Observations of the emissivity of snow and ice surfaces from the SAAMEX and MACSI airborne campaigns.

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Abstract—This paper presents results from an airborne campaign over snow and ice (SAAMEX). Observations of millimetre wavelength channel sensitivity to snow depth, wetness and vegetation cover have been collected using an airborne microwave radiometer (MARSS). Snow was found to substantially reduce the emissivity of dry snow at 157 GHz, although this effect was lost as the snow wetness increased. The sensitivity to snow was smaller at 89 GHz than at 157 GHz. Vegetation was found to mask the appearance of underlying snow if the snow was dry. For wet snow there was little difference between forest and open spaces. The sea ice experienced pressure ridging against the coastline: the observed brightness temperature was higher and more variable when viewing parallel to the ridges than when viewing perpendicular, if the ridges were snow covered. Bare ridges showed no azimuthal dependence.

I. INTRODUCTION

In March 1990 the UK Meteorological Office C-130 participated in the SAAMEX experiment measuring emission and scattering from snow and ice. The C-130 aircraft flew over designated test sites in the Gulf of Bothnia and Finland. The Microwave Airborne Radiometer Scanning System (MARSS) had two channels at 89 and 157 GHz scanning along the aircraft track but otherwise configured almost identically to the two similar AMSU-B window channels. The Microwave Airborne Campaign over Snow and Ice (MACSI) in March & April 1995 has provided the opportunity to repeat and add to the SAAMEX measurements with new channels at 23.8 and 50.3 GHz (Deimos). Throughout the SAAMEX experiment the snow was wet with the water content increasing from 2.5% at the start of the observational period to 13% at the end. In addition the snow thickness on both sea ice and forest test sites declined during the period. For the sea ice the snow depth fell from 11-18cm at the start to 3-8cm at the end. At millimetre wavelengths the penetration depth for snow with a water content of 2% is only 1.5 and 3cm at 157 and 89 GHz. Consequently a snow depth of over 10cm represents an optically thick layer of snow at these frequencies. It is therefore reasonable to assume that for snow of depth greater than 10cm the emission is determined by the snow wetness.

Past results [1] have shown that the 89 GHz emissivity is increased linearly as snow thickness is reduced from 15cm to zero. Between 20 and 90 GHz varying results have been reported varying from a modest rise of brightness temperature as snow depth falls to no sensitivity at all. This disparity is probably due to variability in the snow wetness and snow grain size in the various observation datasets. Below 20 GHz there is a reasonable consensus that the emission is insensitive to snow depth. In this frequency range the penetration depth is increasing rapidly with decreasing frequency such that the penetration depth at 5 GHz exceeds 1m for very dry snow (0.5% water content). It is natural therefore to assume that sensitivity to snow cover increases with increasing frequency.

The SAAMEX experiment also consisted of forest sites. Observations from one of these sites have previously been reported [2] for low frequencies (24, 34, 48 GHz). In open areas dry snow scattered strongly even at low frequency, although in forested areas this was almost completely masked by warmer emission from the forest canopy.

II. INSTRUMENTATION

The MARSS radiometer has been described in detail in [3] where the calibration procedure is also outlined. The calibration method, which relies on two internal calibration targets viewed once per scan and external liquid nitrogen and cold space views is described in [4]-[5]. The MARSS noise sensitivity temperature is 0.15 K and 0.3 K at 89 and 157 GHz and the error bars on the observations are typically between 1.5 K and 3 K. The new radiometer, Deimos, which has been operated in the recent MACSI experiment, has a design similar to MARSS except it only scans from nadir to 40 degrees forward assuming a 5° aircraft pitch. It can not view above the aircraft. The aircraft is fitted with instrumentation to measure meteorological variables (temperature, humidity, cloud liquid water, surface temperature, surface windspeed, pressure) and navigational aids (altitude, GPS latitude, GPS longitude). For descriptions of the relevant C-130 instrumentation the reader is directed to [5]-[6].

III. SAAMEX RESULTS

The SAAMEX experiment and the MARSS observations are described in detail in [7]. SAAMEX comprised of two observational lines in the Gulf of Bothnia, two forest sites and one lake ice site in Finland. The sea ice lines both run from Marjaniemi (65°02.380N 24°33.913E) at a heading of 212°. The first line, the Marjaniemi line, was 2480m long comprising of detailed measurements of snow

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depth, density, water content and temperature at intervals of 80m. Sea ice thickness was also measured and ridges were mapped in detail.

During SAAMEX the snow depth reduced on the Marjaniemi line leading to a few bare patches - typically the snow cover halved from about 15cm to about 8cm. The major change however was from a dry snow regime (water content 2%) to a very wet regime (water content 13%). The emissivity of the two channels is plotted in Fig. 1 as the water content rose. As the snow wetness increased the emissivity for both channels initially rose, most rapidly at 157 GHz (0.78 to 0.96) but also at 89 GHz (0.84 to 0.94). However after this initial rise both channels observed falling mean emissivity (to 0.84 at 157 GHz and 0.80 at 89 GHz). This can be interpreted in terms of the melting phase. In Fig. 1 it is observed that dry snow is separable from bare ice, wet snow and melting snow by the strong scattering signature. Wet snow is very emissive, as would be expected for water coated snow grains at this frequency. Wet snow shows no spectral emissivity change between 89 and 157 GHz. However as the snow wetness continues to rise to untenable levels ($\geq$12%) and the snow starts to melt the emissivity tends towards that of open water.

The second line continued at the heading of 212° towards Nahkiainen, Ulkokalla and Kokkola (the 'MaNUK' line). This line was overflown by a Bell Jet Ranger helicopter making detailed observations of ice and snow conditions. This line provided measurements over a gradual transition from the conditions at Marjaniemi (15cm snow) to bare young floes with flat new ice on the ice edge. It also provided an opportunity to overfly open water just beyond the ice edge. The mean emissivity from bare young floes, flat new ice and open water are also shown on Fig. 1. The brightness temperature along the MaNUK line is shown for 89 and 157 GHz in Fig. 2 for flight H987 where the snow was relatively cold and dry in Marjaniemi. The brightness temperature increases rapidly, especially at 157 GHz, as the snow cover falls before reaching a steady figure over the bare ice in the south. When the snow was melting in the north this change was no longer observed and generally the brightness temperatures were higher and more noisy. New flat ice is observed to be very emissive; older ridged ice floes are slightly less emissive.

Fig. 3 summarises the data by plotting brightness temperature against frequency for bare ice and 15cm snow cover. The low frequency measurements are taken from [1]. At low frequency the results from [1] show no sensitivity to snow depth (tp to 15cm). At around 89 GHz our SAAMEX results and [1] show a fall in brightness temperature for the snow covered ice. The SAAMEX results at 157 GHz show this trend continues and a very large sensitivity to snow depth is observed.

The influence of ridges was investigated. Ridges are easily identifiable in active microwave images because of the dispersion of the backscattered radiation. In passive images the impact of ridges is less well defined. A comparison of the effect of ridges in 33 GHz passive data was conducted by [8] where it was found that 82% of deformational features (ridges and fractures) had radiometric features, usually appearing warmer than the surrounding area. During SAAMEX the ridging was aligned perpendicular to the prevailing south-westerly wind as the ice packed against the Finnish coastline. Therefore the MANUK runs (at heading of 212° or 32°) were perpendicular to the ridging. A number of runs were also flown parallel to the ridge axes. In the south of the MaNUK line, where the snow cover was bare or patchy, there was no difference in the measured brightness temperature (or its variability) flying parallel or perpendicular to the ridges. However in the north where the snow was deeper but wet the parallel runs were warmer and had a higher variability along the run than the perpendicular runs.

Of the inland sites only results from the Muhos forest site are discussed here. The brightness temperatures were much higher than the ice sites, corresponding to an emissivity of nearly one. However for the early flights when the snow was still quite dry the clearings along the run were observed to have much lower brightness temperatures, especially at 157 GHz. The effect of the forest canopy is to mask this scattering signature of the underlying snow. This gives rise to a substantial fall in the standard deviation for the Muhos run from 4.2K and 4.9K at 89 GHz and 157 GHz for flight H988 (snow depth = 0.3m, snow density = 0.26 kg m^{-3}) to 1.6K and 1.4K for flight H990 (snow depth = 0.23m, snow density = 0.31 kg m^{-3}). When the snow became wetter the overall emissivity rose slightly and the clearings no longer appeared cold. Therefore the overall emissivity of the forest, defined with respect to the temperature on the snow surface, rose from 0.98 to 1.00.

IV. CONCLUSIONS

Data from the SAAMEX experiment in Finland have been presented. Results show a distinct correlation of emissivity at 89 and 157 GHz with snow conditions. Dry snow is separable from wet snow or bare ice by the scattering signature from the snow grains, particularly at 157 GHz. Wet snow is characterised by high emissivity and a flat spectral response, although this is difficult to separate from emission by new ice. Older ice floes, which have been heavily ridged, also show a flat spectral response but lower emissivity. When the snow water content rises above 10% the snow starts to melt rapidly and the emissivity of both channels falls towards the value for open water. Forest sites show a very high emissivity and are separable from all sea ice sites. However forest clearings give a snow emissivity more similar to snow on sea ice which the forest masks. There is evidence of an azimuthal dependence of the brightness temperature of ridged sea ice, when the ridges are aligned. The MACSI experiment has provided a dataset with a greater range of channels and snow conditions.

VI. FIGURES

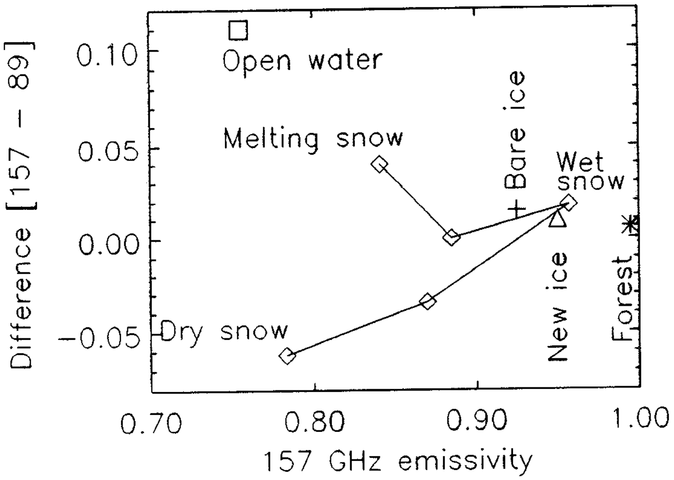

Fig. 1 Specular emissivity at 89 and 157 GHz deduced from MARSS observations during melting period.

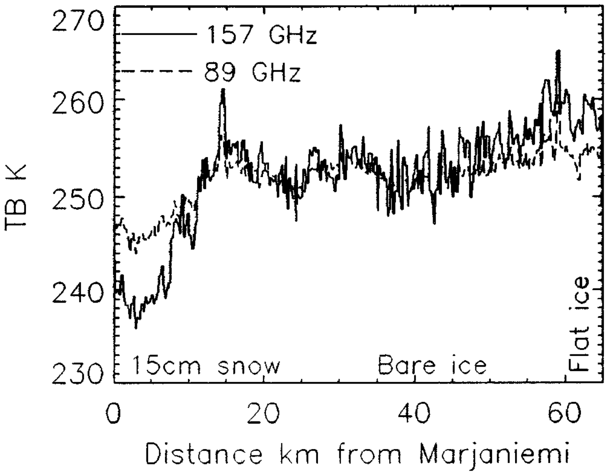

Fig. 2 Change in 89 and 157 GHz brightness temperature along MaNUK line for flight H987.

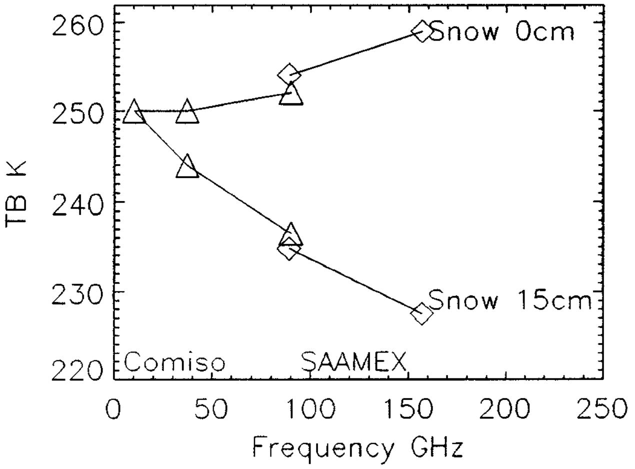

Fig. 3 Change in brightness temperature with frequency for 15cm of dry snow and bare ice from Comiso *et al* (1989) [triangles] and our SAAMEX results [Diamonds].

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