Field verification of SAR wet snow mapping in a non-Alpine environment

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ABSTRACT

Snow covered area is an important variable in snowmelt runoff modelling. Methods have been developed for mapping wet snow cover in alpine basins using SAR. This paper discusses the applicability of this method to a non-alpine basin, specifically the Spey in Scotland. The methodology is briefly described and differences between applying it to alpine and higher latitude basins are highlighted. Field observations and measurements collected during an ERS pass in March 1998 are used to identify a suitable threshold for detection of wet snow. The results of wet snow detection over the whole basin are presented. These accord with field observations. Detection is constrained by areas of missing coverage caused by relief. The extent and elevation dependence of missing coverage are quantified. While rapidly changing snow conditions limit the application of the method in the Spey it should prove more viable in other non-alpine basins having greater and more stable snow cover.

INTRODUCTION

The HYDALP project aims to use Earth Observation (EO) data to improve the monitoring and forecasting of snowmelt runoff from alpine and higher latitude basins, and to prepare a basis for the operational use of this information. A crucial variable in snowmelt runoff modelling is snow covered area (SCA). Optical EO methods have previously been developed for mapping SCA but their application to basins of interest is often limited by cloud cover. Cloud cover does not affect synthetic aperture radar (SAR) which has previously been used for mapping *wet* snow cover in alpine basins [1]. Total SCA must then be inferred from wet SCA. An objective of HYDALP is to determine the applicability of these methods to higher latitude basins. This paper assesses the generality of the SAR wet snow mapping method by applying it to such a basin, specifically the Spey basin in the Scottish Highlands (57° N 4° W, area 1271 km^2, and elevation range 198 to 1288 m).

The nature of snowpacks in the Scottish Highlands

The nature of snow accumulation and ablation in the Scottish Highlands is quite different from that in the Alps. Methods developed for the latter may not work in the former where snow tends to be transitory, is often thin and unevenly distributed and can change greatly in depth and extent. In addition, the snowpack can experience many melt-thaw cycles during a winter. These create buried crusts and ice lenses within the snowpack which may affect the backscatter response of dry snow. The backscatter change due to wet snow may be reduced by boulder and vegetation protrusions and snow patchiness even at the start of the melt season.

The main melt period in the Scottish Highlands occurs during March and April when low sun angles result in low melt rates (2 to 3 cm/day) from short wave radiative forcing, although energy may be advected into the basin by low pressure systems at any time of the year. This energy advection allows frequent melting to occur during the winter, such that it is highly unlikely that a homogeneous dry snowpack will develop at any stage during snow cover accumulation and ablation. A further characteristic of snowpacks in the Scottish Highlands is a significant likelihood that the snow cover rests on a wet or even saturated substrate. This is due to the wet climate, low slope angles and poorly drained soils found in the area.

Outline

We first briefly describe the SAR wet snow mapping method. The problems of missing coverage caused by layover and other geometric effects due to relief are highlighted. The results from fieldwork conducted during an ERS pass in March 1998 are then described. These are used to identify a suitable threshold for detection of wet snow. The results of wet snow detection over the whole basin are then presented. Detections are limited by areas of missing coverage. The area affected, its elevation dependence, and consequences are quantified.

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THE SAR WET SNOW MAPPING METHOD

At C-band (5.6 cm) the radar backscatter from a surface is usually reduced when it is covered by wet snow. By comparison, dry snow is transparent at C-band and has little effect on the backscatter from the underlying surface. Thus wet snow can be detected in a C-band SAR image by comparing calibrated backscatter values, pixel by pixel, with those in a reference image from a period of no or dry snow cover. This is done by ratioing the two images and then thresholding. For wet snow detection in alpine areas a threshold of less than or equal to -3 dB is applied to intensity ratios derived from ERS C-band images [1,2]. A major aim of this paper is to determine whether this threshold can be used to detect wet snow in a non-alpine basin and if not what threshold should be used instead.

As backscatter is dependent on the local incidence angle the imaging geometry must be exactly the same in the wet snow and reference images. Such repeat pass SAR image pairs are provided by the ERS series of satellites and by Radarsat. Registration of repeat pass images requires only translation. Prior to ratioing, images are filtered to reduce the effects of speckle.

The Effect of Relief

In areas of high relief, such as those studied in HYDALP, areas of missing coverage arise in SAR images due to layover and radar shadow. As the intensity ratio method for wet snow detection performs poorly at local incidence angles less than 17° and greater than 78° we also class such areas as *missing coverage* [2]. The lower bound is due to foreshortening and specular effects at low incidence angles and the upper bound is due to poor signal to noise ratio at grazing angles.

It is possible to appreciably reduce missing coverage by combining images of a scene taken from different viewing directions, e.g. images from the ascending and descending passes of a spaceborne SAR. Image combination is based on the optimal resolution approach (ORA) and is applied between the ratioing and thresholding operations [3]. It requires prior geocoding of both ratio images to an accuracy of one pixel and calculation of the local incidence angle at each pixel in the two geocoded ratio images. The combined ratio image is formed by selecting each pixel value from the ratio image with the greater incidence angle (i.e. finer ground range resolution) at that point, except in areas of shadow/grazing where the non-shadow/grazing value is always chosen, if it exist. Areas with missing coverage in both passes are masked out and are excluded from further analysis.

Temporal Constraints

For the ORA combination to be used for wet snow cover detection both images must be taken close together in time during a period of little change in snow conditions, e.g. 2 to 3 days in the Alps. For ERS the minimum lag between ascending and descending passes is half a day. This occurs over the Alps, where the wet snow detection method has previously been applied. For the higher latitude basins in Scotland and Sweden studied within HYDALP, the time lags are respectively 1.5 and 6.5 days, during which snow conditions can change substantially in the respective basins. Hence, inferences on wet snow covered area based on ascending/descending pass combinations can be less valid than in the Alps.

APPLICATION TO NON-ALPINE BASINS

ERS images have been regularly acquired to monitor wet snow cover in the Spey basin during the 1998 melt season (January to May). Fieldwork was conducted to coincide with an ERS descending pass at 11:16 on 11 March 1998 (frame/track 2457/223). There was also an ascending pass over the basin one and a half days later at 22:10 on 12 March (1143/244). No coincident fieldwork was conducted for this night-time pass.

Planning and Execution of Fieldwork

Criteria for Choice of Fieldwork Area
The site used for fieldwork had to satisfy two main criteria: 1) the need for a diverse range of slopes, elevations and aspects; 2) the need for wet and dry snow to be present within the site to permit the signatures of both to be characterised. Additionally, the site needed to be reasonably accessible, easy to traverse and safe. Prior to the fieldwork neither the extent of the snowpack nor the level of the freezing line were known. Hence a number of potential survey routes were planned for a suite of likely snow cover conditions on the day of the fieldwork.

Development of the Winter Snowpack
The very mild winter of 1997/98 prevented the development of an extensive seasonal snowpack in the Spey basin, so that two weeks before the start of the proposed fieldwork there was almost no snow in the catchment. However, an extensive snowfall event did occur between 2-3 March which resulted in the whole of the Spey basin receiving some snow. A thaw over the weekend of 6-8 March caused the removal of snow from lower areas of the basin, but westerly winds induced drifting at higher altitudes.

The Area used for Fieldwork
Snow conditions dictated that the only viable survey traverses were those radiating from the Cairn Gorm Ski Centre. The ski area itself was avoided because backscatter is likely to be affected by the ski lifts and snow fences. Snow cover observations were taken along transects covering: the Coire an t-Sneachda sub-basin; the vicinity of Cairn Gorm summit, and the Coire Laogh Mór sub-basin.

Fieldwork Observations
Observations were taken over a range of elevations and aspects along the three transects. The observations taken included GPS-derived position, elevation, slope, aspect, snow depth, the extent of snow, protruding vegetation and bare ground, the depth of wet snow horizons and underlying vegetation type. A number of qualitative observations were also made: snow surface hardness, snow/vegetation/soil thermal state (frozen, dry, wet), the presence of saturated soils underlying the snow cover and the presence and characteristics of snow surface windforms. These measurements were used to characterise snow cover conditions within 100×100 m survey sites along the three traverses. The size of the sites was considered to be representative of post-processing SAR image resolution.

The snow depth, hardness and wetness characteristics were sampled at 5 points within each site. Sampling involved following a checklist which only allowed the estimates of snow, vegetation and bare ground extents to be placed into 5 categories (1-20%, 21-40%, 41-60%.......). Although this reduced the resolution of the potential extent estimates, the procedure will have reduced user-based variance considerably. Photographs were also taken in areas below the cloud base.

Timing of Fieldwork
Surveying was planned to coincide with the SAR descending pass at 11:16. Poor weather conditions resulted in a late start to the surveying (due to closure of the access road) and significantly affected navigation once the surveying had begun. As a result, observations were collected between 10:30 and 14:45 with only 38 sites being characterised over this interval.

Fieldwork Results

Here we just summarise the results of fieldwork. A more detailed description is given in [4]. Missing coverage affects 13 of the 38 sites on one or other pass (6 layover, 1 radar shadow, 10 foreshortening). These are excluded from analysis, leaving a remainder of 25 sites.

Elevation
The sites range between 531 and 1208 m with most (20) concentrated between 600 and 900 m. Of the remainder, 3 sites lie above this range and 2 below.

Aspect and slope
A limited number of slopes were covered. All sites but one are distributed between NW and NE aspects and slope angles of 7° and 21°. Within these bounds the distribution of aspect and slope is fairly uniform.

Local incidence angle
In both the descending and ascending images local incidence angles at field sites are uniformly distributed between 20° and 41°.

Snow extent
During fieldwork the snowline lay at around 500 m. Of the sites visited, 75% were occupied by a continuous snow cover (with only minor vegetation and boulder protrusions above the snow surface), 20% were occupied by a discontinuous snow cover (with more extensive vegetation and boulder protrusions as well as significant bare ground exposures), whilst 5% were occupied by a sporadic snow cover.

Temperature
Lapse rates derived from data from Cairn Gorm summit (1245 m) and Aviemore (210 m) meteorological stations predict that the freezing line rose from 445 m to 545 m during the survey period. Based on this, no sites were above freezing for the descending pass when the temperature at Cairn Gorm summit was -5°C.

Early on 12 March the temperature rose sharply and a rapid thaw set in. The temperature at Cairn Gorm summit remained around 0° from 11:00 through to the time of the ascending pass at 22:10. Hence, it is likely that the snowpack was wet at all levels for this pass.

Snow depth
Mean snow depth varied between 5 cm and over a metre. Analysis revealed only a weak correlation between snow depth and elevation. This is indicative of the complexity of the snowpack. The limited range of slopes and aspects covered preclude an analysis of snow depth against these characteristics.

The depth of melt between the descending and ascending passes was calculated based on the lapse rates between the Aviemore and Cairn Gorm summit meteorological stations, a melt factor of 6 mm per degree per day and a snow density of 0.3 g cm^{-3}. This gave 5 cm of melt at the lowest site reducing linearly to almost zero at the highest. During fieldwork the snow cover was noted to be as thin as 5 cm over parts of some sites, hence we would expect the lower of these areas to be no longer covered by snow for the ascending pass.

Thermal state
Dry/frozen conditions were found at the 12 sites above 704 m, while wet conditions were found at the 4 sites below 632m. In the intermediate zone (9 sites) an almost equal mix of wet and dry conditions was found. These observations imply that the actual freezing line is higher than that estimated from meteorological data.

Analysis of intensity ratios

Intensity ratio images were formed by dividing the 11 and 12 March images by corresponding repeat pass images taken towards the end of long dry periods in the summer (9 Aug. 1995 and 19 June 1996 respectively).

Elevation dependence
Fig. 1 (at end) plots the intensity ratios in the descending and ascending images against elevation for each site. The error bars represent one standard deviation (SD) of the intensity ratio. This was calculated based on the assumption that intensities are gamma distributed with an equivalent number of looks *n* determined by the amount of smoothing. For the data analysed here a 2×2 pixel block average was first applied to reduce correlation. This changes the original 3-look data to approximately 5 equivalent looks. A 5×5 pixel Frost filter was then applied to give a maximum of 125 equivalent looks. The SD of a gamma distributed random variable transformed to a dB scale is given by

$$\sigma = \frac{10}{\ln 10}\sqrt{\psi'(n)}, \quad (1)$$

where $\psi(\cdot)$ is the digamma function. Hence, the SD of the difference of two such random variables, i.e. the SD of the ratio of two intensity values transformed to a dB scale, is given by $\sqrt{2}\sigma$. For n=125 the SD is 0.55.

In Fig. 1, there is no simple pattern of variation of intensity ratio against elevation for either pass, particularly at mid elevations between 600 and 900 m where the intensity ratio is highly erratic. If the intensity ratio behaved the same as in alpine areas, we would expect all sites above the freezing line to have values around 0 dB (i.e. all but the lowest sites in the descending image), and all sites below it to have values of -3 dB or less (i.e. the remaining sites in the descending image and all sites in the ascending images).

There does appear to be a broad correlation between the intensity ratios in the descending and ascending images, but this is not evident from any one site: at some the intensity ratio decreases between the descending and ascending passes while at others it increases. If we define a significant change as being greater than 2σ (1.1 dB) we can classify the sites into those exhibiting a significant increase, a significant decrease and no significant change. Above 856 m the majority of sites exhibit a significant decrease; indicating a change from dry to wet snow. Below 619 m the majority of sites exhibit a significant increase, possibly due to a decrease in the area covered by wet snow due to melting. The area between these elevations partially corresponds with the transition zone between dry and wet snow conditions. While all three classes occur within this area, the majority of sites exhibit no significant change.

Histograms
Interpretation of the results becomes clearer when histograms of the intensity ratios are examined. Fig. 2 shows histograms of the intensity ratio measured at field sites in the descending and ascending passes. The descending pass histogram has a main peak at 0 dB and a secondary peak at -4 dB. The ascending pass histogram has equal sized peaks at 0 dB and -3 dB.

These histograms accord with observations from both fieldwork and studies in alpine areas. The histograms are clearly bimodal with peaks occurring at data values associated with no-change (0 dB) and wet snow (-3 to -4 dB). Also, going from the descending to the ascending pass there is a marked increase in the latter peak, which we associate with wet snow, corresponding with an expected increase in the wet snow area.

Threshold selection
The dip in both histograms at around -2 dB suggests that this could be a suitable choice of threshold for wet snow detection. To investigate this further, thresholds of -3 dB up to -1 dB were applied at intervals of 0.5 dB. Detection occurs when the intensity ratio is less than or equal to the threshold. Fig. 3 plots the thresholds at which sites are first detected against elevation.

With a -3 dB threshold, as used in the Alps, only four

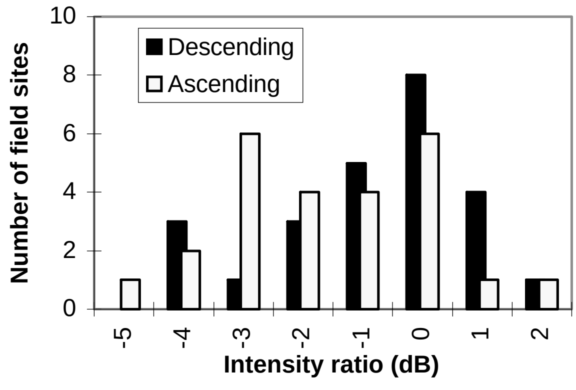

Fig. 2: Histograms of the intensity ratio (dB) for the descending and ascending passes (bin size 1 dB).

sites are detected in the descending image (elevation range 550 to 757 m) and five in the ascending (684 to 1208 m); one site is detected in both. At -2.5 dB just one extra site is detected in the descending image (664 m) while this and three other sites are detected in the ascending (664 to 1187 m). At -2 dB no extra sites are detected in the descending image and two in the ascending (688 and 747 m). At higher thresholds similar number of sites are detected in both images.

The fact that twice as many sites are detected at or below -2 dB in the ascending image than in the descending image and that detected sites in the ascending image span a higher and greater range of elevation (664 to 1208 m) than those in the descending image (550 to 757 m), corresponds with the greater extent and elevation range of wet snow at the time of the ascending pass. However, if wet snow is the cause of backscatter change, it appears, particularly from the ascending image, that not all sites within the same elevation range are detected as wet snow even though snow is known to lie at these sites. We investigated whether this was due to differences in snow depth. Scatterplots (not shown) of intensity ratio against snow depth failed to reveal any relation between snow depth and intensity ratio.

The Effect of Local Incidence Angle

A possible alternative explanation is that intensity ratios contain some remnant effect of incidence angle. Ratioing of the snow and reference images removes the geometric effect of topography as long as registration is precise. However, as backscatter is dependent, amongst other things, on the local incidence angle, there should be some correlation between the intensity of the reference and snow images and the local incidence angle. These relations were checked for the field sites using linear regression. The reference image intensity (dBs) and the local incidence angle (degrees) generated R^2 values of 0.28 and 0.54 respectively for the descending and ascending images. The corresponding values when intensity ratio was plotted against local incidence angle were 0.09 and 0.19. These results confirm that there is some correlation between the reference image intensity and the local incidence angle and little, if any, correlation between the intensity ratio and the local incidence angle.

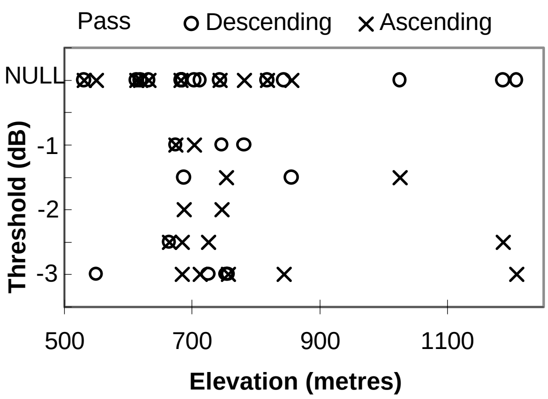

Fig. 3: Elevation dependence of detections. Sites are plotted where they are first detected as the threshold is raised. NULL indicates undetected sites

Wet Snow detection in the Spey Basin

To detect wet snow over the whole of the Spey basin the -2 dB threshold was applied to the intensity ratio images derived from the descending and ascending passes. Wet snow was detected over 50 and 161 km^2 respectively in the descending and ascending images (5 and 15% of the imaged basin area). The greater area detected in the ascending image accords with fieldwork observations and meteorological data. Note: the descending and ascending passes cover slightly different parts of the basin (968 and 1053 km^2 respectively). In both cases part of the western end of the basin is not imaged. However, the distribution of imaged basin area by elevation is similar for both.

The elevation distribution of wet snow is plotted in Fig. 4. It shows the distribution of imaged area in 100 m elevation bands (right axis) and percentage area of wet snow detected within each elevation band (left axis) for both passes. The area within each elevation band steadily decreases as elevation increases. 48% of the basin lies above 500 m but less than 2% lies above 1000 m.

For the descending pass, wet snow never covers more than 12% of an elevation band and is centred around 500 to 800 metres with little wet snow detected above

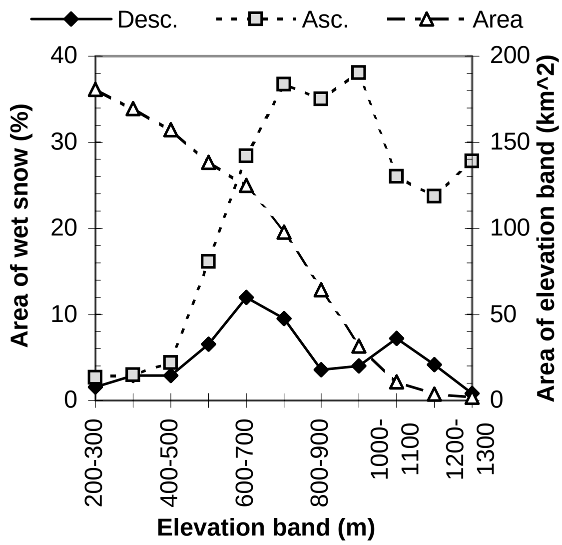

Fig. 4: Distribution of imaged area by 100 m elevation bands and percentage area of snow detected within each elevation band (-2 dB threshold).

or below this range. This accords with field observations of a 500 m snowline with wet snow up to 800 m.

For the ascending pass there is considerably more wet snow at all elevations at or above the snowline and it is also more evenly distributed across these elevations. This accords with the freezing level being around the highest summits and a thaw occurring at all lower elevations at the time of the pass.

A comparison of the results from both passes with land cover information revealed that backscatter changes detected at elevations below 400 metres are mainly due to wind effects over open water or agricultural activity rather than wet snow. Such areas need to be masked out prior to estimation of wet snow covered area.

THE EFFECT OF MISSING COVERAGE

We have already noted that geometric effects such as layover and foreshortening generate significant amounts of missing cover in ERS SAR images of areas of high relief. While this can be reduced by combining descending and ascending images the rapid changes in snow conditions occurring in the Spey negate the validity and utility of any such combination. Hence, any interpretation of SAR wet snow maps of such basins must take the area affected by missing coverage into account. We quantify this below. Results are also given for the Tjaktjajaure basin in northern Sweden (67° N 17° E, area 2249 km^2, elevation range 450 to 2058 m) which is also being studied within the HYDALP project.

The missing coverage in a number of ERS scenes covering the two basins was determined using SAR image simulations and local incidence angle maps derived from DEMs with a planimetric resolution of 50 m. These were used to generate layover, radar shadow, foreshortening and grazing masks. Table 1 (at end) lists the total area of missing coverage due to geometric effects, and the breakdown into areas affected by layover, radar shadow, foreshortening and grazing.

Within each scene the predominant source of missing coverage is foreshortening (between 67% and 85% of the total area of missing coverage) though layover is also significant (between 33% and 50%); note there is some overlap in the area affected by these two effects. Compared to layover and foreshortening the areas affected by radar shadow and grazing angles are insignificant (less than 0.12%). This is as we would expect given the steep look angle of the ERS SAR.

The total amount of missing coverage varies between 11.4% and 21.4% of imaged basin area. These are appreciable areas which any image classification must take into account. The variation in area is due to the range position of the basin within the scene and the spatial distribution of relief within the basin. At near range, where the incidence angle is steeper, layover and foreshortening increase while radar shadow and grazing decrease. The effect of the spatial distribution of relief is apparent in the descending and ascending scenes 257/495 and 1143/15. In both scenes the Spey basin is imaged at mid range but the roughest topography is in the south east of the Spey. Hence, as the ERS SAR views to the right, more missing coverage occurs in the descending scene than in the ascending scene.

The scenes of Tjaktjajaure exhibit approximately the same proportion of missing coverage as those of the Spey, even though the elevation range is 50% greater. This indicates that missing coverage is dependent more on the spatial distribution of relief than elevation range.

Whenever descending and ascending scenes of the Spey basin are combined the missing coverage can be reduced to only 5.77 km^2 (scenes 1143/15 and 2457/495) and 4.26 km^2 (scenes 1143/244 and 2457/223), i.e. less than 0.5% of the basin. However, as already noted, such a combination is only useful when snow conditions remain stable over the one and a half days between acquisition of the two images. While this may occur during a cold period of no snow melt, it is by definition, less likely to occur during melt periods which are of interest for hydrological modelling as is illustrated by the scenes analysed in previous sections.

Elevation Dependence of Missing Coverage

As snow cover is elevation dependent, the elevation dependence of missing coverage must also be considered. Fig. 5 plots the area of the Spey basin within 100 m elevation bands, and the percentage area of layover, foreshortening and total combined missing coverage per elevation band for one of the ERS scenes.

While missing coverage affects 17.5% of the basin as a whole there is a marked variation with elevation. Below 400 m, missing coverage affects at most 12% but at certain mid to high elevations it affects more than 20% and reaches a maximum of 25% between 1000 and 1100 m. The cause of missing coverage also varies with elevation. Missing coverage is mainly due to foreshortening at mid elevations and layover at high elevations. The reason for this difference is due to the rounded topography, with the steepest slopes occurring at mid elevations and a plateau at higher elevations. In terms of total area, missing coverage most affects mid elevations with foreshortening being the primary cause. This is a consequence of the decrease in the total area within elevation bands as elevation increases.

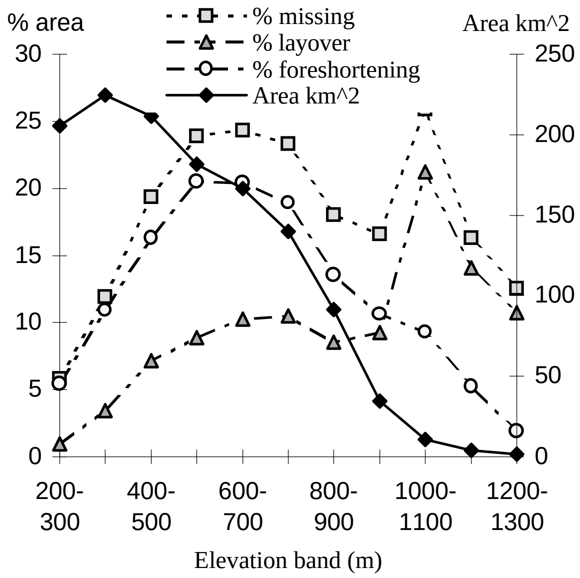

Fig. 5: Area of the Spey basin within 100 m elevation bands, and percentage area of layover, foreshortening and total combined missing coverage per elevation band occurring in ERS scene 2457/495.

Similar patterns of elevation dependence of missing coverage were observed to differing degrees in the other scenes. In certain cases the area of missing coverage was as great as 50% at particular elevations.

The Effect of Incidence Angle on Missing Coverage

An alternative solution to the problem of missing coverage is to image the scene at a less steep incidence angle. The near range incidence angle in an ERS scene is about 19°. With Radarsat (and ENVISAT) it is possible to increase this to 40°. Table 2 shows how such an incidence angle would affect missing cover in two of the scenes listed in Table 1. Layover and foreshortening are now reduced to less than 1% of the basin area. Radar shadow and grazing increase but the total area of missing cover is no more than a few percent.

CONCLUSION

An intensity ratio method developed for detecting wet snow in repeat pass SAR images of alpine areas has been tested on ERS images of a non-alpine basin, the Spey (Scotland). Intensity ratios derived from an ERS descending pass exhibit erratic behaviour when compared with coincident field observations including snow depth, wetness and elevation. For the intensity images of the Spey, a threshold of -2 dB was identified as considerably more suitable than the -3 dB previously used in alpine areas, for distinguishing areas of wet snow cover from areas of no or dry snow. The -2 dB threshold was applied to intensity ratio images of the whole

Table 2: Percentage of the Spey and Tjaktjajaure basins affected by missing cover when imaged with a near range incidence angle of 40°.

Frame/Track	Foreshort.	Layover	Shadow	Grazing	Total
1143/244	0.91	0.56	0.29	0.20	1.74
2241/251	0.28	0.42	0.86	0.66	2.11

basin. It detected a band of wet snow at mid elevations in the descending image and a much larger area of wet snow at mid to high elevations in an ascending image taken one and a half days later. Both results accord with field and meteorological observations.

These results demonstrate that given limited field measurements of snow elevation, depth, extent and wetness it is possible to identify a threshold for wet snow detection in a non-alpine basin. However, we have only considered one non-alpine basin during a year of poor snow cover. The snow and weather conditions occurring at the time of image acquisition and the range of slopes covered by field sites limit general applicability of the results. In particular, we do not know how site and time dependent the detection threshold is.

It is not possible to answer this important question without independent methods of verifying wet snow cover. An alternative to further field campaigns is to compare the wet SCA detected in SAR imagery with the SCA detected in coincident cloud free optical imagery, where available. Work on this is ongoing. Similar analysis is planned for the Tjaktjajaure basin where the snow covered area is greater than in Scotland and less transient. Hopefully, the method should prove more viable for providing wet snow covered area measurements for input to runoff models. However, no field measurements are available for this basin.

The area of missing coverage due to geometric effects was also analysed. Significant amounts of missing coverage were shown to occur in ERS images of the Spey and Tjaktjajaure basins (between 11 and 22% of imaged basin area). The predominant cause was foreshortening though layover was also significant. The amount of missing coverage is dependent on the range distribution of relief within the imaged scene, and affects mid to high elevations, where snow is most likely to occur, more than low elevations. This is potentially a serious problem. While missing coverage can be reduced by combining descending and ascending passes, in non-alpine areas the time lag between passes often invalidates any wet snow cover inferences based on such a combination. As illustrated by the change in snow conditions between passes over the Spey basin.

It may be possible to reduce the effect of missing coverage on wet snow mapping by extrapolating results from areas unaffected by missing coverage to areas of missing coverage with similar elevation and aspect. This is an area of future work. A major problem could be that most areas of a given elevation and aspect are affected by missing coverage. An analysis of the aspect dependence as well as the elevation dependence of missing coverage is needed to determine if this is the case.

For future studies a better solution to the problem of missing coverage may be to use data from a SAR with a less steep incidence angle, though the performance of the intensity ratio method for wet snow detection at such incidence angles is unknown. The choice of incidence angles and swaths provided by the SARs onboard Radarsat and ENVISAT provide a means of both reducing missing coverage and increasing temporal coverage. It is likely that these systems are much more suited than ERS for monitoring wet snow cover in the higher latitude basins studied here.

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Table 1 Area (km^2) of the Spey and Tjaktjajaure basins covered by different ERS passes and the percentage area of missing coverage due to geometric effects including the breakdown into layover, radar shadow, foreshortening and grazing. The range position of the basin within each scene and the direction of the ERS pass are also listed.

BASIN	Frame/ Track	Pass	Range position	Area of basin covered km^2	Total missing cover % area	Foreshorten -ing % area	Layover % area	Shadow % area	Grazing % area
Spey	1143/15	Asc	Mid	1272	14.2	12.0	4.8	0.070	0.004
Spey	1143/244	Asc	Near	1054	21.8	18.6	7.4	0.062	0.003
Spey	2457/495	Desc	Mid	1272	17.5	14.6	6.8	0.085	0.001
Spey	2457/223	Desc	Far	980	11.4	9.2	4.7	0.116	0.002
Tjakt.	2241/22	Desc	Mid	2198	16.7	11.8	7.7	0.058	0.008
Tjakt.	2241/251	Desc	Far	2249	12.0	8.0	6.0	0.084	0.015

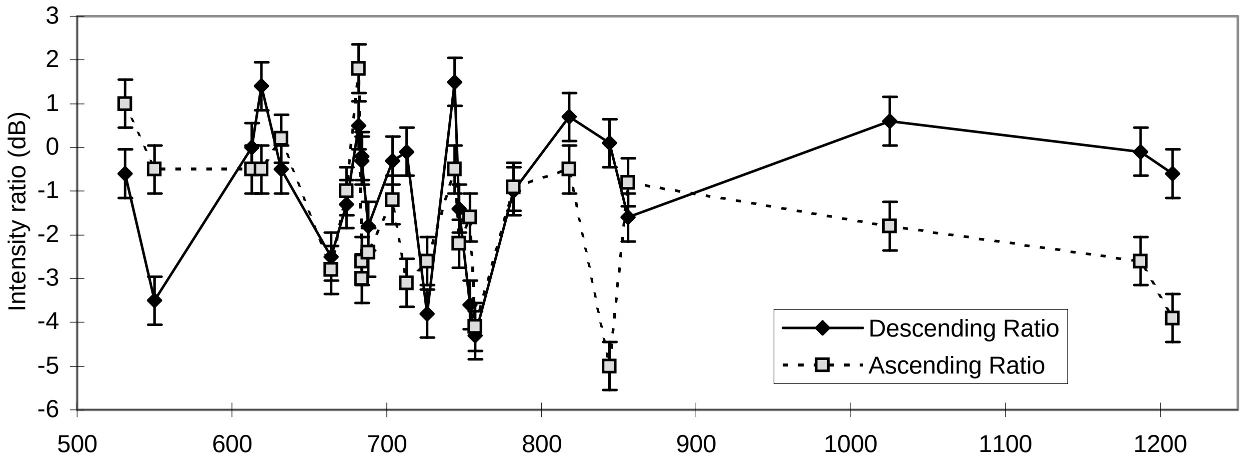

Fig: 1: Intensity ratios (dB) for each site in the descending and ascending images plotted against elevation. The error bars represent one standard deviation (0.55 dB).