An impulse radar measurement in NE Greenland

By Peter Jonsson

Abstract

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A snowmobile towed impulse radar measurement was used to produce detailed maps of ice-thickness in two areas, one on a local dome (the Hans Tausen ice cap), and one on an outlet glacier north thereof. A constant spatial sampling was achieved by using a device attached to the snowmobile's odometer. The bedrock reflection was automatically detected in the majority of the data, by using digital signal processing techniques. After merging with differential GPS positions and elevations, a digital database of these parameters and the bedrock reflection times is presented as contour maps.

Keywords: Impulse radar, ice-thickness, constant spatial sampling

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Introduction

The Hans Tausen ice cap, Western Peary Land, Northeast Greenland, has previously been investigated by shallow drillings in 1994 and 1995, and by an airborne radar survey in 1993, as well as earlier (Gundestrup *et al.* 2001). The objective of the survey described in this paper was to produce detailed maps of ice-thickness for two areas, one on the ice cap and one on an outlet glacier north thereof. The ice cap measurements should assist in locating an ice core drilling to bedrock made by the Department of Geophysics, University of Copenhagen, on a dome situated near 82°50′N, 37°50′W, in the SE part of the ice cap. The surveyed outlet glacier is located near 82°80′N, 36°60′W. These measurements were made for the Geological Survey of Denmark and Greenland (GEUS), formerly the Greenland Geological Survey (GGU), along and perpendicular to assumed flow lines, and on a local dome (Thomsen *et al.*, 1996).

Data collection equipment

The measurements were made with a snowmobile towed impulse radar system. All equipment was powered by a gasoline generator and pre-assembled so that the system could be operational in a few hours after arrival. The impulse radar system used was a Geophysical Survey Systems, Inc. (GSSI) model SIR-8, which was modified for glacier soundings to allow for a longer range (7765 ns) than the standard instrument. A technical description of the radar and antenna is found in Morey (1974), while the system performance figures stated below were compiled from Annan and

Davis (1977), Morey and Kovacs (1982) and Schutz (*pers.comm)*.

The transmitter, attached directly to the transmitting antenna, is a high voltage (1 kV) pulse generator, which produces impulses with a pulse repetition frequency (PRF) of 25.6 kHz, an applied peak pulse power of 5 kW, a rise time of 2 ns, and a duration of less than 10 ns. Two identical antennae of folded dipole type, GSSI type 3100, were used in a bistatic mode with an antenna separation of 4 meters. The antennae have a center frequency of 120 MHz, an antenna gain of 2 dB, and an efficiency of –13 dB. The transmitted broadband signal had a total pulse length of 12 ns and an estimated –3dB bandwidth of 60% of the center frequency, or approximately 120±35 MHz. The receiver operates as a repetitive sampling device, synchronized to the PRF. After applying a voltage gain of 19 dB, the signal is downsampled to provide 25.6 sampled signal scans per second. The downsampled scans are in the audio range, and with each downsampled signal scan a start-of-scan strobe is generated. The minimum detectable signal power at the center frequency is estimated to $4 \cdot 10^{-11}$ W, which combined with the parameters above yields a system Q value of –141 dB. The maximum possible range is 7765 ns. To establish the time scale a crystal controlled calibrator that sends out a calibrated 100 MHz signal was substituted for the antennae and recorded after each profile was measured.

The antennae were towed on wooden sleighs behind a snowmobile, separated by 3 m long, 1” aluminum distance rods. To facilitate downhill measurement the towlines were crossed. This crossing design, in combination with the rigid distance rods, made the antennae sleighs steer in a zigzag pattern, much like a downhill skier, which decreases speed.

To provide data recordings with a uniform spatial sampling distance, a device was used that distributes the recorded signals evenly along the track without loss of synchronization between the radar start-of-scan strobes (see above) and the recorded signals. The device works by blocking the start-of-scan strobes (SOS) from the radar control unit until an adjustable number of pulses have appeared from a rotary sensor fitted to the snowmobile odometer. When the desired pulse count is reached, the next occuring SOS is allowed to pass. The number of odometer pulses that must occur before the device lets a SOS through is adjustable, to allow for different spatial sampling rates, i.e. different scales. The settings used in the measurement gave three recorded pulses per meter of track length. The maximum delay between an odometer pulse and a SOS pulse is less than the distance in time between two SOS, which is 39 ms. At a nominal speed of 1.5 m/s this corresponds to a horizontal, along-track, positioning error of less than 6 cm.

A four-channel audiocassette tape recorder was used to store the data. All received radar scans were stored on one channel, and their corresponding SOS pulses on another. The length scale sorted SOS pulses were stored on a third channel. By storing both sorted and unsorted SOS pulses, maximum flexibility was retained. For example post-processing such as stacking, could be performed without any loss of length scale fidelity.

A hand-held GPS receiver in standard positioning (SPS) mode was used to perform on-site navigation. In addition, stakes and flags were used to define endpoints and flowlines. Positioning of the measured lines was made with kinematic post processed, differential GPS with a precision better than one centimeter, which was provided by Department of Geophysics, University of Copenhagen, in 1994 and by GEUS in 1995. The reference station was established locally, tied to a reference station at Station Nord.

Data set and post-processing

The data were in field recorded as an analog signal on standard audiocassette tapes, and also on paper, as a backup and for immediate in-field quality control. The ice cap measurement consists of approximately 135 km of profiles on 22 tapes. The outlet glacier data set is slightly more than 70 km of profiles, on 20 tapes.

In the first post-processing stage, the tapes were computer digitized with a sampling frequency of 50 kHz, in a semi-automated process. The recorded analog scans were band pass filtered (200 Hz—10 kHz) prior to digitizing to remove noise, and to provide anti-aliasing. In the digitizing process, each digitized scan was assigned a header with a time-tag showing the time it was collected. Using a lookup-table with time as key and the GPS positions measured in field as values, a position was assigned to each scan.

To identify the bedrock reflection, an automatic method was used. The envelope $E(t)$ of each digitized scan $s(t)$ was calculated as the magnitude of a (complex) synthetic analytic signal:

$$E(t) = |s(t) + j\mathbf{H}(t)|),$$

where **H** denotes the Hilbert transform. After blanking of the first 800 ns of the scan, which contains the transmit pulse and surface effects, the position of the maximum value in the squared envelope of the scan, $E^2(t)$, could be used to detect the bedrock reflection. An example of a digitized profile, named N6, and the detected bedrock reflection, are shown in Fig. 1.

The detection method described above was successfully used for all the ice cap data, but it failed in more than 30% of the outlet glacier data set, mainly due to shallower ice depth, which made the bedrock reflection interfere with the initial part of the signal. The signal-to-noise ratio for the outlet glacier data was also lower in some areas. When automatic detection failed, the segment in question was manually interpreted, and data was interpolated to the same data density as the automatically processed

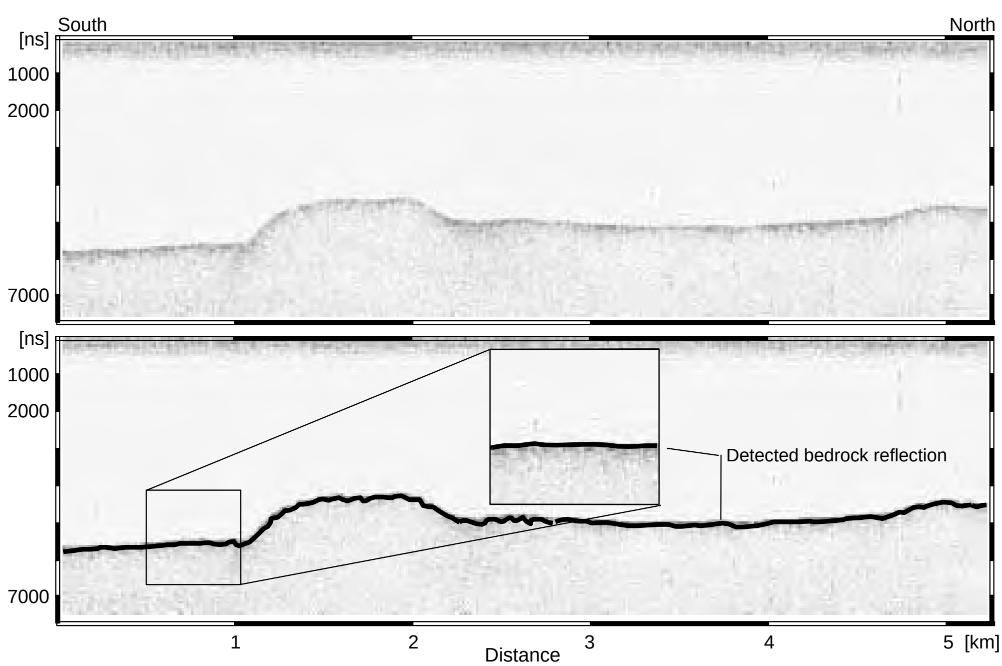

Fig. 1. An example of a digitized profile, northbound N6 in the ice cap dome area – see Fig. 2 for a location map. The two-way time range of the plot is 7765 ns, and the length is 5.2 km. In the upper part of the figure a raw plot of the profile is shown. Below is shown the resulting computer detected bedrock reflection, together with a detail.

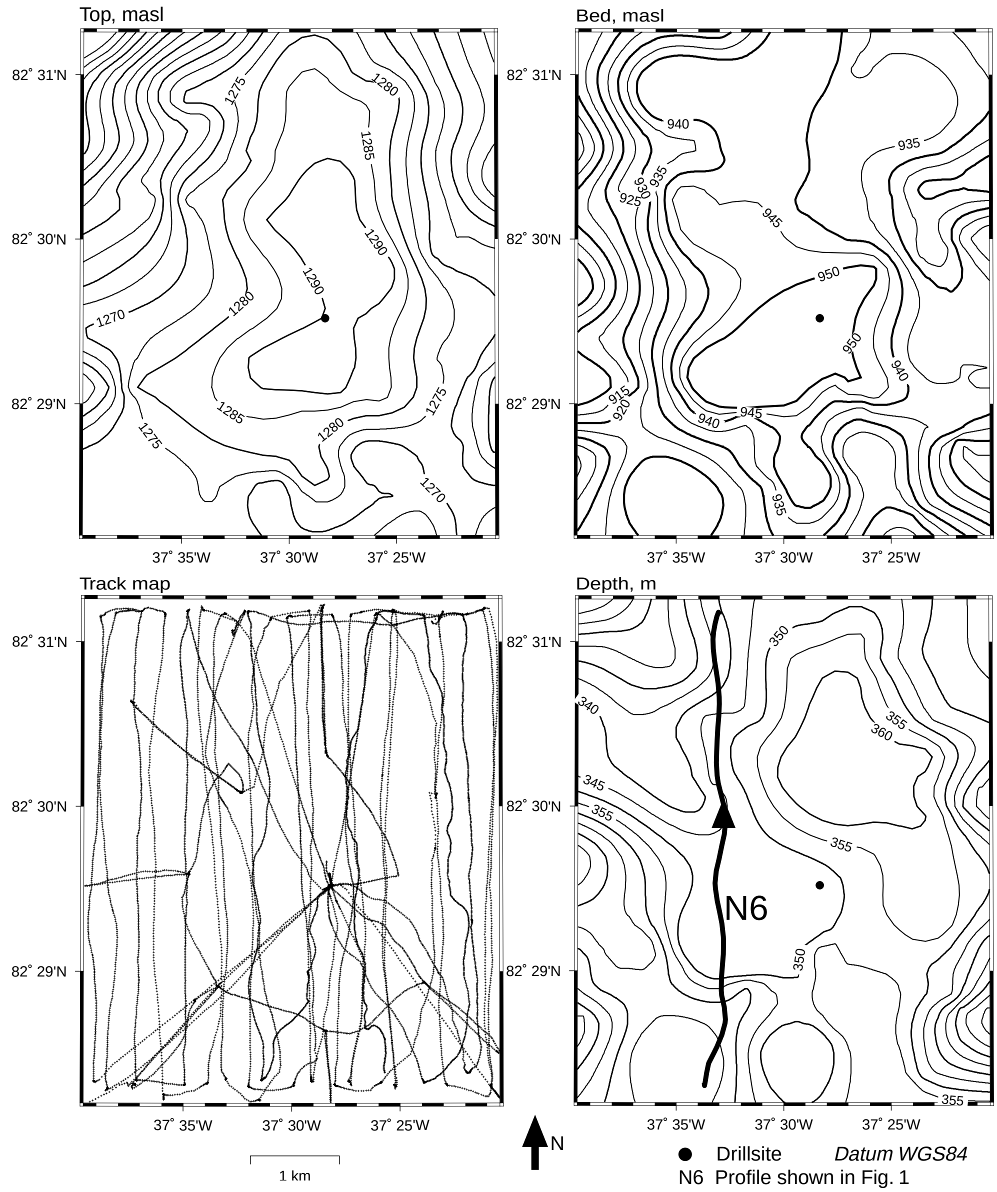

Fig. 2. Result from the evaluation of the measurement in the ice cap dome area. Isoline distance 50 m. The lower left figure shows the surface tracks where profiling was performed, the lower right is the resulting ice depth model (see text). The line N6 in this figure is the location of the profile shown in Fig 1. The upper left figure shows the snow surface elevations from the GPS measurements, while the upper right is the glacier subsurface model, resulting from the elevations and the thickness measurements.

profiles. As a final step, the information in the headers was updated to include the detected time-of-flight to bedrock reflection in nanoseconds. In all profiles, a recorded 100 MHz signal from a calibrator was used to establish the time scale. The result is a database with digitized raw radar scans for each of the two field areas, their corresponding positional data and time of acquisition, and detected bedrock reflex time-of-flight.

To reduce the amount of data, the reflection times were gridded to a lower resolution grid, with divisions of approximately 100x100 m (ice cap data) and 150x150 m (outlet glacier data). The median value of the detected times falling inside a division was used. After gridding, the ice cap data consisted of a database with 8065 entries, whereas the outlet glacier data totals 7203 entries. Each entry consists of a GPS position for the grid division center, the time of acquisition, the height above geoid and the detected bedrock reflex time-of-flight.

To create a model of the subsurface, interpolation with a continuous curva-

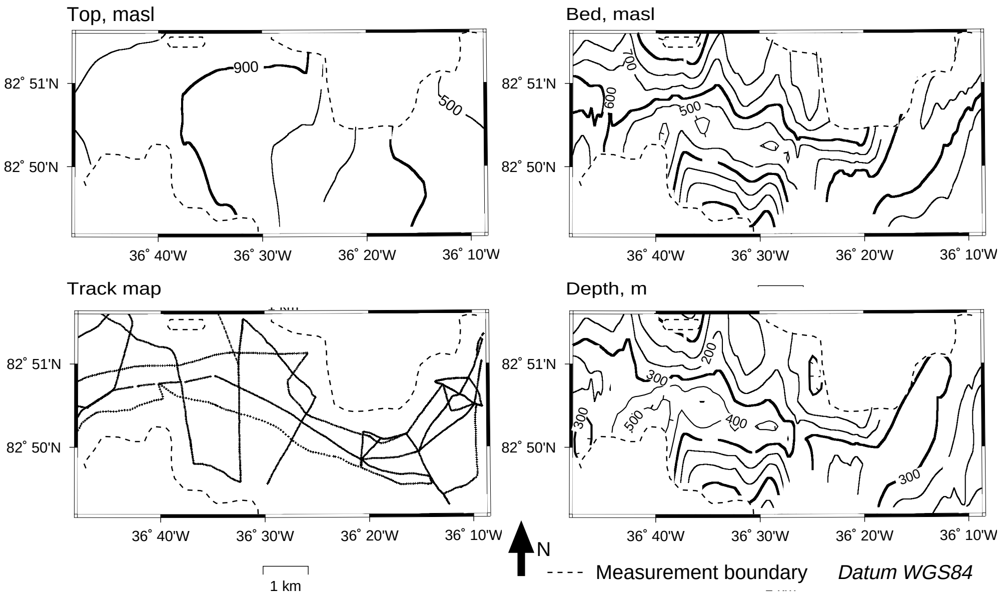

Fig. 3. Result from the evaluation of the measurement in the outlet glacier area. Isoline distance 100 m. The lower left figure shows those surface tracks where profiling was performed, where there was less than 1 km between neighbouring profiles. The lower right figure shows the resulting ice depth model (see text). The upper left figure shows the snow surface elevations from the GPS measurements, while the upper right is the glacier subsurface model, resulting from the elevations and the thickness measurements.

ture method (Smith 1990) was used, which assumed a smooth, relatively level basement under the ice. The interpolated data were then resampled to a regular grid. For conversion between time-of-flight and depth, an average velocity including velocity changes due to ice density variations, of 171±1.5 m/µs was selected rather that the velocity for pure ice of 168 m/µs, based on the compilation of data found in Bogorodsky *et al*. (1985). The used velocity gives a good agreement compared to the depths at the known control points; the core drilling to bedrock on the ice cap by Department of Geophysics, University of Copenhagen, and one hot water drilling performed by GEUS in 1995 (*Thomsen et al.*, 1996). Some profiles on the outlet glacier and some lying perpendicular to the assumed flow line were also measured to zero depth.

By analyzing digitized 100 MHz signals from the calibrator, an absolute timing error of less than ±10 ns was estimated. The error in the detection process was estimated to be ±50 ns, based on observations of signals where the antennae were stationary. These error estimates yield an instrumentation related uncertainty in the reflection times to less that ±60 ns, or ±10 m. The depth uncertainty for the selected mean velocity of 171 m/µs compared to a pure ice velocity of 168 m/µs is less than 8 m at the maximum reflection time.

Results

A detailed depth map has been produced for a 5x5 km area on the ice cap, using measurements taken in 1994. The detected two-way reflection times are here between 3220 ns and 4610 ns. This corresponds, with the assumptions above, to a minimum depth of 275 m and a maximum depth of 395 m. A map of the measured tracks is shown in Fig. 2, together with the calculated ice depths and surface elevations, and the resulting model of the ice subsurface in the 5x5 km area.

Reflection times in the northern outlet glacier area range between 0 and 4670 ns, or 0 and 399 m, respectively. Results for this area are presented in Fig. 3.

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