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Microwave Physics

LABORATORY STUDIES ON THE MICROWAVE RESPONSE OF SOIL WITH PARTICULAR REFERENCE TO REMOTE SENSING

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The response of the earth surfaces at microwave frequency depends upon the soil composition, moisture content and vegetation cover. The dependence of dielectric constant of soil on moisture has been measured in the X-band of microwave. The scattering parameter of soil has been measured in the laboratory and a significant change is seen with changing parameters (composition and moisture). The scattering parameters govern the actual response in case of ground-based and air-borne satellite remote sensing. The application and interpretation of these results in remote sensing of earth surfaces by microwave system is discussed.

Keywords: Microwave Response; Frequency; Remote Sensing; Dielectric Constant of Soil; Coaxial Cable Technique

INTRODUCTION

THE use and applicability of infrared sensors is limited and provides information under highly restricted conditions. The microwave sensors have much higher operational duty and potentiality to penetrate clouds, fog, and darkness. The selection of operating electromagnetic frequency for remote sensing depends on the nature of desired information about the terrain or the atmosphere. The dielectric properties of soils at microwave frequencies are particularly important because they are quite sensitive to changes in the moisture content. However, the microwave frequencies have very small penetration and are capable of giving only surface information. From multi-frequency radiometric measurements, it is established that the frequency range of 1 to 5 GHz are most appropriate for soil moisture sensing (Blinn *et al.*, 1972; Hipp, 1974; Schmugge *et al.*, 1974; Idso *et al.*, 1975; and Hoekstra & Delaney, 1976).

The objective of this laboratory investigation is to develop electromagnetic response from soil samples with varying moisture. The dependence of dielectric properties of soil with varying moisture content in the X-band of microwave has been determined using the transmission line technique (von Hippel, 1954; Sucher & Fox, 1963; Lytle, 1974; and Dakermandji & Joines, 1977). The measurement procedures consisted of the measurement of standing wave on the slotted waveguide (von Hippel, 1954; Sucher & Fox, 1963; and Lytle, 1974) and attenuation and phase constant using coaxial cable technique (Dakermandji & Joines, 1977) for low and high

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*Present address: Department of Physics, Post-Graduate College, Ghazipur (U.P.), India moisture content soil samples respectively. The incident electromagnetic wave in the medium determines the emissive and reflective properties of the sample. Using the measured dielectric data, we have computed the reflectivity, emissivity and brightness temperature of the sample at room temperature and compared with the reported results of air-borne measurements (Ulaby *et al.*, 1974; Tsang & Kong, 1974; Eagleman & Lin, 1976; Njoku & Kong, 1977; and Burke *et al.*, 1979). The emissivity and the brightness temperature is found to decrease with soil moisture content but is found to be almost independent of frequency variations in the X-band of microwave frequency.

THEORY

The outer conductor of 50 Ω standard coaxial cable is replaced by the dielectric material (wet soil). The isometric and cross-sectional view of the dielectric surrounded coaxial cable is shown in Fig. 1. The dielectric surrounded cable is terminated at both ends with the original coaxial cable. We have neglected the small losses in the metallic inner and outer conductors of original line and in the dielectric insulating material. In the dielectric surrounded cable, the electromagnetic wave is mainly TM wave. Maxwell's equation for the homogeneous and isotropic dielectric medium is written as

$$\nabla \times \mathbf{E} = -j\omega\mu\mathbf{H}. \quad \text{...(1)}$$

$$\nabla \times \mathbf{H} = (\sigma + j\omega\epsilon)\,\mathbf{E}. \quad \text{...(2)}$$

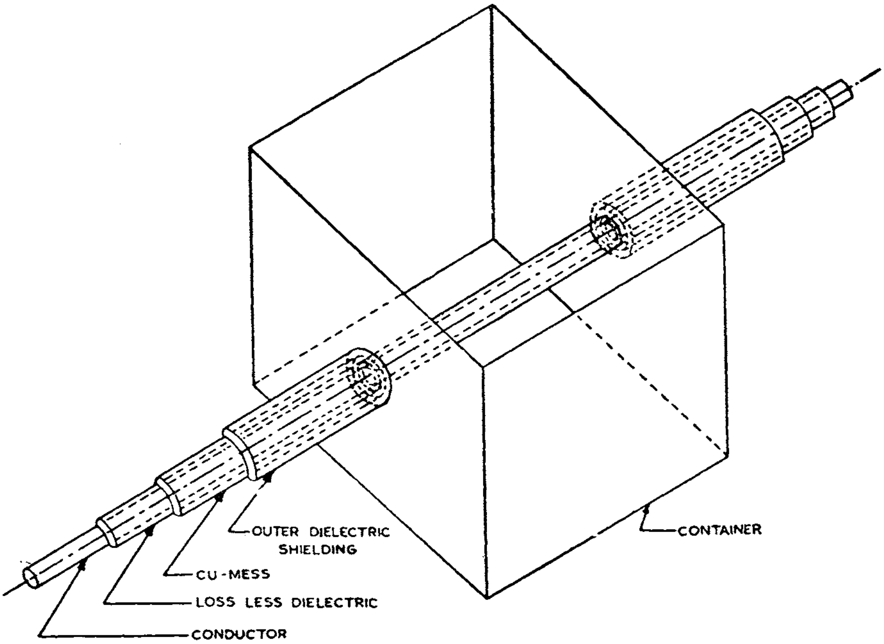

FIG. 1. Isometric and cross-sectional view of the dielectric surrounded coaxial cable.

The solution of wave equation with suitable boundary conditions at the metal-dielectric and dielectric sample interface gives the magnetic field in the three regions which is written in cylindrical coordinates as (Stratton, 1941)

$$H_1 = A\beta_1 H_0'^{(2)}(\beta_1\rho)\, I(z) \qquad \ldots(3)$$

and

$$H_2 = [B\beta_2 J_0'(\beta_2\rho) + C\beta_2 N_0'(\beta_2\rho)]\, I(z) \qquad \ldots(4)$$

where ρ is reflection coefficient,

$$I(z) = A_1 \exp(-\gamma_z z) + A_2 \exp(\gamma_z z).$$

$$\beta_i^2 = \gamma_z^2 - \gamma_i^2,\ i = 1, 2, 3. \qquad \ldots(5)$$

and

$$\gamma_i^2 = j\omega\mu\ (\sigma_i + j\omega\epsilon_i). \qquad \ldots(6)$$

γ_z is the propagation constant of the dielectric surrounded coaxial cable and is given by

$$\gamma_z = \alpha_z + j\beta_z. \qquad \ldots(7)$$

where α_z is the attenuation constant and β_z is the phase constant. The desired relation between the dielectric constant of the material is obtained by matching the tangential components of the electric and magnetic field at the boundaries between the region (1–2) and (2–3). The final non-linear expression for the dielectric constant of the material is given by (Dakermandji & Joines, 1977)

$$\epsilon_1 = \frac{\epsilon_2\beta_1}{\beta_2}\left[\frac{H_0^2(\beta_1 b)}{H_1^2(\beta_1 b)}\right]\left[\frac{J_0(\beta_2 a)\ Y_1(\beta_2 b) - J_1(\beta_2 b)\ Y_0(\beta_2 a)}{J_0(\beta_2 a)\ Y_0(\beta_2 b) - J_0(\beta_2 b)\ Y_0(\beta_2 a)}\right] \qquad \ldots(8)$$

Now β_1 and β_2 have been computed using the relation (5) with the measured values of α_z and β_z of dielectric surrounded cable. The values of the functions $J_0(\beta_2 a)$, $J_1(\beta_2 b)$, $Y_0(\beta_2\ a)$, $Y_1(\beta_2 b)$, $H_0^2(\beta_1 b)$ and $H_1^2(\beta_1 b)$ for varying values of arguments have been obtained from the table (Abramowitz & Stegun, 1965). Substituting these values, equation (8) is solved for ϵ_1 by linear iteration method (Conte, 1965). In this method, initially an approximate value of ϵ_1 is assumed and substituted in equation (8). The successive approximations have been made so that convergence is obtained which gives desired value of ϵ_1.

The other technique which has been extensively used for the measurement of complex dielectric constant of low loss sandy soil is the infinite sample technique

(Sucher & Fox, 1963). In this technique, the dielectric constant has been computed using the following equation with the measured parameters

$$\epsilon_r = \frac{1}{1+\left(\frac{\lambda_c}{\lambda_g}\right)^2} + \frac{1}{1+\left(\frac{\lambda_g}{\lambda_c}\right)^2}\left[\frac{R-j\tan k\,(D-D_R)}{1-jR\tan k\,(D-D_R)}\right]^2 \qquad ...(9)$$

where λ_c is the cut off wave length and is equal to $2a$, a being the largest cross sectional dimension of the wave-guide. λ_g is the guide wave length, in the region of the wave-guide not occupied by the sample and is given by

$$\lambda_g = \lambda_0\left[1-\left(\frac{\lambda_0}{\lambda_c}\right)^2\right]^{-1/2} \qquad ...(10)$$

λ_0 is free space wave length, $\mathbf{k}$ is wave vector and is also expressed as $\mathbf{k} = \frac{2\pi}{\lambda_g}$. R is the voltage standing wave ratio, D and D_R are the positions of the first voltage minima in the slotted waveguide with and without the sample.

SAMPLE PREPARATION AND EXPERIMENTAL TECHNIQUES

Soil samples chosen for the measurement of electromagnetic parameter were grounded thoroughly and sieved through a 70 mesh sieve and collected in 100 mesh sieve. Each sample to be tested was oven dried overnight at 120 °C and the known weight of water was thoroughly mixed and stirred. The moist sample was carefully packed and consolidated at desired pressure of 2.5 kg/cm^2 into the shell and waveguide. The water content of the soil on the weight basis was determined by the relation:

$$\text{Moisture content } (\%) = \frac{\text{Wet weight} - \text{Dry weight}}{\text{Dry weight}} \times 100\,(\%) \qquad ..(11)$$

The block schematic of the experimental set up to measure the attenuation constant of dielectric material (wet soil) surrounded coaxial cable is shown in Figs. 2 & 3. With the help of 20 db, 10 db, and 3 db directional couplers the incident, reflected

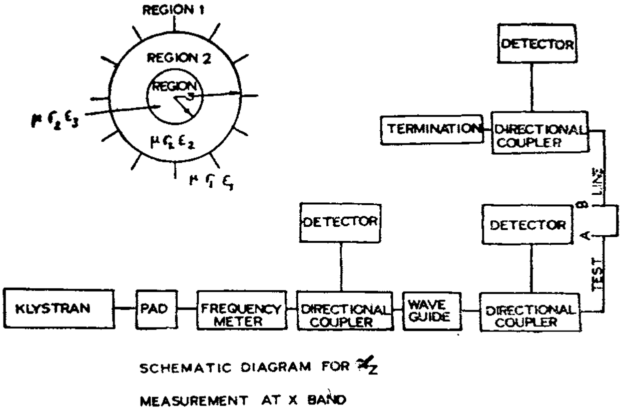

FIG. 2. Schematic diagram of experimental set up for the measurement of α_z.

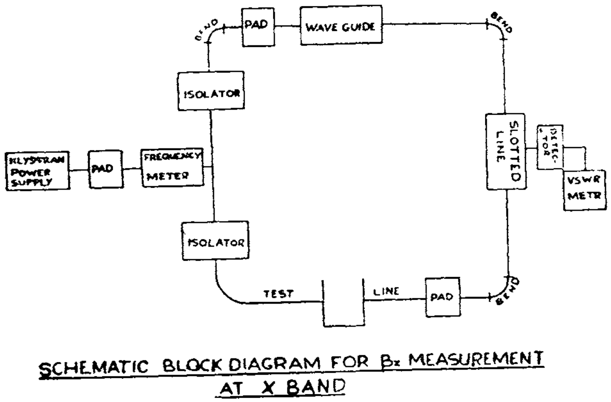

FIG. 3. Schematic diagram of experimental set up for the measurement of β_z.

and transmitted power is measured. The attenuation constant is computed using the relation (Dakermandji & Joines, 1977)

$$\alpha_z = -\frac{1}{2l}\log\frac{P_{in}\,P_t}{(P_{in}-P_r)^2} \qquad \ldots(12)$$

where P_{in}, P_r and P_t are the incident, reflected and transmitted power measured at the couplers 1, 2 and 3 respectively and l is the length of the dielectric material surrounded cable.

The experimental set up used for measuring the phase constant is shown in Fig. 3. The phase constant of the dielectric surrounded cable is measured by substitution method. In this method, the position of voltage minimum in the slotted line is noted by placing the dielectric surrounded cable in the circuit. Next, the dielectric surrounded cable is replaced by the original cable of exactly same length and the shift in position of voltage minimum is noted. The phase constant of the dielectric material surrounded cable is computed using the relation (Dakermandji & Joines, 1977)

$$\beta_z = \beta_{coax} + \frac{4\pi}{\lambda}\left(Z_2 - Z_1\right) + \frac{n\pi}{L} \qquad \ldots(13)$$

where β_{coax} is the known phase constant of the original coaxial cable, L is the length of the test line, and n is the number of half wavelengths contained in the shift in the position of minimum and Z_1 and Z_2 are the positions of voltage minima in the reference and test line. λ is the wavelength in the slotted line.

The imaginary part of the complex dielectric constant has been computed using the relation

$$\sigma = \omega\epsilon_0\epsilon_\gamma''$$

or

$$\epsilon_\gamma'' = \frac{\sigma}{\omega\epsilon_0} \qquad \ldots(14)$$

where $\omega = 2\pi f$ is the angular operating frequency and ϵ_0 is the permittivity of the free space. No equipment exists to measure the electrical conductivity of the material in this range of frequency. Therefore, the extrapolated values of σ for wet soil have been obtained from Arulandan and Smith (1973).

The basic experimental set up used in the wave-guide transmission technique is shown in Fig. 4. The positions of the first voltage minima D and D_R in the slotted line with and without sample were measured with respect to an arbitrary reference plane by terminating the slotted line with a short circuit. The voltage standing wave ratio (R) is obtained by terminating the wave-guide, containing the sample, with metallic short.

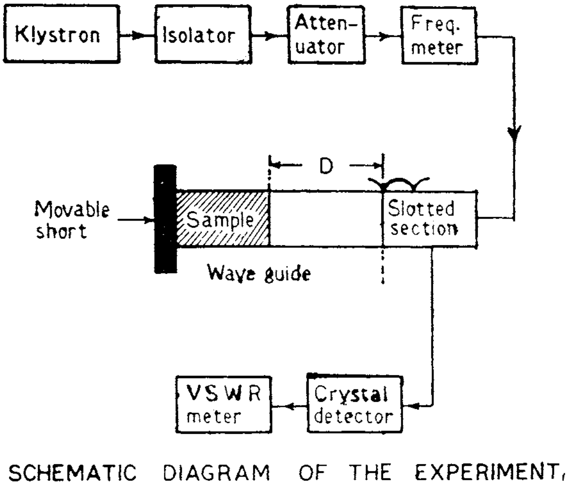

FIG. 4. Schematic diagram of experimental set up for the measurement of complex dielectric constant by infinite sample technique.

RESULTS AND DISCUSSION

The real and imaginary part of the complex dielectric constant of sandy soil have been shown in Figs. (5 & 6) as a function of frequencies and moisture content on the weight basis. The measurements have been made in the X-band of microwave frequencies (in the range of 8.0–10 GHz) at room temperature. The measured data shows that the value of dielectric constant of dry soils ranges from 2.5 to 3.0. It has been observed from the Figs. (5 & 6) that the dielectric constant of soil is strongly dependent on moisture content. The graph shows that the dielectric constant of soil increases with increasing moisture content. The increase in dielectric constant is slow for low moisture content and is found to increase sharply with increasing moisture content. Various investigators (von Hippel, 1954; Schmugge *et al.*, 1974; Hipp, 1974; and Hoekstra & Delaney, 1976) have also reported on a series of measurements on soils with varying moisture content up to 20 per cent at few discrete frequencies in the microwave band of frequencies. A qualitative difference between the present

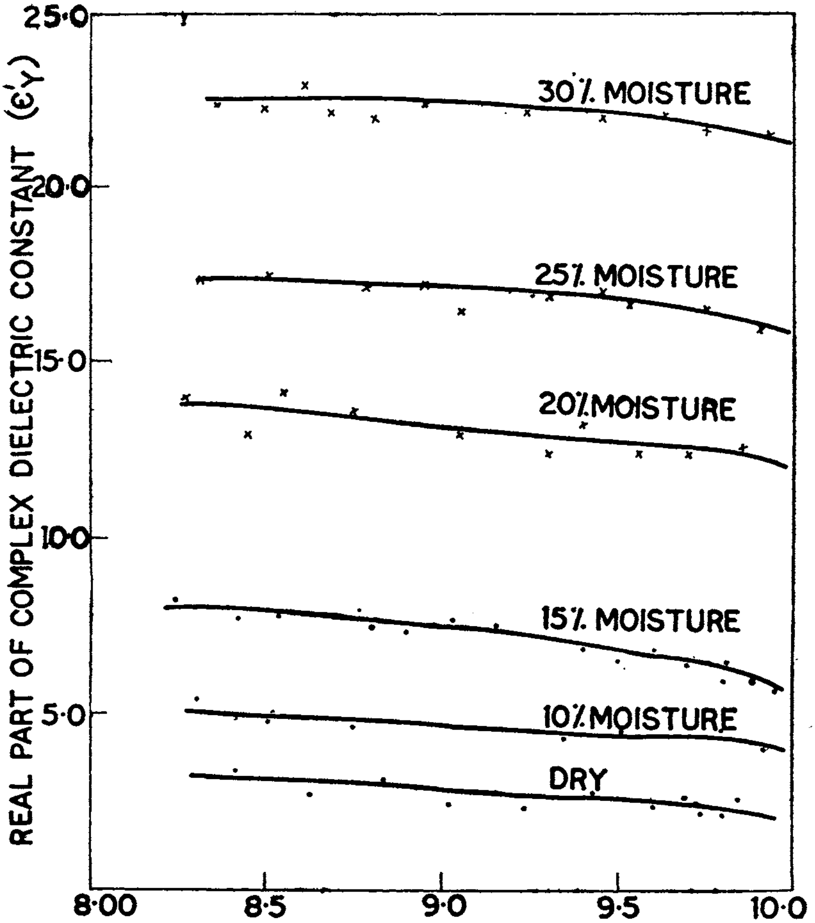

FIG.5

Fig. 5. Variation of real part of complex dielectric constant with moisture and frequency.

calculation and Njoku and Kong (1977) is that the rate of increase in real part of complex dielectric constant is more in case of 15 per cent to 30 per cent moisture content whereas in case of Njoku and Kong (1977) the rate of increase is seen to be uniform. Such a difference between the results can be interpreted in terms of different types of soil used in the two experiments. This increase in dielectric constant can be attributed due to the presence of free water molecules in the soil. The mobility of these loosely held water molecules in the soil gives rise to high dielectric values of the soil. The imaginary part of the complex dielectric constant has been found to be smaller than the real part and it also increases monotonically with increasing moisture content which can be explained by attenuation effect of ions present in the soil.

The power reflection coefficient (γ) for a plane surface has been computed using these laboratory measured values of dielectric constant of soil with varying moisture content employing the relation (Stratton, 1941)

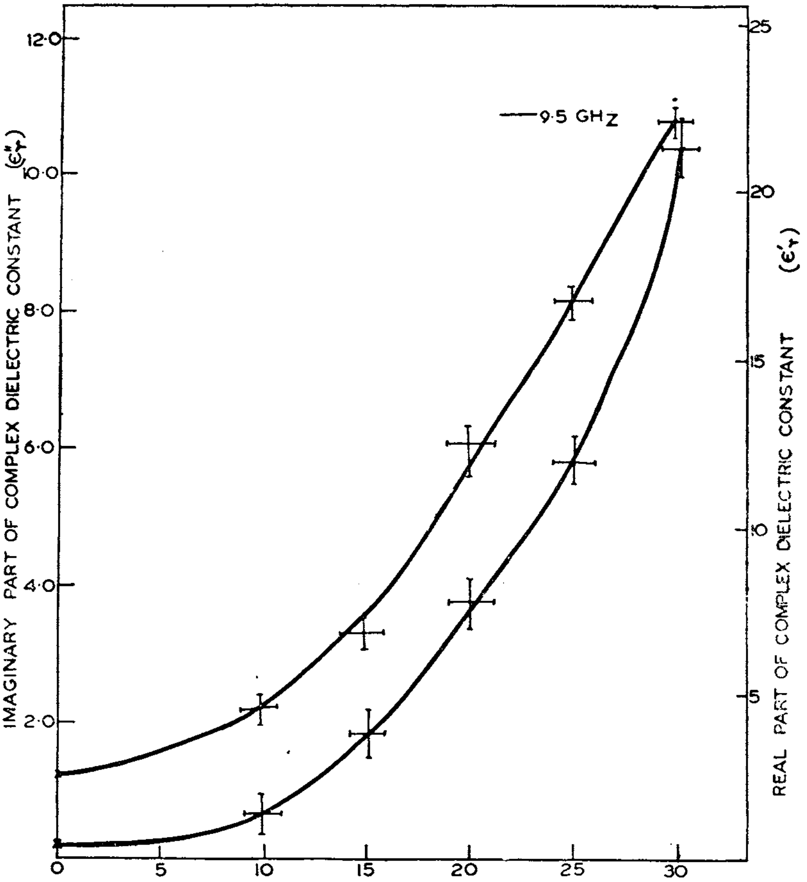

FIG. 6. Variation of real and imaginary part of complex dielectric constant with moisture.

$$\gamma = \left| \frac{1 - \sqrt{\epsilon_r'}}{1 + \sqrt{\epsilon_r'}} \right|^2. \qquad \ldots(15)$$

In case of homogeneous medium and for opaque surfaces, the emissivity (e) of the medium is computed using the relation

$$e = (1 - \gamma). \qquad \ldots(16)$$

The brightness temperature of the medium is a function of the surface temperature and emissivity of the medium. Assuming the medium to be plane with uniform temperature distribution and ignoring the loss of signal power by scattering, the brightness temperature of the surface of the medium has been computed using the relation

$$T_B = (1 - \gamma)\, T_0 \qquad \ldots(17)$$

where T_0 is the surface temperature of the medium. The dependence of reflectivity and emissivity of the medium on the moisture content at $\theta = 0$ has been shown in Fig. (7). The results show that the presence of moisture in soil causes a marked change in power reflection coefficient and emissivity. The reflectivity is found to vary from 0.05 to 0.5 whereas emissivity changes in opposite direction and varies from 0.95 to 0.55 for dry to 30 per cent most surfaces. The experimental results thus obtained have been compared with that obtained by Njoku and Kong (1977) at 0.3. GHz and 14.0 GHz (Fig. 7). The measurement of Njoku and Kong (1977) clearly show that the emissivity of the medium does not depend on the frequency. For uniform moisture content and temperature distribution, the dependence of brightness temperature has been shown in Fig. (8). It is observed that brightness temperature of the medium is found to chage from 285 °K for dry soil down to 170 °K for 30 per cent moist soil. The results obtained in X-band of microwaves (9.5 GHz) on the basis of laboratory studies has been compared with that obtained by Burke *et al.* (1979) at 10.7 GHz by microwave radiometer and is found to be in good agreement. Passive radiometers have a temperature resolution capability of about 1 °K and are very sensitive to brightness temperature variation. These parameters (emissivity and brightness temperature) have been widely used developing inversion models which is

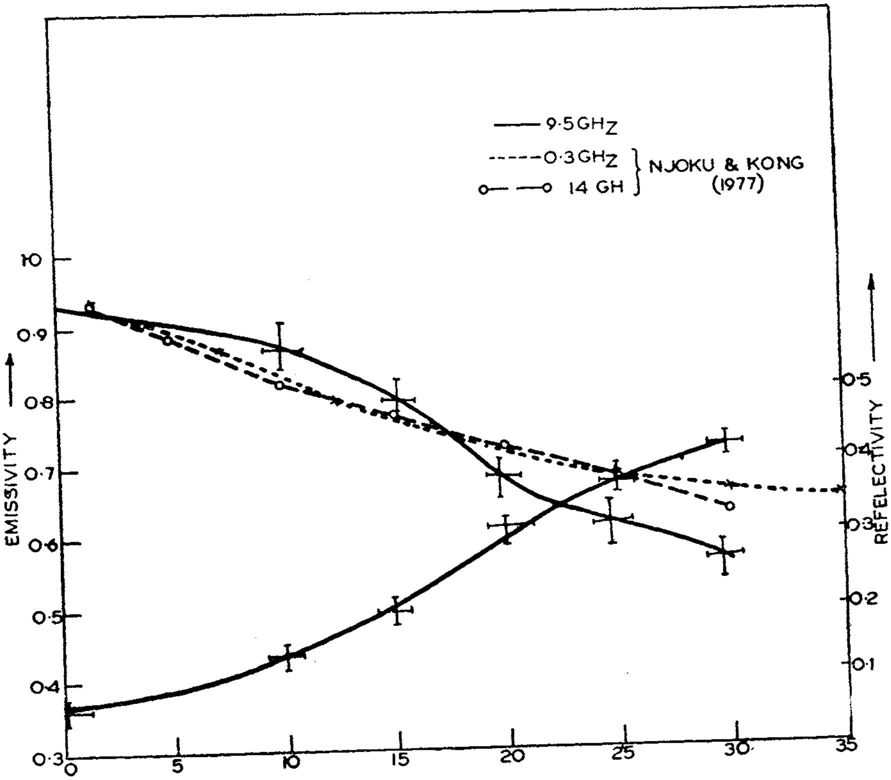

FIG. 7. Variation of reflectivity and emissivity with moisture content.

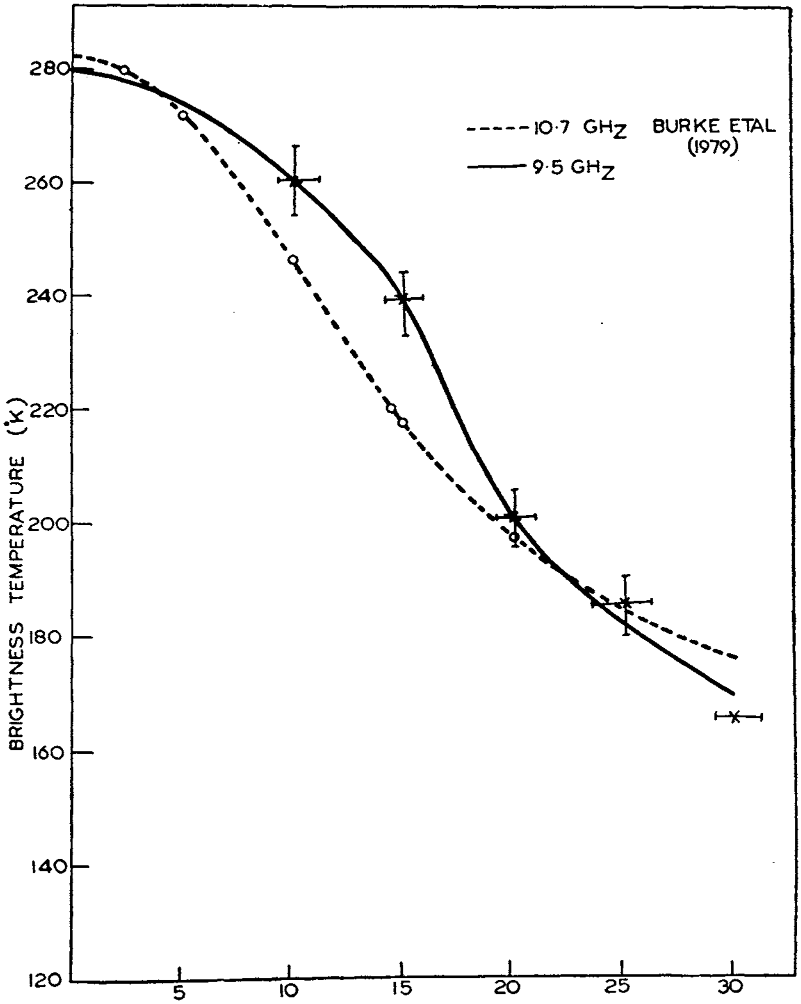

FIG. 8. Variation of brightness temperature with moisture content.

helpful for interpretation of remote sensing data obtained by air-borne and ground-based satellites.

CONCLUSION

The laboratory measurements at microwaves exhibit significant variations in the dielectric constant and the related surface parameters. The moisture content plays an important role in determining the microwave response. The laboratory measurements show that the microwave sensors can be effectively used for survey of aquifers, mapping of vegetation and determining the extent of dry and irrigated area. The plains, mountains, desert and sea can be effectively surveyed using microwave sensors. These observations are limited to the earth's surfaces because the microwave penetration is small.

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