Interferometric SAR for Observation of Glacier Motion and Firn Penetration

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Abstract

Study of the great ice sheets has been severely constrained by the difficulty of measuring their topographies and flow patterns. Recent successes with satellite altimetry contribute much to topographic measurement in regions with small surface slopes, but encounter difficulties in high-slope areas and do not directly measure flow. Interferometric synthetic aperture radar (InSAR) has made possible measurements of both topography and flow in unprecedented detail.

We present a digital elevation model for a swath in west Greenland above Jakobshavn Isbrae derived from a number ERS-1 interferograms combined so as to reduce phase errors and other problems. The DEM shows a wealth of kilometer-scale, dynamically supported topgraphy, which arises from ice sheet flow over the rough bed. We show a correlation between topography and interferometric phase due solely to ice sheet motion, which clearly shows the translations of scatterers in the surface up- and downslope in the topography. Finally, the low correlation in interferograms of ice sheet dry snow zones motivates investigation the depth-locus of backscattering. We present a scattering model including realistic firn grain size distributions and layering, which shows that layering helps to localize backscattering from dry firn to shallower depths than would otherwise be expected.

Keywords: Inteferometric SAR, ice sheets, flow, penetration)

Introduction

Observations of ice sheet surface elevation and motion are essential for the investigation of ice sheet dynamics and mass balance. Understanding the relations between bed topography, dynamically supported ice sheet surface topography, and large scale ice sheet flow, will require elevation and motion observations with spatial resolutions of hundreds of meters over regions tens to hundreds of kilometers in extent. Such observations are very difficult to obtain by traditional, surface-based methods, but interferometric synthetic aperture radar (InSAR)using the ERS-1 SAR has recently provided an exceptional wealth of data (see, for example, Joughin et al. 1996a, b and c; Rignot 1996; and Joughin et al. 1995).

There is strong evidence that surface topography inferred with the 5.3 GHz, VV-polarized ERS-1 SAR agrees in detail with the true surface topography, to within (at worst) an offset of less than a few meters, for seasonally melting ice facies in Greenland (Joughin et al., 1996a). It is likely, however, that the SAR illumination and locus of backscattering depths extend much deeper in perennially dry firn, both at higher elevations in Greenland and over most of Antarctica. Topographic and motion observations in these latter cases may therefore require understanding of the range of depths contributing to backscattering and the consequences for InSAR correlation and variations in the inferred surface elevation.

Here we first review recent results on ice sheet elevation and motion in Greenland obtained using the ERS-1 SAR, showing especially the relation between km-scale, dynamically supported surface topography and ice sheet motion on that same scale. We then present a few results from modeling the depth distribution of backscattering in perennially dry firn. These latter results suggest that significant backscattering may arise from depths greater than 5 m, and that the polarization dependence of penetration may be significant.

Mapping Ice Sheet Topography And Motion

Complex SAR images of a given surface location obtained on successive orbits are acquired from slightly different locations in space, with offsets in sensor locations ranging from a few meters to hundreds of meters. Thus an interferogram formed from two such images typically displays fringes due both to surface topography and to differential surface motion between image acquisitions (Joughin et al., 1995). By using at least three complex images acquired on separate passes, and assuming that the rates of differential surface motion are constant, we can separately estimate surface topography and relative motion (Joughin et al., 1996a).

Figure 1 shows a map of surface topography in western Greenland, derived from interferometry with ERS-1 SAR data, and draped over an example of the best previously available topographic maps (in this case, that of Simon Eckholm compiled from surface and satellite radar altimetry data). Note that dynamically supported surface topography due to flow over obstacles at the bed is clearly shown in the InSAR map. A detailed comparison of InSAR-derived topography with airborne laser altimetric observations of topography is shown in the lower part of figure 1. Using various combinations of 4 complex images to form interferograms and averaging errors, we found that rms errors in surface topography (assuming the airborne laser data reflect the true topography) could be reduced, in this case, to less than 4 meters.

Figure 2 shows a shaded surface representation of part of the topographic map in figure 1, with the light source directed from the top right. Thus regions with slopes along which tangential surface transport is toward the ERS-1 radar are light, whereas those along which transport is away from the radar are dark. Superimposed on the shaded surface relief are contours of interferometric phase due solely to ice sheet motion. There is a remarkable correspondence between positive phases (corresponding to motion away from the radar) with down-slopes, and vice versa. We conclude that short-scale phase variations at this location, after subtraction of topographic effects, are dominated by the effects of vertical displacement because of the relatively steep incidence angle of the ERS-1 SAR.

A full description of all of these results is provided by Joughin et al. (1996a).

Depth Distribution Of Backscattering In Dry Firn

Modeling the depth distribution of backscattered returns from firn requires knowledge, or assumptions, as to the dominant physical mechanism(s) by which energy is returned to the radar, given the radar polarization, incidence angle, and wavelength. The relative importances at 5.7 cm wavelength (5.3 GHz) of scattering from the rough air/snow interface, from rough interfaces between layers of differing density in the firn, and from individual ice particles or particle clusters in the firn, are not yet clear. But for a start, we (plausibly) model perennially dry firn as a stack of planar layers with random thicknesses (independently exponentially distributed with a mean layer thickness specified below), within which are contained spherical ice particles with a log-normal size distribution at a packing fraction specified by the layer density. The layer density is also random, specifically, Gaussian (independent of the value in any other layer), with a specified depth-varying mean and specified standard deviation. We generate single realizations of such a random medium and compute the backscattering from that realization for purposes of Monte Carlo averaging.

Physically, the backscattering in this model is due to Rayleigh scattering from the ice particles within the individual layers (the density of which requires consideration of dense medium effects). The local illumination in each layer, however, consists of direct (i.e., unscattered) illumination reduced by transmission through layer interfaces above that layer, up-going radiation reflected from the lower interface of that layer, and down-going singly and multiply scattered radiation from layers above that layer. Because each actual, cm-scale layer in firn is optically thin at 5.3 GHz, scattering in each layer is approximated by single scattering of both (previously) unscattered illumination and radiation scattered out of the illumination (and possibly scattered again) in layers above. We use an invariant embedding method applied to Dense Medium Radiative Transfer to keep track of all these interactions. An examination of the strength of multiple scattering events, relative to simple single scattering, is clearly needed and is in progress, but they appear so far to be weak.

Present results showing the cumulative total of backscattering from firn at the surface down to depth d, as a function of d, are shown in figure 3. The numerous traces on each plot are curves for 10 single realizations of firn layering -- the overall mean as well as the spread of individual results is thus shown. The incidence angle for all calculations is 23 degrees and the wavelength is 5.7 cm. The firn parameters in these examples are based on the grain size vs. depth parameterization of Zwally (1977) for Plateau station and layering parameters typical of Dronning Maud Land in the study of West et al. (1996). Full details will be given in a forthcoming journal publication.

Figure 3a shows results for VV-polarization. The first 5 meters of firn contribute at least half of the total, but the increment between depths of 5 and 15 m is significant. This suggests that baseline dependent decorrelation due to firn penetration will be significant for the ERS-1 SAR. Figure 3b shows results for HH-polarization. The effect of polarization is evidently fairly minor, both in this case and in others examined to date, which suggests that dry snow decorrelation due to this mechanism is likely to be similar for ERS-1/2 and RADARSAT interferograms.

Conclusions

Interferometric SAR implemented by repeated ERS satellite passes has now been demonstrated to provide glaciological valuable information on ice sheet surface topography and motion in Greenland. Mapping of perennially dry snow zones in Greenland and Antarctica may involve significant baseline-dependent decorrelation due to backscattering from a range of depths in the firn. If backscattering is indeed dominated by scattering from ice grains but modulated by random, cm-scale density layering, such decorrelation can be expected to be reduced for HH-, as opposed to VV-polarization.

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