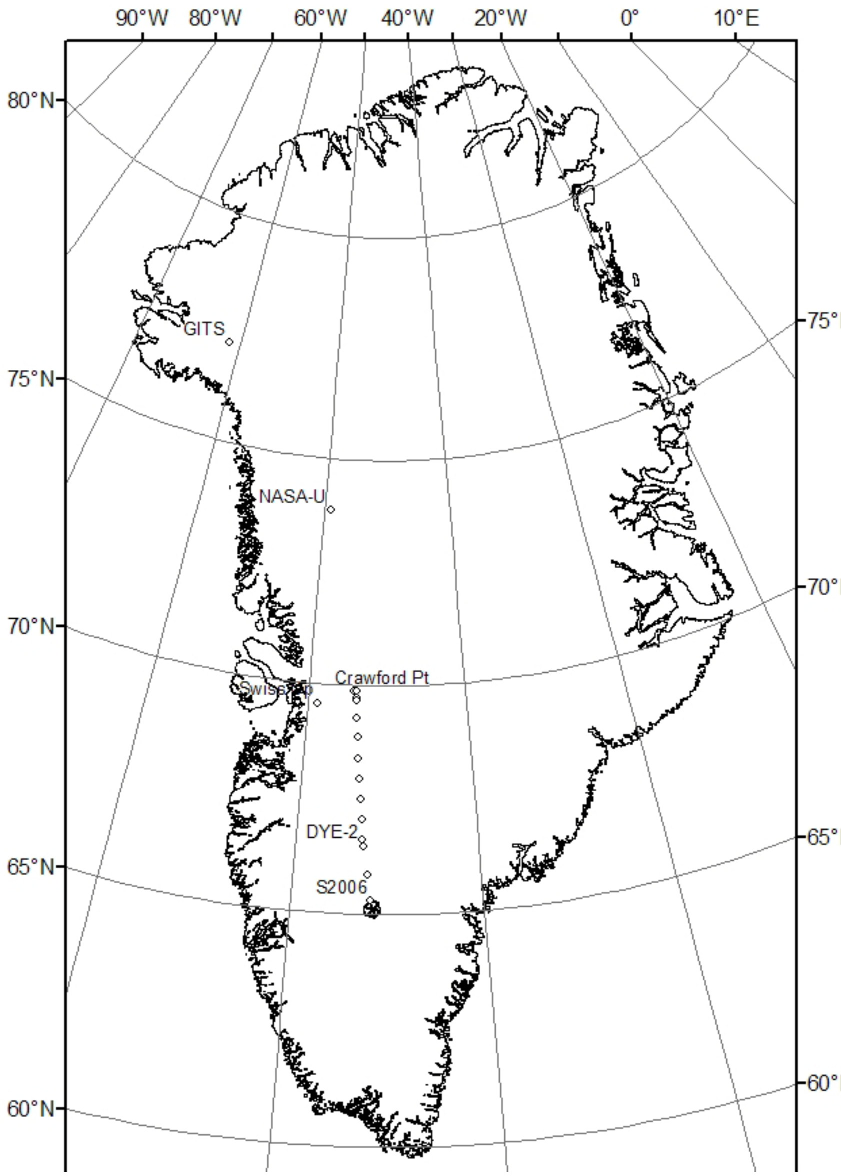
Surface Roughness Measurements on the Western Greenland Ice Sheet



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Surface Roughness Measurements on the Western Greenland Ice Sheet

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1.0 Introduction

This report summarizes in situ observations of snow surface roughness in relatively benign regions of the western Greenland Ice Sheet (Figure 1). The data were collected in June and August, 1991, June 1992, June 1993 and June 1995. The observations were used to support the interpretation of airborne SAR and laser measurements as well as ERS-1 and JERS-1 spaceborne SAR observations. Surface characterization measurements complemented other, coincident, in situ experiments including C and Ku band surface scatterometer observations, ultra-wideband (operations from 0.5 to 18 GHz) scatterometer measurements, large scale surface topography measured by leveling, and the deployment of radar corner reflectors (Baumgartner and others, 1999; Baumgartner and others 2002; Jezek and Gogineni, 1992; Jezek and others, 1994; Lytle and Jezek, 1994; Munk and others, 2000, Rignot and others, 1993; Roman and others, 1997; Zabel and others, 1994; Zabel and others, 1995).

This report focuses on snow-surface roughness measurements, both quantitative and anecdotal. Quantitative surface roughness was measured with a large, 1 m long comb gauge and with hand-held comb gauges. Included in the report are qualitative observations of peak-to-peak surface roughness which were frequently commented upon in field notebooks. Also included are numerous photographs.

Selecting type areas for measuring roughness was challenging because of the number of surface morphologies distributed in each study areas. A severe limitation of the data is likely to be the short length of the roughness measurements. Sampling length may lead to biased estimates of correlation length.

Additional measurements were made of the near surface firn by excavating 1-2 m deep pits. These observations included firn density, grain size, grain shape, temperature, and stratigraphy. 10 m or deeper firn cores were collected from a few sites and analyzed for density, grain size and shape. Surface roughness was frequently measured on ice layers and other inclusions observed in the firn column and some of these data are included for comparison to the snow-surface properties. These data are available from the author and will be compiled into a later report.

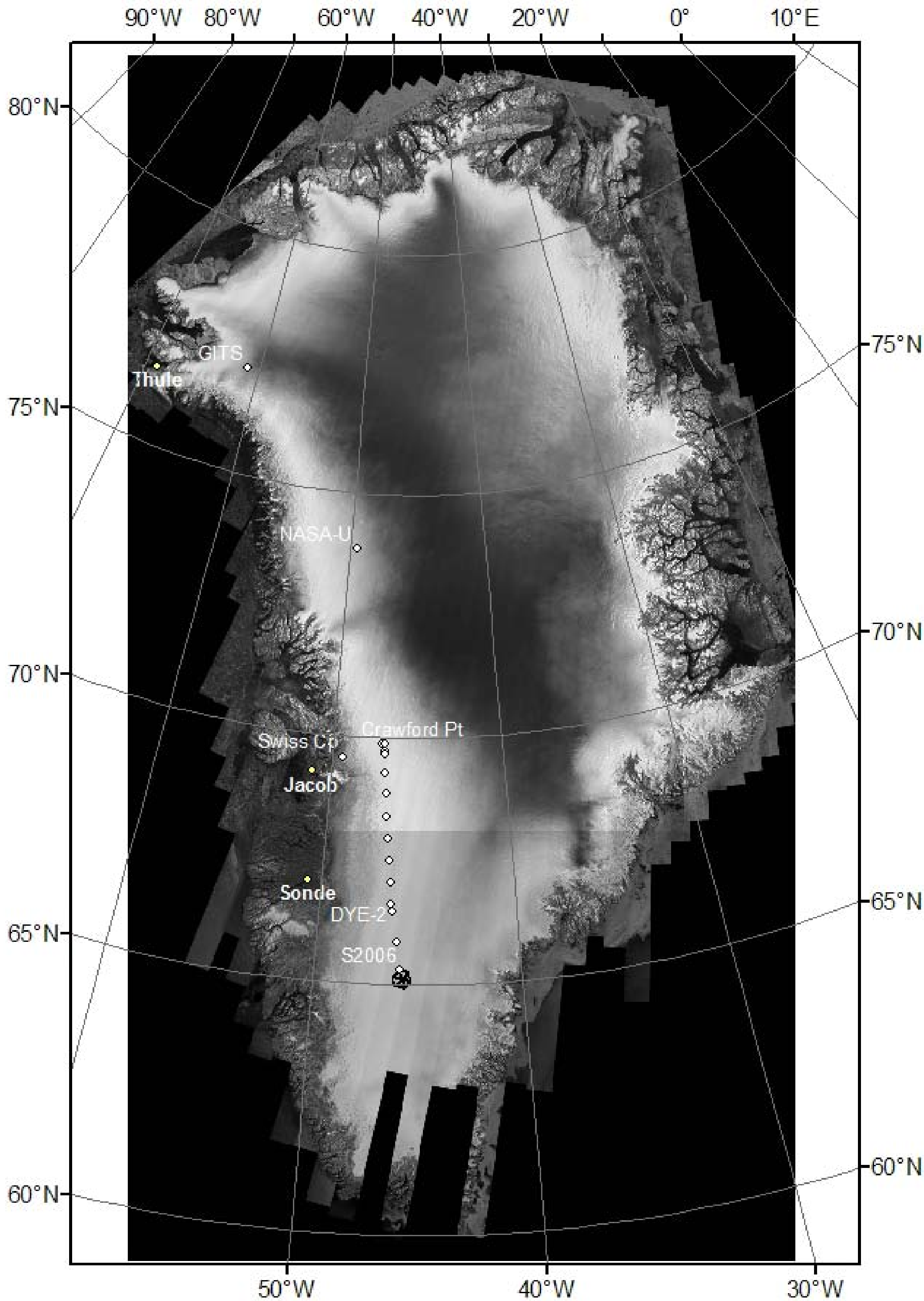

Figure 1. Location of measurement sites superimposed on a Radarsat-1 mosaic of Greenland courtesy of I. Joughin.

2.0 Crawford Point, June 1991

We characterized the upper firn layer at Crawford Point on June 11, 1991. We made surface roughness measurements using a 1 m long comb gauge. The gauge was leveled horizontal over the surface using 3 foot pads attached to adjustable vertical shafts. The vertical rods (graduated at 1 cm intervals where then gently lowered onto the surface and a photograph was taken. The photos were later digitized and surface roughness parameters were computed.

Crawford Point is located on the western flank of the Central Greenland Ice Sheet at about 69^{o} 52' N, 47^{o} 7'W. The surface elevation at Crawford above the WGS84 Ellipsoid is about 1900 m. The terrain in the vicinity of Crawford Point is gently undulating with amplitudes of 20-40 m over distances of about 15 km. The site is situated in the percolation facies where summer melt results in the formation of large (10's of cm) ice inclusions distributed within the previous winter snow layer. Figure 2 shows the general surface roughness features observed at Crawford Point in June 1991.

Figure 2. Roughness patterns around Crawford Point on June 11.

We noted at least three surface types. There were large dunes aligned with the prevailing wind direction (116^{o} from true north). These had peak heights of about 10 cm and comprised about 10% of the surface based on visual inspection. We observed a stucco-like surface that might have been an older, erosion surface. The amplitude of the stucco was about 5 cm and this type comprised some 45% of the surface. We also observed well scoured smooth surface interrupted by occasional dimples. This was probably the oldest surface with roughness amplitudes of 1 cm or less. It also covered about 45% of the area. Portions of the surface were covered with at thin (1 cm) layer of fresh snow. These are further illustrated in figures 3-7

Figure 3. Surface patterns around a 1.5 m corner reflector erected at Crawford Point.

Figure 4. Details on eroding dunes. Lens cap is shown for scale

Figure 5. Crusted, dimpled surface. Dimples form from surface melt.

Figure 6. Smooth surface probably with some glazing from early melt.


Figure 7. View about Crawford Point.

2.1 Surface Roughness Measurements

We made surface roughness measurements with a large comb gauge. We made measurements over the different surface types. Photographs and derived statistical parameters are provided in figures 8 – 17. Prior to each photograph, the comb gauge was leveled and then the individual rods gently lowered on to the surface using a vertically adjustable horizontal bar. A limitation of the data is that the gauge was only 1 m long. That probably implies that the correlation length estimates will be biased.

Figure 8. Dune surface measured in wind direction. Page 14/15 from Guenther Lab book. RMS Height: 1.54 cm; Correlation Length: 10 cm. Peak to Peak roughness is about 5. 8 cm.

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Figure 9. Dune surface measured across wind direction: Page 26/27 G book. RMS Height: 1.57 cm; Correlation Length: 11 cm

Figure 10. Duplicate from above

Figure 11. Rods tapped lightly through upper (~1 cm) fresh snow layer. P 28/29 G Book. Measured across wind direction. RMS Height: 0.6 cm; Correlation Length: 7.32 cm

Figure 12. Rods tapped lightly through upper (~ 1cm) fresh snow. Page 11 in G Book. RMS Height: 0.75 cm. Correlation length 10 cm.

Figure 13. 'Stucco' Surface along wind field. Low rods punched through surface crust. P. 24/25 G Book. RMS Height: 0.34 cm. Correlation Length: 3.91 cm.

Figure 14. Same location as figure 6. Rods tapped into the upper surface layer. No computation of surface parameters. P. 7 in G. Book.

Figure 15. 'Stucco' surface across wind field. P 20/221 G Book. RMS Height: 0.48 cm. Correlation length: 2.87 cm

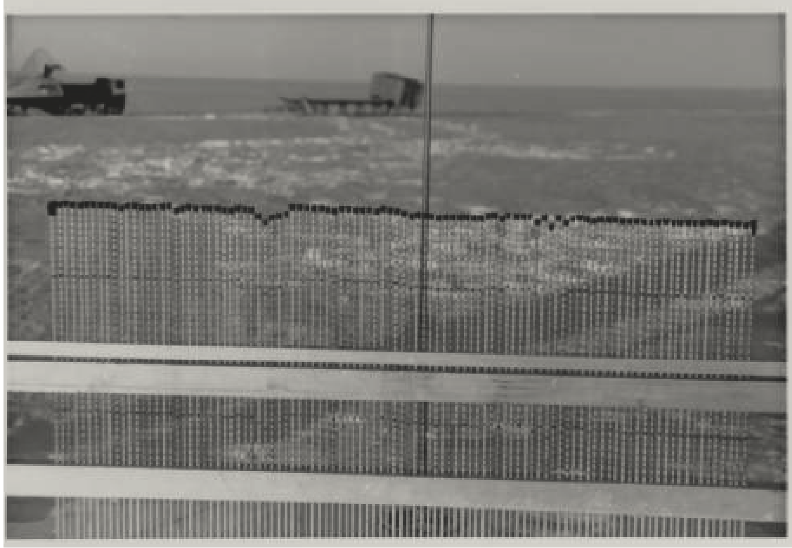

Figure 16. Flat area along axis of a surface dimple. Measured across wind flow direction. P. 22/23 G Book. RMS Roughness 0.39 cm. Correlation length 2 cm.

Figure 17. Flat area along dimple shown in figure 9 and along the wind direction. P. 16/17 in G Book. RMS Height: 0.37 cm. Correlation Length 6 cm.

Table 1. Crawford Point Surface Roughness

Figure Number	Surface	RMS Height (cm)	Corr. Length (cm)
8	Dune (along)	1.54	10
9	Dune (across)	1.57	11
11	Dune (subsurface)	0.6	7.32
12	Dune (subsurface)	0.75	10
13	Stucco (along)	0.34	3.91
14	Stucco (sublayer)	N/A	N/A
15	Stucco (across)	0.48	2.87
16	Melt Dimple (across)	0.39	2.0
17	Melt Dimple (along)	0.37	6.0

3.0 Crawford Point, August 1991.

We revisited Crawford Point from August 22 to August 31 1991. At this time, about 20 cm of fresh snow overlaid a hard crust, which presumably represented the refreezing of the summer surface. Below this layer, we uncovered evidence of the substantial surface melt preserved in the form of large ice pipes (Figure 18).

Figure 18. 70 cm long ice pipe uncovered at Crawford Point.

We did not collect quantitative surface roughness data during this trip but did notice some characteristics of roughness development. On August 28 we made surface elevation measurements south of our camp and into a large valley (Figure 19).

Figure 19. Leveling into a valley (background) south of Crawford Point.

The surface was quite smooth in the morning and we had little difficulty driving across it. As morning progresses, small scale (few cm) dunes developed upwind of our skidoo tracks. Apparently, the downwind side was snow-starved with the locally blowing snow infilling our tracks. Later, larger crescent shaped barcan dune started to develop and subsequently erode across the entire surface. Upon reaching the far side of the valley, the surface became smooth again. We began our return in late afternoon and found a startling change in the valley. The isolated barcan dunes were now connected into sinuous sastrugi a few 10s of cm high. While the snow was still largely unconsolidated, they amount of snow in each sastrugi was sufficient to make travel very difficult (Figure 20).

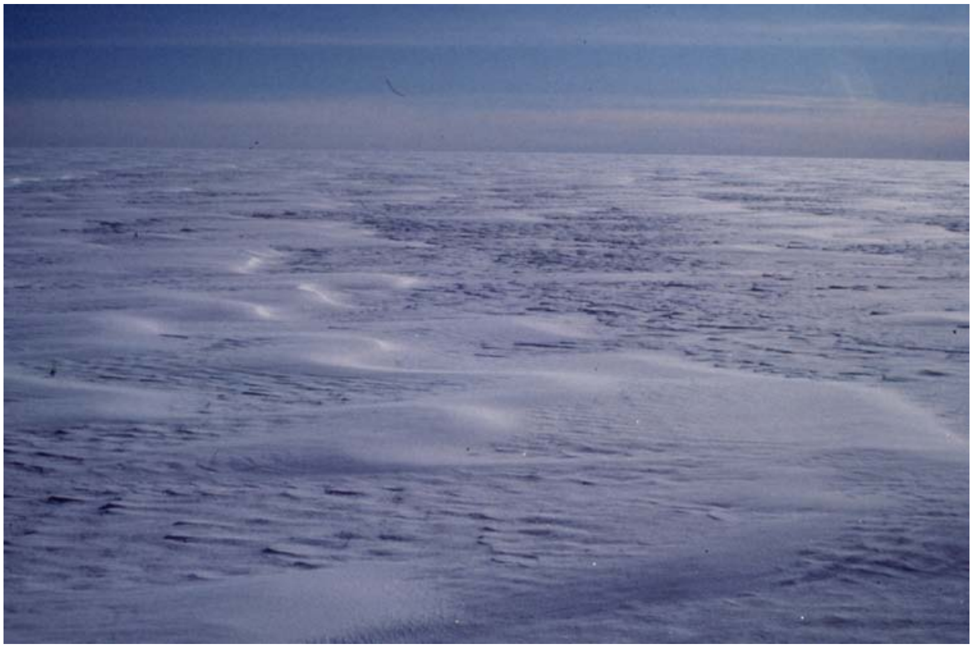

Figure 20. Dune build up.

The surface smoothed again once we left the valley and return to the local plateau upon which our camp was situated. On August 30 I drove west from our camp and found the surface there to be very rough. They were 20 cm high sastrugi faces aligned against the wind. The wavelength of the features was about 10 m (Figure 21).

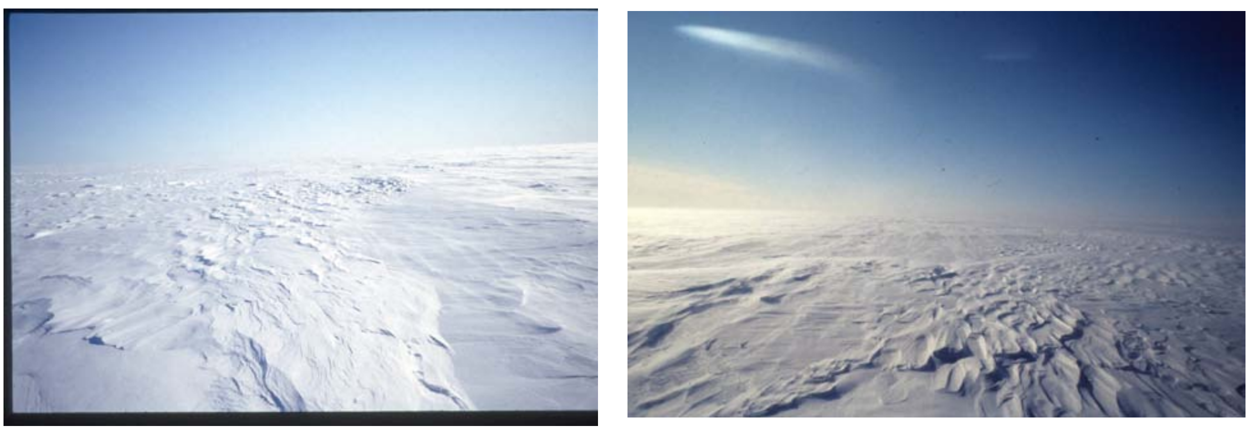

Figure 21. Roughness elements developing at Crawford point.

4.0 Crawford Point 1992

We visited Crawford point from June 3 to June 20, 1992. Our primary objective was to collect microwave radar backscatter data, to remeasure surface elevation, and to measure gravity. We conducted more snow studies including excavating several snow pits including the one shown on the left in figure 22. The pit is about 160 cm deep. Snow from the previous summer is located at about 140 cm depth. Note the number stratigraphic layers. This section does not have any ice pipes or large ice lenses present.

We did not make any measurements of surface roughness. Qualitatively, the surface appeared about the same as in June 1991, perhaps slightly smoother. We did make measurements of ice layer surface roughness using a small hand held comb gauge. The ice layer surface varied by about 1 cm over a length of about 15 cm (Figure 23). It was difficult to select a representative roughness feature given the complex shapes of the ice layers, ice lenses and ice pipes. Additional data on ice pipes, layers and lenses are available but are not presented in this report.

Figure 22. Back lit pit wall from Crawford Point illustrating layering in the winter snows (Left). Pit is about 160 cm deep.

Figure 23. Ice layer surface roughness. Gauge on cm scale graph paper (above).

5.0 Crawford Point to Clusters Traverse and Dye-2

Two, near simultaneous field campaigns occurred from June 18 to July 11, 1993. The primary experiment involved a surface GPS and gravity traverse from Crawford point to the OSU Central Cluster via DYE-2. In addition, personnel were deployed to DYE-2 to collect in situ radar and firn physical properties data.

The traverse party measured surface topography using kinematic GPS techniques. In as much as one of the GPS units was stationary for part of the day (to serve as local control), pit studies were also conducted along the traverse route. The near surface snow was usually damp during the mid-day hours. Otherwise the surface was glazed by an icy crust. Stormy conditions persisted during the southern most leg of the traverse and there was substantial blowing snow. The blowing snow formed into medium scale dunes that were about 10-15 m long, about 4 m wide and 20 cm high. Individual dunes were separated on the order of 100 m.

Conditions were much the same at DYE-2. Warmer days resulted in surface melt and some percolation to form a near surface ice layer. Melting also caused dimples to form in the surface. After storms, fresh snow blanketed the surface which was generally very smooth. Shallow sastrugi formed as illustrated in Figure 24

Figure 24. Shallow sastrugi and dimples on the surface at Dye 2. June 28, 1993.

Surface roughness was measured along a 3 m line using the large comb gauge on June 29 (Figure 25). Surface statistics have not been determined but the peak roughness is only about 2 cm. Rods easily fell through the upper snow onto the ice crust below.

Figure 25. Three, 1-m long measurements of surface roughness. Rod height varies abruptly where the rod falls through the upper thin crust and is stopped by the near surface ice layer. The surface is gently undulating with a peak roughness of less than 2 cm. Upper, middle and lower photos are each displaced by about 1 m along the strike of the gauge.

Examples of the ice crust surface roughness recently formed just below the near surface firn layer is shown in figure 26. A piece of the ice layer is shown in figure 27.

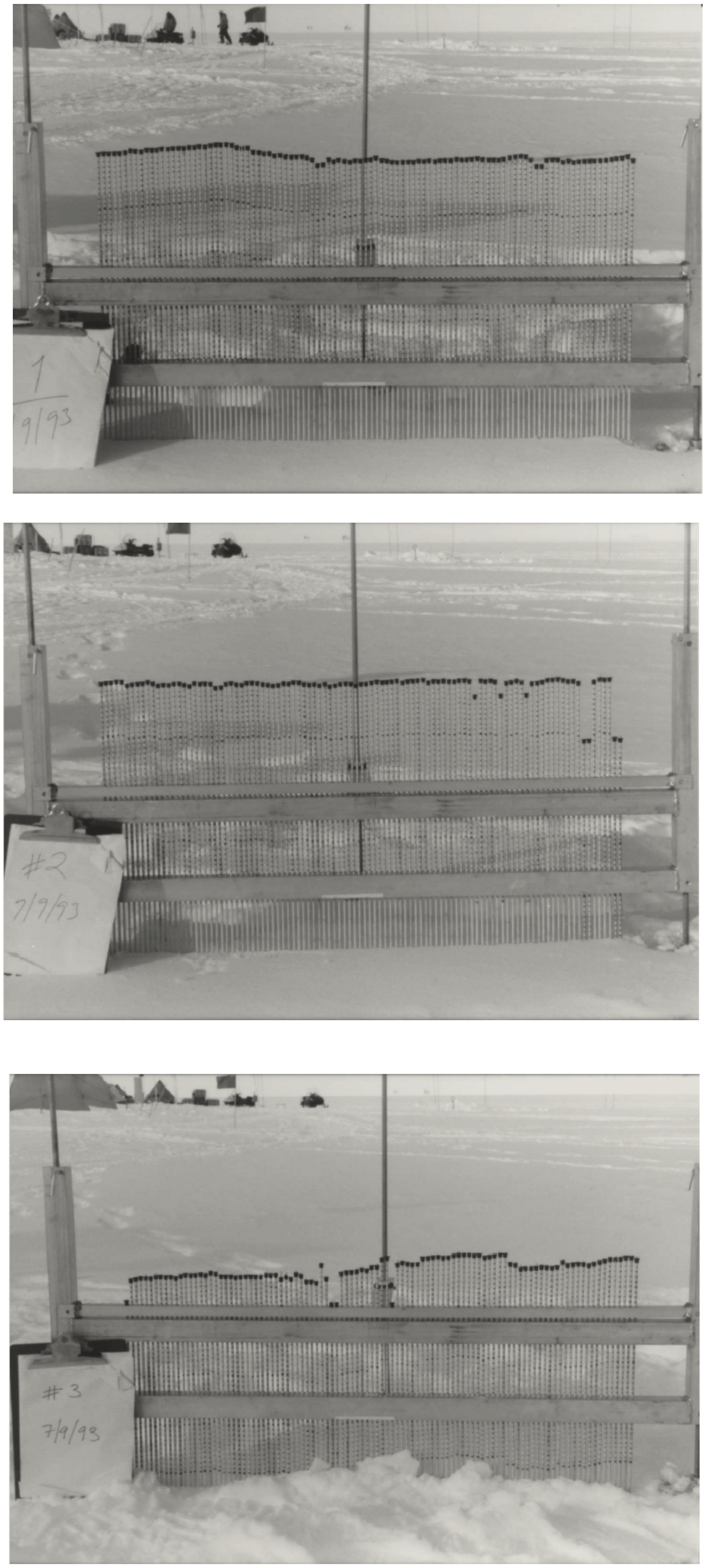

Figure 26. Surface roughness along the recently formed ice layer. Photos taken on July 9. 1993. Rods were pushed into the snow to measure crust surface. Occasionally, rods penetrated the crust at site likely to be drainage features...

Figure 27. Length of ice layer formed just beneath the surface at Dye 2 in July, 1993.

Several measurements of ice layer roughness were made at DYE-2. These data are presented in table 2 for comparison with the surface observations presented earlier.

Table 2. Surface Statistics of Imbedded Ice Layers

Sample	Description	RMS Height	Corr. Length	Best Fit
1	30 inch sample of ice layer at 144 cm depth	0.268	2.35	exponential
2	Previous summer melt layer (30 inch sample)	0.516	3.65	Gaussian
3	Second observation of 2	0.484	2.06	exponential
4	Third observation of 2	0.283	0.87	Guassian
5	Ice layer at 213 cm depth	0.30	3.69	exponential
6	12 inch sample of ice lens	0.193	2.74	Gaussian

6.0 Ultra-wideband Radar Measurements in Western Greenland

An ultra-wideband radar was operated at several sites on the western flank of the Greenland Ice Sheet from May 10 through May 28, 1995. The radar was operated from 0.5 to 18 GHz. Calibration was done using a luneberg lens. A Ku-band radar was also operated and used to profile across the surface. The experimental objective was to acquire backscatter data as a function of incidence angle from different glacial regimes. The wet snow facies were sampled at Swiss Camp in west central Greenland. The nearly ice-free, transitional percolation facies were sampled at NASA U Camp in North Central Greenland. Finally the dry snow facies were sampled at GITS camp (within a few km of Camp Century) in Northwest Greenland.

Terrain about the Swiss Camp was the most complex of the three sites visited. Aside from some exceptional sites, the surface was typical of other areas of the ice sheet – relatively smooth with 1-2 cm peak to peak roughness. Several surface lakes were within easy travel of the camp. These were still frozen and in some cases covered in patches by large overturned blocks of ice. Narrow drainage channels became evident later in the summer months as did numerous crevasses fields where some of the cracks were only a few cm wide (Figure 28). The spring time near-surface consisted of 10 – 70 cm of snow/firn overlaying thick, superimposed ice.

Surface conditions at NASA U were not particularly noteworthy. The surface roughness was on the order of a few centimeters peak to peak and the correlation lengths were probably on the order of 10s of cm to meters. Similar conditions were observed at GITS.

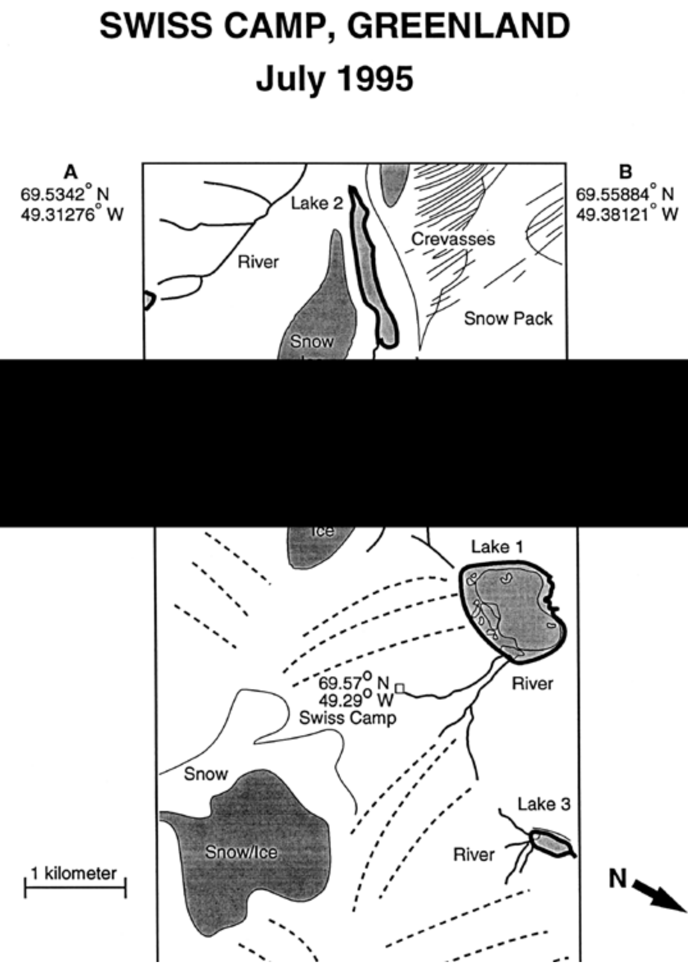

Figure 28. Terrain map about Swiss Camp.

7.0 Conclusions

Surface roughness was quantitatively measured and/or qualitatively observed during several experiments in western Greenland from 1991 to 1995. Conditions varied between locations and between seasons. It appears that the percolation and dry snow facies are rougher than during the summer months, at least based on observations at Crawford Point and Dye-2. Local topography and storm conditions can change the roughness within a matter of hours.

Surface roughness types vary within local areas. This is controlled partly by the rate at which erosion and deposition occurs across the surface. Variation also occurs because of the influence of the persistence seasonal winds and the occasional storm winds, which tend to also flow from a preferred direction. The result is a commonly observed checkerboard surface that forms at scales of 100 m or more.

The important scattering surface can be deduced from surface radar experiments. As illustrated from measurements at Dye-2, the primary scattering surface may be below the surface separating air from snow. Moreover and as illustrated in numerous firn stratigraphy studies in Greenland and Antarctica, thin but numerous density layers form throughout the deposition season. The integrated effect of these layers may contribute to the near surface radar response.

The complex surface textures (several surface roughness types, checkerboard surfaces) that extend over distance scales from a few centimeters to 100s of meters complicate estimates of surface correlation length. A good procedure for capturing the 3-dimensional roughness illuminated by a wide radar beam operated from high elevation remains to be developed. Similarly, the near surface firn structure can mean that subsurface layers are the source of the dominant backscatter. This is difficult to determine without in situ observations.

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