Direct measurements of ice-shelf bottom melting rates by phase sensitive radar.

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Abstract

This paper describes the novel technique of using a phase-sensitive radio-echo system to determine the basal melt rate along a short profile near Halley Station on the Brunt Ice Shelf. After an interval of nine days the change in the thickness of ice, between a near surface reflecting horizon and the ice-shelf base, was measured. The utilization of internal reflectors as a reference horizon corrects for the effects of accumulation and densification that might occur over the measurement interval. During the nine-day interval the ice shelf thinned by 0.032 ± 0.004 m, the strain rate contribution to this thinning was 0.003 ± 0.001 m, giving a localized melt rate of 1.17 ± 0.17 m/yr. Our measured value agrees well with a traditional continuity method. The accuracy of the phase sensitive radar system allows the spatial variation in basal melt-rate to be measured over a short time interval, permitting for the first time a measurement of the seasonal variation in melt rate

Introduction

Knowledge of the basal melt rate is an important component in mass balance calculation, as it has been estimated to account for more than 20% of the ice mass shed from Antarctica every year (Jacobs and others,1992). However, it is believed that the best estimate of the volume of ice removed by basal melting could be in error by as much as 50% (Jacobs and others,1992). The origin and volume of melt water generated by basal melting is an important consideration for the understanding of the water masses that encircle the continent and indeed the globe (Foldvik, and Gammelsrød, 1988). Another pressing reason for quantifying the spatial pattern of basal melting is in the validation of numerical models that describe the ice-ocean interaction. Direct measurements of basal melting, through boreholes in the ice-shelf, are the most accurate but the difficulty and expense is confirmed by their sparsity. Generally, basal melt-rates are derived from indirect measurements and the conservation of volume relationship from either ice-ocean interaction models or surface glaciological measurements (Jenkins and Doake, 1991). The inaccuracies in velocity, accumulation and strain rates mean that the error in the basal melt rate becomes extremely large if the area of interest, or the measurement interval, is reduced. The technique of using a phase-sensitive radar to measure the change in thickness of an ice shelf is described.

Procedure

The first step in determining the basal melt-rate is to measure the thinning rate of the ice shelf. Our equipment consisted of a network analyzer (HP8751A), configured as a step-frequency radar and a pair of broadband aerials. One aerial was used for transmit and an identical aerial for reception. The aerials have a bandwidth of 150 MHz and centre frequency 300 MHz. The transmit power was 10 mW. The main advantages of using a step-frequency radar are the relatively wide bandwidth (which permits the separation of closely spaced reflectors) and that both the amplitude and phase of the radar echoes can be recorded. The system was deployed on the Brunt Ice Shelf near Halley Station (S75.6^{o}, W26.5^{o}). Ice thickness measurements were taken at 20 cm intervals along a 15 m long profile. After nine days the site was revisited and the same profile was re-measured. Analysis of the two data sets shows there is a remarkable stability in the internal layer signature, or fading pattern. Radar shots from the first visit could be accurately matched with shots from the second visit. Choosing the internal layer signature that occurs between 15 m and 40 m depth we were able to shift, in time, the second visit relative to the first visit until the patterns correlated. This process of time shifting effectively calibrates the radar by moving the phase reference (or time zero) from the surface to a depth of 40 m. Figure 1 shows the amount of correction applied to match the internal layer signature from one pair of repeat-visit radar shots. The radar calibration corrects for the effects of accumulation and near surface densification that might occur between the two visits. For each pair of corrected shots the radar returns from the ice-shelf base can then be directly compared. Figure 2 shows a polar plot (amplitude versus phase) of the two basal echoes from one such repeat visit. The phase difference between the bottom returns is then measured and from solid ice parameters, the change in ice shelf thickness that occurred between the two visits is calculated. In the nine-day interval the average ice thickness change along the profile was 0.032 m. We estimate the accuracy of the method to be $\lambda/133 = 0.004$ m, where λ is the wavelength in ice.

Results

Having obtained a measure of the ice-shelf thinning rate the next step is to apportion this thinning to the appropriate constituents, one of which is the basal melt rate. The classical continuity equation that describes the volume conservation of an ice shelf can be expressed as:

$$\frac{\partial H}{\partial t} + \underline{u} \cdot \nabla H = H\dot{\varepsilon}_z + a_s - m_b$$

where H is the ice thickness, $\underline{u}$ is the horizontal velocity, t is time, ε_z is the vertical strain, and the surface accumulation and basal-melting rates are represented by a_s and m_b respectively (see Thomas, 1973a, for discussion of the assumptions made in the derivation of the formula). The radar measures the Total, or Lagrangian, Derivative of the thickness (*DH/DT*), represented by the left-hand side of the equation. The formula states that the ice-shelf thinning rate is exactly balanced by the sum of the surface accumulation rate, basal melt-rate and lateral spreading. Our measurements, using the phase sensitive radar, of the ice-shelf thinning rate include the non-steady state term, $\partial H/\partial t$, which in most flow line models is assumed to be zero. Since, by calibration, we have also removed the effects of surface accumulation the basal-melt rate is simply the ice-shelf thinning rate minus the lateral spreading rate. Although the value used for the vertical strain rate comes from measurements made almost two decades before our study (Thomas, 1973b), we do not anticipate significant changes as the ice thickness in the vicinity of Halley has not changed over this period. Taking H to be the measured value of ice thickness between our reference horizon and the ice-shelf base, then over the nine day period the ice-shelf thinned through lateral spreading by 0.003 $\pm$ 0.001 m, which accounts for less than a tenth of the total thinning. Therefore, the basal melt rate over one year is 1.17 ± 0.17 m/yr, a value that also agrees very well with the value derived from the flow-line model of Thomas (1973b).

We have presented a novel method of obtaining ice-shelf basal-melt rates by using a phase sensitive echo sounder. The technique explicitly accounts for any non-steady state thickness variations and implicitly removes the need to account for accumulation rates. Since the strain rate of an ice shelf is determined by the creep properties of ice, an ice-shelf will respond relatively slowly to changes to its geometry. Thus, due to the measurement accuracy of our method it becomes possibly to measure seasonal and spatial variations in the basal melt rate.

References

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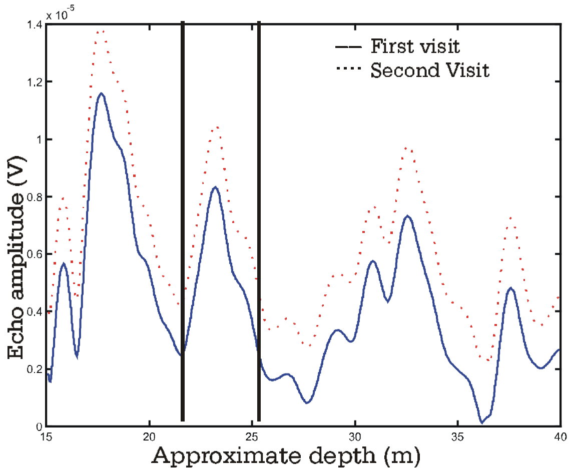
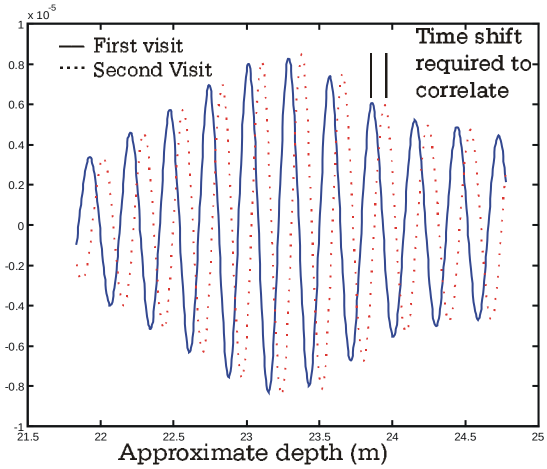
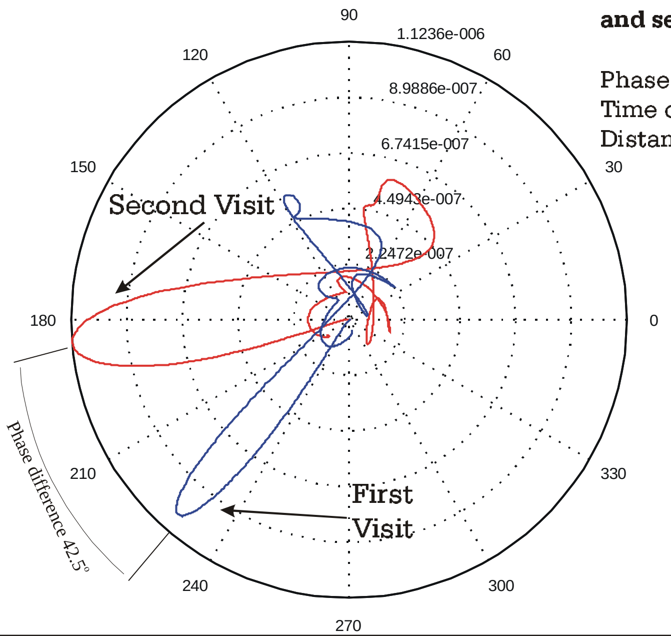
Fig. 1. Calibration of radar by correlating internal layering signature.



1(a). Radar returns from internal layering between a depth of 15 and 40m for one pair of repeat-visit shots. The radar returns have been demodulated and for clarity of display the amplitude of the second has been shifted, relative to the amplitude of the first visit. The similarity between the radar returns is striking. The returns between the vertical lines are shown in more detail in Figure 1b.



1(b). An expanded view of the radar returns from one pair of repeat-visit shots. The radar returns have not been demodulated and show the radar carrier frequency. For maximum correlation between the shots, the returns from the second visit have to delayed (shifted to the left) by 1.1 ns relative to the first visit. The time shift is approximated a distance of 9 cm in solid ice



Difference between first visit and second visit

Phase difference = - 42.5° ± 5.4°
Time difference = 0.39 ± 0.05 ns
Distance difference = 3.3 ± 0.42 cm

Fig. 2. Polar (amplitude/phase) Plot Of Bottom Returns