

Correspondence

Detection of main channel thickness from radar data at Jakobshavn Isbræ, Greenland

Glaciologists seek the mass balance of the polar ice sheets to understand the contribution of the ice masses to the rising global sea level (Asrar and Dozier, 1994). One method of mass-balance monitoring requires knowledge of the changing input and output mass fluxes from the ice sheets. The outflow from ice streams and fast-flowing outlet glaciers is a major factor influencing the total mass balance of ice sheets.

Whereas ice-sheet surface dynamics can be inferred from space-borne remote-sensing data (Joughin and others, 1996), ice thickness remains a major unknown for a number of outlet glaciers; moreover, ice thickness is a critical term in the mass continuity equation. In particular, ice-thickness data across a glacier (perpendicular to the direction of ice flow) are useful for calculating its ice flux (Rignot and others, 2001). Modern airborne radar depth sounders are having great success in measuring ice thickness over an overwhelming majority of the ice sheets (Bogorodsky and others, 1985; Gogineni and others, 2001). However, modern radars have been challenged at Jakobshavn Isbræ, mainly by signal absorption loss through relatively warm ice or melt conditions and by clutter from the crevassed surfaces (Braaten and others, 2002). Seismic surveys remain a proven method for measuring the ice thickness in heavily crevassed outlet areas such as Jakobshavn Isbræ (Weidick, 1992), but the large-scale application is limited by several factors such as logistics, cost, time and safety.

Jakobshavn Isbræ is the most active glacier in Greenland, with a discharge of up to $50 \text{ km}^3 \text{ a}^{-1}$ of ice (Joughin and others, 2004). The glacier's fast-moving surface indicators (e.g. shear margins, crevasse bands and flow stripes) extend from the margin to deep into the ice sheet's interior (Krabill and others, 2000). Because of the scientific interest of fast-moving outlets, several missions using a modern radar ice sounder acquired data from Jakobshavn Isbræ under the NASA Program for Arctic Regional Climate Assessment (PARCA).

PARCA ice-sounding data have been collected in Greenland since 1993 using the University of Kansas ice-sounding radar system on a NASA P-3 aircraft (Gogineni and others, 2001). The ice sounder is a pulse compression radar system that operates at a center frequency of 150 MHz. A four-element dipole array with a 3 dB beamwidth of 72° is mounted on each wing of the P-3 aircraft platform. The output power of the transmitter is about 200 W. The coherent system records the in-phase and quadrature components of the radar return signal every 53.3 ns (about 4.5 m in ice, assuming a velocity of propagation of $169 \text{ m } \mu\text{s}^{-1}$). During collection of data for this study the radar transmitted $9200 \text{ pulses s}^{-1}$, while the aircraft speed was about 130 m s^{-1} at an altitude of about 500 m.

We explored about 38 km worth of data from the Jakobshavn area (Tee and others, 1999). Figure 1a illustrates the location of the Jakobshavn study site as a box near the western coast of Greenland, and Figure 1b shows the flightline. A strong clutter region is present in the radar echogram along the flightline as shown in Figure 1c. The main channel of the Jakobshavn outlet glacier lies in this

high-clutter region. The channel width appears to be less than 15 km (Fig. 1c from about 12 km to 27 km) at this location.

Along-track SAR (synthetic aperture radar) processing of glacial ice-sounding data (Legarsky and others, 2001) has improved the detection of weak bed echoes in parts of Jakobshavn Isbræ (Braaten and others, 2002) and other glaciers (e.g. Peters and others, 2005). SAR processing can improve the signal-to-noise ratio and help reduce along-track clutter. At Jakobshavn Isbræ, Braaten and others (2002) detected the main channel 36 km upstream from our study site with a 1–2 dB improvement using SAR processing. SAR processing helped reduce the surface clutter from the radar echogram at our study site (Fig. 1e); however, the bottom signature could not be clearly identified. The along-track SAR is suboptimal for the Jakobshavn Isbræ data because it does not account for the presence of strong cross-track surface clutter.

To aid in ice-thickness detection at Jakobshavn Isbræ where SAR processing does not reveal the bottom signature, we developed a processing strategy for the Jakobshavn Isbræ main channel from the radar data at the coordinates $69^\circ 05' \text{ N}$, $49^\circ 28' \text{ W}$. To detect signal edges associated with the bedrock, each row in the radar echogram is differenced with the preceding row. Thus, a bedrock signal would have a positive difference followed by a negative difference in depth. However, after differencing, many positive and negative values are present throughout the image in a near-random way as shown in Figure 1d. A smoothing window (230 m in depth by 20 m along the flightline) is applied to the image to average the positive and negative differences. The smoothing reduces enough surface clutter to reveal the underlying hyperbolic signatures as shown in Figure 1f. Finally, we applied a threshold to the image to display the positive difference, which is associated with the signal's first return.

We applied the processing to the radar echogram along the flightline from about 13 km to 26 km for thickness values greater than $\sim 1200 \text{ m}$. Figure 1g illustrates the processed area superimposed on an expanded portion of the flightline. We noticed a near-hyperbolic-looking signature ($>10 \text{ dB}$ signal-to-noise clutter ratio) centered horizontally at about the 20 km location on the flightline. Upon further examination, we found the signature to be dominated by two closely spaced hyperbolic signatures. To aid visualization, we superimposed a hyperbolic response on Figure 1g for each signature, which corresponds to a radar propagation velocity of $169 \text{ m } \mu\text{s}^{-1}$. Hyperbolic signatures are a characteristic of a strong scatterer with the peak associated with the first return, and the remaining signature from the off-nadir returns. The fact that the points observed behave as scattering points implies that to either side of this feature the ice must be thicker. We believe the signatures are from a hill near the bottom of the main channel. Thus, the ice-thickness values using a radar propagation velocity of $169 \text{ m } \mu\text{s}^{-1}$ are found from the peak of the hyperbolic signatures. The ice thickness above the hill ranges from about 2160 m to 2300 m ($\pm 230 \text{ m}$ due to smoothing) around the 20 km location.

Braaten and others (2002) reported ice-thickness measurements from two traverses of Jakobshavn Isbræ. Ice-thickness values of 2192 and 2014 m were reported for the

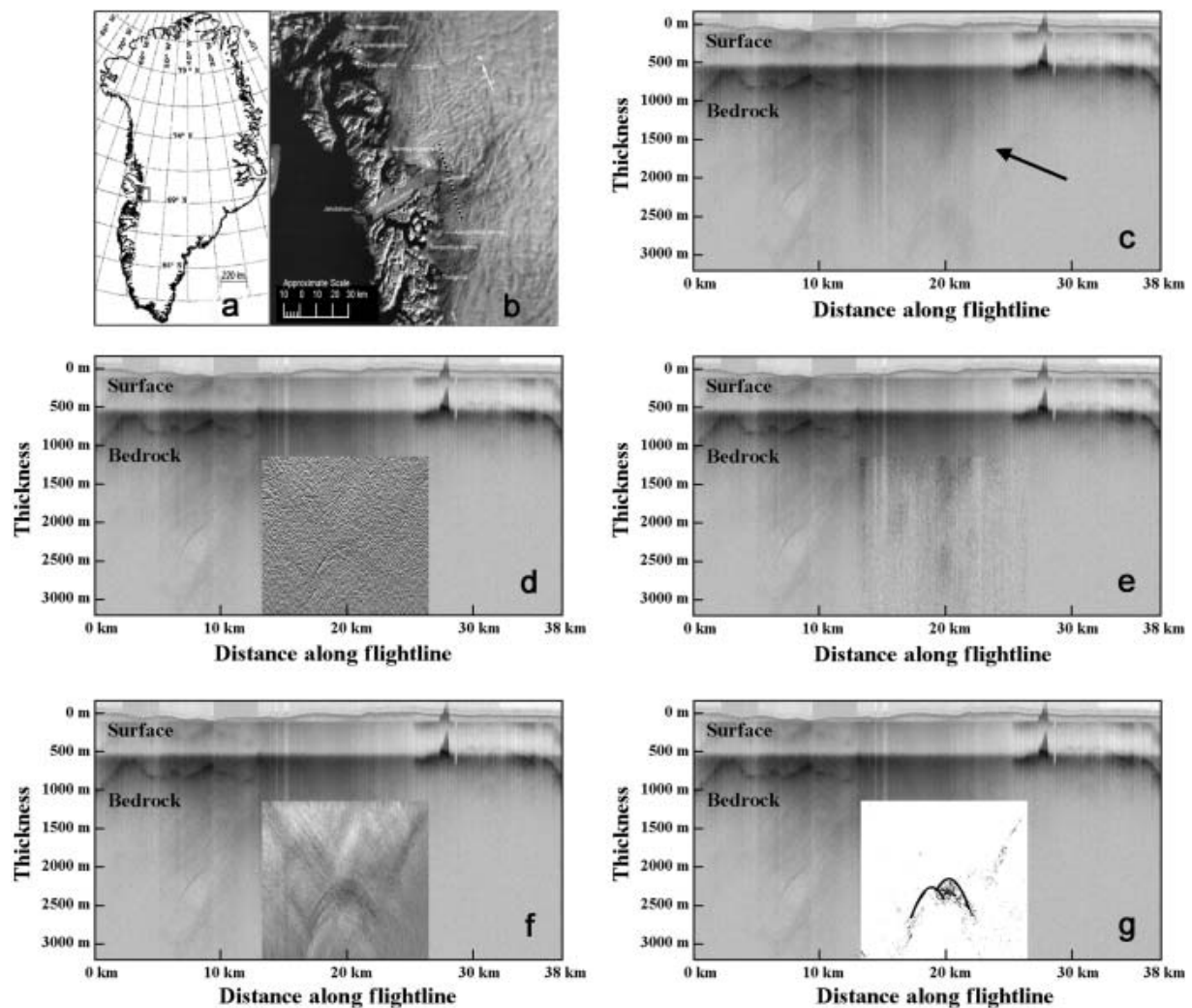


Fig. 1. (a) Greenland map with the Jakobshavn Isbræ study site shown as a box on the western coast. (b) Flightline (dashed line) superimposed on a satellite image of the Jakobshavn region. (c) Radar echogram of ice thickness recorded from a flight over the Jakobshavn main channel. An arrow points to subsurface returns corrupted by strong surface clutter. (d) Image after differencing. (e) Image after SAR processing. (f) Image after smoothing the difference result. (g) After processing, radar echogram of ice thickness recorded from a flight over the Jakobshavn main channel. The hyperbolic-looking signatures are probably from a hill near the bottom of the main channel. The ice-thickness scale is given for 0 km on the flightline. For other distances along the flightline the scale should be shifted with the 0 m thickness always at the ice surface.

thickest portion of the channel, at 36 and 79 km upstream from our site, respectively. A hill 81 and 85 m above the deepest portion of the channel is seen for the reported traverses, 36 and 79 km upstream from our site, respectively. It seems likely that the maximum ice thickness from our site is the ice thickness above the bedrock hill plus an additional 81 m or more.

A recent map of Greenland ice thickness (Bamber and others, 2001) shows significant discrepancy (about 1400 m) at our Jakobshavn Isbræ site. The discrepancy mainly occurs because of interpolation over the main channel areas where ice-thickness data were missing. The discrepancy is not surprising since the ice-thickness map does not include either Braaten and others' (2002) data or our values of the main channel thickness. By including the new ice-thickness data from the main channel, the ice-thickness map can be improved over the Jakobshavn Isbræ region.

We believe the detected signatures are from the Jakobshavn main channel in a location where strong surface clutter masks the unprocessed radar echogram. We observed more

than a 10 dB improvement in the signal-to-clutter ratio after processing. In addition, the processing strategy developed for the Jakobshavn main channel may be beneficial in radar echograms from other locations where clutter signals mask the bedrock return.

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