EQUILIBRIUM- AND FIRN-LINE DETECTION WITH MULTI-POLARIZATION SAR – FIRST RESULTS

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ABSTRACT

We examine the capability of multipolarisation SAR for glacier monitoring on Austre Okstindbreen in mid-Norway using airborne and geocoded EMISAR images in C- and L-Band from the EMAC '95 campaign. The crosspolarisation SAR images (HV and VH) contain more backscatter variation and reveal more details on the glacier than the HH and VV polarised images. HH and VV images are very similar, as well are HV and VH images. An icefall is clearly visible, and crevasses are visible in L-Band. The present year's equilibrium line cannot be seen on the SAR images, however a distinct line is visible on the C-Band SAR images. Photographs from Austre Okstindbreen show that this line represents the firn line created by previous year's layers. Monitoring of the firn line will be a valuable source of information. The firn line is itself not affected by yearly variations in equilibrium-line altitude, but a permanent change in the average equilibrium-line altitude will eventually result in a change in firn-line altitude. The firn-line altitude serves thus as a valuable climate indicator and appears to be easily detectable on SAR images due to strong difference in backscatter between ice and firn. Eventually, this may call for the development of correlation factors between firn-line altitude (FLA) and mass balance in contrast to today's use of equilibrium-line altitude (ELA) in order to use SAR for routine mass-balance monitoring.

INTRODUCTION

Mass balance observations of glaciers provide valuable information about climate condition and possible changes (1). Glacier extent and the annual equilibrium-line altitude, i.e. the point on the glacier which divides accumulation and ablation areas, have been measured for a long time on many glaciers (e.g. (2)). These measurements, however, require intensive fieldwork and it is therefore advisable to find additional ways of glacier monitoring. Satellite remote sensing is such an alternative, and here especially the Synthetic Aperture Radar (SAR) located in the microwave region, which in contrast to optical sensors is unaffected by cloud or night-time conditions.

Many studies have been done with SAR to detect equilibrium line and glacier facies. A summary of these studies can be found in (3). On large ice sheets it appears to be possible to detect different glacier facies (4), (5), (6), while many studies on smaller glaciers suggest to have identified the equilibrium line (7), (8). However, most of these studies lack ground observations and there has been doubt recently that these studies indeed have identified the equilibrium line but rather the firn line. An example of this can be found on Kongsvegen glacier on Svalbard. Kongsvegen was studied by (8) using an ERS SAR image. They found excellent agreement between equilibrium-line altitude and an observed boundary on the SAR image. However, (9) looked at an eight-year time series of SAR images on the same glacier and found that this apparent agreement has been accidental. The observed boundary occupied the same position year after year and (9) conclude that this line represents the average firn-line altitude. Similarly, (10) find for Hofsjökull, Iceland, that the firn line may obscure the equilibrium line.

Based on these observations, we will examine our findings on Austre Okstindbreen, Norway. We will take a special look at the capability of multipolarisation SAR for glacier monitoring. This will give valuable information regarding future sensors, like the ASAR on Envisat (launch planned in June 2001) and RADARSAT-2 (launch planned in October 2002), which both will provide SAR images in various polarisations.

An expanded version of this paper, containing a more detailed discussion and additional analysis, has been submitted to the Journal of Glaciology.

METHODS

Austre Okstindbreen is located in mid-Norway (Figure 1) at 66° 01' N 14° 18' E. The total area of the glacier is 14 km^2 and the glacier extends between ca. 730-m and 1700-m elevation (Figure 1). A heavily crevassed icefall extends between ca. 1000 and 1200-metres elevation, having an average slope of about 18°. The glaciers in the Okstindan area have been studied since 1970 within a cooperation project between the University of Manchester, UK, and the University of Aarhus, Denmark. Since 1976, the studies concentrate on Austre Okstindbreen. Mass balance was measured between 1985 and 1996 by (11), (12), (13), (14), (15), (16), (17), (18), (19), and (20). Six out of the nine years before 1996 had a positive balance. Generally, however, the glacier has been retreating throughout the last century and is now 2 km shorter than in 1908 (21). Field observations were made during the overflight of the EMISAR and have been published in part in (22).

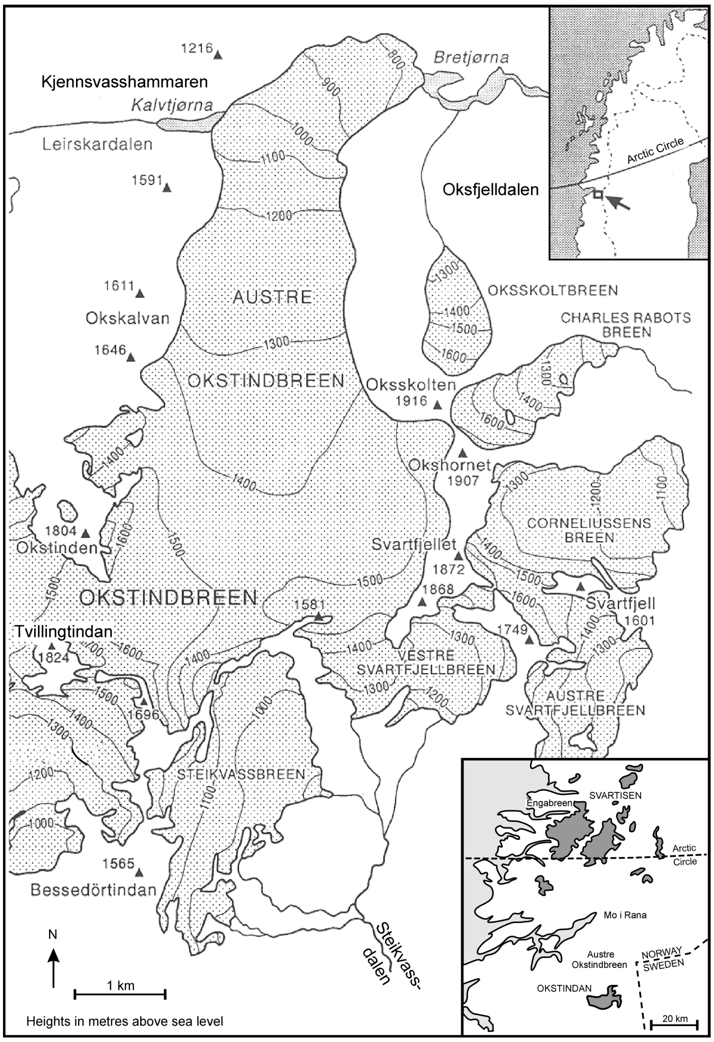

Figure 1: Austre Okstindbreen and adjacent glaciers

In spring 1995, the European Multisensor Airborne Campaign EMAC '95 collected SAR images on March 23rd (as well as May 1st and July 5th, which we do not consider here) with the EMISAR sensor. EMISAR is an airborne, dual-frequency (C-Band, 5.3 GHz, and L-Band, 1.25 GHz), multipolarisation SAR sensor from the Electromagnetic Institute of the Technical University of Denmark. Incidence angle of the SAR signal is between 35° and 60°. The raw images have been calibrated and geocoded by NORUT-IT, Tromsø, Norway, using an algorithm described in (23). Pixel size of the SAR images is 20 metres. A digital elevation model (DEM) from the Norwegian mapping authority, Statens Kartverk, has been used for geocoding. The DEM has a grid size of ca. 100-metres with an accuracy of ±20 metres elevation. It has been resampled to a grid size of 20 metres for geocoding. There has been developed a more detailed and more recent DEM available from Austre Okstindbreen (24), which, however, was not available at the time of geocoding.

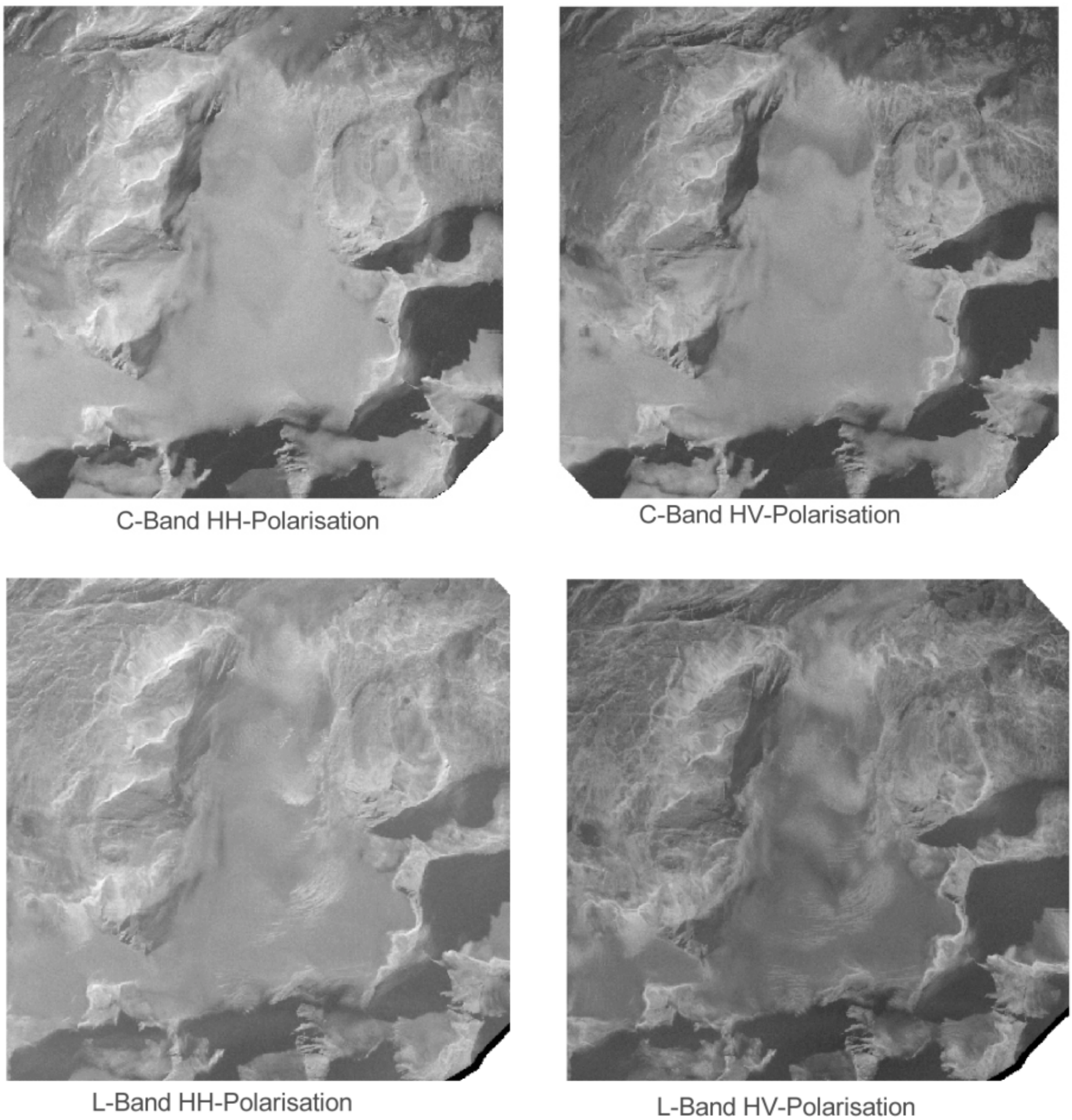

Figure 2: The EMISAR images in C- and L-Band and different polarisations for Austre Okstindbreen. VH and VV-polarisation are not shown.

RESULTS

The SAR C- and L-Band images in HH- and HV-polarisation are presented in Figure 2, with a more detailed version of the C-Band HV-polarisation image in Figure 3. As a first observation we note that in both C- and L-Band the HH and the VV images are very similar (Figure 4). This is even more valid for the crosspolarisation images HV and VH, which are almost identical. The crosspolarisation images (HV and VH) contain more variation in backscatter compared to the HH and VV images. This is valid for both C- and L-Band data. L-Band penetrates deeper into the glacier and reveals, for example, crevasses and the bergschrund, as seen in Figure 2. In the following we will concentrate on the C-Band images and here especially on the HV polarisation (Figure 3), where most variation is seen.

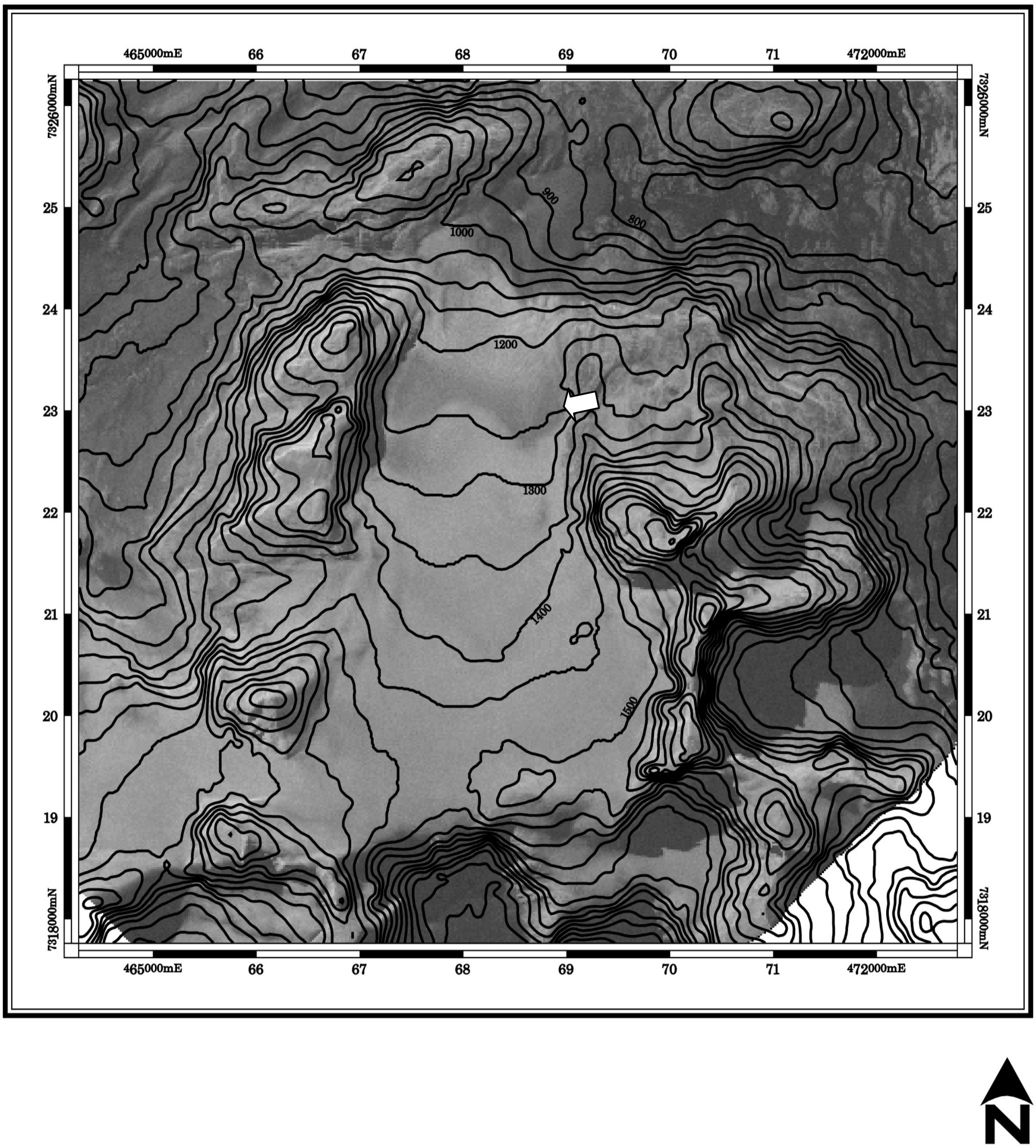

Figure 3: The C-Band HV-Polarisation image with elevation lines in 50-metre intervall. The arrow marks the view direction in Figure 5.

Low backscatter is seen on the glacier tongue (Figure 3). The smooth glacier ice surface constitutes a specular reflector and as such does not reflect much energy back to the SAR sensor. At higher elevations in the glacier bend, between ca. 1050 and 1200 metres elevation, we find an area of high backscatter. Right here, there is a large icefall with a highly crevassed and rough surface, which reflects much of the SAR signal and leads to high backscatter. Afterwards, between ca. 1220 and 1250 metres elevation, we again find low backscatter, more distinct in the HV than the HH polarisation. Snowpit data at 1230 metres from (20) show a smooth glacier ice surface and (22) report that glacier ice is exposed towards the end of the ablation period in this area.

At around 1250 metres we find a distinct boundary, above which the backscatter is considerably higher, especially in the crosspolarisation images. In the remaining part of this paper we will analyse the nature of this boundary, which we will call the 1250-metre line. We believe that this is a boundary, which has been reported on many other glaciers with SAR images and which often has been assumed to be the equilibrium line.

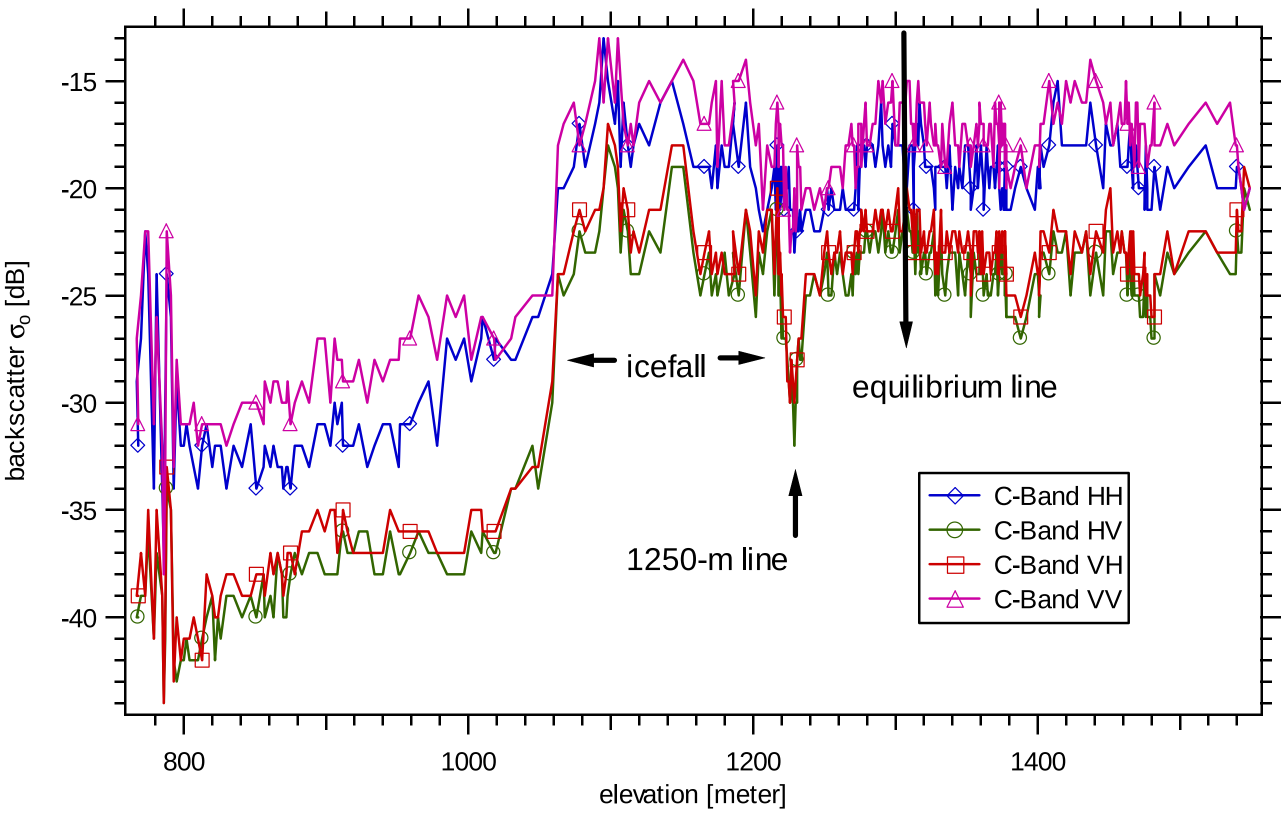

Figure 4: Backscatter along the centreline of Austre Okstindbreen for C-Band in all available polarisations. The high backscatter of the icefall can be seen between about 1050-m and 1250-m elevation. A distinct increase in backscatter at 1230-m elevation is seen in HV- and VH-polarisation, the equilibrium line, however, is located much higher at 1310 m.

We can immediately see that the 1250-metre line is not equal to the 1993/94-equilibrium line. The latter is located at 1310-metres elevation, and is ca. 700 metres away from the 1250-metre line in ground distance (19). The 1250-metre line is also situated lower than any equilibrium line since 1985/86, the lowest being 1270 metres in 1988/89 (Table 1). A simple average equilibrium line altitude for the years 1985 -1994 is 1290 metres.

The best evidence on the origin of the 1250-metre line can be found on a photograph from August 1995 (Figure 5), whose view direction is marked in Figure 3. The snow line, i.e. the equilibrium line, was at 1280 metres at the end of the balance year, but in August 1995 it was close to 1250 metres. In August 1994, the year represented by the SAR images (Figures 2 and 3), the snow line was much higher at about 1300 metres. Below the snow line from August 1995 is the old firn, to the right in Figure 5. The firn line, i.e. the boundary between firn and ice, in Figure 5 has the same shape as the 1250-metre line on the SAR images.

Table 1: Equilibrium Line Altitude from 1985-1995

Mass Balance Year	Equilibrium Line Altitude
1985/86	1300 m
1986/87	1300 m
1987/88	No line - net loss over whole glacier
1988/89	1270 m
1989/90	1275 m
1990/91	1300 m
1991/92	1270 m
1992/93	1290 m
1993/94	1310 m
1994/95	1280 m

The shape of the 1250-metre line suggests that it has been affected by glacier movement. It is at lower elevations around the faster flowing centreline and at higher elevations at the slower flowing sides of the glacier. We therefore conclude that the 1250-metre line is the firn line created by previous years' layers, which is affected by the ice movement.

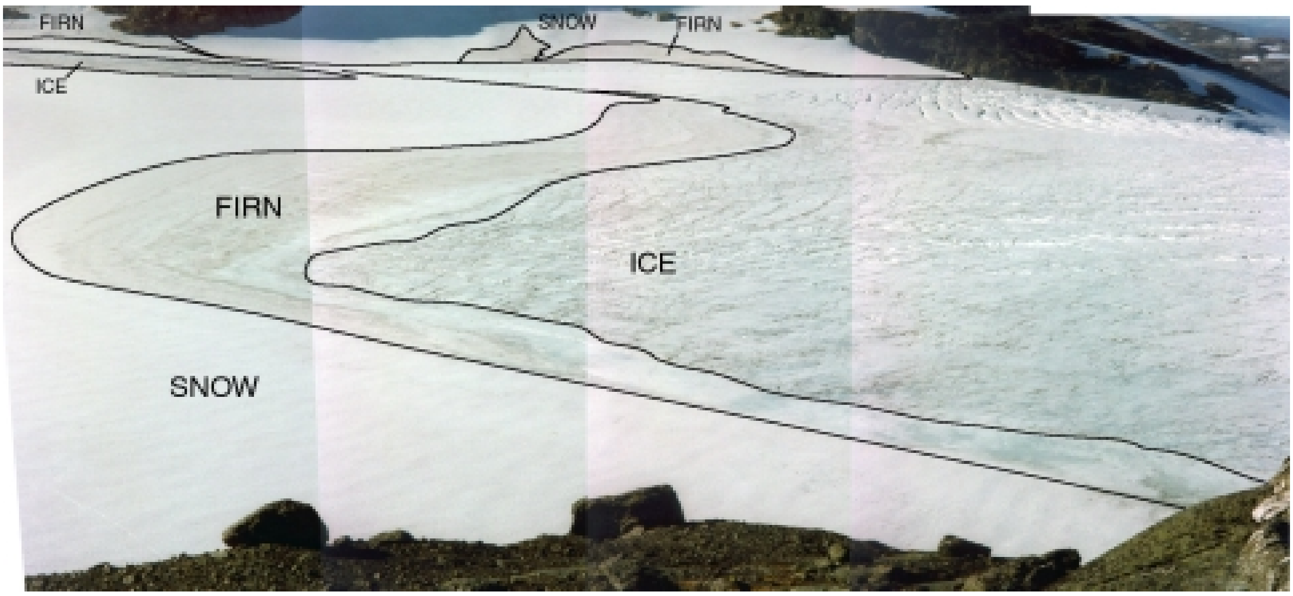

Figure 5: A photography from August 1995 showing snow and firn line of Austre Okstindbreen at around 1250 metres elevation. The location and view direction of this photo is marked in Figure 3. The flow direction is to the right and crevasses can be seen. The firn line follows the same shape as the 1250-metre line. The snow line, which was located at 1250 metres in August 1995, was much higher at about 1300 metres in August 1994, i.e. the year represented by Figure 3.

CONCLUSIONS

Our study suggests that multipolarisation SAR, like the future ASAR or RADARSAT-2, will be a better tool for glacier monitoring than previous single-polarisation SAR sensors. HH and VV images, and equally HV and VH images, are very similar to each other, but the crosspolarisation images differ distinctly from the single-polarisation ones and reveal greater details of the glacier surface. C-Band is preferred for mass-balance observations. L-Band penetrates much deeper and can be used to detect crevasses. The equilibrium line could not be detected with the SAR data; a distinct line was visible on the glacier, however, which from photographic evidence we conclude to be the firn line created by previous years' layers.

Monitoring of the firn line will be a valuable source of information. The firn line is itself not affected by yearly variations in equilibrium-line altitude, but a permanent change in the average equilibrium-line altitude will eventually result in a change in firn-line altitude. The firn line therefore seems to smooth out short-term variations and to show trends on a larger time-scale. The firn-line altitude serves thus as a valuable climate indicator and appears to be easily detectable on SAR images due to strong difference in backscatter between ice and firn. This suggests that the connection between firn-line altitude and mass balance needs to be studied further in order to use SAR for routine mass-balance observations. Eventually, this may call for the development of correlation factors between firn-line altitude (FLA) and mass balance in contrast to today's use of equilibrium-line altitude (ELA) in order to use SAR for routine mass-balance monitoring.

Further work needs also to be done regarding verification of firn-line detection with SAR. We suggest detailed surveying of the firn line on the ground in order to verify satellite observations. Determining glacier stratigraphy with ground-penetrating radar has already proven to be useful for the interpretation of SAR images (9). The Norwegian Polar Institute will continue this work on Kongsvegen, Svalbard. Here, nine years of SAR data are available, as well as yearly mass-balance measurements and other supporting glaciological studies.

ACKNOWLEDGEMENTS

We want to thank Inge Lauknes from NORUT-IT, Tromsø, who did the geocoding of the SAR images. Discussions with Rune Engeset (Norges Vassdrags- og Energiverk, NVE, Oslo) and Jack Kohler (Norsk Polarinstitutt, Tromsø), provided helpful insights. Thanks go also to W. H. Theakstone (University of Manchester) for information on Austre Okstindbreen. This project is funded by the European Space Agency and the Norwegian Space Centre (PRODEX Implementation Contract No. 13505/99/NL/VJ(1C)) and the Norwegian Polar Institute (NP).

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