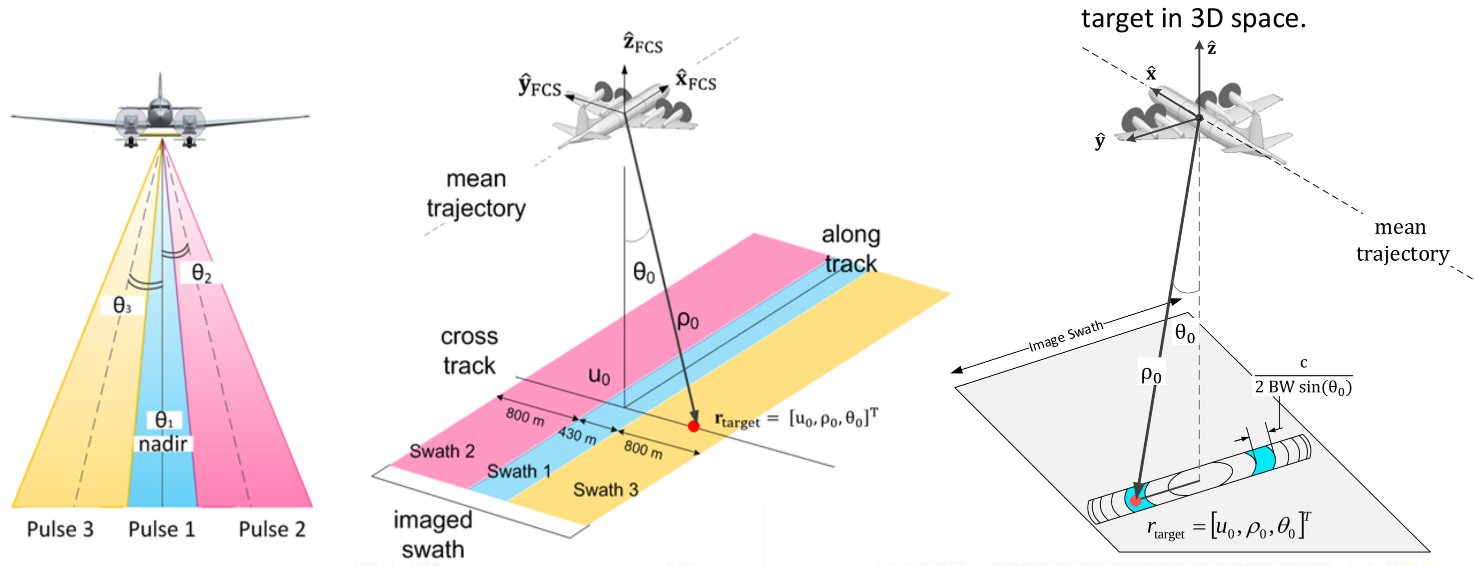
3D Image Processing Steps

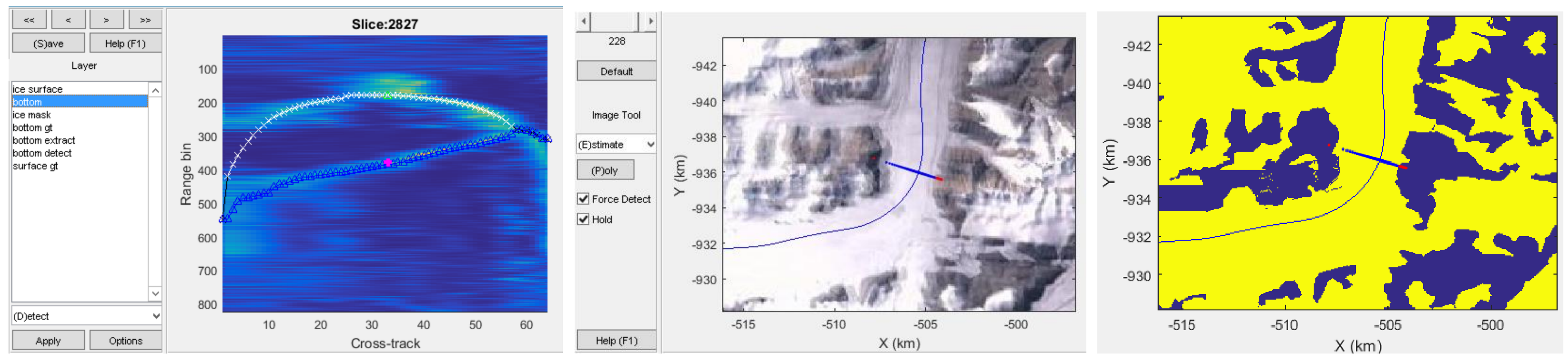
Ice sheet bed mapping with airborne synthetic aperture radar (SAR) is similar to side looking radar mapping except that the imaging swath is near or at the surface normal as shown in the "3D Image Processing Steps" figure below. An example target is indicated with a red dot. The target's along track position, u_0 is resolved with SAR processing. Its range, ρ_0, is resolved with range bandwidth and pulse compression. A cross-track antenna array mounted on the aircraft resolves the angle of arrival θ_0. We seek optimal methods for estimating the angle of arrival since the angular resolution using the same matched filter methods that are used to resolve targets in the other dimensions is usually an order of magnitude or more worse than the resolution in the other dimensions. The direction of arrival estimation method that we use is based on Paden et al. 2010 which describes a Multiple Signal Classification (MUSIC) based algorithm to produce a 3D image of the scene.

Since there are usually errors in the individual antenna patterns and phase centers that make up the cross-track antenna array, we introduced a calibration method to correct for these errors. Using fine resolution surface DEMs from SPOT-5 imagery, we calibrated our algorithms so that the surface in the radar image showed up at the same location as indicated by the SPOT-5 DEM. The image above shows the SPOT-5 DEMs projected into radar coordinates and overlaid on the radar image. There is generally good agreement between the radar images and the SPOT-5 DEM which are indicated by the curve of black 'x' markers.

The images above show the left, nadir, and right beams. Each beam best resolves targets in the direction of transmission. For the current ice bottom tracking results, a single synthetic beam was created by fusing these three images into one using a normalized weighting method that emphasized the beam for targets in that beam's direction of transmission.

3D Image Processing Steps: Resolution of a target in 3D space.

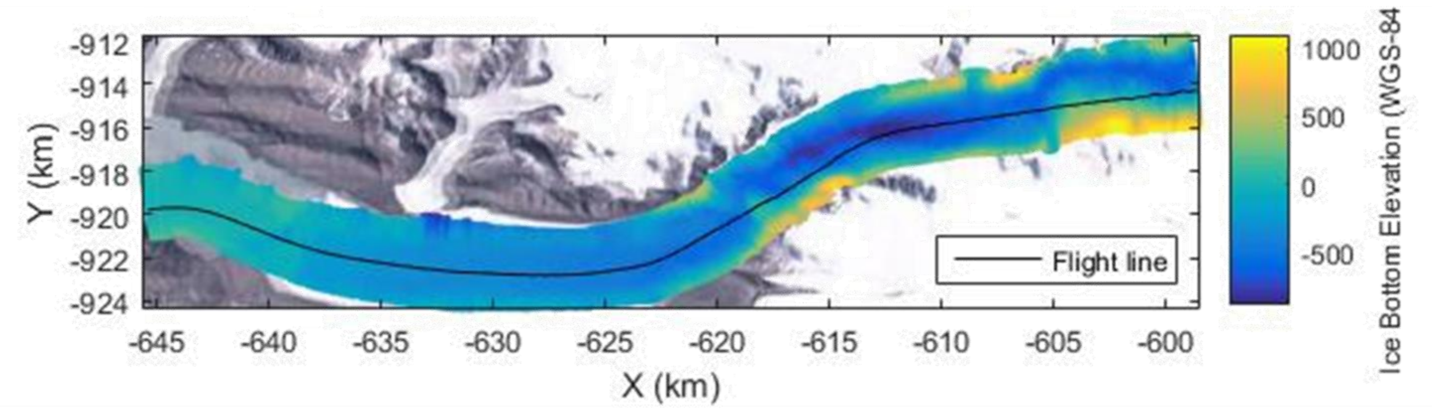




Ice Bottom Tracking

We have implemented an automated technique for extracting ice-bottom surfaces by viewing the task as an inference problem on a probabilistic graphical model. We first generate a seed surface subject to a set of constraints which account for both the mismatch between the radar data and the model parameters as well as the smoothness of the estimated surface, formulated as a Markov Random Field. Additional sources of evidence are then incorporated to refine the surface in a discrete energy minimization formulation, using the Sequential Tree Reweighted Message Passing (TRW) algorithm (Koller 2009, Kolmogorov 2006). We used 7 topographical sequences (results for each shown along the bottom of the poster), each with over 3000 radar images which corresponds to about 50km of flight line data. For each of these images, we also have the air-ice surfaces, which come from digital elevation models produced using photogrammetry applied to electro-optical (EO) satellite images, as ground truth. Since the air-ice surface and the ice-bottom surface usually share the same pattern, we learned the parameters of the template model from the air-ice surfaces in the topographical sequences. We then ran the inference on each of the topographical sequences and measured the accuracy by comparing our estimated surfaces to human-labeled ground truth. But these labels are not always accurate at the pixel-level since the radar images are often noisy and material boundaries are difficult to track precisely by human annotators. To decouple from the ground truth errors, we consider two labels as the same when their difference is within a few pixels. Additional evidence can be easily incorporated into our energy minimization formulation. For instance, actual ground truth data (e.g. ice masks) may be available for some particular slices, and human operators can also provide feedback by marking true surface boundaries for a set of pixels.

After the automated routine is run, we use a 3D image browser that we developed for this problem to quality control the results. The primary browsing windows are shown above. The windows from left to right are: a cross-track view of a single vertical slice from the 3D image, a map view showing the location of this slice, and the ice mask associated with the map view. Using this tool, where necessary, we added additional ground truth for the ice surface and ice bottom and corrected the ice mask. The tool also provided a convenient GUI for rerunning the automated algorithms on subsets of the data with the new and corrected ground truth. This process is iterated until the tracking algorithm had no noticeable tracking errors.



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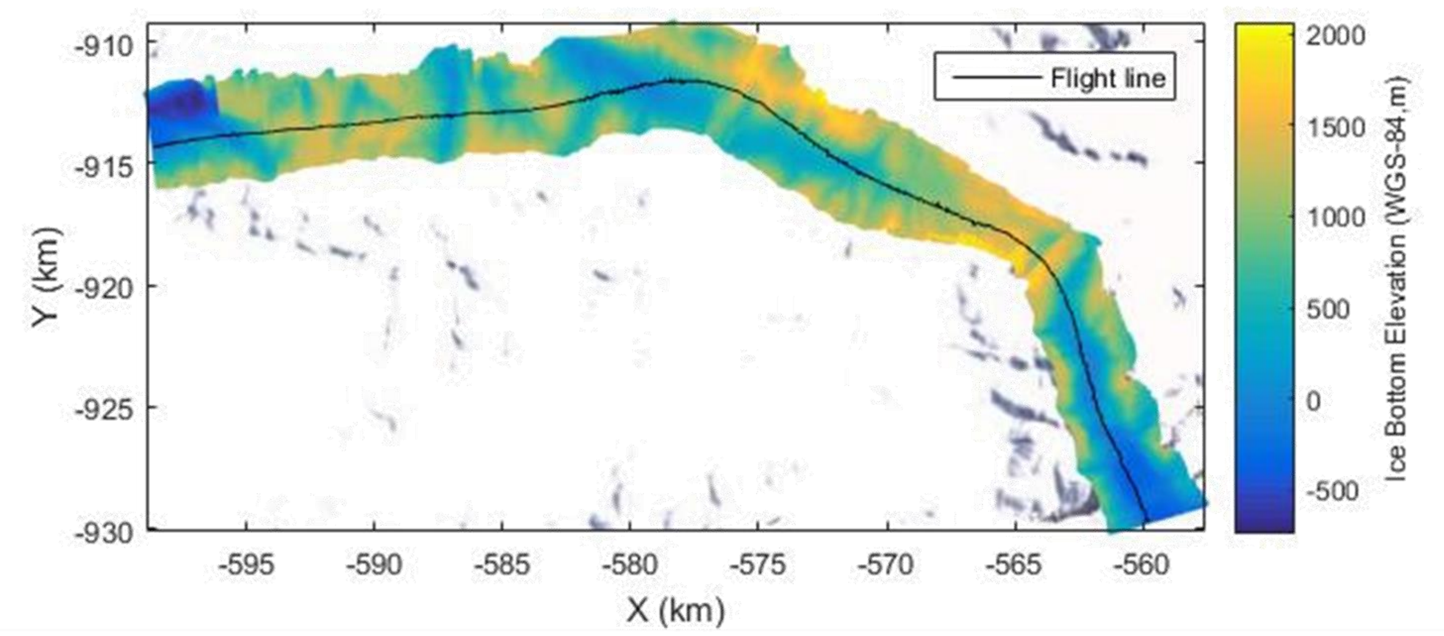

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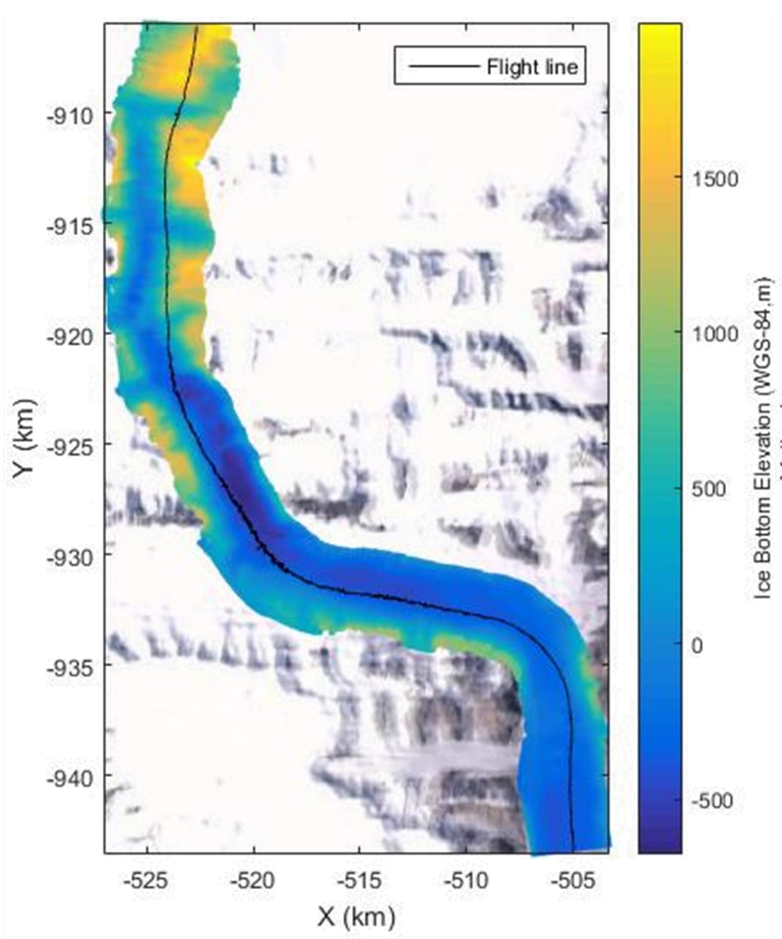

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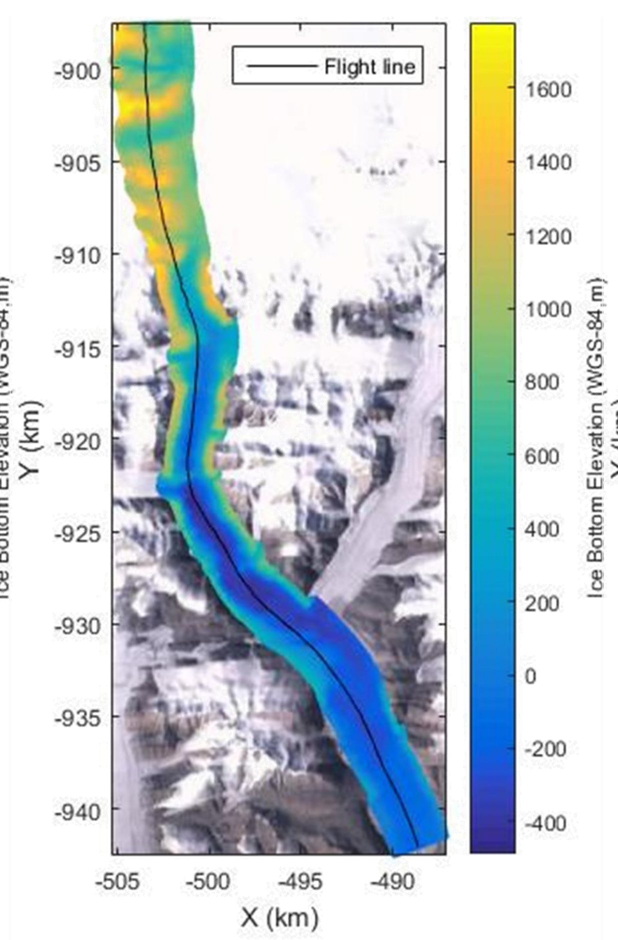

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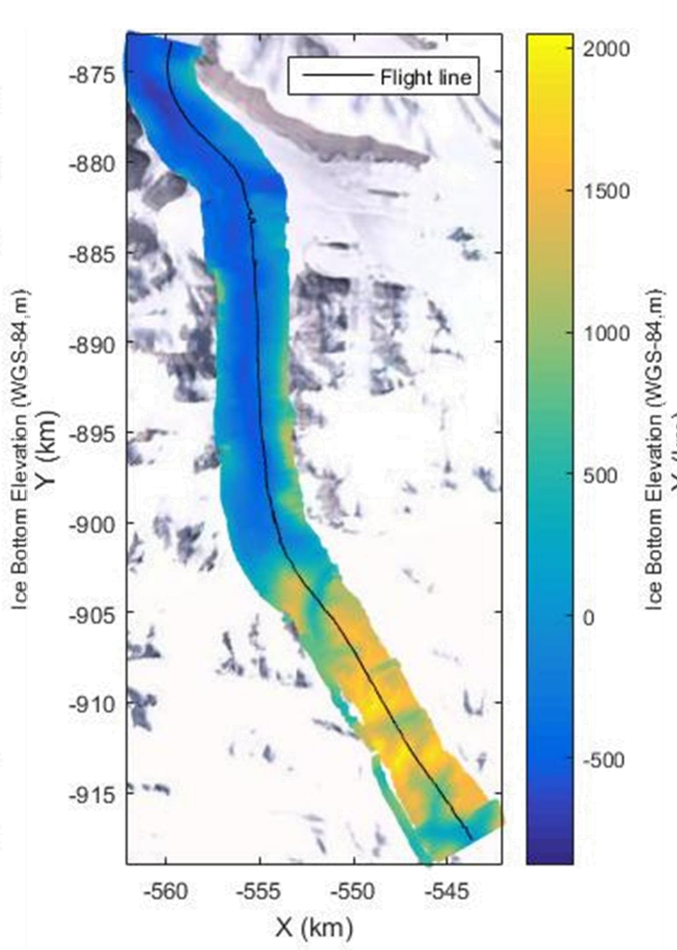

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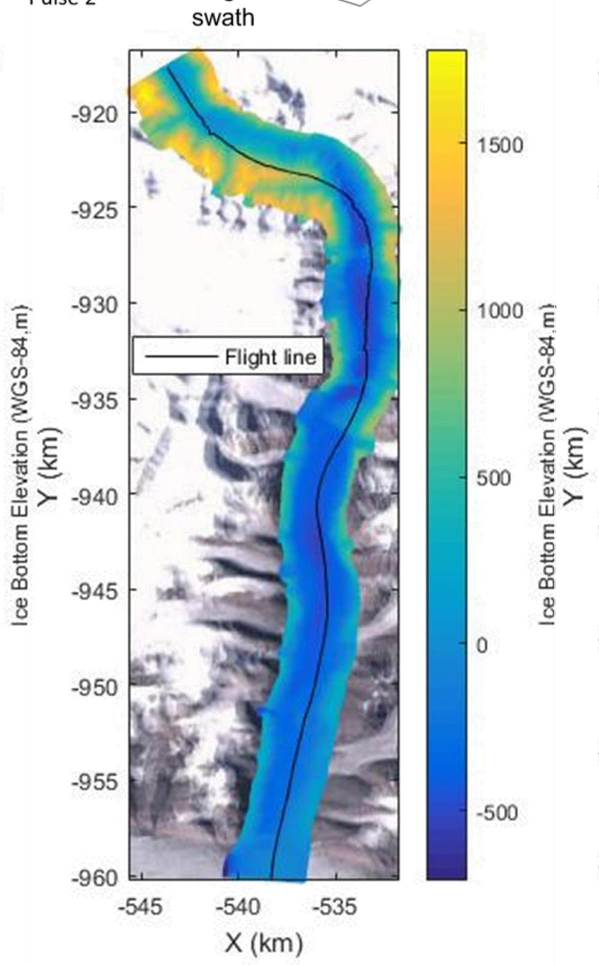

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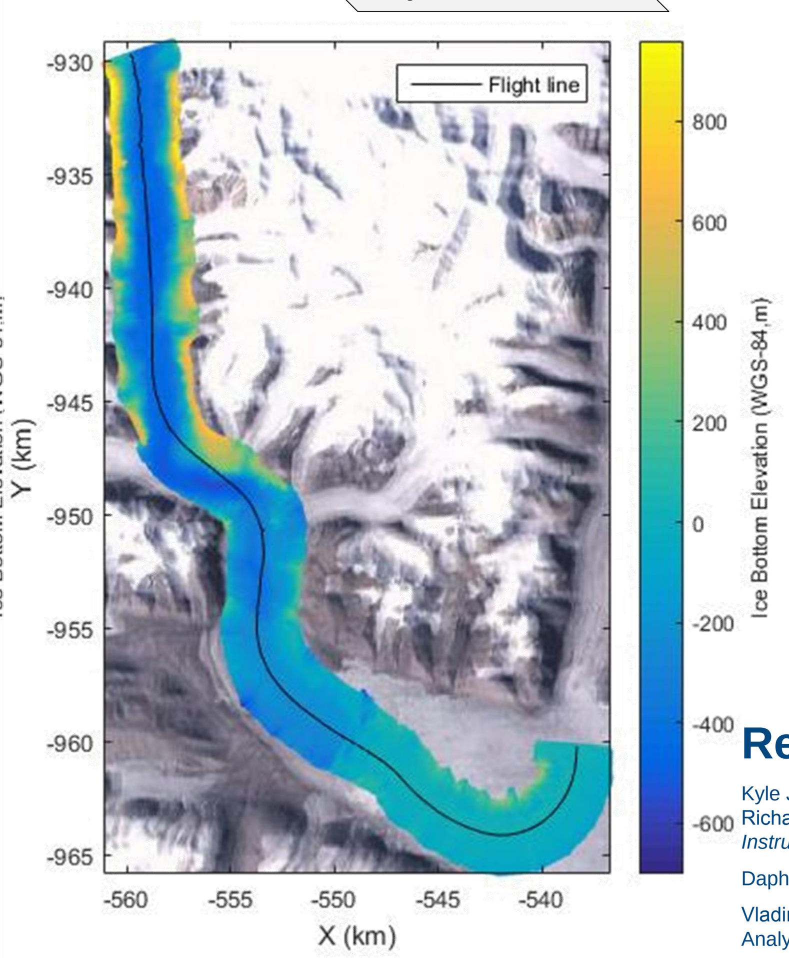

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Acknowledgements

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