ESTIMATION OF THE WATER EQUIVALENT IN DRY SNOWPACK
USING A FM-CW MICROWAVE SENSOR

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1. Introduction

Recently, remote sensing techniques using electromagnetic wave for determining and monitoring the depth, water equivalent and other physical properties of snowpack have been remarkably developed [1][2].

In this several years, we have been concerned with the development of the active microwave sensing technique and measurement of the behavior of microwave in a snowpack, such as propagation properties in dry snowpack, back scatter from melting snowpack and so forth [3][4]. Also, we have tried to interpret the data obtained and to determine the stratigraphy and water equivalent [5].

This paper reports on the results of field experiments carried out in the dry snow season in 1984, using the active microwave sensor which is called the FM-CW microwave system. By analysing the spectra obtained by this microwave sensor, depth and relative dielectric constant are determined. Then average density of snowpack is obtainable through the mixing formulas for snow and time variations of water equivalent are finally estimated.

2. Experiment

The principle of the FM-CW system is well known and the details have been reported in elsewhere [5][6]. In our system, the microwave frequency was swept linearly over the range, 6 - 12 GHz, in 10 ms. A single antenna of rectangular aperture horn was used for transmitting and receiving the microwave. The microwave was emitted toward the snowpack surface at the near-normal incident to get a reflection from various interfaces in the snowpack. The received signal was transformed to the audio frequencies and was displayed on a spectrum analyser screen.

Two series of field experiments were carried out at the same test site on February 8 and March 8, 1984, when it was dry snow season in northern Hokkaido, Japan. In each series of experiment, the microwave measurement was continued for about 24 hours.

The stratigraphy and the profile of physical parameters such as grain size, density and temperature in the snowpack were observed at the same time by preparing an observation pit near the test site.

3. Determination of depth and relative dielectric constant

Typical spectra obtained from our microwave sensor, at 14:00 on February 8, is given in Fig. 1. In the figure, two peaks which may be corresponding to the surface of snowpack and the ground are clearly recognized.

At the start of this measurement, the depth of snowpack was 105 cm and the frequency corresponding to the snow surface was 9000 Hz. However, when the data of Fig. 1 was obtained the frequency corresponding to that was sifted by 150 Hz from the initial frequency. As the distance of 1 cm in air, that is, $\varepsilon = 1$, was calibrated to give 40 Hz frequency sift, we can conclude that the total depth of the snowpack was reduced to 101.3 cm during the measurement.

The average dielectric constant of a snowpack can be obtained from

$$\varepsilon = [c \; \Delta f \; /(2d \; df/dt)]^2, \qquad\qquad (1)$$

where c is the velocity of light, Δf the frequency difference between spectra corresponding to the surface and the ground, d snow depth and df/dt sweeping rate of frequency. By substituting d = 101.3 cm, Δf = 5200 Hz and df/dt = 0.6 GHz/ms, we obtain the average dielectric constant of the snowpack, that is, $\varepsilon = 1.65$.

4. Relations between relative dielectric constant and density

Many kinds of equation called mixing formulas which give the relation between the dielectric constant and the density of dry and wet snowpack have been previously presented [7]. Following simple formulas will be applicable to dry snowpack.

$$\varepsilon = 1 + 2.3 \, \rho \qquad\qquad \text{(Kuroiwa formula)} \qquad\qquad (2)$$
$$\varepsilon = (1 + 0.508 \, \rho \,)^3 \qquad\qquad \text{(Looyenga formula)} \qquad\qquad (3)$$

where, ε is the real part of relative dielectric constant and ρ is the density of dry snowpack.

Given in Fig. 2 is the stratigraphy and the profile of density of a snowpack which were observed in the pit near the test site at the same time when Fig. 1 was obtained.

In the figure, we see that the density of the snow layers increases gradually as a function of the depth and the average value is 0.30 g/cm^3.

By applying the average density to formulas (2) and (3), we can finally obtain 1.69 and 1.53, respectively, as the average dielectric constants. These values are close to the value obtained by using the microwave sensor, that is 1.65.

5. Estimation of the water equivalent in dry snowpack

Given in Fig.3 is plots of the frequencies at the two peak lines corresponding to the snow surface and the ground, respectively. These are obtained from the data of February 8 – 9. As is clear from the figure, the frequencies corresponding to the snow surface increases gradually with time. This means that the depth was decreased with time.

Figure 4 shows a variation of average relative dielectric constant obtained through the equation (1), and the densities from equations (2) and (3), respectively, using the measured values on the depth and the frequency difference between ground and surface. Both curves exhibit similar increase to the observation time.

The water equivalent of snow cover is defined by the integral [8];

$$W = \int_0^d \rho \, (z) \; dz \qquad\qquad (4)$$

where W is water equivalent [cm], ρ (z) is density profile [g/cm^3], and d is apparent depth [cm] of snowpack. For an average density, $W = \rho \, d$.

In Fig. 5, the water equivalents calculated by using above mentioned relations and the data of February 8 – 9 are compared. The point marked by "o" in the figure shows the water equivalent obtained for the average value of density profile in Fig. 2. This point is seen close more to Kuroiwa

curve.
　　Figure 6 shows similar plots to Fig. 4, but based on the data of March 8 - 9.

6. Discussion

　　In the previous chapters, we have described about the results of field experiments and the methods for estimating the water equivalent of snowpack. We discuss here more critically.

　　As shown in Fig. 3, the depth of the snowpack decreases with time. In contrast, the average values of relative dielectric constant and densities, as shown in Fig. 4, increase. These effect may be caused by the densification and metamorphism of fresh fallen snow layer of the surface.

　　Note that, even though the depth and average density are changed with time, the water equivalent are steady after 13:00 on February 8. Before 13:00, however,the water equivalent changes rapidly. This implies that the mixing formulas used here are not suited to obtain the density if fresh fallen snow layer exists.

　　The depth measured in March was approximately equal to that measured in February (~ 1 m). But, in March, the estimated water equivalent increased by 5 cm in depth comparing to that in February. We image that the densification of the snow layers may be quickly developed even if there were a lot of snowfall in the mean time, and then the depth of that was apparently not so much changed comparing to the water equivalent.

　　The experimental results in field demonstrate the potentiality of the microwave sensing technique in determining the water equivalent for dry snowpack. The following further investigations are undergoing: 1) experimental study for understanding the relation between the physical parameters of snowpack and electrical parameters. 2) theoretical modeling the snowpack.

References
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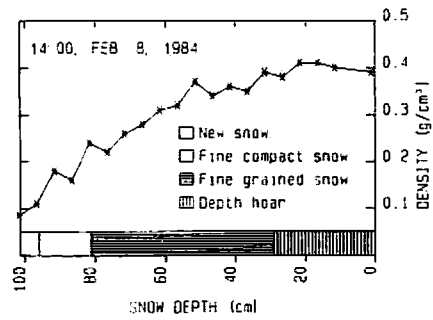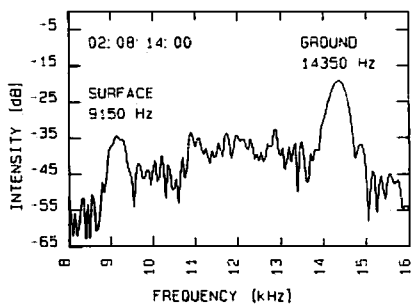
Fig. 1. Spectra obtained using a FM-CW microwave sensor.(L)
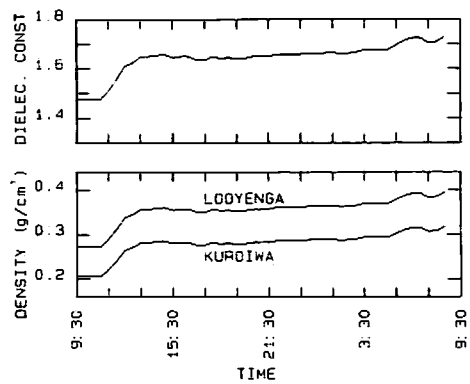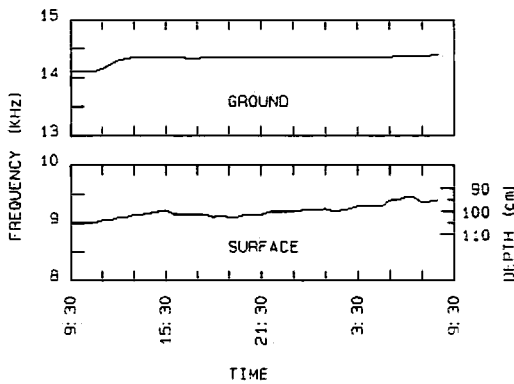Fig. 2. Structure and density profile of a snowpack.(R)

Fig. 3. Variations in frequencies of the peak positions corresponding to the
surface and the ground. Data obtained on February 8 - 9, 1984. (L)
Fig. 4. Variations in average values of relative dielectric constant and
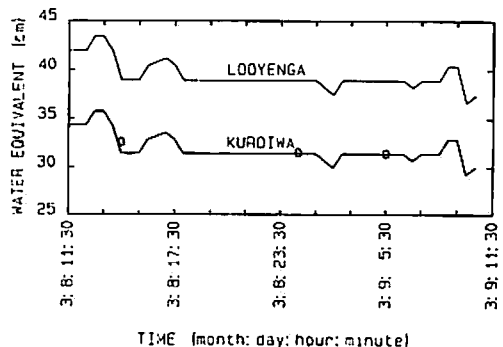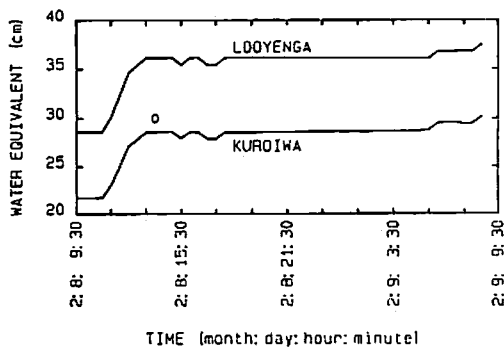densities. Data obtained on February 8 - 9. (R)

Fig. 5. Plots of the estimated water equivalent for the data of February 8 -
9, 1984. (L)
Fig. 6. Plots of the estimated water equivalent for the data of March 8 - 9,
1984. (R)