SWISS IMPROVEMENTS OF THE FMCW RADAR FOR SNOW MEASUREMENTS

BY

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INTRODUCTION

A method of monitoring snowpack water equivalent that could replace the troublesome snow pillow is nearing the operational stage. Because it involves microwave technology, the method--based on frequency-modulated, continuous-wave (FMCW) radar--may not be applied as rapidly as it merits. The objectives of this paper are to document recent improvements, and present examples of its use in snow research. The improved system (Figure 1) has provided data on avalanche flow depths, snowcover over a traverse with the system sled-mounted, and snowpack accumulation at a fixed location during three winters (Gubler and Hiller, in press).

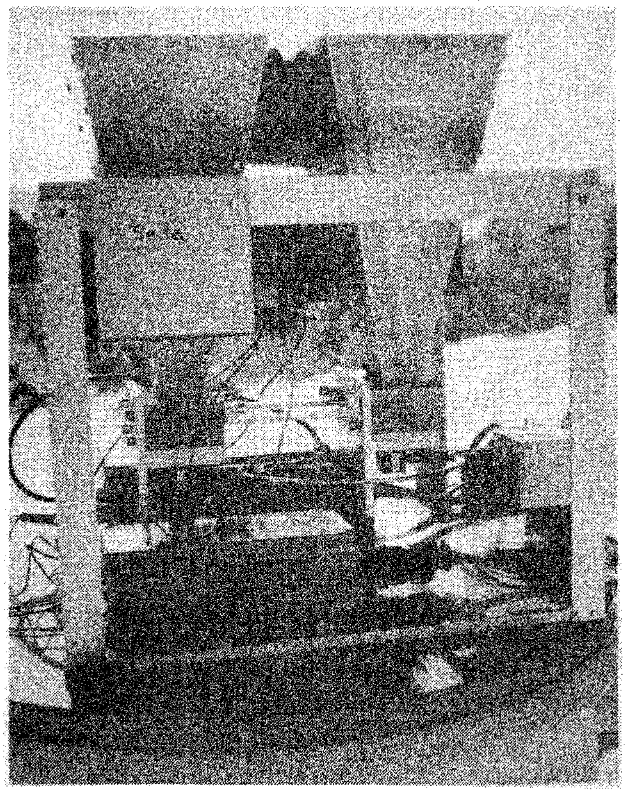

Figure 1.
The Swiss FMCW radar includes antennas, batteries, and electronics in a unit with dimensions roughly 50 cm on a side.

From the beginning of research on the use of backscattered microwaves to measure snow and ice, the method appears to have developed without serious doubts that the concept was viable. Lundien (1972) measured thickness of stratified material in roadbeds with swept frequency radar. Vickers and Rose (1972) clearly demonstrated that the depth or density of a dry snowpack could be measured with short-pulse radar. Ellerbruch et al. (1977) and Ellerbruch and Boyne (1980) showed that continuous-wave radar also measures either snow depth or density. These papers provide reference to earlier work, for the reader interested in tracing the development of the concept.

Presented at the 52nd Annual Western Snow Conference, April 1984, at Ketchem, Idaho.

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PRINCIPLES

A review of the method will help in understanding the new improvements. Electromagnetic radiation from the transmitting antenna (Figure 2) is beamed vertically at the snowpack, either from above the snow surface, or from below ground. A modulation oscillator sweeps the frequency of the microwave signal as a linear function of time, between the band limits (in this case, 8 to 12.4 GHz). The second antenna receives radiation backscattered from layers within the pack, and from the soil-snow and snow-air interfaces. The electrical path length, from antenna to target and back, determines a difference in frequency between the signal being transmitted, and that received at any instant. This frequency difference Δf, determined by mixing the reference signal (Figure 2), and the backscattered signal, is related to electrical snow depth ℓ by the equation,

$$\Delta f = (4D/\tau c)\ell. \tag{1}$$

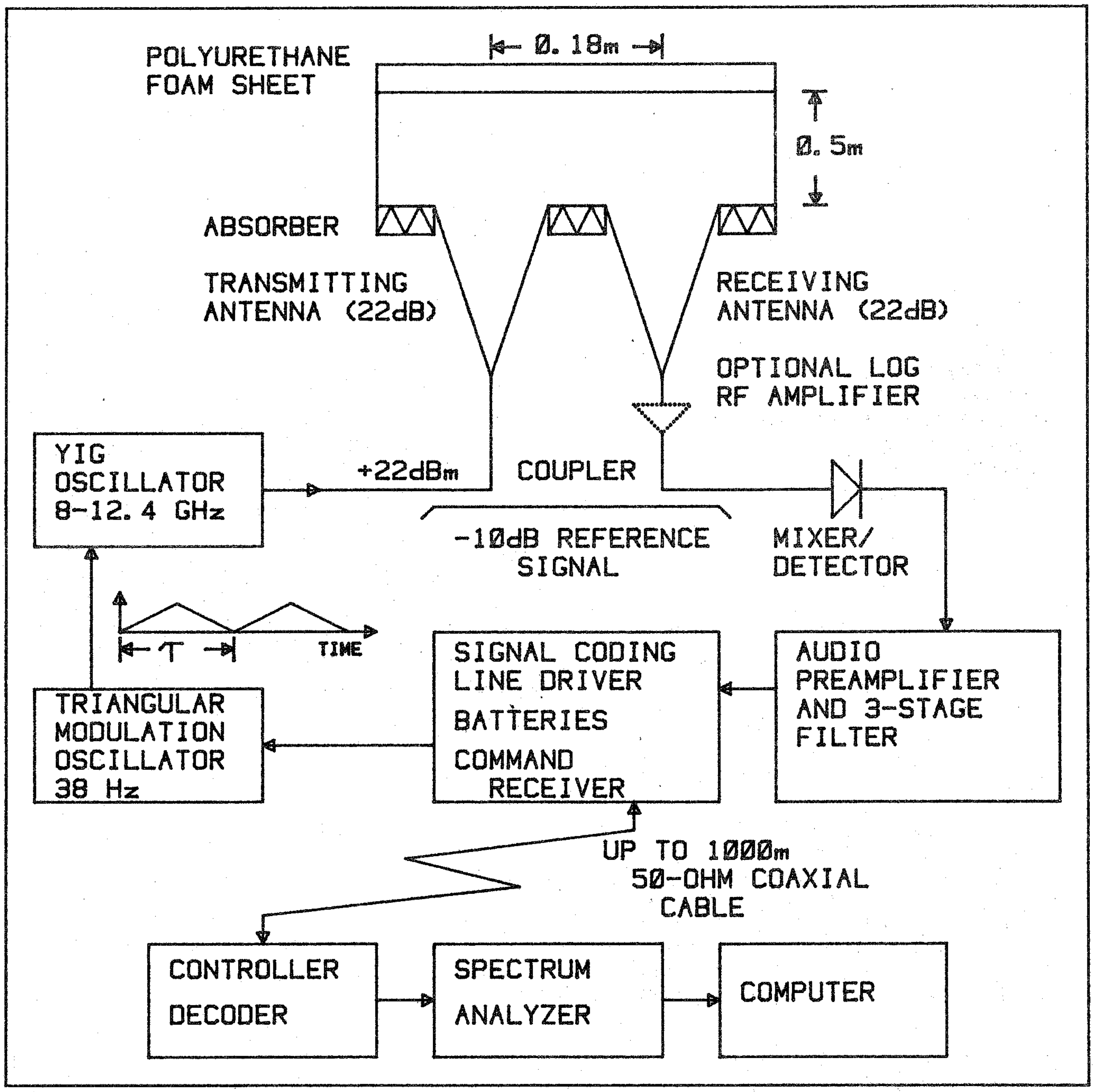

Figure 2. Diagram of the FMCW radar, showing the signal path and main components

The term $(4D/\tau c)$ is constant for a radar system with total frequency deviation D, and sweep period τ, where c denotes the speed of light. The X-band system described by Gubler and Hiller (in press) has the value $(4D/\tau c) = 2172 \text{ Hz m}^{-1}$.

Converting the electrical depth to geometrical snow depth requires knowledge of the dielectric constant of snow, a subject that has occupied researchers for the last decade. That work, although essential to develop this technique, will not be reviewed in this paper. Instead, readers are referred to Gubler and Hiller (in press) as a starting point for such a review. For dry snow, their measurements and other work supported the relationship,

$$(\varepsilon_s)^{\frac{1}{2}} - 1 = 0.771(\rho_s/\rho_i) \qquad (2)$$

where ε_s is the dielectric constant for dry snow with density ρ_s, and ρ_i is ice density.

To determine snowpack density or water equivalent with the FMCW radar, an independent measure of snowpack depth, d, must be available. The equation $(\varepsilon_s)^{\frac{1}{2}} = \ell/d$ determines ε_s from the FMCW measure of electrical snow depth ℓ. Equation (1) gives $\ell = \Delta f/(2172\text{Hz/m})$ so that $(\varepsilon_s)^{\frac{1}{2}} = \Delta f/2172d$, where d is in meters. The mean snowpack density from (2) is

$$\rho_s = [(\Delta f/2172d) - 1](\rho_i/0.771) \qquad (3)$$

Liquid water in the snowpack increases the dielectric constant. If the volume percentage of water, W, is less than 10%, Gubler and Hiller (in press) use the relationship $\varepsilon_w = \varepsilon_s + 0.48(W)^{1.5}$ to estimate ε_s from the measured ε_w.

What remains to be described is the way in which Δf is determined from the FMCW system. The strength of the reflected signal as a function of the frequency difference is determined by sampling the amplified signal from the mixer-detector. A computational algorithm, known as a Fast Fourier Transform (FFT), produces a spectrum from the voltage samples. An example of the spectrum display (Figure 3) shows the output most commonly employed by researchers using the system. The value Δf is read between the spectral peaks that correspond to the air-snow and snow-soil interfaces. For the example measurement of Figure 3, $\Delta f = 5.92$ kHz, and measured depth was 2.08 m, giving a mean snowpack density of 370 kg m^{-3}, by Equation (3).

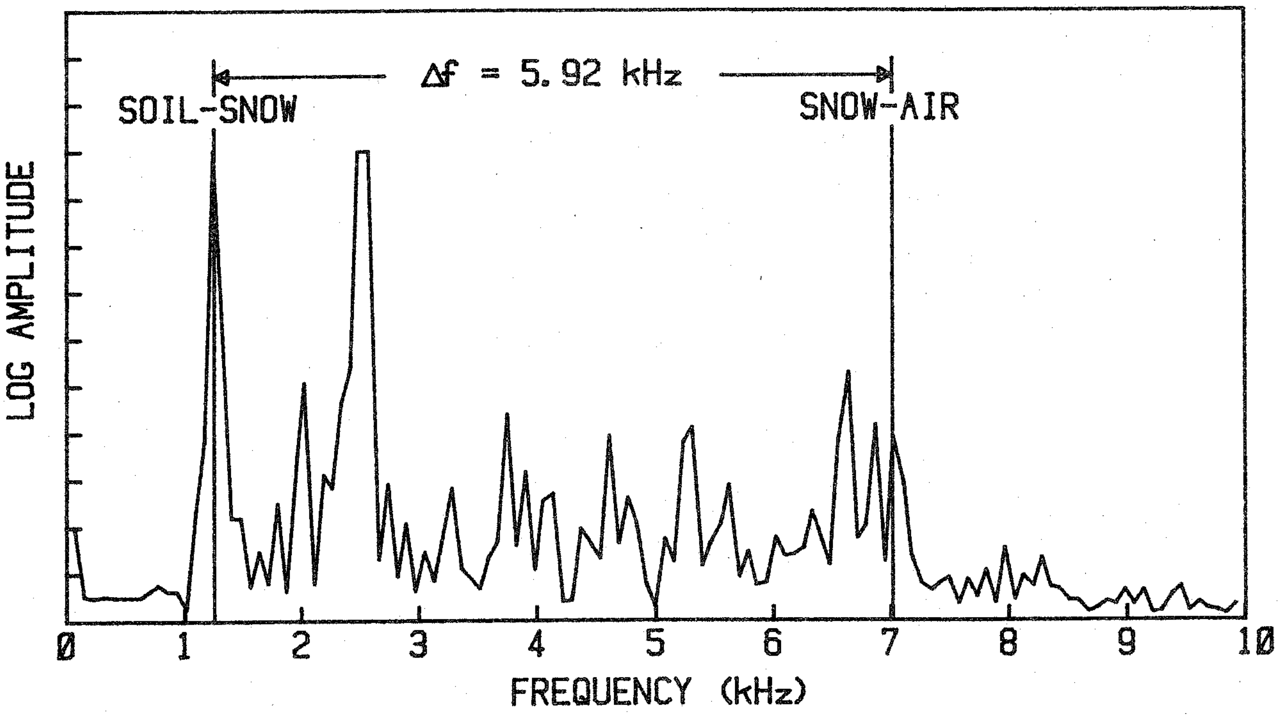

Figure 3. An example of the spectrum measured through a snowpack by a system from below ground level. Snow depth was 2.08 m, and the corresponding Δf is 5.92 kHz.

SWISS IMPROVEMENTS

The Swiss FMCW takes full advantage of improved microwave components. The YIG oscillator has 10 times the output power previously available, and operates at that power over a wide temperature range that includes the lows experienced in most snow measurements. However, the improvements to be discussed are circuits and data-handling techniques that optimize the potential of the new components.

The sweep oscillator (Figure 2) is perhaps the most critical improvement. Any nonlinearity or amplitude drift in the sweep oscillator translates directly to an error in Δf. In addition to high stability, the sweep frequency is designed to match the time window used for spectrum analysis. For the Swiss FMCW, the time domain window is 12.5 ms. That is, the signal is sampled for 12.5 ms to provide the points that the FFT converts to the frequency domain, or spectrum. The sweep frequency is 38 Hz, and the sweep is triangular, rather than "sawtoothed", as in some earlier systems. With an oscillator period of 26.4 ms, the increasing ramp of the triangular wave is 13.2 ms, slightly longer than the time window. This avoids problems with linearity at each end of the ramp, and gives time for syncronizing the sample with the sweep, using a trigger generated during the falling limb of the triangular wave.

A second improvement is the audio amplifier, (Figure 2) designed to increase signal-to-noise ratio by the addition of three filters. A high-pass filter reduces 1/f noise, and one low-pass filter normalizes signal amplitude from targets of different distances. A second low-pass filter reduces noise from above the measuring range, 0-25 kHz. An optional logarithmic radio-frequency amplifier (between receiving antenna and coupler) also improves signal-to-noise ratio (Figure 2).

The electronics includes provisions to turn the system on and off remotely, allowing the radar to operate from two 12v, 5.7 Ah batteries, at distances up to one kilometer from the controller (Figure 2). All battery charging and signals are transmitted through a single 50-ohm coaxial cable. If the batteries are charged by solar cells, the data transmission may be extended by a radio link with 30 kHz bandwidth. In a snowpack monitoring situation, the system takes a measurement in less than 1 min, including warm-up time. Bandwidth can be drastically reduced by transmitting resulting frequency domain signals (FFT spectrum), instead of on-line time domain signals. The Swiss group has recently developed an FFT analyzer matched to the FMCW system, using a low-power microprocessor. Conversion time for the FFT is about 2 s.

APPLICATION EXAMPLES

The motivation for the Swiss improvements was to measure avalanche flow depths, as part of a research program in avalanche dynamics. The success of this effort is demonstrated by Figure 4. An FMCW radar, buried in the track of an avalanche path near the research institute at Weissfluhjoch (near Davos), was turned on whenever explosive control of the avalanche was initiated. The signal was recorded on analog magnetic tape and replayed at a slower speed to improve time resolution (26 ms). Flow depth resolution is 0.1 m (Gubler and Hiller, in press).

To test the feasibility of measuring transects of snow depth in avalanche starting zones, an FMCW system was sled-mounted (Figure 5) and towed by an over-snow vehicle. The first tests were made on a study site where detailed snowpack stratigraphy was routinely measured. Spectra produced by the FFT analysis of tape recordings provided the data on snow depth and stratigraphy plotted in Figure 6. Snowpack density was determined from the routine measurements to allow snow depth measurements with the FMCW.

At the same test field, a buried FMCW system is interrogated at least once on almost every winter day, to produce spectra such as those plotted in Figure 7. Snow depth is measured independently by an ultrasonic snow height gage (Gubler, 1981), allowing a corresponding plot of snow water equivalent (Figure 8). Early in the winter, shallow snow depths must be determined to within about 1%, in order to calculate the water equivalence with less than 5% error. The uncertainty decreases as the pack becomes deeper.

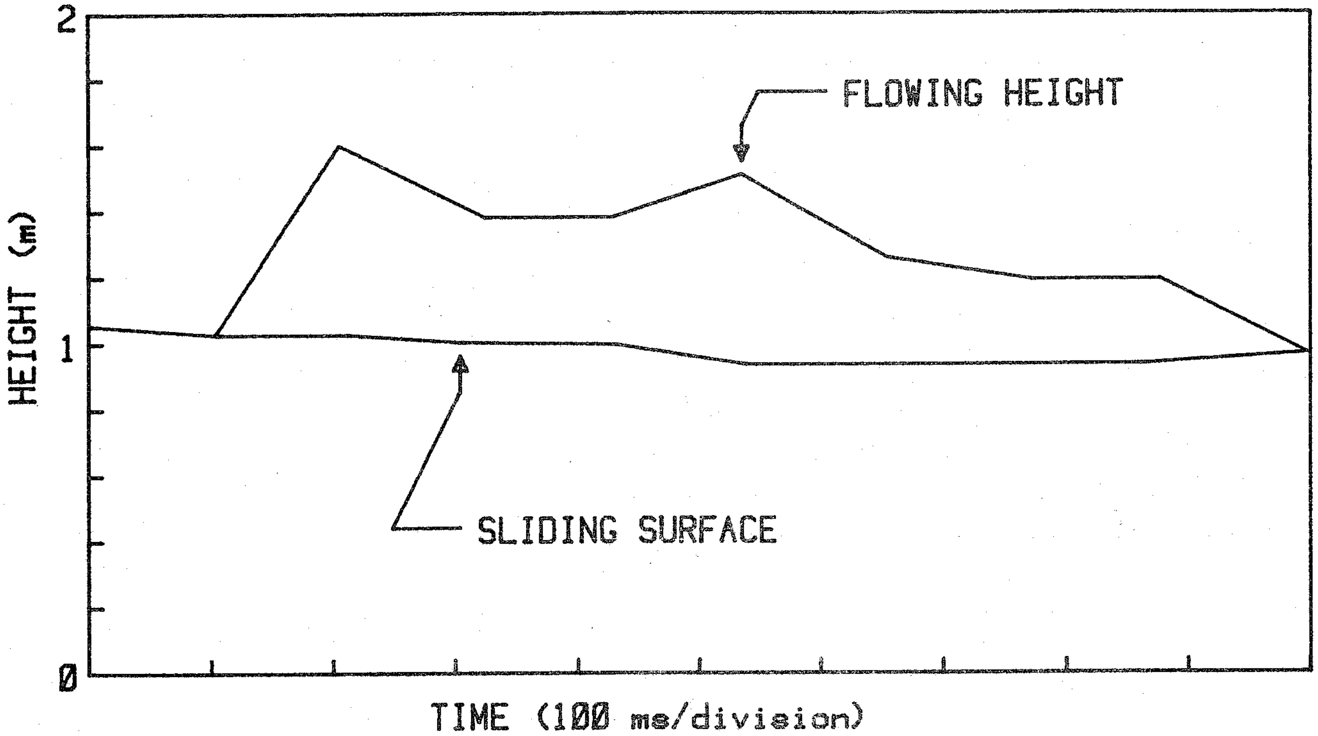

Figure 4. Avalanche flow depth as a function of time, measured by an FMCW system from below the ground surface. Four spectra were averaged to determine each point, and the average density in the lower part of the flow was assumed to be 150-200 kg m^{-3}.

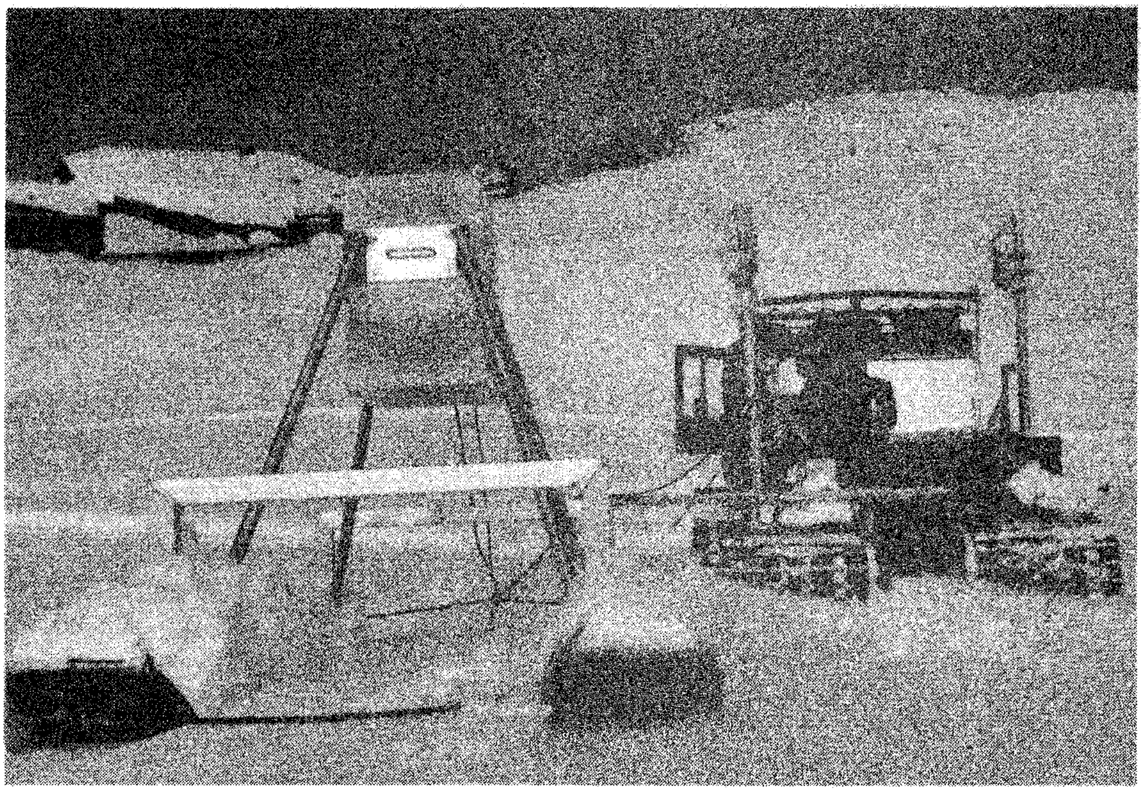

Figure 5. Initial tests of the FMCW radar in a sled-mounted configuration for traversing, at the test field below the Weissfluhjoch, Switzerland.

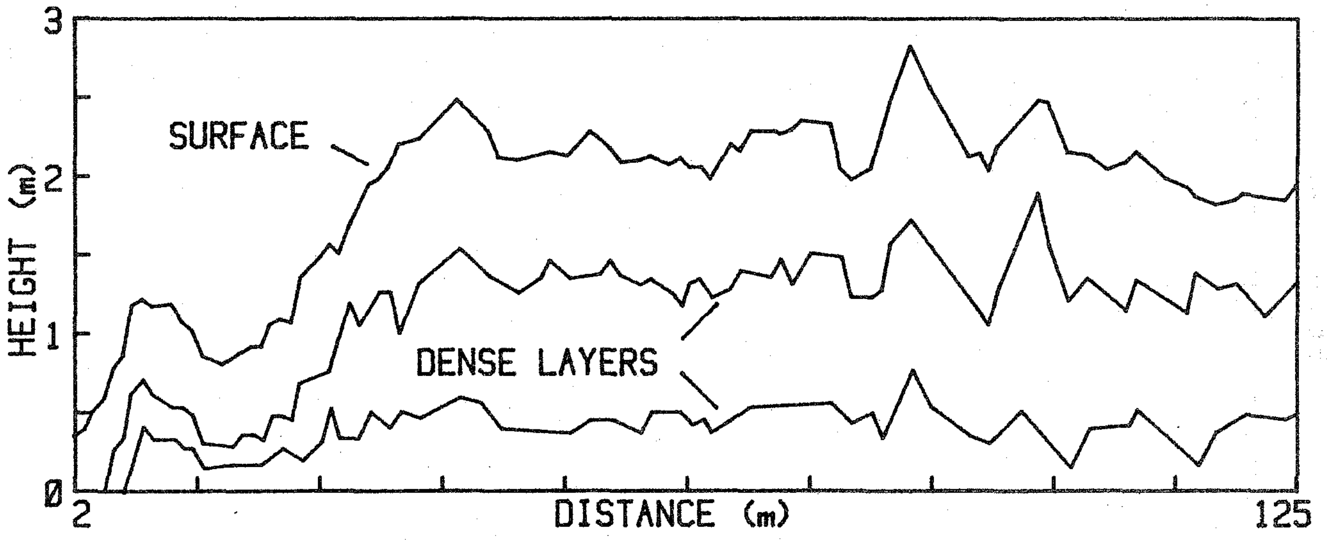

Figure 6. Snow depth and stratigraphy along a traverse measured with the sled-mounted system of Figure 5, calculated from mean snowpack density at a nearby location.

Testing the Swiss FMCW in the U.S. began with drift profile measurements behind a snow fence, in March 1984. The object was to compare the snow depth measured by probing with that computed from the FMCW, using an average depth-density relationship previously developed by Tabler (1980). A lightweight sled (Figure 9) allowed the radar to view the snowdepth vertically, even on steeper portions of the drift. The experiments showed excellent agreement between depth estimated by radar and that determined by probing (Figure 10). Measurements on another snow fence drift gave similar results up to 6 m depths, the limit of the particular spectrum analyzer used.

Several other applications of the improved system are reported by Gubler and Hiller (in press). The meltwater interface was tracked downward in the snowpack during initial melting. An exciting set of data with an FMCW system aimed horizontally through a snowpack showed that the layers in the pack act as waveguides, greatly extending the range of the system. This horizontal application may be useful in studies of the deformation and collapse of deposition layers in avalanche starting zones.

ACCURACY AND RESOLUTION

Comparisons of gravimetric water equivalence with that estimated from FMCW spectra were within 5% for all tests performed on snow in the density range, 200-400 kg m^{-3} (Gubler and Hiller, in press). The percentage error in water equivalent (%WE) was related to the percentage error in snow depth determination (%d) by the equation (%WE) = $0.5[1-(1250/\rho_s)](\%d)$. Analysis of the backscattered energy showed that layers of ice as thin as 0.5 mm could be detected within the snowpack. The 0.1 m resolution in measuring flow depths in avalanches has already been noted.

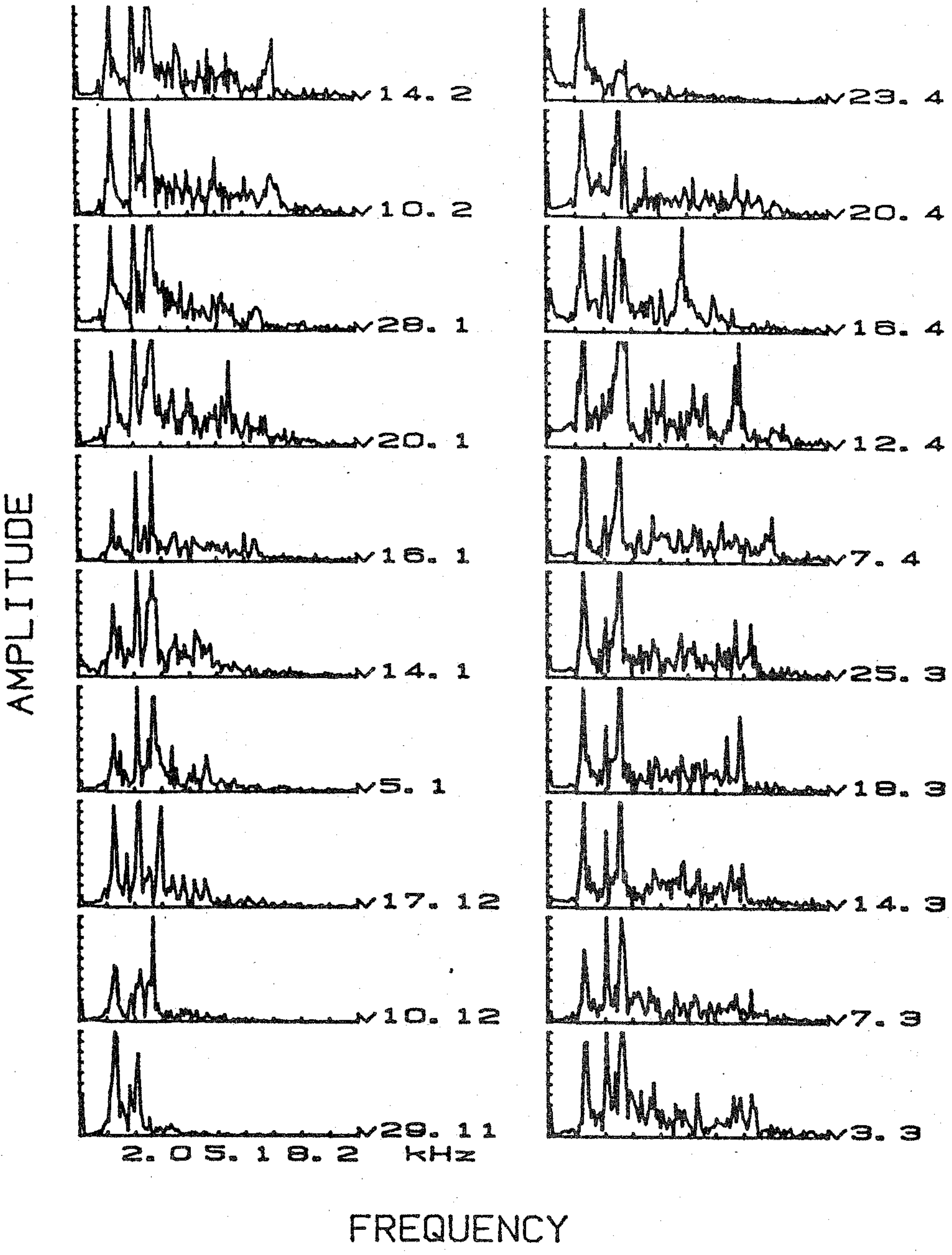

Figure 7. Sequential spectra from a buried system show the accumulation and settlement of the winter snowpack (29 November - 23 April).

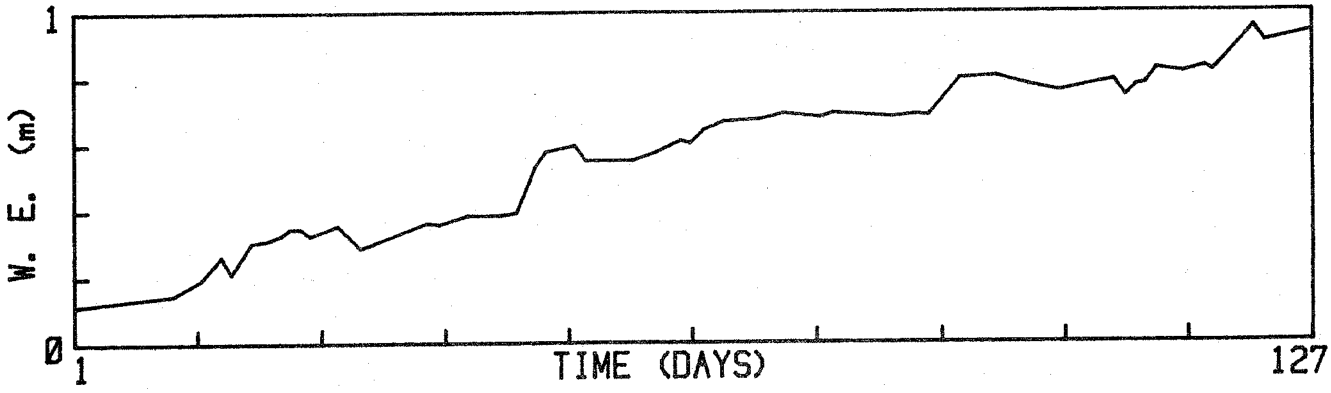

Figure 8. Independent measurements of snow depth and Δf from spectra in Figure 7 produced this plot of the seasonal accumulation of water equivalent in the snowpack near Weissfluhjoch, Davos, Switzerland.

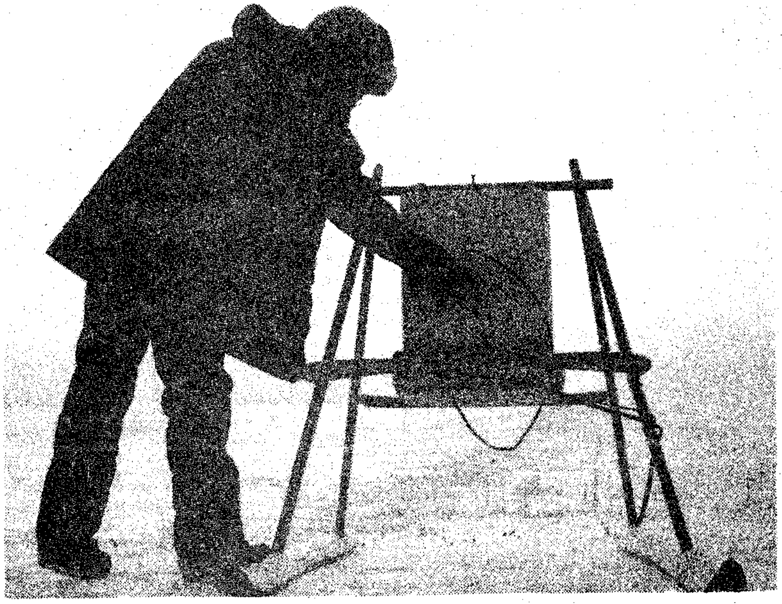

Figure 9. A light sled supported the radar during measurements behind snow fences in southeastern Wyoming, U.S.A.

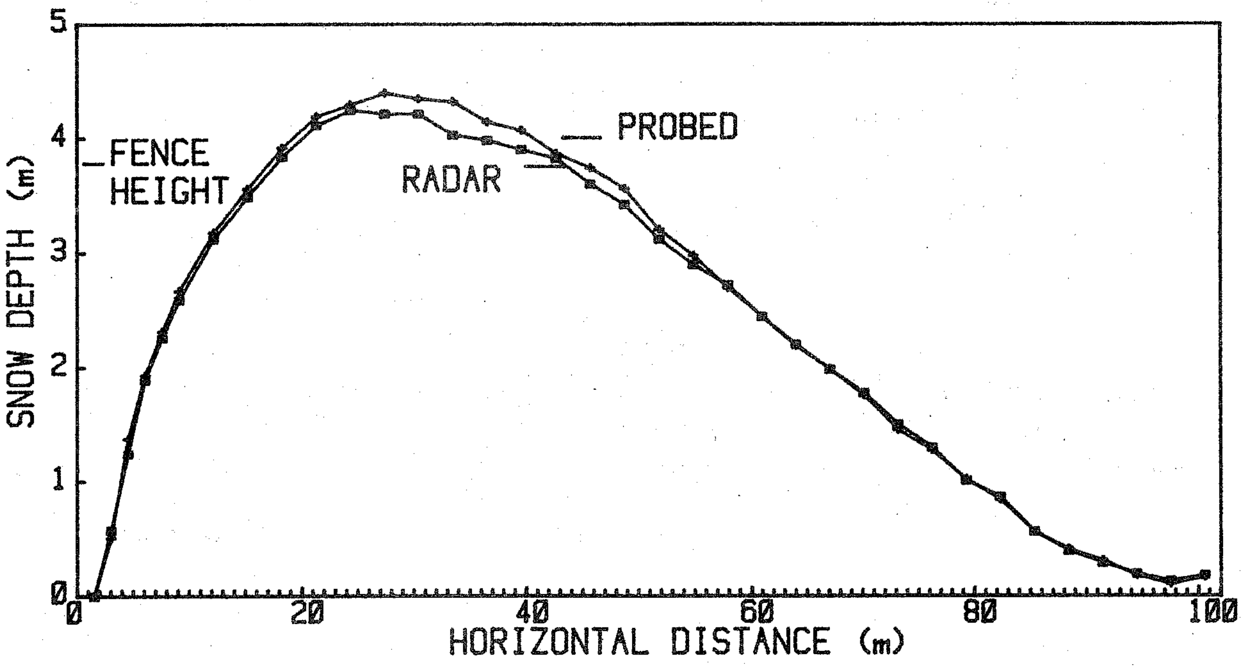

Figure 10. The FMCW radar estimates of snowdepth behind a 3.78 m snow fence were in excellent agreement with depths measured by probing.

SUMMARY

Improvements in the X-band FMCW radar, designed to measure avalanche flow depth, provide a system capable of monitoring water equivalent of a dry snowpack at remote locations. For snow with density between 200 and 400 kg m^{-3}, water equivalence is determined with less than 5% error when snow depth is determined within 1%. In situations where mean snowpack density is known, the system can be sled-mounted to provide rapid transects of snow depth and snowpack stratigraphy.

ACKNOWLEDGEMENTS

The developments presented in this paper are a direct result of a scientist exchange program between the Swiss Federal Institute for Snow and Avalanche Research, at Davos, Switzerland and the Rocky Mountain Forest and Range Experiment Station, in Fort Collins, Colorado, U.S.A. The first and second authors wish to thank those at their home institutions who provided this opportunity. The senior author thanks his Swiss colleagues for providing an FMCW radar for experiments in the U.S., and to Dr. R. D. Tabler (who suggested this paper), for his help and enthusiasm during those experiments.

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