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COHERENT MICROWAVE BACKSCATTER OF NATURAL SNOWPACKS

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Abstract

The backscatter of natural snowpacks has been measured using a swept-frequency system operating from 5.8 to 8.0 GHz. Snow layering produces sequences of maxima and minima in backscatter intensity, with typical peak-to-valley ratios of 15 dB. Furthermore, wetness produced in the upper portion of the snowpack by solar heat input enhances the effect of layering. The layer response persists for incidence angles up to 45°, showing that the backscatter at oblique incidence exhibits predominantly coherent properties. Frequency modulation of the incident signal "masks" the layer response by averaging the unmodulated response over the bandwidth represented by the modulation. Further changes in backscatter are attributed to changes in wetness in the surface regions of the snowpack — for a fixed frequency of 13.5 GHz and incidence angle of 39°, the backscatter decreased typically 15 dB between 11 AM and noon, and returned to approximately its initial level of overnight.

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Introduction

Management of reservoirs in the western U. S. for flood control, irrigation schedules, and hydroelectric energy production requires information on the total mass of snow in the watersheds, and also on the wetness state. Synoptic remote sensing systems based on electromagnetic (EM) techniques may help in assessment of snowpack resources.

Evidently passive and active EM systems can supply complementary information; this paper is limited to active systems in the microwave region. Reflection coefficients and dielectric properties of snow and ice have been reported by Saxton (1950), Cumming (1952), Vickers and Rose (1972), Hoekstra and Spanogle (1972), Royer (1973), Ulaby et al (1977), and Ellerbruch et al (1977). These authors have demonstrated various correlations of snowpacks with the observed EM responses. Theoretical studies by Linlor and Jiracek (1975) show layering effects of snow on earth for a variety of modeled snowpacks.

The objective of this paper is to report on the investigation of swept-frequency microwave characteristics of natural snowpacks. Experimental results show backscatter dependence on: a) snow conditions (time of day); b) frequency (5.8 - 8.0 GHz); c) angle of incidence (0 - 45°); and d) frequency modulation (0 - 400 MHz).

The data were obtained during March 1977 at the Central Sierra Snow Laboratory, at sites whose physical characteristics are given below. The snow depth was less than 80 cm because of the extremely limited snowfall.

The instrumentation consisted basically of a sweep-oscillator connected to a transmitter horn with a similar horn receiving the backscattered response from the snowpack. Other equipment concurrently measured the density profiles and air temperature.

Measurements

Measurements on natural snowpacks are given in Figs. 1-8, test conditions being summarized in Table 1. Variation of backscatter with snow conditions, at fixed frequency and fixed angle, is shown in Fig. 1. This is a continuous recording (except for short times when data were not taken) during March 5 and 6 (1977) of the backscatter at 13.5 GHz and incidence angle of 39° from vertical. Figures 2 and 3 show the EM response of snow on March 5, taken at 11:30 and 12:07 for the swept frequency of 5.8 to 8.0 GHz, at perpendicular incidence. The sweep oscillator was operated at a very slow rate, approximately 10 seconds for the total range, so that the measurements were essentially steady-state.

The effect of incidence angle on steady-state EM response is shown in Figs. 4 through 7, for the swept-frequency range of 5.8 - 8.0 GHz. Data of Figs. 4 (0°) and 5 (10°) were taken five minutes apart, while those of Fig. 6 (39°) were taken earlier.

The effect of signal frequency modulation is shown in Fig. 7, for the incidence angle of 39° from vertical. The curve labelled "S" is the unmodulated response for a slow sweep of the frequency from 5.8 to 8.0 GHz. Shortly after data for this curve were taken (within two minutes), the oscillator was manually set at the frequencies corresponding to the various maxima and minima of curve S and at each such selected frequency a modulation was superimposed. For the + points the modulation was ±100 MHz; and for the 0 points the modulation was ±200 MHz. To illustrate, the first maximum of curve S is at 6.00 GHz; the + point plotted at 6.00 GHz represents the (average) reading on a SWR meter for 6.00 ± 0.10 GHz; and the 0 point is the (average) reading for 6.00 ± 0.20 GHz.

Discussion

The decrease in backscatter shortly before noon, shown in Fig. 1, was initially observed by us in March 1976 for a snowpack 150 cm deep, and has been confirmed at other frequencies by several groups (Currie et al, 1976, Ulaby et al, 1977). Evidently the increase in surface snow wetness by solar heating is the reason for the backscatter decrease, totaling about 15 dB. The air temperature variation included is useful in correlating the phenomenological effects.

Snow wetness produced during a few hours of sunlight can significantly affect the frequency response. March 5, 1977, when the measurements were taken, was a clear, warm day with a temperature of about 10° C between noon and 16:00, so the snow was essentially saturated with water in the upper surface. The data (Figs. 2, 3 and 4) demonstrate that the backscatter at normal incidence is frequency-dependent because of coherence effects due to snow layering, and that wetness increases the layering effect. The ordinate for these figures is the customary microwave backscatter coefficient, namely the radar echo area of the illuminated region divided by the physical area of the illuminated region, expressed in dB. But as shown by the interference-effects of the layers, the backscatter response should be calculated on the basis of coherence in the return signal. Because of space limitation, such theoretical aspects are not considered here.

Dependence of backscatter on angle is shown in Figs. 4 and 5, taken within five minutes to minimize the effect of snow state changes. Interference patterns are evident in Fig. 5, suggesting that the backscatter is predominantly coherent even at the angle of 10° from vertical. Similar results are shown in Fig. 6 for 39° incidence. The return signal shows a clear interference pattern and since the incidence signal intensity was held constant this implies that the backscatter is affected by coherent reflections at layer boundaries.

The effect of frequency modulation of the signal is shown in Fig. 7. As explained above, curve S is the backscatter intensity for a monochromatic incident signal. The + and 0 points, connected by straight lines, show the responses for selected center frequencies upon which modulation of ±100 MHz and ±200 MHz was added in succession. Evidently the effect of frequency modulation is merely the averaging of the unmodulated response over the bandwidth represented by the modulation. This conclusion is further supported by noting that the + points (for ±100 MHz) follow the peaks and valleys of curve S more closely than do the 0 points. The modulation of ±200 MHz for the 0 points produces so much averaging that the interferences produced by the layers is masked. The effect produced by modulation of the signal can be deduced by averaging the curve S over the modulation bandwidth. Stated alternatively, one can obtain the + and 0 points from curve S by averaging over bandwidths, but one cannot obtain curve S from the + or 0 points. Hence, signal modulation for snowpack measurements produces "masking" of the response.

The considerable changes in backscatter shown in Figs. 2, 3, and 4 for March 5, 1977 seem to be caused mainly by snow wetness in the upper portion of the snowpack. This statement is based on snow density versus depth data shown in Fig. 8, taken with the Smith profiling gamma-ray instrument that does not disturb the snow by the measurement. Melting and consolidation of the upper portion of the snowpack is evident, but very little change in snow density profile occurred in the lower 40 cm, during the dates of March 4 to 7 (i.e., Friday to Monday).

Instrumentation

The instrumentation consisted of a sweep-oscillator operated at a slow rate, so that the measurements were essentially steady-state. The frequency range of 5.8 to 8.0 GHz was traversed in about 10 seconds.

Transmitter and receiver horns having nominally 20-dB gain were employed, with the electric field vector parallel to the snow surface (H-H configuration). The full width of the radiation pattern at the half-power points was approximately 15 degrees. The angle of incidence was variable from 0° (perpendicular to the snow) to 45°. For some of the measurements the oscillator was fixed at a selected center frequency, and various amounts of modulation were superimposed, thus yielding the average of the backscatter over the bandwidth represented by the modulation. The sweep-oscillator was operated in the "leveled" mode; system responses, obtained with the horns facing each other, showed a variation of less than 1 dB from the average signal for the frequency range of 5.8 to 8.0 GHz. With the horns in the "measurement configuration" (i.e., side-by-side) but facing the sky, the coupling was independent of frequency within 1 dB.

Measurements also were obtained for the fixed frequency of 13.5 GHz and fixed angle of 39° from vertical, showing backscatter intensity as a function of snow conditions that changed with time. Here, too H-H polarization was employed.

Snowpack Site Characteristics

The location of the snowpacks is the Central Sierra Snow Laboratory near Donner Pass in the Sierra Nevada Mountains operated by the U. S. Forest Service, under the direction of Dr. James L. Smith.

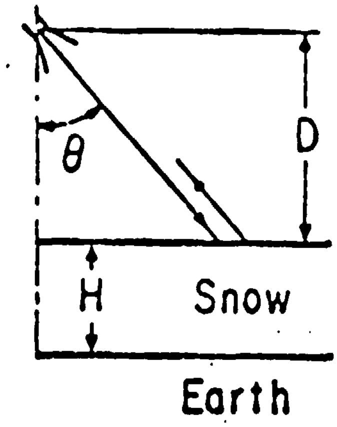
Two sites were utilized during March 1977, labelled "L" and "T", having snow depths as listed in Table 1. The Table also lists the microwave horn angles from vertical for both incidence and backscatter and the height of the horn throat above the snow. The column headings in Table 1 are defined in the sketch.

Located between the test sites was an undisturbed area for which density profiles were taken every day with the gamma-ray profiling instrument (Smith et al, 1972). The density profiles for this monitor site for March 4 and 7 are plotted in Fig. 8.

Table 1

Test Conditions

Fig.	Date	Time	Site	H-cm	D-cm	θ°
1	Mar. 5,6	Two days	T	73	350	39
2	Mar. 5	11:30	L	36	292	0
3	Mar. 5	12:07	L	36	292	0
4	Mar. 5	13:07	L	36	292	0
5	Mar. 5	13:02	L	36	292	10
6	Mar. 3	14:15	T	70	353	39
7	Mar. 2	12:30	T	70	353	39



Conclusions

The measurements reported here lead to the following conclusions:

1. Snow layering affects backscatter by as much as 15 dB from maxima to minima, for swept-frequency measurements.

2. Snow wetness affects layering phenomena, changing signficantly in less than an hour on sunny days with air temperature near 0° C.

3. Changes in snow wetness can modify the backscatter for a single-frequency system, operating at oblique incidence, by as much as 15 dB.

4. The layer response persists for incidence angles up to 45°.

5. The backscatter of snowpacks at oblique incidence exhibits coherent properties.

6. Frequency modulation of the signal "masks" the layer response.

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Figure Captions

Fig. 1. Fixed-frequency backscatter as a function of temperature and time of day.

Fig. 2. Swept-frequency backscatter taken 11:30, 3/5/77.

Fig. 3. Swept-frequency backscatter taken 12:07, 3/5/77.

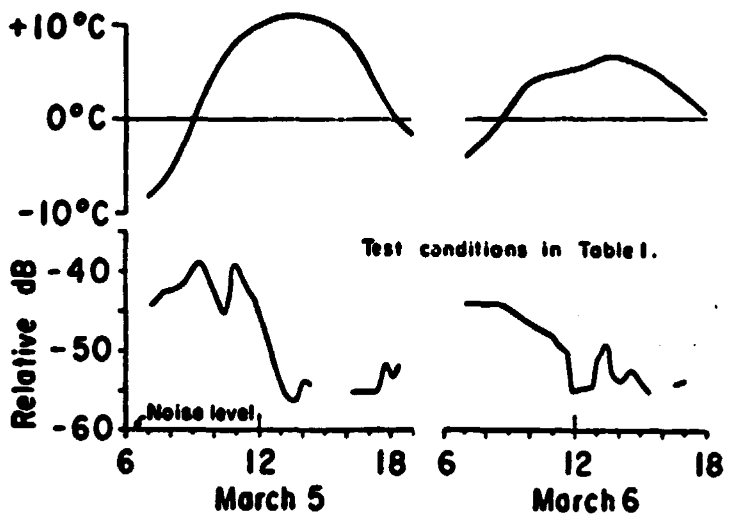
Fig. 4. Swept-frequency backscatter taken at 0° incidence at 13:07, 3/5/77.

Fig. 5. Swept-frequency backscatter taken at 10° incidence, at 13:02, 3/5/77.

Fig. 6. Swept-frequency backscatter taken at 39° incidence, at 14:15, 3/3/77.

Fig. 7. Dependence of backscatter on amount of signal frequency modulation.

Fig. 8. Snow density profile for 3/4/77 (solid line) and 3/7/77 (dashed line) for monitor site.



+10°C
0°C
-10°C
Relative dB
-40
-50
-60
Noise level
Test conditions in Table I.
6
12
18
March 5
6
12
18
March 6

Fig. 1

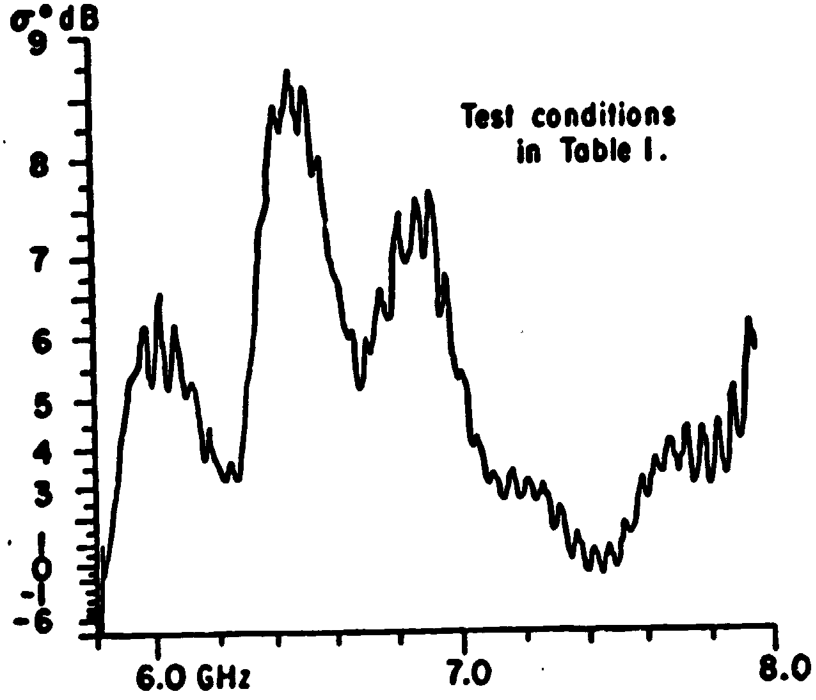


Fig. 2

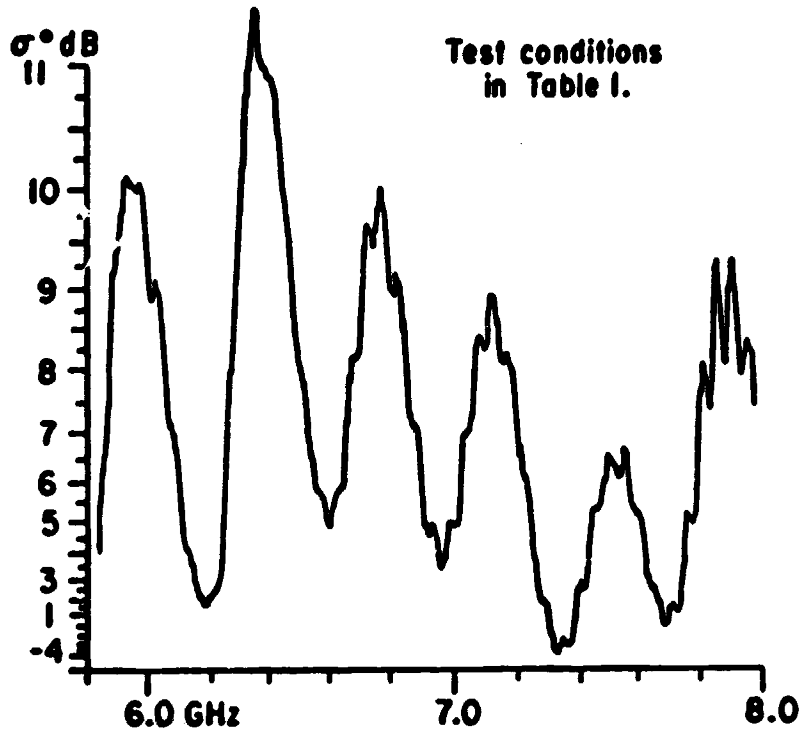


Fig. 3

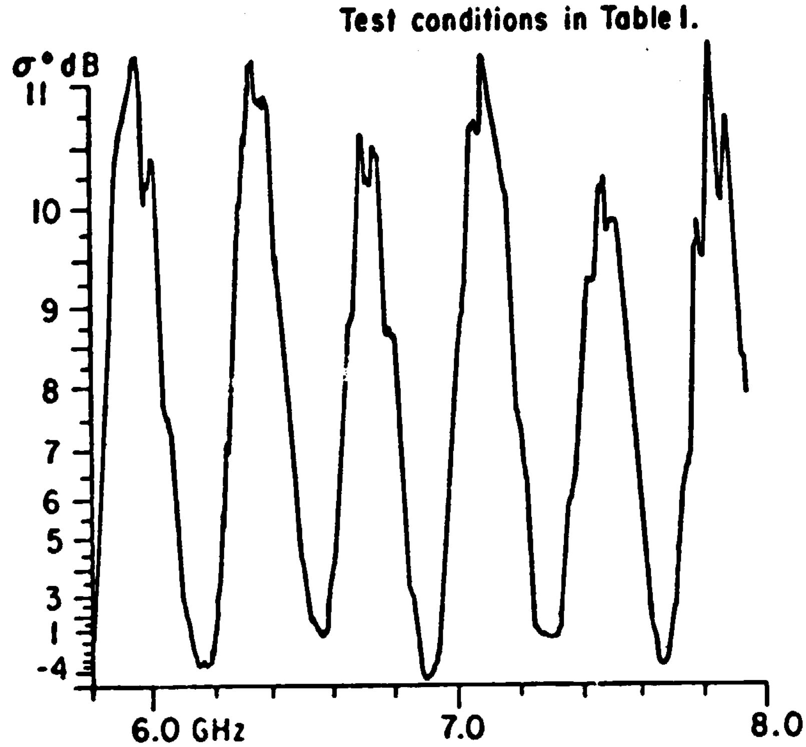


Fig. 4

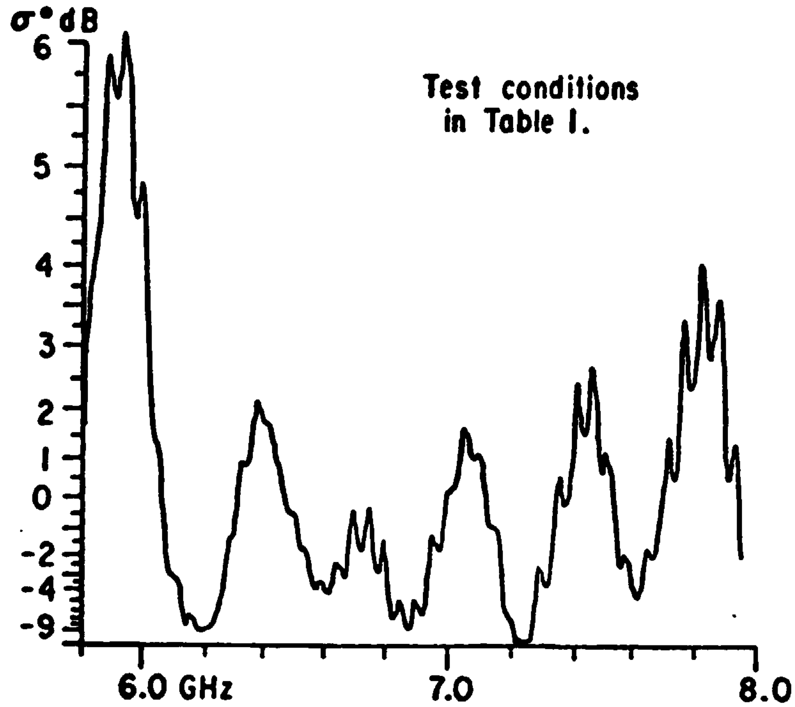


Fig. 5

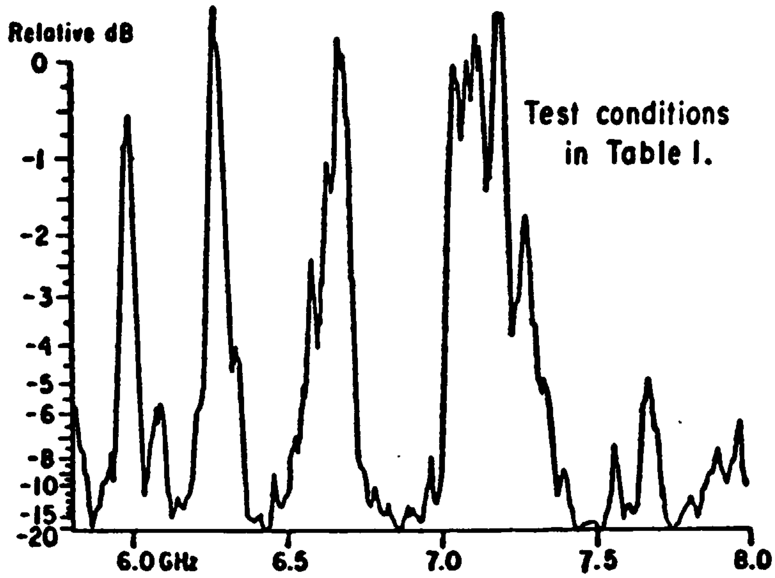

Relative dB
0
-1
-2
-3
-4
-5
-6
-8
-10
-15
-20
Test conditions
in Table I.
6.0 GHz
6.5
7.0
7.5
8.0

Fig. 6

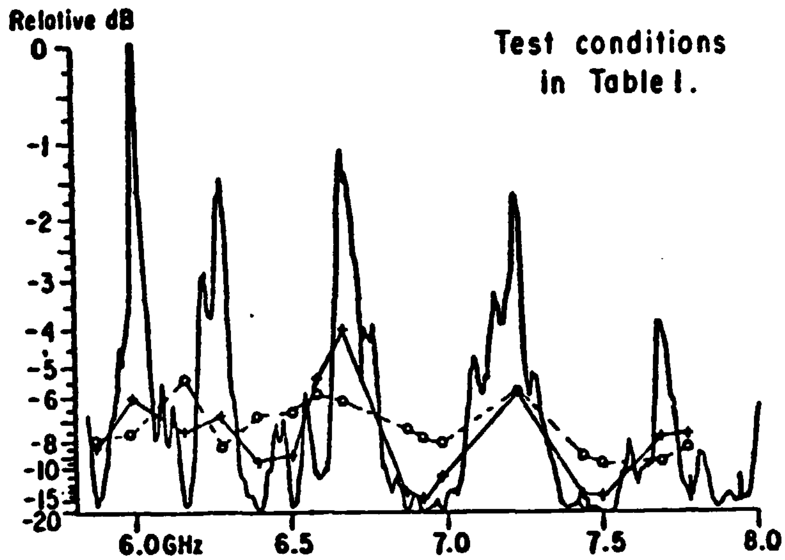

Relative dB
0
-1
-2
-3
-4
-5
-6
-8
-10
-15
-20
6.0GHz
6.5
7.0
7.5
8.0
Test conditions
in Table I.

Fig. 7

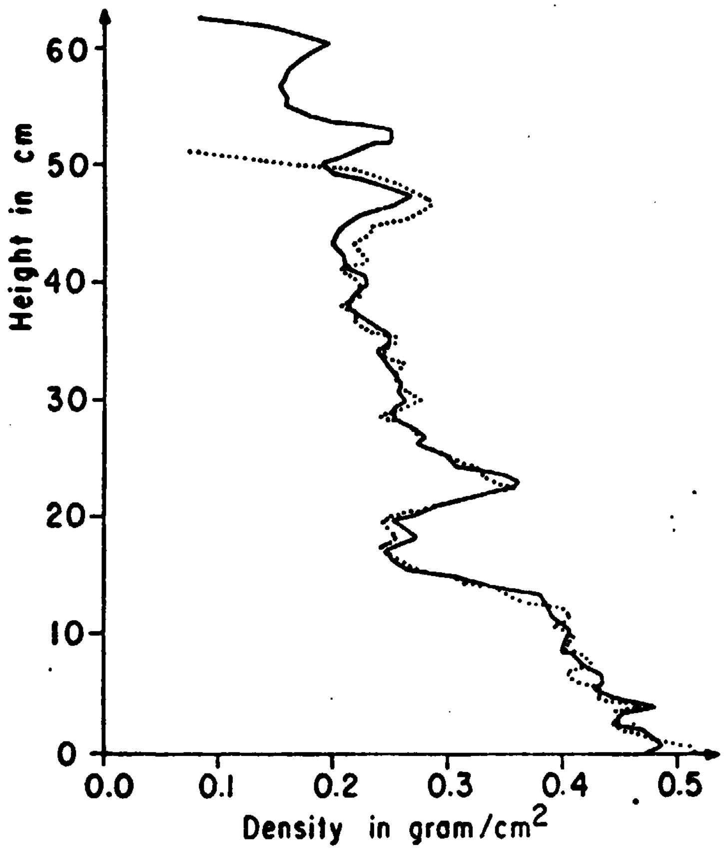

60
50
40
30
20
10
0
Height in cm
0.0
0.1
0.2
0.3
0.4
0.5
Density in gram/cm2

Fig. 8