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Passive and Active Microwave Studies of Wet Snowpack Properties

Results of March 4, 1981, Aircraft Mission

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Microwave signatures have been found to be related to variations in snow conditions found on the earth's surface. Most of these observations have been obtained by passive microwave radiometry. In general, inverse relationships between microwave brightness temperature (T_B) and snow depth were observed for dry snowpacks. The results from truck-mounted scatterometers indicated that the backscattering cross sections from snowpacks increased with snow depths, also in dry snow conditions. The reported aircraft mission was the first trial in which simultaneous active and passive microwave measurements were made over a wet snowpack. The test site was located in the Colorado Rocky Mountains. The results from this experiment suggest that microwave techniques using both radiometers and scatterometers may be useful in determining snow water equivalent even when the snowpack is wet.

Introduction

Snow cover is an important factor in the Earth's climate system. Approximately one-sixth of the surface of the Earth is covered by snow and ice. Due to its high albedo, high thermal emissivity and low thermal conductivity, snow cover strongly influences the overlying atmosphere. Knowledge of snow cover distribution, extent, depth and water equivalent is vital for improving medium and long range weather forecasts and for perfecting general circulation models. Since the areal extent of snow varies rapidly, timely observation of snow parameters are needed.

Visible and near-infrared data have recently come into operational use for snow covered area determinations. However, these data acquisition are frequently hampered by cloud cover, sometimes at crucial times. Furthermore, information on water equivalent, free water content, and other properties pertinent to climate research and hydrology applications are not currently obtainable using visible and near-infrared techniques. Microwaves which are mostly unaffected by clouds and can penetrate through various snow depths, are potentially capable of remotely sensing these needed snow parameters.

An inverse relationship has been found to exist between passive microwave brightness temperature (T_B) and snow depth in dry snowpacks in homogeneous land areas. This finding has been confirmed by truck-mounted, airborne and satellite systems (Chang et al. 1979, Ulaby and Stiles 1981, Hall et al. 1978, Foster et al. 1980, Chang et al. 1982, Kunzi et al. 1982, Tiuri and Hallikainen 1981). Similar results were reported by active microwave techniques but the backscattering cross-section increased with snow depth (Ulaby and Stiles 1981). Because of these relationships, hydrologists may ultimately be able to use space-borne microwave sensors to assess the water equivalent of snowpacks which is an important parameter in forecasting the spring snowmelt runoff.

When the snowpack is wet, drastic changes in the microwave brightness at 37 GHz have been reported (e.g. Stiles and Ulaby 1981). At 37 GHz penetration is negligible in a wet snowpack. Depth of microwave penetration is, in part, dependent upon frequency or wavelength. Even for the longer wavelength, e.g. 6 cm (5 GHz) data, it is not certain that the microwave radiation can penetrate into wet snowpack with any substantial depth. The purpose of this experiment was to resolve the penetration capability of both active and passive microwave sensors for melting snowpacks.

The Airborne Microwave Experiment

There have been no simultaneous airborne passive and active microwave observations and ground information data sets available for studying the snow properties. In this paper, we describe an experiment which was taken the first time at a place in the Colorado Rockies with airborne active and passive microwave sensors and concurrent ground truth data.

The NASA C-130 aircraft equipped with active and passive microwave sensors was flown in the Colorado Rockies during the winter of 1980-1981. Steamboat Springs, Colorado was the major study site. Steamboat Springs (elevation 2,140 m) is located in northwestern Colorado on the western flank (windward side) of the Park Range Mountains. The Steamboat Springs flight line is approximately 8 km in length in the Yampa River Valley, a few km south of the town of Steamboat

Springs. This flight line is located in an area of flat pasture and meadow land with the southermost kilometer being hilly and covered by sagebrush and grasses. The valley receives an average of approximately 445 cm of snowfall; its windward location and the fact that there are no major mountain ranges in the immediate vicinity to intercept precipitation coming from the west contribute to the large amount of snowfall. Ground truth data, which include snow density, depth, water equivalent, were measured along the flight line at intervals of 30 m. Detailed ground truth data have been reported by Jones (1981).

The NASA C-130 aircraft was equipped with four non-imaging, microwave radiometers known as the Multifrequency Microwave Radiometer (MFMR) at the time of the flights. It consisted of four frequencies (5, 18, 22.2 and 37 GHz) and the characteristics of the MFMR are shown in Table 1. These are Dicke type radiometers, which were internally calibrated by using warm and cold references. External calibrations were performed before and after the flights by passing over a water target. For water calibration during the winter season, the aircraft overflew a reservoir on the Rio Grande River near Sante Fe, New Mexico. To assess the quality of observed brightness temperature, the expected brightness temperatures for water targets are calculated based on the onboard infrared surface temperature measurement and the radiative transfer model using a mid-latitude winter atmosphere profile. The comparison of the observed and the calculated brightness temperatures was consistently within several Kelvins for all the radiometers. Thus, good calibration was achieved.

There were four scatterometers on board the C-130 aircraft. The frequencies were 0.4, 1.6, 4.75 and 13.3 GHz respectively. These scatterometers consisted of an FM-CW fan beam transmitter and receiver. The Doppler effect is used to achieve the angular resolution along track. Cross track resolution for each frequency is based on the beam width of each antenna. The spatial resolution for these processed data are approximately 150, 75, 50 and 25 m, respectively, for an aircraft altitude of 400 m. The scatterometer data were processed for incidence angles ranging between 5° and 50°. The backscattering coefficients obtained by these scatterometers are believed to be accurate to ±1 dB level. Since there were

Table 1 – MFMR Characteristics

Wavelength (cm)	Frequency (GHz)	Beamwidth (degree)	Look Direction	Resolution at an Aircraft Altitude of 600 m (50° nadir angle)
0.8	37.0	6	backward	91 × 143 m
1.4	22.2	6	backward	91 × 143 m
1.7	18.0	6	backward	91 × 143 m
6.0	5.0	6	forward	91 × 143 m

no external reference targets prepared for this experiment, we could only qualitively compare these data with the truck-mounted scatterometer data obtained in previous years by the University of Kansas (Ulaby and Stiles 1981).

Results from the Microwave Instruments

During the March 4, 1981 aircraft mission, a total of five overpasses was made for the Steamboat Springs valley test site. Three of these runs employed the radiometers at incidence angles of 0°, 30° and 50° respectively. The radiometer data were integrated to form half second samples. The other two runs were reserved for obtaining scatterometer data. These data were processed to half second intervals for 4.75 and 13.3 GHz and one second intervals for 0.4 and 1.6 GHz. The time of the overflight was approximately 1 p.m. MST. The snow depth varied from 63 cm to 23 cm over the entire flight line with an average of 43 cm, and the snow water equivalent varied from 16.5 cm to 2.5 cm with an average of 8.5 cm (Fig. 1). During the overflight the snowpack was actively melting in the top 10 cm. The wet snow signatures as seen in the radiometer data are completely different from signatures of a dry snowpack. The brightness temperatures for the 37 GHz radiometer over the snowpack for nadir incidence were observed to have fairly uniform signatures with average of 265K and a standard deviation of 2.5K regardless of changes in the snow depths along the flight line (Fig. 2). This suggests that at 37 GHz the observed radiation was totally from the melting surface layer which emits microwave radiation almost as a blackbody (Chang and Gloersen 1975). This brightness temperature (265K for 43 cm averaged snow depth) is quite different from the calculated dry snow signature of 200K for 40 cm thickness of snow with a 0.3 mm mean radius (Chang et al. 1982). This is because in the dry snowpack,

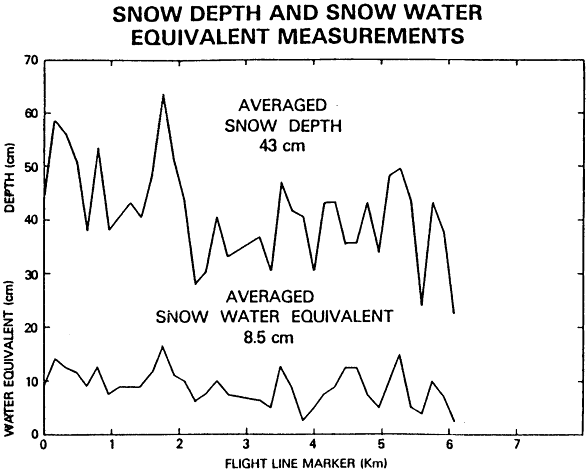

Fig. 1.
Measured snow depth and snow water equivalent along the flight line.

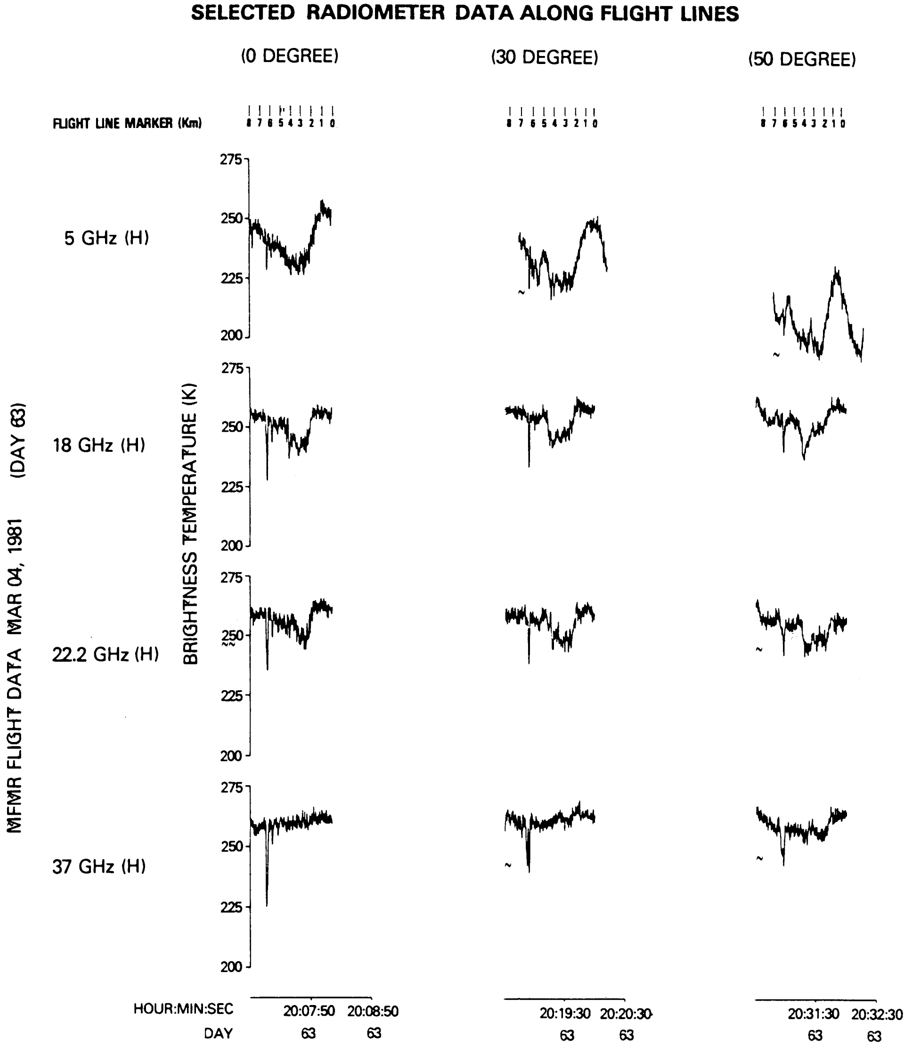

Fig. 2. Horizontally polarized microwave brightness temperatures along the flight line for 5 GHz (C Band), 18 GHz (Ku Band), 22.2 GHz (K Band) and 37 GHz (K_A Band) at 0°, 30° and 50° incidence angles.

snow crystals scatter and redistribute the microwave radiation emerging from the underlying soil. At 37 GHz the scattering coefficient of snow is much larger than the absorption coefficient. Below 20 GHz, absorption becomes the dominate effect in snowpack. When the snow is wet, the absorption coefficient of snow increases drastically and becomes the dominant effect in the radiative transfer processes. For 37 GHz radiation, the change of scattering to absorption mechanism makes wet snowpack radiate like a blackbody. The abrupt change in the 37 GHz brightness for wet and dry snow can be utilized for monitoring the wetness of a snowpack.

The observed brightness temperatures for the 18 and 22 GHz showed more variation along the 8 km (5 mile) flight line. A gentle slope of decreasing brightness was observed between 3 and 8 km and a change of 20K was observed. By inspecting the aerial photo, the snow condition was not distinctly different along the flight line. This suggests that aerial photo could not provide snow depth information other than snow coverage. The deeper snow at the eighth kilometer location corresponded to observed higher brightnesses and the shallower snow at the third kilometer location corresponded to lower brightnesses. This indicates that microwave radiation at these two frequencies could penetrate into a melting snowpack and provide some depth information.

The brightness temperature for the 5 GHz radiometer showed substantial slope along the flight line. For 0° incidence angle it varied from 220K to 260K along the flight line and the T_B seemed roughly proportional to the depth of the snow. The maximum brightness temperature happened at the beginning of the first kilometer mark where the snow depth was 63 cm. The minimum brightness happened at the end of the third kilometer with snow depth of 30 cm. Apparently at this frequency, the scattering effect of snow crystals does not contribute much to the brightness variations. The observed brightness temperature is the sum of radiation emerged from underlying soil and snowpack. Under this condition the snow depth/water equivalent might be inferred by using the 5 GHz radiometer.

Active microwave sensors have been utilized in the last several years for snow monitoring purposes (Ulaby and Stiles 1981, Rott 1984). In the 10 GHz region, the backscattering coefficients for completely dry snowpacks are not sensitive to snow depth up to a snow water equivalent of 64 cm (Matzler and Schanda 1984). This is because the penetration depth at 10 GHz is about 10 m (Hofer and Mazler 1980). A completely different situation occurs when the snowpack becomes opaque for wet snow. The high relaxation losses of liquid water reduce the penetration depth to about one wavelength at the typical water content of 3-4 percent by volume (Stiles and Ulaby 1981) and the radar backscattering coefficients have been found to be lower than in the dry snow cases. The low backscattering coefficient of wet snow compared with dry snow or snow free land provides an opportunity to distinguish these signatures (Matzler and Schanda 1984) as long as the snow depth is greater than one wavelength.

By inspecting the processed scatterometer data over the flight lines, the variation for the measured scattering coefficients was approximately 20 dB for natural snow covered terrain. Radar backscattering from snowpack is not only sensitive to snowpack characteristics but also sensitive to surface topography features. The backscattering coefficients obtained by all four scatterometers correlated well with one another along the flight line. Fig. 3 shows the scatterometer returns for

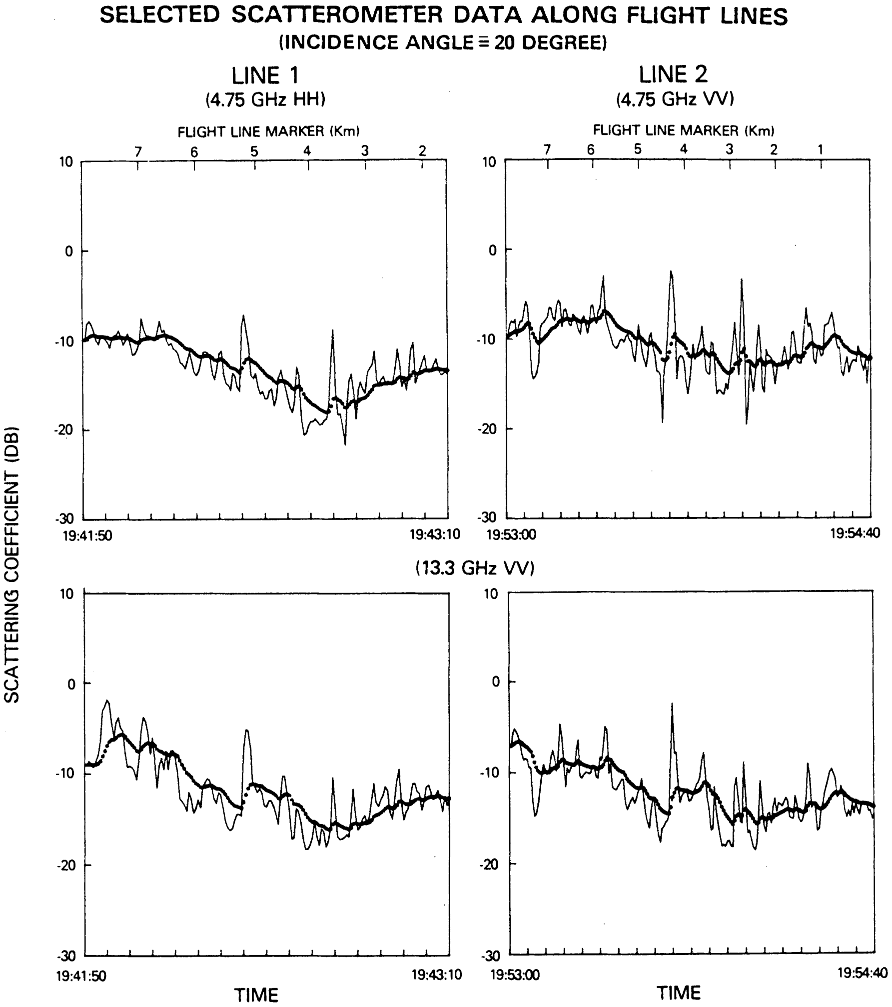

Fig. 3. Scatterometer returns for the 4.75 GHz *HH* and *VV* polarization and 13.3 GHz *VV* polarization along two flight lines.

the 4.75 GHz *HH* and *VV* polarization and 13.3 GHz *VV* polarization with 20° nadir angle. These two frequencies are used because they are more responsive to the snow depth variation (Ulaby and Stiles 1981). A quick glance of this figure gives one an impression that the scatterometer data are dominated by surface protrusions and underlying soil surface features. After applying a low pass filter to these data, the dotted curves in Fig. 3 started to qualitatively resemble snow depth information. The backscattering coefficients of 4.75 GHz *HH* at the sixth kilometer with 45 cm of snow were higher than those at the third kilometer with 35 cm of snow. However, the deepest snow at the end of the third kilometer was not

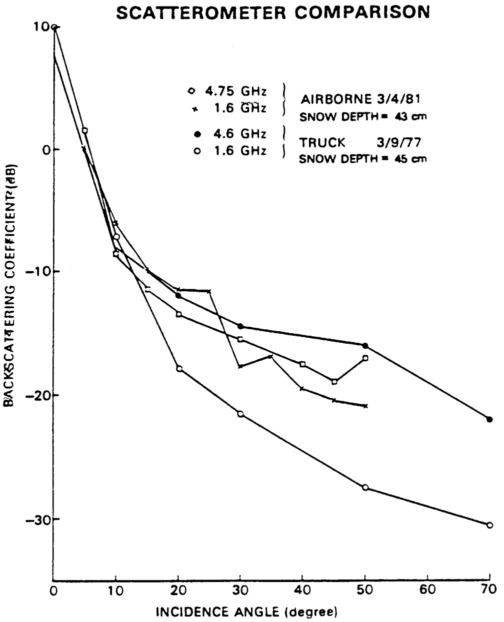

Fig. 4.
Comparison of scatterometer returns obtained by aircraft sensors and the truck system.

shown with high return. These data also showed that $\sigma_{VV} > \sigma_{HH}$ for 4.75 GHz, similar to those at 10 GHz reported by Matzler and Schanda (1984), and σ_{HV} were about 10 dB lower than σ_{HH} with σ_{HV} 4 dB higher than σ_{VH} for wet snow. The average return of 13.3 GHz *VV* scatterometer compared well between two subsequent flight lines thus providing confidence on the quality of the scatterometer data.

Generally, the backscattering coefficients from these airborne scatterometers were similar to those results from a truck experiment by Stiles and Ulaby (1979). For comparison, the truck data collected on March 7, 1977 were used. The snowpack was 45 cm in depth and with surface melting, thus conditions were similar to the snow conditions present when the aircraft data for this study were acquired. The comparisons were made between the averaged return along the entire flight line and the truck results at different angles. Fig. 4 shows the 1.6 and 4.75 GHz data from aircraft observations and 1.6 and 4.6 GHz data from truck experiment. The data from these two experiments were consistently within several dB for all the incidence angles. Since these differences are much smaller than the difference of dry and wet snow (~ 10 dB), active microwave sensors indeed could be used for wet snow discrimination.

Both active and passive microwave signatures are strongly influenced by the melting of a snowpack. In order to further understand the interaction of microwaves with wet snow grains, detailed wetness information is required. However, these rapid changes in the amount of water held in a melting snowpack could not be easily verified by conventional methods for measuring liquid water content, such as freezing calorimetry used in the ground truth observations. The dilution method recently reported by Davids and Dozier (1984) can sample snow wetness in minutes and should be used in the future experiment to improve the understanding of actual snow conditions when the microwave data are taken.

Conclusions

Microwave signatures have been found to be related to variations in dry snow conditions. The results from this aircraft mission indicate that the microwave radiation emerging and scattered by snowpack can also provide information when the snowpack is wet. Previously, it was believed that wet snowpack radiated as blackbody and would not provide any depth information other than wetness. Both passive and active microwave data from this experiment qualitatively showed resemblence between the measured snow dephts and microwave signatures along the flight lines, except the 37 GHz data. More detailed microwave experimental observations of wet snowpack in the future should be considered in order to quantify the relationships between microwave signatures and snow depth/water equivalent and wetness.

Due to the dynamic changes of snowfall and snowmelt in the late snow season, snowpack information obtained when the snow is melting is pertinent for hydrologists to improve their forecasting of snowmelt runoff. At present, no remote sensing technique can provide this information during melting. Most of snowmelt runoff models are totally based on an empirical recession equation plus temperature and snow covered area information without knowing the actual water storage of the snowpack. If this technique proved to be feasible, then the capability of using microwave in monitoring the snowpack condition could be extended into spring melting season.

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References

Chang, A. T. C., Shiue, J. C., Boyne, H., Ellerbruch, D. E., Counas, G., Wittman, R., and Jones, R. (1979) Preliminary results of a passive microwave snow experiment during February and March, 1978, NASA Technical Paper No. 1408, 112 pp.

Chang, A. T. C., Foster, J. L. Hall, D. K., Rango, A., and Hartline, B. K. (1982) Snow water equivalent estimation by microwave radiometry, Cold region Science and Technology, 5, pp. 259-267.

Chang, T. C., and Gloersen, P. (1975) Microwave emission from dry and wet snow, NASA SP-391, Operational Applications of Satellite Snowcover Observation, pp. 399-407.

Davis, R. E., and Dozier, J. (1984) Snow wetness measurement by flourescent dye dilution, to be published in Journal of Glaciology.

Hall, D. K., Chang, A., Foster, J. L., Rango, A., and Schmugge, T. (1978) Passive microwave studies of snowpack properties, Proceedings of the 46th Annual Western Snow Conference, pp. 33-39.

Hofer, R., and Matzler, C. (1980) Investigations of snow parameters by radiometry in the 3 to 60 mm wavelength region, *Journal of Geophysics Research, Vol. 85,* pp. 453.

Foster, J. L., Rango, A., Hall, D. K., Chang, A. T. C., Allison, L. J., and Diesen, B. C. (1980) Snowpack monitoring in North America and Eurasia using passive microwave satellite data, *Remote Sensing of Environment, Vol. 10,* pp. 285-298.

Jones, E. B. (1981) Snowpack characterization and associated ground truth, Summary Report, Contract No. NAS5-26062, Goddard Space Flight Center, 15 pp. + Appendices.

Kunzi, K. F., Patil, S., and Rott, H. (1982) Snow-cover parameters retrieved from Nimbus-7 Scanning Multichannel Microwave Radiometer (SMMR) data, IEEE Transactions of Geoscience and Remote Sensing, GE-20, pp. 452-467.

Matzler, C., and Schanda, E. (1984) Snow mapping with active microwave sensors, *International Journal of Remote Sensing, Vol. 5,* pp. 409-422.

Rott, H. (1984) The analysis of backscattering properties from SAR data of Mountain regions, to be published in IEEE Journal of Oceanic Engineer.

Stiles, W. H., and Ulaby, F. T. (1979) Microwave remote sensing of snowpacks, NASA CR-3263.

Stiles, W. H., and Ulaby, F. T. (1981) The active and passive microwave response to snow parameters 1. wetness, *Journal of Geophysical Research,* pp. 1037-1044.

Tiuri, M., and Hallikainen, M. (1981) Microwave emission characteristics of snow covered earth surface measured by the Nimbus-7 satellite, 11th European Microwave Conference, Amsterdam.

Ulaby, F. T., and Stiles, W. H. (1981) The active and passive microwave response to snow parameters 2. water equivalent of dry snow, *Journal of Geophysical Research, Vol. 85,* pp. 1045-1049.

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