MICROWAVE MEASUREMENTS OF SNOW STRATIGRAPHY AND WATER EQUIVALENCE 651-79

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Introduction

This paper reports on a continuation of research on the relationship between the electromagnetic scattering properties and physical properties of snowpack (see Ellerbruch, et al., 1977). An FM-CW active microwave radar system operating in the frequency range 8-12 GHz is used to scatter electromagnetic radiation from surface and subsurface stratigraphic layers in the snowpack. The amplitude of the scattered radiation as a function of depth in the snowpack can be correlated with such physical characteristics as density, hardness, stratigraphy, and moisture content. A direct determination of snowpack-water equivalence can be made from these observations.

The major part of these investigations was done in cooperation with the U.S. Forest Service Rocky Mountain Forest and Range Experiment Station at its field site on Berthoud Pass, Colorado. Additional investigations to verify snowpack-water equivalence were made at Loveland Pass, Colorado; Fraser, Colorado; and the Central Sierra Snow Laboratories, Soda Springs, California.

Experimental Results

The microwave system used for these experiments is a portable FM-CW system operating in the frequency range 8-12 GHz. The principles of operation have been described elsewhere (see Ellerbruch and Belsher, 1978). The output of the system is a plot of the amplitude of the backscattered radiation as a function of the swept frequency, Δf, of an FM-CW radar, which is in turn related to the depth of the snowpack through the equation

$$\Delta f = K \sqrt{\varepsilon_s}\, d_s \qquad (1)$$

where K is a constant, ε_s is the dielectric constant of snow, and d_s is the depth of snow.

At the Berthoud Pass site, transmitting and receiving antennas were buried in a waterproof plastic enclosure beneath the gound prior to the 1977-78 snow season. The undisturbed snowpack was then monitored for several months. Representative samples of microwave responses of amplitude versus depth of snowpack from February 16, 1978, to May 25, 1978 are shown in Figures 1 and 2. The amplitude variations as a function of depth indicate stratigrahic layering which has been verified by physical analysis of pit data taken approximately two meters from the buried antennas. Figure 3 is a representative plot of the physical characteristics of the pack. The stratigraphy and ramsonde measurements correlate well with the lower trace of Figure 2. The large amplitude responses in the upper layers of the pack for the top trace of Figure 1 and the two lower traces of Figure 2 represent ice layers formed by surface melt-freeze conditions. The pack progressed from temperature gradient to equitemperature metamorphism with the ET condition starting around April 5, 1978. Note the apparent loss of stratigraphy in the three upper traces of Figure 2.

Measurements of snowpack-water equivalence were made by comparing a known volume of snow with the volume of water produced by melting the snow. We observed a correlation between the snowpack-water equivalence and the frequency, Δf, swept by the FM-CW system between the top and bottom of the snowpack (Figures 1 and 2). Using a two-component model of ice and air for the snowpack, we can relate the frequency, Δf, to the snowpack-water equivalence in the following way

$$\Delta f = K \sqrt{\varepsilon_s}\, d_s$$

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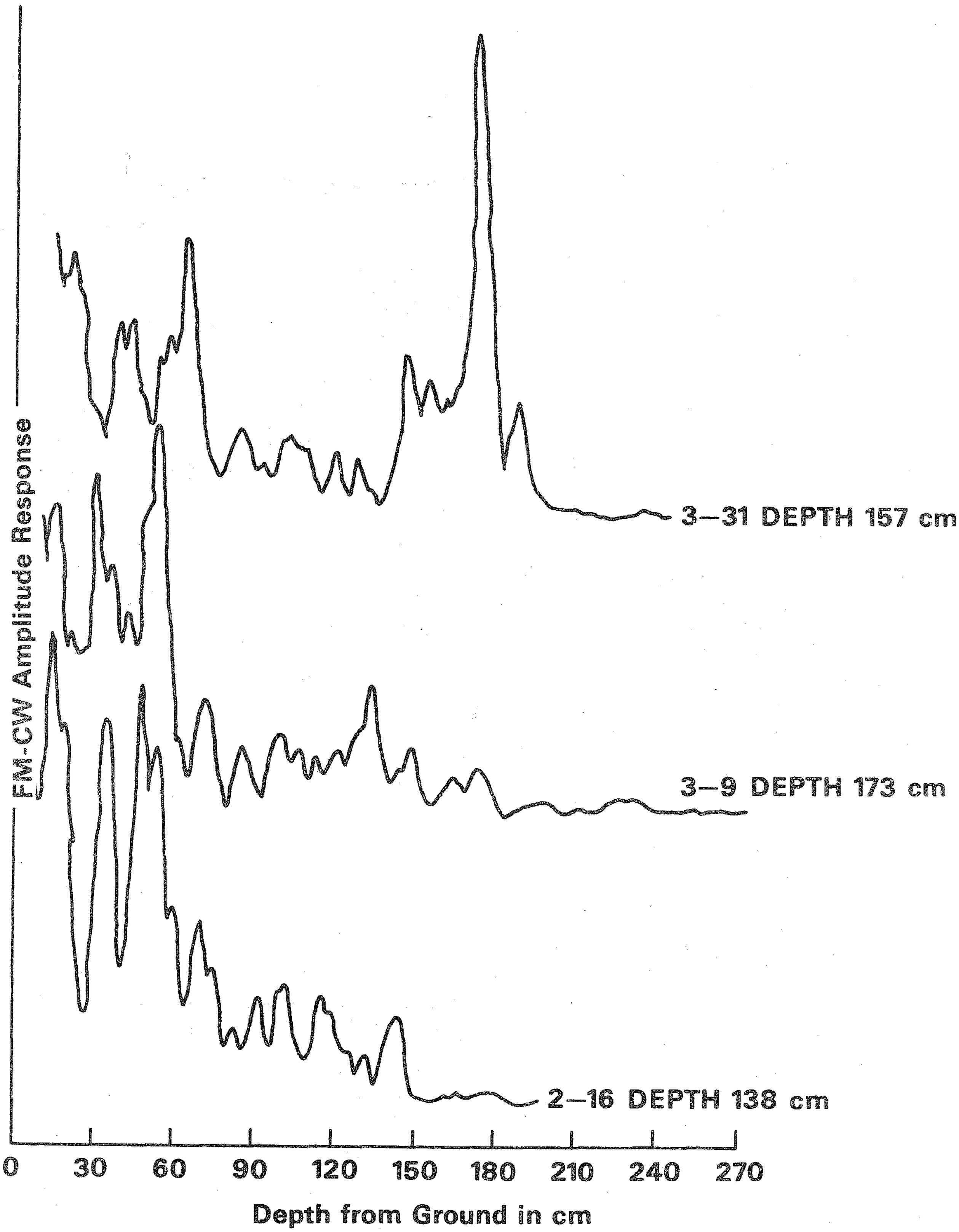


Fig. 1. Plot of FM-CW Amplitude Response as a Function of Depth for the Period 2/16/78 to 3/31/78.

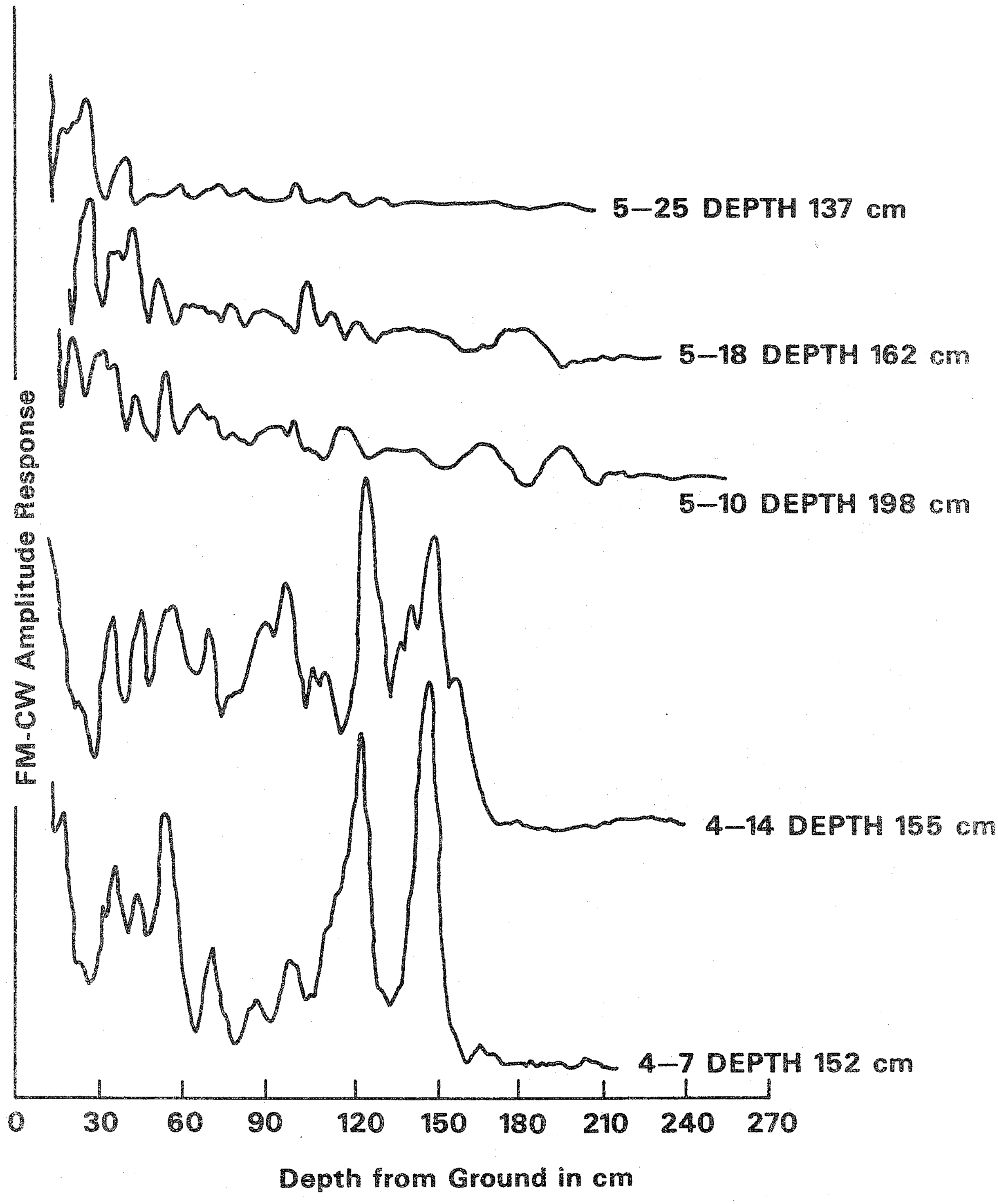


Fig. 2. Plot of FM-CW Amplitude Response as a Function of Depth for the Period 4/7/78 to 5/25/78.

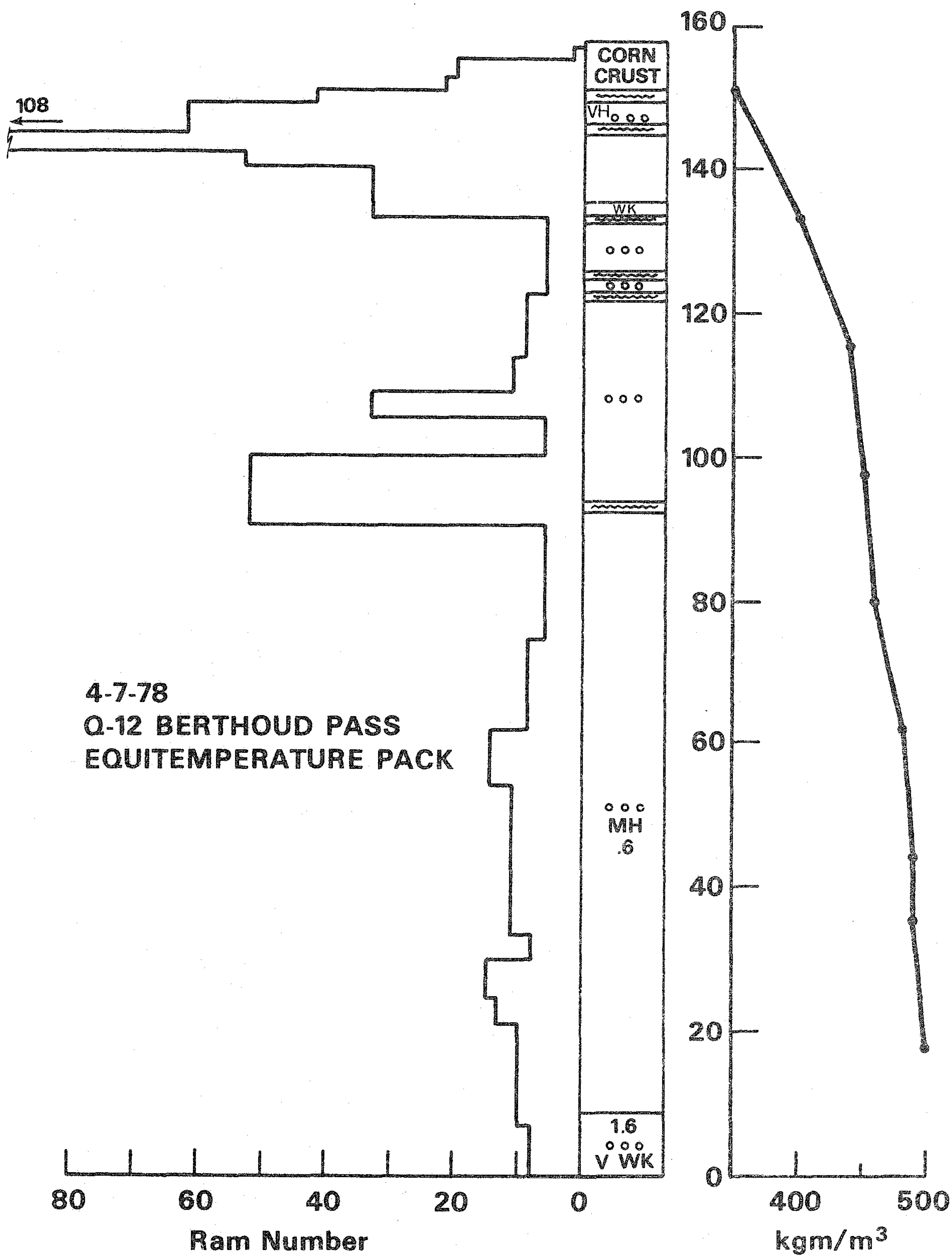


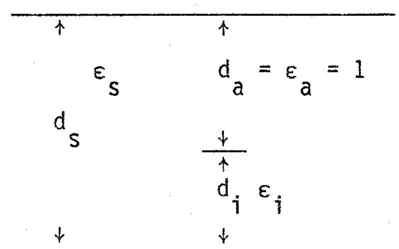
Fig. 3. Physical Analysis of Snowpack, Berthoud Pass, 4/7/78.

and

$$K = \frac{2(f_2 - f_1)f_n}{c}$$

where

$f_2 - f_1 \equiv$ maximum sweep range of the FM-CW system
$f_n \equiv$ number of sweeps/sec
$c \equiv$ speed of light.



In the two-component model, $d_s = d_i + d_a$ where d_i and d_a are the depth of ice and air, respectively. Therefore,

$$\Delta f = K(\sqrt{\varepsilon_i}\, d_i + d_a)$$

$$= K(\sqrt{\varepsilon_i}\, d_i + d_s - d_i)$$

and

$$d_i = \frac{\Delta f/K - d_s}{\sqrt{\varepsilon_i} - 1} \quad . \qquad (2)$$

Because our snowpack water equivalence measurements are volumentric, the depth of ice, d_i, can be equated to the depth of water, d_w, with an error of about 2 percent. Therefore,

$$d_i = d_w = \frac{\Delta f/K - d_s}{\sqrt{\varepsilon_i} - 1} \qquad (3)$$

where Δf and d_s are measured. For these measurements, $f_2 - f_1 = 4$ GHz and $f_n = 100$ so that $K = 1.33 \times 10^3$. A graph of the measured versus the calculated snowpack-water equivalence is shown in Figure 4. For an alpine snowpack we have observed that the average dielectric constant of snow, ε_{save}, is 1.35 so that d_s can be calculated from equation (1).

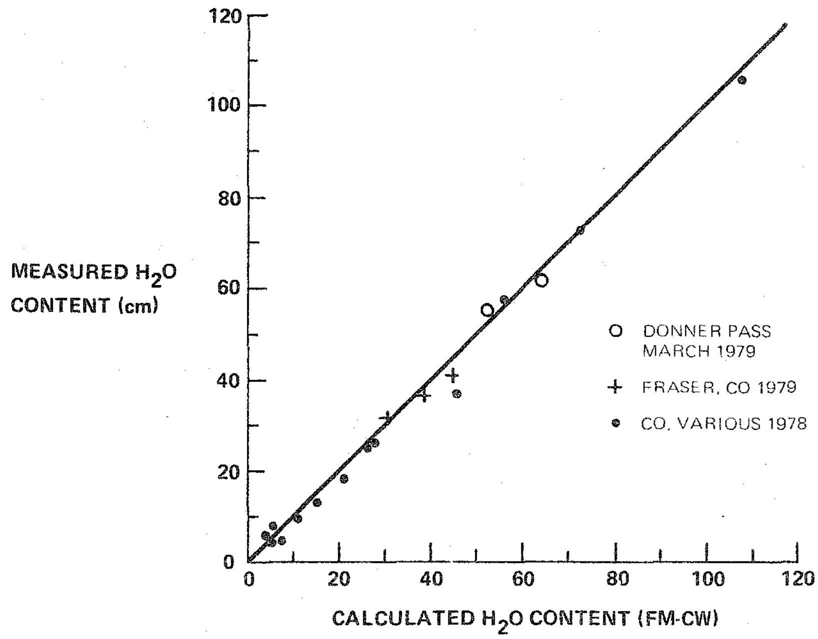


Fig. 4. Graph of Measured Water Equivalence vs. Calculated Water Equivalence from FM-CW Response.

Conclusions

We have observed changes in the snowpack stratigraphy over a snow season. We have been able to use the FM-CW system to measure snowpack-water equivalence to ±5 percent accuracy. There are indications that the disappearance of layers in the snowpack may be related to the "ripeness" of the pack. Also there is evidence that while the pack depth diminishes, the snowpack-water equivalence remains constant over long periods during the early spring. These latter two observations will be the subject of further investigation.

Acknowledgments

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References

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