DELINEATION OF DISCONTINUOUS PERMAFROST AT SCHEFFERVILLE USING RADARSAT IN INTERFEROMETRIC MODE

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Abstract

The coherence of interferometric synthetic aperture radar (InSAR) is adversely affected by snow added into the radar path between two successive imaging events. This feature of InSAR can be employed to map those parts of open terrain which do not retain snow at a given time of the winter. Differential InSAR can thus be used to identify areas where the difference between average long-term air and near-surface ground temperatures due to insulation by the snow cover is small. In locations where the average annual air temperature is below 0°C, permafrost is usually present in those parts of the terrain where there is no snow retention.

Two RADARSAT InSAR coherence images were computed for the Schefferville Digital Transect. These images show that areas which do not retain snow over the imaging interval can be identified. A comparison with a regional permafrost map produced by the Iron Ore Company of Canada (IOCC) shows a strong spatial correlation between the distribution of high-coherence zones and discontinuous permafrost.

Introduction

A difference, $T_d$, between the long-term average ground surface temperature, $T_g$, and the long-term average air temperature, $T_a$, is observed in snowcovered regions. This thermal offset, $T_d = T_g - T_a$, is a complex function of many variables, however, temporal variations in the properties of the snow cover have a major influence. At Schefferville ($55°N$, $67°W$), the offset varies from zero to about $+10°C$, mainly depending on snowcover conditions. Those parts of the terrain which retain no snow experience a near-zero offset, while areas where the snow cover is protected from wind erosion exhibit the greatest offset. Permafrost is present in areas where $T_d + T_a < 0$. Since at Schefferville $T_a$ is approximately $-5°C$, areas where the value of $T_d$ is less than about $+5°C$ can be expected to exhibit permafrost.

Estimation of the thermal offset caused by the snow cover was an essential component of permafrost prediction which was an important and challenging aspect of the iron ore mining operations at Schefferville. A variety of snowcover mapping methods were used as part of the prediction effort. Initially, snow depth maps were produced by depth probing and linear interpolation (Bonnlander and Major-Marothy, 1964; Annersten, 1964; Barnett, 1963). Snow abrasion scars on the local vegetation were also employed to map snow depth variations spatially (Garg et al., 1973; Garg and Jones, 1974). Abrasion of vegetation by drifting snow occurs particularly at very low temperatures and in a zone just above the snow surface; therefore, abrasion scars are indicative of the depth of snow at the coldest time of the year. Radar backscatter is strongly influenced by the presence or absence of brush vegetation and this allows identification of those areas which experience shallow snow at the coldest time of the year. Woody plants are absent from such parts as a result of strong snow abrasion but probably also as a result of an unfavorable root-zone microclimate and this enables their delineation in airborne HH-polarized C-band SAR images (Granberg, 1994). Aerial photographs of the snow melt sequence may be used to reconstruct the approximate snow depth distribution at the end of the previous winter (Granberg, 1973; Nicholson, 1975) and over the period 1969-1976, aerial photo surveys were flown annually for this purpose. However, the geometry of permafrost is not just related to late winter snowcover conditions. It is influenced by temporal variations in snowcover properties throughout the winter season. These are much more difficult to determine. Field measurements are not practical because of the enormous field effort involved.
To get a better control on the temporal variations in snowcover properties and to develop a snowcover hindcasting capability, GIS-techniques were employed to quantify the relationship between snow cover properties and environmental variables such as topography and vegetation cover (Granberg, 1973; Nicholson and Granberg, 1973). Efforts to spatially model seasonal snow cover properties are still in progress at Schefferville (Granberg and Irwin, 1991). However, such modeling is difficult for several reasons. One major problem is the lack of ground truth for model validation. Another is the large effort required for digitizing the terrain at a level of detail necessary for meaningful snowcover modeling. Interferometric Synthetic Aperture Radar (InSAR) (Zebker et al., 1992; Bamler and Schattler, 1993; Gray and Ferris-Manning, 1993; Vachon et al., 1995) is currently being explored in an attempt to address both of these problems and in this paper we describe how RADARSAT can be used in interferometric mode to map the extent of areas which do not retain snow between successive radar overpasses. This enables identification of those areas which exhibit the smallest thermal offset and which thus are likely locations of bodies of discontinuous permafrost. We assess the potential usefulness of this new technique by comparing two RADARSAT coherence scenes to regional permafrost predictions produced by Garg et al. (1973) and Garg and Jones (1974).

The field area

The field area is the Schefferville Digital Transect (SDT), which has been described in greater detail elsewhere (Granberg and Irwin, 1991; Granberg et al., 1994; Granberg, 1994). It is centered on 54°53'N, 67°08'W, some 30 km northwest of the Schefferville townsite. A wintertime (March) Landsat Thematic Mapper (TM; Band 3) image shows the general distribution of forests (dark) and open areas (white) at the SDT and its surroundings (Figure 1a). At lower elevations lakes and wetlands alternate with forests. A band of alpine tundra runs diagonally from the upper left to the lower right of the image. A second area of alpine tundra occurs in the...
lower left corner of the image. The size of the area covered by Figures 1a to 1d is approximately 12 by 18 km.

**Interferometric synthetic aperture radar**

A single-look complex image, calculated using a phase-preserving SAR processor, contains information on both the amplitude and the phase-angle of the radiation backscattered from each resolution element. The phase angle varies from 0 to 2\(\pi\) over one wavelength (which for RADARSAT, a C-band radar, is 56 mm), so the phase angle in a single image behaves essentially as a random variable and carries no apparently useful information. An image produced from the phase angle information has a uniform "pepper and salt" appearance. If, however, two SAR images, obtained from slightly different positions, are precisely co-registered, then the difference between the respective phase angles will usually show spatial order (Figure 2a). The banded appearance of such an image is due primarily to the difference in viewing geometry which adds a constant slope. This constant slope can be removed. The remaining phase angle differences (Figure 2b) resemble map contours, for they are mainly related to topographic variations seen from two slightly different vantage points. Digital elevation models (DEM) can be produced by phase unwrapping (Goldstein et al., 1988) but they are more or less noisy, for there are additional influences on the exact phase angle differences. Slight displacements of the reflecting surface, due to frost-heave, lake ice growth, moisture variations in the soil surface layer and swaying of trees also influence the difference in phase angle. In addition, variations in electron density in the ionosphere and variations in the amount of mass present in the radiation path influence the speed of the radar wave and, hence, the phase angle at the receiving antenna. One particularly important source of such variation is the accumulation of snow between successive imaging events.

**Ice and snow and radar wave propagation**

When dry, ice is transparent to C-band radiation. Therefore, the backscatter in a winter scene is from the underlying ground surface rather than from the snow cover and, accordingly, the radar wave passes through the snowcover twice on its return trip from the antenna to the reflecting surface. The refractive index of ice is 1.79 at C-band; therefore the radar wavelength is compressed to 56/1.79~31.3 mm in ice. Available data on the relationship between the dielectric properties of dry snow and its density (Hallikainen et al., 1986) show that the resulting phase-shift, as snow is added into the path of C-band radiation may, without much error, be regarded as a linear function of the mass added. To string out \(n+1\) wavelengths in vacuo for the equivalent distance, \(d\), requires a value of \(n\) of about 1.26, giving \(d=1.26\times56\approx71\) mm. Thus, the change in water equivalent, that would cause a full phase shift during the return passage through the snow cover, is equal to 0.5 (for two passes)*\(d\)*density of ice = 0.5*71*0.917=32.6 mm at vertical incidence. If uniform or only gradually varying spatially, snow accumulation would just result in a falsified topography. Depending on orbit differences, one full phase shift can represent from a few meters to a few hundred meters of topographic distortion. However, in the windy environment of Schefferville, snow accumulation is never uniform and therefore it additionally causes local variations in phase-angle shift, quantifiable by a statistic called interferometric phase coherence or just coherence, for short. It represents essentially the root mean square of the local variations in phase angle difference.

**Snow accumulation in forest-tundra**

In the forest-tundra environment near Schefferville, snow accumulation patterns are controlled by strong winds that accompany the snow storms. Zones of
locally greater wind speed, notably ridge crests, experience a continual loss of snow due to wind erosion and remain very nearly devoid of snow throughout the winter. The snow accumulation sequence is controlled by interactions between the wind and local surface roughness, so that initially the first few centimeters of snow that fall are retained by the surface roughness. However, areas lacking vegetation, such as ridge crests, quickly become aerodynamically smooth and cease to retain snow. Instead, the snow is transported along the surface, often as migrating snow dunes, and accumulates at the downwind edge of the smooth areas which, accordingly, grow in the downwind direction. Little or no further accumulation occurs in areas which have become aerodynamically smooth. Because the snow is fragmented during the drift transport, the number of intergranular bonds that form per unit volume is very large. Therefore, the accumulated snow quickly becomes quite hard and is not easily eroded by subsequent winds of other directions. The downwind edges of the smooth areas often drop off sharply, causing zones of boundary layer separation to form. In such zones the sharply diminished surface wind stress locally reduces wind erosion to values close to zero, creating very efficient traps for drifting snow. As long as such traps are common, the distance over which the drifting snow is transported is relatively short. Eventually, however, as they grow outward, adjacent smooth areas begin to merge and when this occurs, snow traps are reduced in number. Snow drifting over a longer distance becomes possible. This further accelerates the accumulation rates at the remaining snow traps and soon the whole alpine tundra becomes aerodynamically smooth. Once this occurs, the snow accumulation changes character. In the absence of efficient snow traps, the transport distance increases and snow fragmentation becomes more complete. This results in a harder snow deposit. It also results in a more gradual variation in snow accumulation across the terrain. Ridge crests still remain snow-free, but there is a gradual increase in snow accumulation from ridge crest towards valley bottom.

In forested parts, the aerodynamic roughness created by the trees diminishes the surface wind stress sufficiently to largely prevent snow drifting. However, trees intercept the falling snow which is later shaken off the crowns, giving much less snow accumulation directly beneath the trees than in the spaces between them. The rather uneven accumulation that results consists of snow of very low density because the minimal wind action leaves the original snow crystals largely intact.

**Radarsat coherence results**

RADARSAT interferometric coherence images were computed from two successive image pairs, the first from December 1 and 25, 1996 (Figure 1b) and the second on February 28 and March 24, 1997 (Figure 1c), both in narrow-beam mode. Methods outlined by Vachon et al. (1995) were followed. Snow accumulation is rendered visible by InSAR coherence which in the two images varies from 0 (black) to 1 (white) representing low and high coherence respectively. Zones with little or no snow accumulation are identifiable as areas where coherence is preserved, while elsewhere snow accumulation reduces coherence to low values. Over the 24-day RADARSAT imaging interval the average snowfall water equivalent is about 38 mm, which at Schefferville is more than sufficient for a complete loss of coherence (Vachon et al., 1995). The exact nature of the relationship between snow accumulation and coherence may vary somewhat, depending on weather and local terrain conditions. However, for the present application, it suffices to note that areas where there has been very little change in snowpack water equivalent can be precisely identified by their high coherence.

Both images exhibit low coherence in the lowland, forested areas. However, coherence is well preserved in the aerodynamically smooth ridge crest areas of the alpine tundra, where snow retention has ceased. In the first image the zones of high coherence are relatively narrow but in the second image they have widened considerably. These patterns of coherence are consistent with the snow accumulation model outlined above, showing that InSAR coherence can be used to map areas where snow has not accumulated between radar overpasses. To assess the potential usefulness of such mapping in permafrost delineation, we will compare the patterns of coherence observed in the RADARSAT images to a regional permafrost map (Figure 1d) produced by the Iron Ore Company of Canada (Garg et al., 1973; Garg and Jones, 1974). This map was produced by air photo interpretation and field observations of snow abrasion effects on the vegetation cover and validated against available thermocable and trenching data. It was intended for use in the planning of exploration activities and was designed to include areas where ground frost might remain until late in the summer season. The amount of frozen ground shown by the map may therefore be somewhat greater than the amount of permafrost present.

Although the original map was produced using methods of data transfer that were not very precise (Sketchmaster, few control points), there is nevertheless considerable similarity between the interferometric coherence images and the permafrost map. The general distribution of areas of little or no snow retention depicted by the coherence images corresponds well to the permafrost areas of the IOCC map, although in the latter there are some areas where permafrost is indicated but where the InSAR imagery would suggest that...
snow accumulates both in December and in March and that therefore the snow cover should be adequate for prevention of permafrost. Field measurements will be needed to resolve whether the coherence images or the map is correct.

Conclusions

InSAR coherence is a useful new tool for studying snowcover dynamics. It enables mapping of areas where snow did not accumulate during the time interval spanned by the interferometric image pair. Combined with climate data, a sequence of such coherence images, obtained at different times during the snow season (ideally of several winters) provides a new tool for high-resolution mapping of discontinuous alpine permafrost.

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References


