RESEARCH ON THE INTERACTION OF MICROWAVES WITH SNOW AND ICE
PART I. A STUDY ON THE MICROWAVE BACKSCATTERING FROM MELTING SNOWPACK

Masahiro SUZUKI, Tadashi MATSUMOTO, Daisuke KUROIWA,

Hokkaido Institute of Technology, 419–2, Teine-Maeda, Nishi-ku, Sapporo 061–24

Kazuo FUJINO and Gorow WAKAHAMA

The Institute of Low Temperature Science, Hokkaido University, Kita-19, Nishi-8, Kita-ku, Sapporo 060

***Abstract*:** The primary objective of this paper is to obtain the basic data on the interaction between microwaves and natural snowpack in the melting season using 9.37 GHz and 31.5 GHz microwaves. The diurnal variations of the back scatter from snowpack were measured through microwave sensors placed above the surface. The obtained results indicated periodic changes in the daytime and relatively monotonous changes in the nighttime. These results suggest that the interference occurred between the reflective wave from snowpack and the original transmitting wave.

In order to confirm these periodic changes of the back scatter, laboratory experiments were carried out by the use of artificially wetted snow.

1. Introduction

Research on the microwave response of snow has been strongly stimulated by the potentiality of remote sensing of seasonal snowcover from the air- and spacecrafts (ULABY, 1982a, b). The microwave remote sensing of snowpack may become a powerful tool to estimate depth or water equivalent of snowcover and to forecast the time of snow melting, flood, avalanche and so forth. Though the usage of an optical sensor is limited to only cloudless condition, the microwave sensor can be used under all weather conditions. However, it seems that there are many ambiguities in the mechanism of the microwave backscattering from snowpack.

The primary purpose of this paper is concerned in the basic research on the microwave back scatter from melting snowpack in fixed frequency. In the beginning of the snow melt, the free water produced at the surface is mainly suspended through necks between snow grains, and pore spaces in snow texture are not fully occupied with the melt water. This state of the melt water in snow texture is called "pendular regime". As the melting proceeds, the melt water begins to occupy continuously the pore spaces, forming highly saturated situation of the free water called "funicular regime". Then the melt water begins to percolate downward and the depression of the snow surface occurs because of the shrinkage of subsurface layers. The level of snow surface descends more quickly in the daytime than in the nighttime. The transition from the pendular to funicular state and percolation of the melt water in snow texture will exert a great influence to the intensity of the back scatter when the snow surface is sensed by a microwave. The present authors tried to measure the diurnal variations of the intensity of microwave back scatter from the melting snowpack at Mt. Asahi (1980 m) in May 1982, using simultaneously 9.37 and 31.5 GHz waves. In our experiment, the microwaves were emitted continuously onto the snow surface with the incident angle of zero degree to measure diurnal variations of the back scatters.

Several interesting phenomena were observed in our experiments. The intensity of the microwave scatters significantly fluctuated in the daytime, but in the nighttime it changed monotonously. The frequency of the fluctuation observed in the daytime was correlated to the variation of the rate of snow melting. These findings suggest that the interference occurred between the reflected microwave from the snowpack and the originally emitted wave. In order to confirm the interference phenomena found in the field observation, many experiments were conducted in the laboratory, using artificially prepared snow blocks where the melting rate of snow was well controlled and monitored.

2. Microwave Experimental Apparatus and Procedures

Figures 1(A) and (B) show block diagrams of the experimental apparatus composed of X and R microwave frequency bands. In the X-band waveguide system,

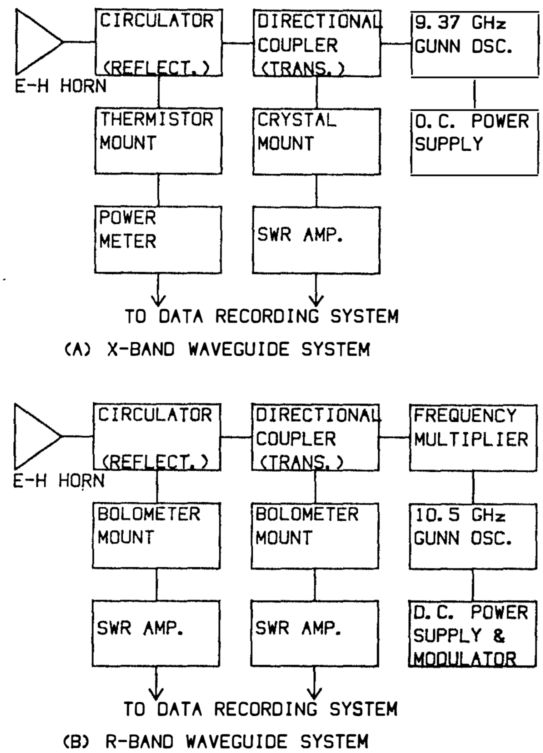

Fig. 1. Block diagrams of the experimental apparatus.

CW (continuous wave) output power of 9.37 GHz from a Gunn oscillator is emitted perpendicularly to the snow surface through a directional coupler, a circulator and an E-H horn. Fluctuations of transmitted power are detected by a crystal mount and are monitored by a SWR (standing-wave ratio) amplifier. The back scatter from snowpack is received by the same horn used as the transmitting horn. The received signal is separated from the transmitted signal by the circulator and is sent toward the power meter through a thermistor mount. However, a part of the original wave transmitted toward the directional coupler leaks out toward the thermistor mount through the circulator and interferes with the reflected wave from the snowpack. If the phase difference between the reflected wave and the original wave changes with time, the fluctuated intensity of the back scatter will be recorded by the power meter. As will be shown later, the period of the fluctuation caused by the interference depends on the surface depression of the snowpack due to melting.

In the R-band waveguide system, the microwave frequency of 31.5 GHz is generated by the aid of frequency multiplier which multiplies the frequency of 10.5 GHz Gunn oscillator output by three times. The amplitude of the Gunn oscillator output is modulated by the rectangular wave signal of 1000 Hz. The bolometer mounts and the SWR amplifiers are used for both of the purposes of the detection of transmitting and backscattering amplitudes. In the case of R-band waveguide system, the similar interference will occur between the reflected wave from snowpack and the original wave which partly comes in the SWR amplifier through the circulator and the bolometer mount, allowing the detection of the surface depression of the snowpack due to melting.

The detected and amplified signals through the apparatus shown in Fig. 1 are sent to the data recording and processing system which consists of a 4-channel A/D converter, a desk top computer and a graphics display. The diurnal variation of the intensity of the back scatter from snowpack and power fluctuation of the transmitting wave are simultaneously recorded every five minutes. The fluctuations of the back scatter with time are monitored through the display apparatus.

3. Results of Field Experiments

The field experiments were conducted at the middle altitude of Mt. Asahi, in Mt. Daisetsu National Park, Hokkaido, Japan, from May 8 to May 13 in 1982. The E-H horns of X-band and R-band frequency transmitters were mounted at the height of 31.5 cm and 72 cm respectively above the snow surface, in such a way that the incident angle of the microwave to the snow surface comes to zero degree. The snowpack was about 3 m in depth and composed of wet granular grains, and the snow temperature was maintained at 0°C, through the day and night. The apparent density of wet snow was 0.49 g/cm^3. The weather was fine and calm during the term of the field experiment.

Figure 2 shows diurnal variations of the back scatter of 9.37 and 31.5 GHz waves obtained from 2030, May 8 to 0830, May 11. As seen in this figure, remarkable fluctuations of the intensity of back scatter of both waves were observed in the daytime, but the fluctuations became relatively monotonous in the nighttime. The period of

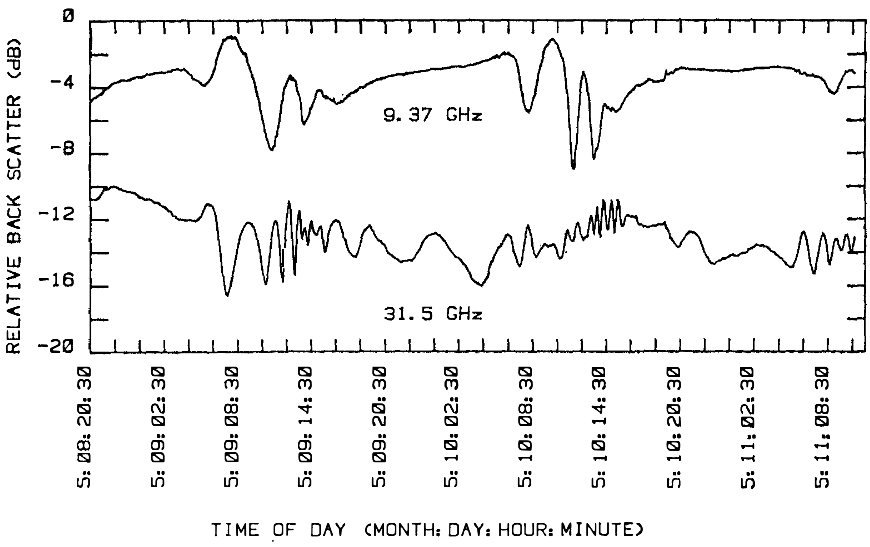

Fig. 2. Diurnal variations of the relative intensity of the back scatter.

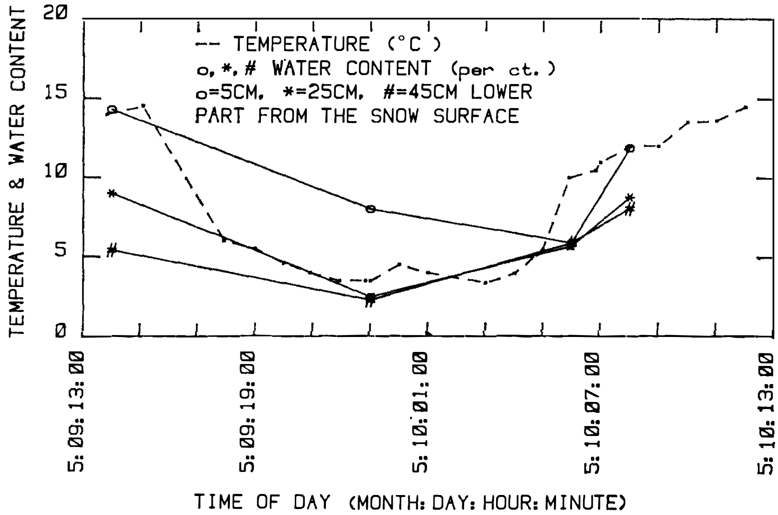

Fig. 3. Diurnal variations of the air temperature and the water content.

fluctuation of 9.37 GHz observed in the daytime was approximately three times larger than the period of 31.5 GHz wave.

Figure 3 shows the variation of the air temperature (in °C) and the free water content (in weight %) measured by a calorimetric method, taking samples from layers underlying the surface of snow at 5, 25 and 45 cm in depth. As seen in this figure, the obtained value of the free water content in snow near the surface was approximately 15% around 1300, May 9, but it decreased with time and became minimum ($\sim$6%) early in the morning of May 10. If we turn to look at Fig. 2, it is evident that the significant fluctuation of back scatter occurred at the time when the free water content increased. In Fig. 2, we have to notice that the period of the fluctuation of 31.5 GHz observed during noontime, 1200–1500, at which snow melting was most severely taking place, was shorter than that observed in the morning, 0700–1000, at which slight melting was proceeding. Similar fluctuation phenomena can also be seen in the intensity of the back scatter of 9.37 GHz wave in Fig. 2. Hence it may be obvious that the period of the fluctuation of microwave back scatters is correlated to the rate of snow melting.

In order to examine if the fluctuation of the microwave back scatter depends on the rate of snow melting, a simple experiment was conducted *in situ*; a polyethylene bag (70 × 70 cm) containing a mixture of $CaCl_2$ and snow was placed on the melting snow surface to freeze wet snow. The air temperature was +4°C and the interfacial temperature between the bag and snow was −18°C. Approximately two hours later, the bag containing the freezing mixture was removed to expose the frozen surface to the microwave emitters. Figure 4 illustrates the variation of the back scatters from the snow surface before and after the freezing. In this figure, fluctuating two

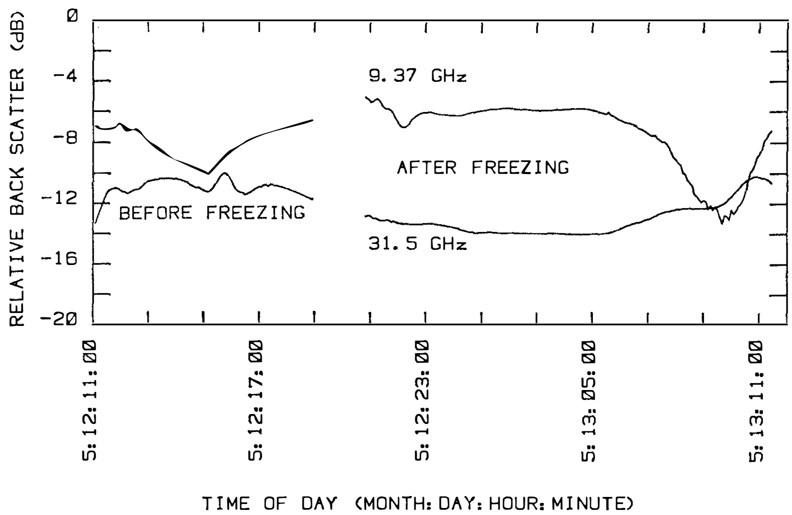

Fig. 4. Variations of the back scatter from wet and frozen snowpack.

curves drawn during the time from 1100 to 1900, May 12, indicate the back scatters from the surface where the melting was proceeding. During the period from 1900 to 2100, the wet snow surface was temporarily frozen by placing the polyethylene bag containing the freezing mixture. Relatively smooth curves of the back scatters were observed after the bag was removed. It should be noted that immediately after the removal of the bag, the surface of snow was frozen but it began to melt gradually again because the air temperature near the surface was maintained just above 0°C and percolation of the melt water did not occur until the air temperature began to rise in the morning of May 13. After 7 o'clock, the intensity of back scatter began to oscillate again with the increase of the rate of melting. This experiment proves that the fluctuations of the back scatter seen in Fig. 2 were dependent upon the rate of snow melting.

4. Results of Laboratory Experiments

In order to ascertain the results of the field observation, many experiments were conducted in a laboratory of Hokkaido Institute of Technology, Sapporo, Japan, in November 1982. Fine-grained rectangular snow slabs, 33×42×27 cm, which had been stored in a cold room, were gradually melted in the room where the air temperature was maintained above 0°C, and the variations of microwave back scatter of 9.37 and 31.5 GHz were measured continuously with time. Two E-H horns were mounted at 12 and 14 cm above the snow slab for X-band and R-band systems respectively. The temperatures of snow were measured at immediately beneath the surface (1 cm in depth) and the center of snow slab with the variation of the room temperature.

Figure 5 illustrates variations of the intensity of back scatter of 9.37 GHz wave and the room and snow temperatures against the time. Immediately after the snow slab was taken out from the cold room to the warm room where the experiment was

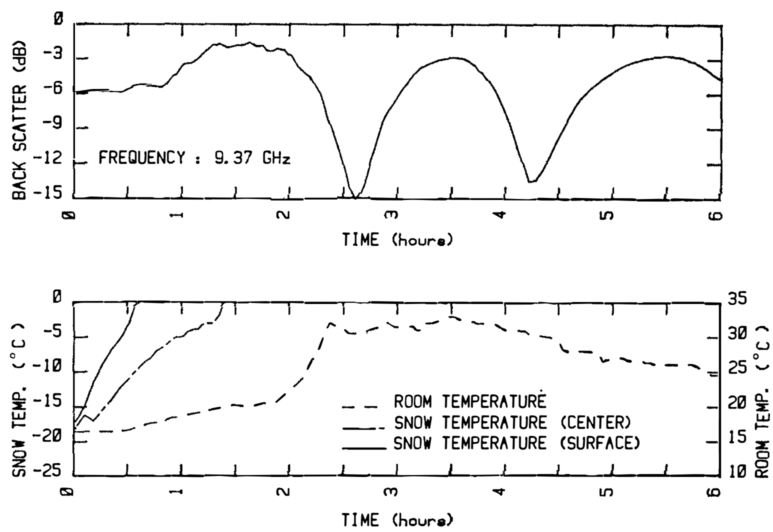

Fig. 5. Variations of the intensity of back scatter of 9.37 GHz wave and the room and snow temperatures against the time.

conducted, the temperature of snow was −20°C and after one and half hours the temperature at the center of slab attained to 0°C. The intensity of back scatter began to oscillate when the surface temperature came to 0°C as shown in the upper diagram of Fig. 5. The oscillation was not sinusoidal, but the peak of the oscillation occurred every about 2 hours.

Figure 6 shows the variations of the intensity of the back scatter of 31.5 GHz wave and the room and snow temperatures against the time. Differently from the oscillation observed in 9.37 GHz wave, the fluctuation of the back scatter of 31.5 GHz wave was fairly sinusoidal and the oscillation began before the surface temperature of the snow slab came to 0°C. It is believable that in this instance the true surface of snow slab began to melt although the surface temperature measured at 1 cm in depth did not attain to 0°C. Hence the back scatter of 31.5 GHz wave was created from very thin layers near the surface where the superficial snow grains were slightly melted. While in the case of 9.37 GHz wave, the back scatter was created from deeper layers where snow grains were fully wetted. In Fig. 6, it should be noted that the period of oscillation of the back scatter observed at about 4 hours later (labeled

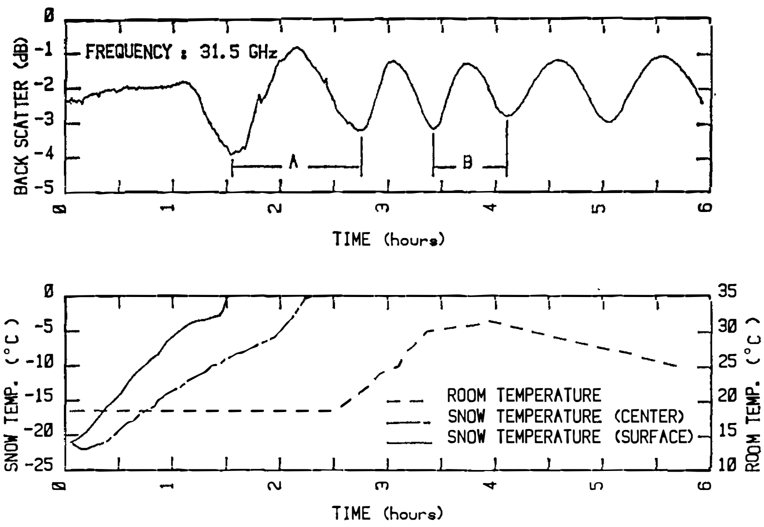

Fig. 6. Variations of the intensity of back scatter of 31.5 GHz wave and the room and snow temperatures against the time.

by B) is shorter than the period observed in the initial stage of the melting (labeled by A). As seen in the lower diagram of this figure, after 4 hours, the room temperature rose to 30°C and the rate of melting at the surface increased very rapidly, causing the percolation of the melt water and the surface depression of snow. After about five hours, the fluctuation again began to show a long period with decreasing room temperature. This experiment suggests that the period of the fluctuation of back scatter from wet snow is dependent upon the rate of melting of snow. The similar phenomena were observed in the diurnal variation of the back scatters obtained on the natural snowpack in Mt. Asahi, Daisetsu National Park (Fig. 2).

Figure 7 demonstrates that the period of fluctuation of the back scatter of 31.5

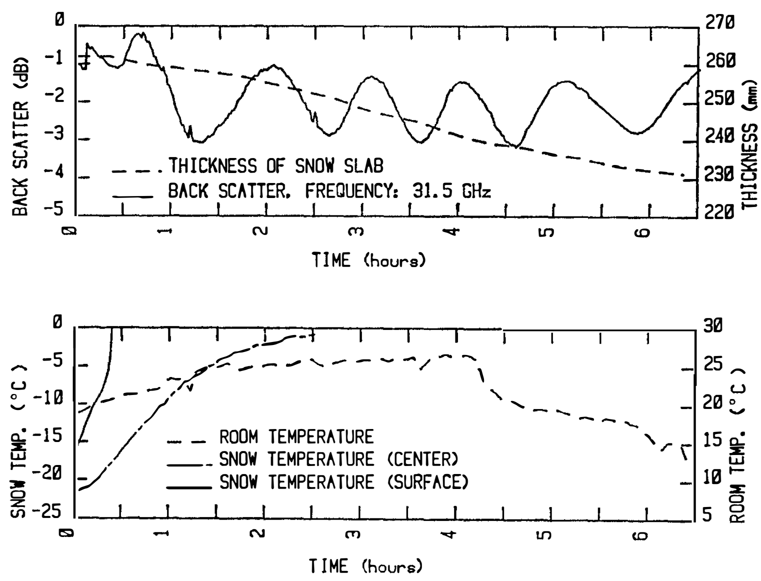

Fig. 7. Relations between the thickness of snow slab and the periodic fluctuation of the back scatter at the frequency of 31.5 GHz.

GHz wave from wet snow depends on the rate of melting of snow, that is, the rate of surface depression of melting snow. In Fig. 7, the upper diagram deliniates the fluctuation of the back scatter as a function of time and decrease of the thickness of the snow slab. The lower diagram depicts the temperature variations of the room and snow slab against the time elapsed. As seen in Fig. 7, the thickness of the snow slab was 263 mm in the beginning of the melting, but it began to decrease with time and came to 230 mm six and half hours later. The room temperature was about 18°C in the beginning of the experiment, but it began to rise gradually with time and attained to 27°C about 4 hours later and then decreased to 14°C. It is obvious that during 2–4 hours at which the room temperature was 25–27°C, the rate of decrease of snow thickness (the slope of the broken line) is larger than that observed before and after this time period. Careful inspection of the upper diagram of Fig. 7 reveals that the period of the fluctuation observed during 2–4 hours at which the rate of decrease of snow thickness was most severe is shorter than that observed before and after this range of time.

Figure 8 shows the result of similar experiment conducted by 9.37 GHz wave. Though the fluctuation of the intensity of back scatter of 9.37 GHz was not sinusoidal, the period of the fluctuation tended to be large when the rate of surface depression of the snow slab decreased.

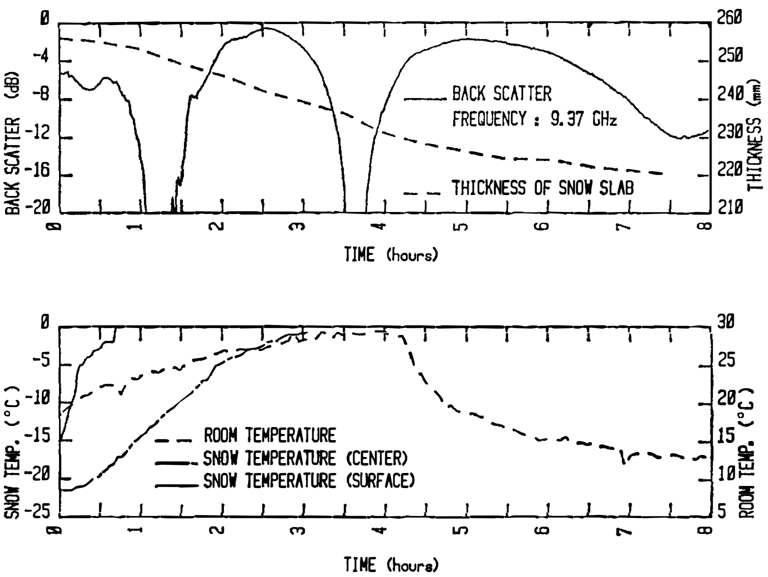

Fig. 8. Relations between the thickness of snow slab and the periodic fluctuation of the back scatter at the frequency of 9.37 GHz.

5. Discussion

According to ULABY's review paper (1982b), many authors have measured the average intensity of microwave back scatters from snowpack lying widely over the ground surface by means of sensors placed far above the snow surface, but it appears that very few measurements on the phase of the backscattering wave have been reported to date.

Since the primary purpose of our experiments was to obtain the basic data on the interaction between the melting snowpack and microwaves actively emitted onto it, the microwave sensors of 9.37 and 31.5 GHz waves were placed at height of 31.5–72 cm above the snow surface and two electromagnetic waves were emitted vertically against the snow surface to measure simultaneously variations of the intensity and phase difference of the back scatters.

Our results obtained on the natural snowpack in Mt. Asahi (Fig. 2) indicated that significant fluctuations of the intensity of the microwave scatters occurred in the daytime at which the melting of snow was severely taking place, and that the period of the fluctuation of 9.37 GHz wave was approximately 3 times larger than that observed in the back scatter of 31.5 GHz wave. These fluctuations or oscillations in the intensity of the back scatter were produced by the interference between the reflected wave from the snow surface and the original wave. The amplitude of oscillation in the intensity of back scatter from snow may be largely dependent upon the physical properties of snow such as density, grain size, and wetness, but we believe that the period of the oscillation of the intensity of the backscattering wave significantly depends on the rate of depression of snow surface due to melting.

In order to investigate this argument, many experiments were conducted in the laboratory, using rectangular snow slabs whose rate of melting was artificially controlled. Variations of the intensity of microwave back scatters from melting snow slabs were measured as a function of the decreases of the thickness of the slabs and time (Figs. 5–8). Figure 5 showed that the oscillation of back scatter of 9.37 GHz wave started when the thermometer buried 1 cm bellow the snow surface indicated 0°C. However, the temperature of snow layers deeper than 1 cm was still maintained below 0°C. This means that the back scatter of 9.37 GHz wave was created from "wet snow layers" having the thickness of 1 cm or more. Whereas Fig. 6 shows that the intensity of the back scatter of 31.5 GHz wave began to oscillate before the indication of the thermometer buried 1 cm bellow the surface came to 0°C. This means that the very thin layers at the surface of slab was slightly melted to create the back scatter of 31.5 GHz wave, although the temperature of snow lying at 1 cm beneath the surface was still maintained bellow the melting point of ice.

It should be noted, in Fig. 6, that the frequency of oscillation of the back scatter of 31.5 GHz wave increased when the room temperature rose to 30°C. This suggests that the period of the oscillation of back scatter depends upon the rate of snow melting at the surface of snow slab. Since the oscillation of the intensity of back scatter is created by the interference between the original wave and the backscattered wave the phase of which was retarded as the result of the long passages of the reflection, the rate of the surface depression due to melting exerts a significant influence to the period of the oscillation. In the experiment shown in Fig. 7, the surface of the snow slab sunk approximately 30 mm in depth because of the melting. If we recognize that the number of maximum of the oscillation for the time interval at which the surface depression of snow slab was taking place is 5, the value of the surface depression per one cycle of the oscillation of the back scatter of 31.5 GHz wave comes to 6 mm. This value is roughly equivalent to the half value of the wavelength of the electromagnetic wave used, that is 4.8 mm.

Figure 8 shows the similar experimental result obtained by 9.37 GHz wave. As seen in the upper diagram of this figure, the difference of the snow thickness measured at the beginning and at the end of this experiment was approximately 32 mm. The mode of the oscillation of the back scatter of 9.37 GHz wave was not sinusoidal because of the large amplitude of the oscillation expressed in terms of dB, but the number of the oscillation which occurred during the continuation of the surface depression of the snow slab can be found to be 2 cycles. Hence the surface depression per one cycle of the oscillation comes to 16 mm. This value is equivalent to the half value of the wavelength of 9.37 GHz wave, 16 mm.

Our experimental results shown above may allow us to suggest that there is a potentiality to predict the rate of snow melting by measuring the interference between an actively emitted microwave and a backscattering wave from the snow surface.

Acknowledgments

Part of this study was carried out as cooperative research of "Basic Research on the Interactions of Microwaves with Snow and Ice" at the National Institute of Polar Research.

Field and laboratory experiments were financially supported by Project No. 56420015 of "Studies on the Microwave Characteristics of Snowpack" from 1981 to 1983 under the Grant-in-Aid for Scientific Research (A), the Ministry of Education, Science and Culture of Japan.

References

ULABY, F. T. (1982a): Snow observation by microwave sensors. First Japan/US Snow and Evapotranspiration workshop, March 16–21, Tokyo, Japan.

ULABY, F. T. (1982b): Radar signatures of terrain; Useful monitors of renewable resources. Proc. IEEE, **70**(12), 1410–1428.

(Received April 11, 1983; Revised manuscript received June 13, 1983)