

Tomographic Observation and Bedmapping of Glaciers in western Greenland with IceBridge sounding radar

Xiaoqing Wu, Jet Propulsion Laboratory, California institute of technology
John Paden, CReSIS, Kansas University
Ken Jezek, Ohio state university
Eric Rignot, University of California at Irvine
Young Gim, Jet Propulsion Laboratory, California institute of technology

ABSTRACT

We produced the high resolution bedmaps of several glaciers in western Greenland from IceBridge Mission sounding radar data using tomographic sounding technique. The bedmaps cover 3 regions: Russell glaciers, Umanaq glaciers and Jakobshavn glaciers of western Greenland. The covered areas is about $20 \times 40 \text{ km}^2$ for Russell glaciers and $300 \times 100 \text{ km}^2$, and $100 \times 80 \text{ km}^2$ for Jakobshavn glaciers. The ground resolution is 50 meters and the average ice thickness accuracy is 10 to 20 meters. There are some void areas within the swath of the tracks in the bedmaps where the ice thickness is not known. Tomographic observations of these void areas indicate that the surface and shallow sub-surface pockets, likely filled with water, are highly reflective and greatly weaken the radar signal and reduce the energy reaching and reflected from the ice sheet bottom.

1. INTRODUCTION

Glaciers and ice sheets modulate global sea level by storing water deposited as snow on the surface and discharging water back into the ocean through melting. Their physical state can be characterized in terms of their mass balance and dynamics. To estimate the current ice mass balance and to predict future changes in the motion of the Greenland and Antarctic ice sheets, we need to know the ice sheet thickness and the physical properties of the ice sheet surface and bed. We require this information at fine resolution and over extensive portions of the ice sheets [1].

In a series of papers [2,3,4,5,6,7,8], we have demonstrated the 3-D bedmapping capability with the airborne tomographic sounding method and to get the required bed topography in desired fine resolution. Using NASA's IceBridge mission data, we demonstrated in this paper that the tomographic sounding can be used for regional bedmapping with examples of the bed maps of Russell glaciers, Umanaq glaciers and Jakobshavn glaciers of western Greenland. The Russell glacier bedmap covers an area of $38 \text{ km} \times 18 \text{ km}$ with 10m average thickness accuracy and 50m ground range resolution using the IceBridge data collected in the spring season of 2011. There are 2 flights in 2011 to cover the Umanaq glaciers. The coverage is over 300km long 100km wide. In addition to the Umanaq glaciers, we are also doing the mapping of the bed of Jakobshavn glaciers in western Greenland with the data collected in the spring season of 2012. Jakobshavn is one of the fastest moving glaciers on the earth surface with surface speed up to 10 km/y.

We present in this paper that the tomographic sounding method we used for mapping the bed and the system calibration procedures in section 2. The the bedmaps of Russell, Umanaq and Jakobshavn glaciers we produced from the IceBridge mission data are shown in section 3. In section 4 we present some interesting observations of the surface and shallow sub-surface pockets, which may be one of the major reasons that causes the reduced SNR for the bed below these pockets.

2. TOMOGRAPHIC SOUNDING AND DATA CALIBRATION

Nadir ice sounding provides one dimensional thickness measurements of the ice sheets along the flight lines of the radar sounder. The along track platform position is obtained by conventional GPS, radar timing provides the range measurement. However, at least 4 locations share these same geospatial characteristics: two points (left/right) on the basal and surface layers will have the same range and azimuth. Discrimination among these points requires at least 4 additional independent measurements. MCoRDS provides these measurements by implementing a 3 antenna array with 15 total dipole elements. By using phase coherent tomographic (or angle of arrival) processing, one can discriminate among all ambiguities (basal and surface clutter) to obtain topographic maps of both the base and ice surface, together with radar reflectivity maps.

The formal basis for ice sheet radar tomography and our implementation of the technique is described in Wu and others [7]. Essentially, we formulate the tomographic basal ice imaging task as a problem of estimating signal arrival angles. The ice mass has two major interfaces, the upper surface interface, between the air and the ice mass, and the basal interface, between the ice mass and bedrock or basal water. In between there are internal layers that originate from slight density changes or from ancient volcanic deposits. Because the reflection of internal layers is highly specular, only their close nadir returns are significant but arrive at the receiver earlier than the bottom returns. Therefore the echoes from these internal layers are ignored in our analysis. When the radar signal reaches the air-ice interface, some of the energy is scattered back and some refracts through the interface and continues travelling through the ice mass. Some of the transmitted signal will scatter back towards the receiver from the basal interface. Simultaneous with the nadir echo arriving from the bedrock the receiver may also detect the surface reflected signal from both the left and right sides of the sensor. Off nadir, there may also be simultaneous echoes from the base originating from the opposite sides of the airplane. In addition, there will be thermal and other noise sources. Radar tomography allows for the separation of these various returns given a sufficient number of independent receiver channels.

For a multi-channel system like MCoRDS, phase and amplitude calibration are very important if either beam steering or tomography are to be successfully achieved. Data calibration includes inter-channel radiometric calibration, antenna geometric calibration, inter-channel phase calibration and time offset between the radar data and the data of associated inertial measurement unit (IMU). We have used the Airborne Topography Mapper (ATM) and the Greenland surface DEM to help do these calibrations. After these careful calibration procedures we apply our time-domain sub-aperture back-projection to the radar raw data of each channel for azimuth compression. The tomography sounding is applied to the azimuth compressed data to estimate the arrival angle of each along track position and range bin. The ice thickness is then derived. The details of the algorithm are described in [7].

3. BEDMAP PRODUCTS

We selected three regions in western Greenland for tomographic bedmapping evaluation: the Russell glaciers, the Umanaq glaciers and the Jakobhavn glaciers. Fig. 1 shows their locations. Fig. 2 shows the aircraft tracks in the background of the surface elevation model. Fig. 3 shows the bed topography derived from the estimated ice thickness map with the tomographic sounding technique. We are in the middle of putting together the results of Umanaq and Jakobshavn glaciers and will be able to finish in the next few weeks.

4. TOMOGRAPHIC OBSERVATIONS OF SHALLOW SUB-SURFACE POCKETS

The ice sheet bed is under the icy cover and is not mappable everywhere. The signal noise ratio (SNR) and the signal (surface) clutter ratio are the two major factors, which affect the detection of the bed. The surface clutter can be greatly reduced by increasing the number of antennas of the sounding system. The SNR, however, is dependent not only on the radar system configuration but also on the characteristics of the ice body, which is the medium between the radar sensor and the bed targets. An example of these shallow sub-surface pockets is shown in Fig. 4. The left image is the intensity radar image, where you see the surface at the left-most, then the surface-

aircraft-surface-radar double bounce returns and the bottom at the right side. The sub-surface pockets are between the surface and the bottom returns, and mostly between the surface and the surface double-bounce returns. The right image is the elevation map of the bed and the sub-surface pockets. An interesting observation is that wherever there is a such pocket, the bottom return is weakened. This observation suggests that a major reason for areas where the bed is not detectable is because these highly reflective pockets reduce the penetrating energy for reaching the bottom.

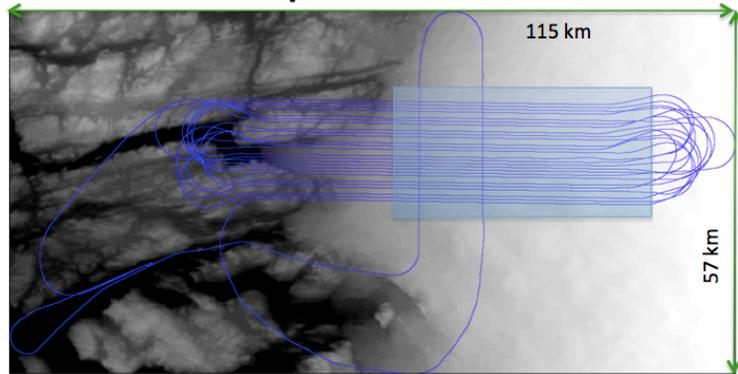


Fig. 2 The background image is a surface DEM in 100m resolution. The shaded box indicates the location of the thickness map. Total 28 tracks of data were collected on April 13, 2011 with P3 platform. Out of the 28 tracks, 25 east-west tracks are used to produce the bedmap.

Fig. 1 locations of Russell, Umanaq and Jakobshavn glaciers.

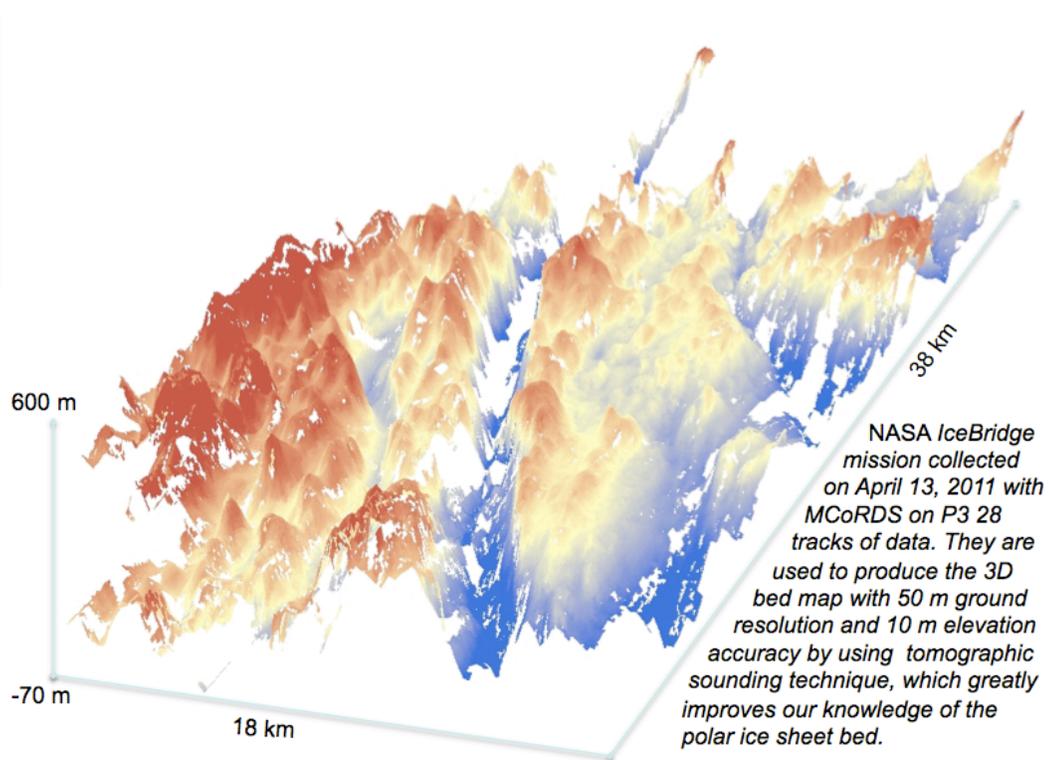


Fig. 3 Bed elevation map of Russell glaciers derived from NASA's IceBridge Mission data using tomographic sounding method.

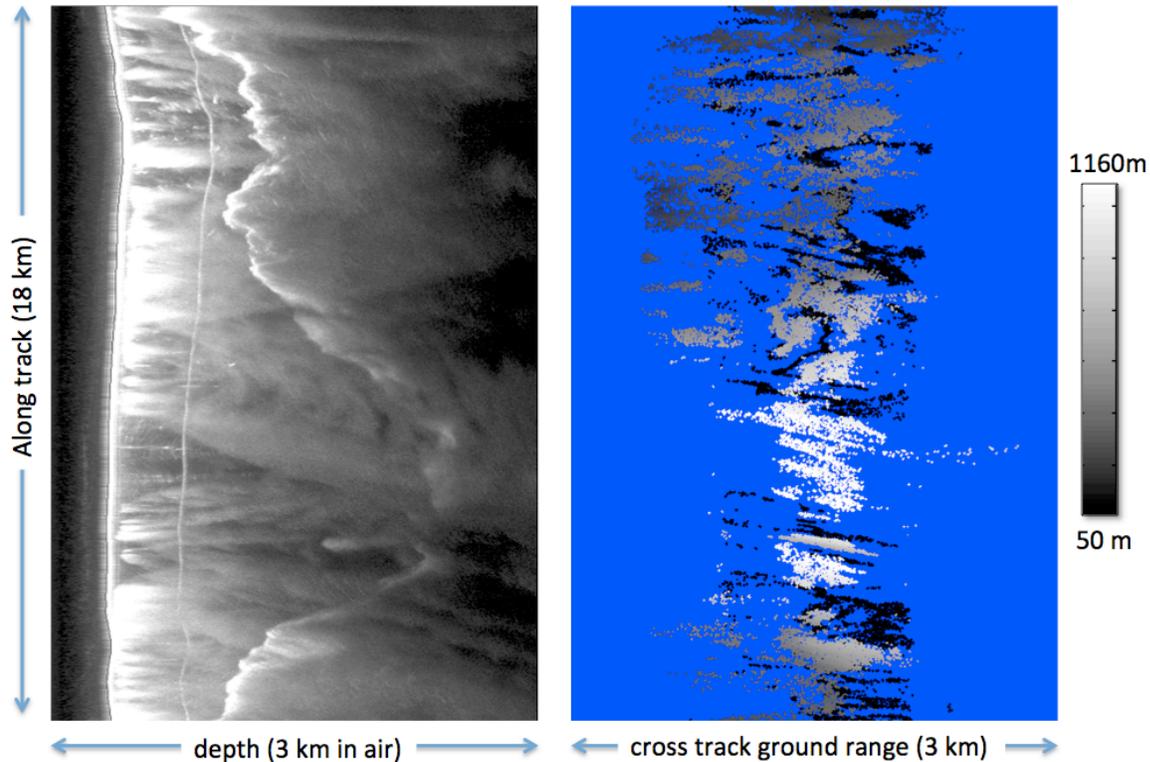


Fig. 4 Intensity (left) and bed thickness overlapped with internal pockets thickness(right)

5. ACKNOWLEDGEMENT

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6. REFERENCES

- [1] The ISMASS Committee, 2004. Recommendations for the collection and synthesis of Antarctic Ice Sheet mass balance data. *Global and Planetary Change*, 42, 1-15.
- [2] K. Jezek, E. Rodriguez, P. Gogineni, A. Freeman, J. Curlander, X. Wu, J. Paden, C. Allen, "Glaciers and Ice Sheets Mapping Orbiter Concept", *Journal of Geophysical Research*, Vol. 111, May 2006.
- [3] Jezek, K., P. Gogineni, E. Rodriguez, X. Wu, J. Sonntag, F. Rodriguez, A. Freeman, and J. Curlander, 2008. *Global Ice Sheet Mapping Observatory – Final Report*. Submitted to NASA ESTO, Greenbelt Maryland, December, 2008, 57p
- [4] Jezek, K., P. Gogineni, X. Wu, E. Rodriguez, A. Freeman, 2009. *Global Ice Sheet Mapping Observatory: Airborne Experiments*. IEEE Radar Conference 2009. Pasadena CA.
- [5] Jezek, K., X. Wu, P. Gogineni, E. Rodriguez, A. Freeman, F. Fernando-Morales, and C. Clark, 2011. Radar images of the bed of the Greenland Ice Sheet, *Geophys. Res. Let.*, vol. 38.
- [6] Jezek, K., S. Gogineni, X. Wu, E. Rodriguez, F. Rodriguez-Morales, A Hoch, A Freeman, and J. Sonntag, 2011. Two-frequency radar experiments for sounding glacier ice and mapping the topography of the glacier bed. *IEEE TGRS*, vol. 49, no.3, p. 920-929
- [7] Xiaoqing Wu, K. Jezek, E. Rodriguez, P. Gogineni, F. Rodriguez, and A. Freeman: Ice sheet bed mapping with Airborne SAR Tomography, *IEEE Trans. on Geoscience and Remote Sensing*, Vol. 49, No. 10, Oct. 2011.
- [8] Xiaoqing Wu, K. Jezek, P. Gogineni, E. Rodriguez, A. Freeman: Airborne SAR tomographic ice sheet sounding. EUASR 2010, Aachen, Germany, June 6-8, 2010.