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Measurements of reflection coefficients of stratified layers using X-band bistatic scatterometers

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Abstract. Laboratory modelling of earth's subsurface stratification has been carried out using X-band microwave bistatic scatterometer system. Look angle variation of reflectivity for various subsurface layers under dry and wet conditions have been measured. From measured reflectivity data and the reciprocity theorem the emissivity and the brightness temperature variations have been computed, and the data are in good agreement with reported results. The importance of laboratory and field measurements and its remote sensing application has been discussed.

Keywords. Bistatic scatterometer; reflectivity; brightness temperature; remote sensing.

1. Introduction

The successful interpretation of microwave radiometer data from remote sensing satellites depends on the extensive knowledge of microwave response of various types of earth-forming materials, their composition, moisture content, salinity, surface roughness, vegetation cover, look angle response, frequency, polarization and integrated atmospheric attenuation. The microwave emitted from the actual earth's or ocean's surface is attenuated by the atmospheric constituents, which have characteristic diurnal, seasonal and short term variations (Batlivala and Ulaby 1977). In order to study subsurface and ocean surface features using satellite radiometer data it is necessary to account for the sky temperature. Further, the ground truths are equally important for deriving surface compositions, moisture content and structural information. Various types of ground-based and laboratory measurements have been carried out on global basis to develop useful signatures for interpretation of remote sensing radiometer data. These studies can be divided into various frequency ranges (*viz* visible, infrared and microwave in various microwave bands), are very well documented (Jha 1982), and have been carried out using scatterometers for which reciprocity theorem holds good. The active scatterometer experiments have been carried out extensively in different modes of operation and have covered different frequency ranges (Reeves 1975). Scatterometry is useful only if its operation is limited for short range, such as from platform, bridge, building, towers etc then it provides the so-called ground truth. By using spaceborne sensors, frequency variation characteristic (*i.e.* measurements in extended frequency range) for various polarization combination and wide angular response is not possible, while scatterometer can be used for extended frequency range, for various polarization combination and it can operate for wide angles also. One of the major drawbacks of scatterometer (ground-based) is that, due to its limited beamwidth the footprint of the antenna used is smaller in size and cannot be used to obtain enough independent samples of the (more or less) Rayleigh type (Reeves 1975), whereas antennas used in airborne or spaceborne sensors cover a large area and provide information for significant number of independent samples. Most of the scatterometer measurements have been carried out in the X-band or still lower frequency of microwaves (Ford and Oliver 1946; Cumming 1952; Cost 1965; Peake 1968). Therefore, in this paper we report the result of scatterometer experiment using a laboratory model tank in X-band of microwaves, whereas many possible parameters are under control. Model tanks have been used earlier (Peake 1968; Caulfield 1978).

The model tank used in this experiment was filled with stratified layers of sand, silt and sandstone of known thickness in dry and wet conditions. The reflection coefficient using bistatic scatterometer was measured and the results are presented. The bistatic forward scatter measurements yielded results consistent with theoretical results. Using reflection coefficient data, the emissivity and brightness temperature were computed for both vertical and horizontal polarizations and these results were compared with similar results reported by other workers.

2. Description and measurements

Figure 1 illustrates the schematic representation of the equipment used. The waterproof holding tank (6 ft × 4 ft wide and 1·5 ft deep), in which the target medium was placed, was constructed of perspex ($\varepsilon_r = 2{\cdot}14$). For reflectivity measurement two identical pyramidal horn antennae (one acting as the transmitter and the other as the receiver having half power beamwidth 19 and 22° in E and H-plane respectively with a gain of 26 dB, operating at frequency 9·52 GHz) were mounted on a specially designed portable stand on either side of the model tank along a straight line. The height and look angle of the horn mounted on this stand can be varied and read from the graduated circular scales and pointer provided on the stand. The polarization of the radiated signal was changed by using 90° E-H twist. The size of the tank, the height of the transmitter and receiver stands, and their distances allow a practical variation of the look angle between 20 and 75°. Sensitivity of look angle (θ) depends on the measurements of horizontal distance from the centre of the tank and height of mounted

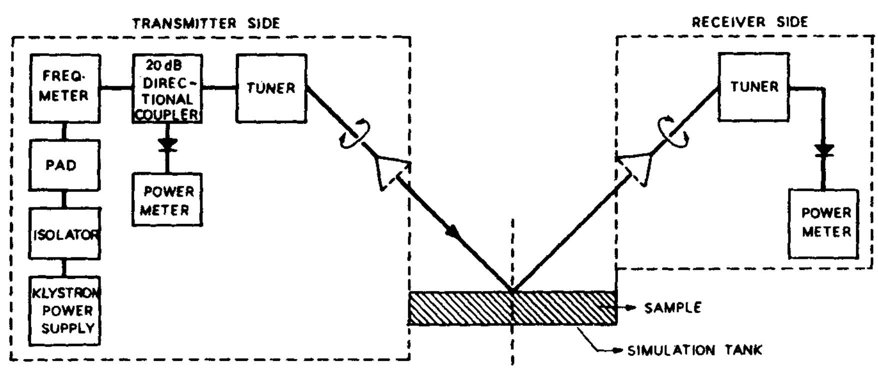

Figure 1. Block diagram of bistatic scatterometer system.

horn which permits measurement of angle of incidence with an accuracy of $\pm 0.5°$. For smaller angles of incidence this sensitivity decreases and for higher angles the sensitivity increases. The angles of incidence of microwave signal were systematically changed and the specularly reflected or scattered component of the signal from the centre of the model target are located. Care was taken to avoid stray reflection under experimental conditions by putting a 30 dB microwave absorber to the exposed part. The antennae were always placed 1 m away in the far field region from the centre of the target to minimize near field interaction.

The equipment is described below. An amplitude-modulated (AM) signal of frequency 9·52 GHz generated by the Klystron source (careful use of electronic tuning and regulated power supplies results in nearly constant power output), was fed through a variable attenuator, 20 dB directional coupler and then on to the transmitting antenna, where it was radiated towards the target. After interaction with the target, located in the far field, an amount of signal returns towards the receiving antenna, which is subsequently demodulated by the rectifying diode detector and then amplified by the tuned audio amplifier. The operation of the diode detector is assured to be in square-law region (*i.e.* the square of the output detector voltage is directly proportional to the input power supplied to it) by adjusting the transmitted power at low level. The overall system was calibrated by noting the signal returned from an aluminium plate placed on top of the target surface. After the measurements were carried out for all possible angles keeping the aluminium plate on the target, the plate was removed and the angular measurements for the target were carried out. The equipment was frequently bistatically calibrated against the direct view of the transmitter and receiver. The calibration of the system was checked at an interval of 30 min during the experiment.

3. Theory

The reflectivity of the target surface was computed from the following practical considerations. Let the power radiated be P_T and gain of the transmitting horn be G_T. For an observer at the receiving point the beam appears to be coming from the image point P'. With this in view, the incident power per unit area, P_i, at the receiving antenna at a distance $(R_1 + R_2)$ from the transmitting horn, presuming no intervening medium existing in between, is given from first principle as

$$P_i = \frac{P_T G_T}{4\pi(R_1 + R_2)^2}, \tag{1}$$

where R_1 and R_2 are the distances of the transmitting and receiving horn respectively to the central point of the target. The incidence and reflection of the microwave power from the target area is shown in figure 2. When the reflecting target is considered, medium characteristics in the form of Fresnel's reflection coefficient $|R|$ is taken into account. Therefore, power received P_R by the receiving antenna after reflection from the target is given by

$$P_R = P_i \times \mathbf{k} A_0 \times |R|^2 \tag{2}$$

where $\mathbf{k}$ is a factor defined by the ratio of capture area A to the aperture area A_0 of the receiving antenna.

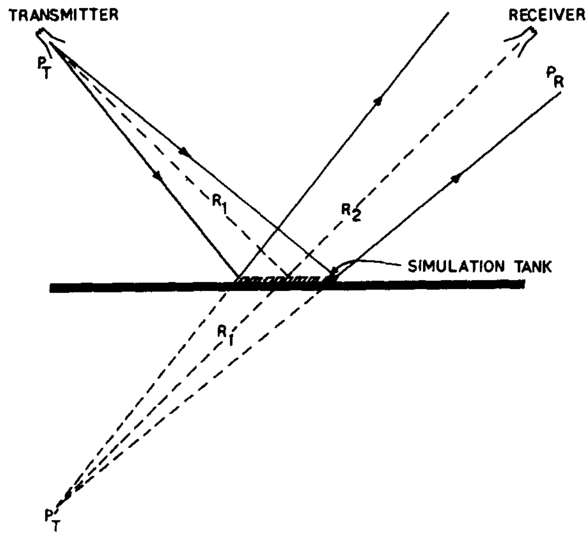

Figure 2. Schematic representation showing reflection from the mocked-up model surface.

The **k** value for the pyramidal horn antenna is taken to be 0·5 in these computations. The reflectivity which is defined as the square of reflection coefficients, is written from (1) and (2) as

$$r = |R|^2 = \frac{P_R \times 4\pi (R_1 + R_2)^2}{P_T G_T \mathbf{k} A_0}. \tag{3}$$

Let X represent the variance of surface height (*i.e.* any irregularity on the target surface). Equation (3) then becomes

$$r = |R|^2 = \frac{P_R \times 4\pi (R_1 + R_2)^2}{P_T G_T \mathbf{k} A_0 X}, \tag{4}$$

where $X = \exp(-2\sigma^2 k^2 \cos^2 \theta) \simeq 1$ in the case of smooth surface, $k = 2\pi/\lambda$ and λ is the operating wavelength. P_T has been kept constant for a set of measurements, and P_R varies with the angle. The reflectivity data obtained by using (4) was compared with the formula reported by Caulfield (1978).

As described earlier, let m_p be the measured output of audio amplifier in dB with aluminium plate in the target surface and m_{NP} be the measured output of audio amplifier in dB with no aluminium plate (*i.e.*, power reflected from the target surface) then,

$$m_p - m_{NP} = 10 \log r, \tag{5}$$

or

$$r = 10^{1/10(m_p - m_{NP})}, \tag{6}$$

where r is the target reflectivity. The data obtained by using (4) and (6) are similar up to three decimal places.

The principle of reciprocity holds good in electromagnetic emission and reflection from a homogeneous dielectric medium in thermodynamic, equilibrium with its surroundings. The emissivity of a stratified target is written as

$$e = 1 - |R|^2(\theta), \tag{7}$$

where $0 \leqslant e \leqslant 1$. The brightness temperature of a practical system is related with the physical temperature T and is written as

$$T_B = eT = (1 - r)T + rT_{\text{sky}} \tag{8}$$

where $r = |R|^2(\theta)$ is the reflectivity of the target. In the laboratory experiments, the sky temperature is taken to be zero due to short range.

4. Reflection of microwave from model target

Model tanks are generally used to simulate either a single layer of chosen material or stratified layers of earth crust forming materials. The number of strata and their thickness have been changed from one setting to another. The reflection coefficient in various settings change considerably due to the variation in complex dielectric constant. The relative effect of variation of the complex dielectric constant has been discussed by England (1976), and Jha (1982, 1983). The incident microwave power in practical cases of stratified layers is not reflected from the upper interface and the incident wave penetrates the stratified surface. A part of the microwave energy is absorbed in the layer. Therefore, the variation in composition with depth or the presence of structural elements such as internal or volume scatterers, plays a major role in reflection of the microwave signal. Thus, the measured reflectivity or its corresponding brightness temperature is indicative of depth to a compositional interface (Blinn *et al* 1972; England and Johnson 1975). The penetration depth of a microwave depends on the complex dielectric constant of the chosen material (Jha 1982). For example, the penetration depth of X-band microwave for dry sand is 11·4 cm (Batliwala and Ulaby 1977, figure 4.1).

In our experiment the model tank, stratified with various layers of subsurface material under investigation, forms the target for incident microwaves. The reflectivity of microwave thus depends on the number of stratified layers, their material and moisture content. In the present investigation, we have used either two or three layers. The theoretical expression for reflectivity of layered medium is well known (Brekhovskibh and Beyer 1980). In the present experiment, the thickness of the stratified layers have been taken to be of the order of the operating wavelength to avoid the interference effect of the signal at the receiving end. This has been done because the variability of layer thickness greater than 15% of the free space wavelength eliminates an interference pattern in the reflected microwave signal (England and Johnson 1977). Similarly, a diffuse interface whose thickness is 15% of the free space wavelength is transparent to microwaves so that effect of interface dies out. At higher angles of incidence, the stray reflections increase and the received power was found to fluctuate. These fluctuations and other practical difficulties inhibited the measurement at higher angles. The measured data have been shown with error bars, which are estimated using 'confidence interval for the mean' of the normal distribution method (Little 1978).

5. Results and discussions

This experiment was carried out at 29°C and the dry sample corresponds to this temperature. The wet layers of sand and silt samples contain 15% moisture content by weight, whereas wet stone sample contains negligible amount of moisture content.

The systematic bistatic measurement of reflection coefficient at varying look angles was carried out by suitably adjusting the position of the source, tank and the receiving system. The reflectivity thus obtained for various stratifications under dry and wet conditions was computed using (4). The computed reflectivity with error-bars is shown in figures 3–5. Similar variations of reflection coefficient with look angle for different targets in the X-band and lower frequency was reported earlier (Peake 1968; Caulfield 1978; Fung and Eom 1981). However, a close comparison of reflection coefficient values was not possible because of the entirely different nature and stratifications of target materials used in this experiment. The reflectivity for horizontal polarization increases with increasing look angle, because the electric vector is perpendicular to the plane of

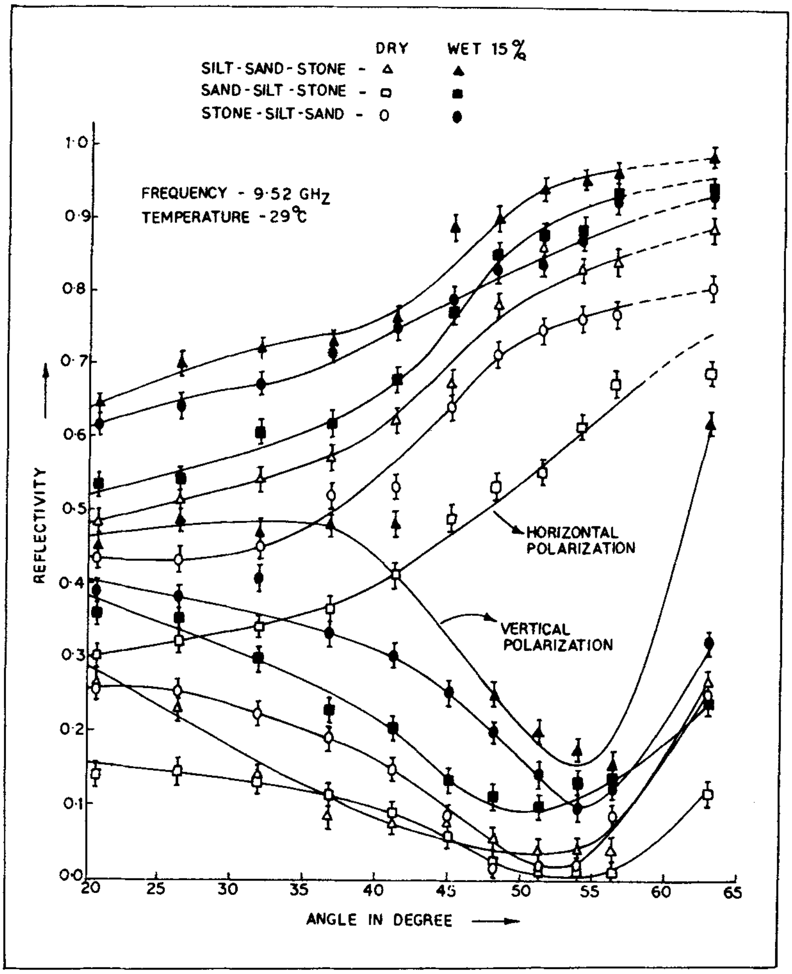

Figure 3. Angular variation of reflectivity for various stratification of subsurface materials.

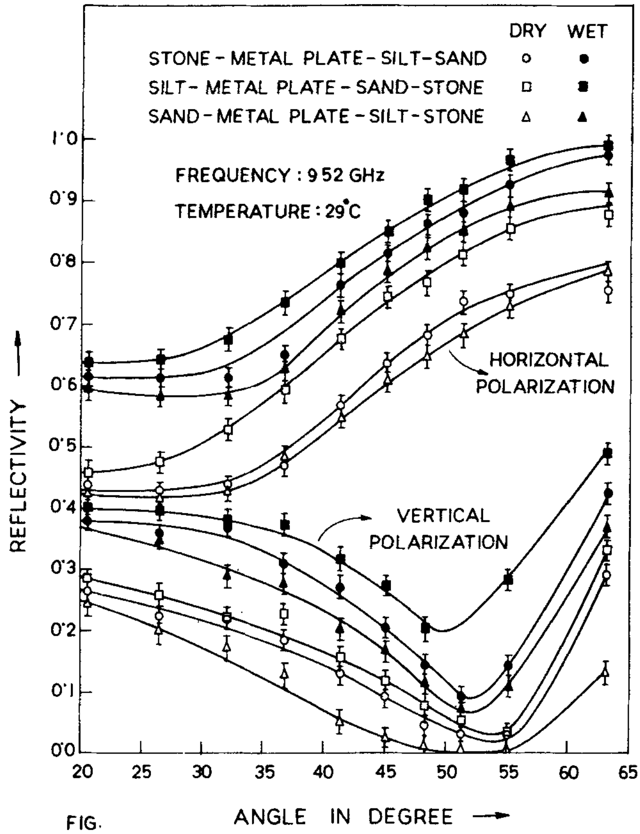

Figure 4. Angular variation of reflectivity for various stratifications of subsurface materials with buried metal plate.

incidence. This means that at the interface the transmitted wave is always in phase with the incident wave. The experimental results show a slow change in reflectivity at lower look angles. The rate of increase in reflectivity enhances around 45° and thereafter the variation becomes slow and saturates at higher angles. It is seen that the reflectivity of the stratified layer changes significantly with the order of stratifications; *e.g.* the sand-silt-stone combination gives small reflectivity and the silt-sand-stone stratification gives the maximum reflectivity. Similarly in figure 4 silt-metal plate-sand and stone stratification gives maximum reflectivity compared to that of sand-metal plate-silt-stone combination. Figure 5 compares the two sets of measurements for stone-silt-sand and stone-metal plate-silt-sand combination. The reflectivity has higher value when metal plate is embedded in the stratified layers. For wet stratifications, invariably the reflectivity is larger than the corresponding dry stratifications. This conforms well with the enhancement of the conductivity of samples with increasing moisture content. Also the soil texture *i.e.* particle size is a factor which controls the reflection coefficient. The moisture retention capacity of clay is more compared to that of silt and sand. This is due to the lower particle size distribution for sand. The surface area per gram of the soil could change by more than three times from the very sandy soils to the high clay content soils. The amount of water required to form one layer of water molecules around the

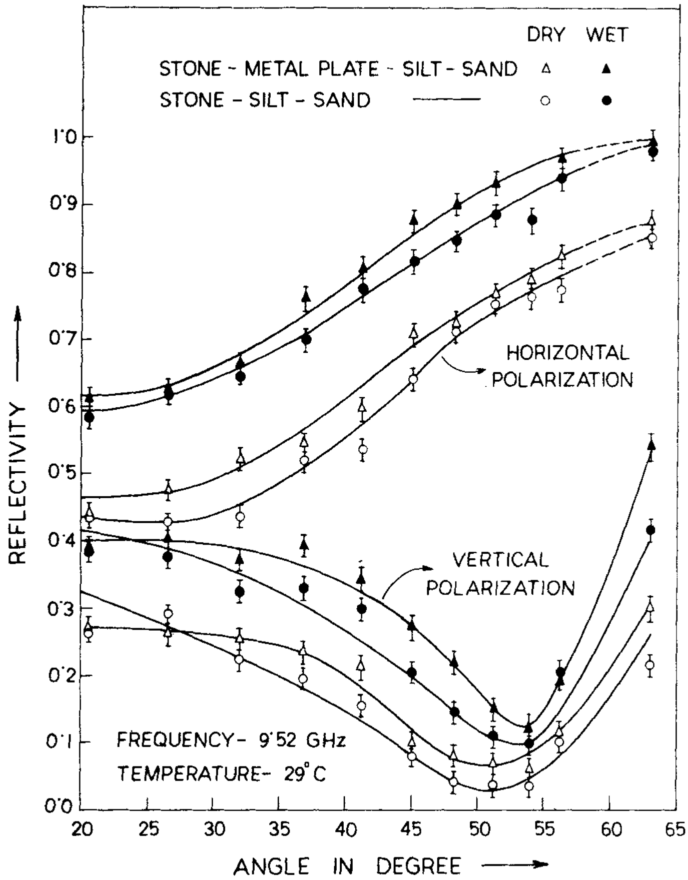

Figure 5. Angular variation of reflectivity for two sets of subsurface condition (comparison).

high clay content soil particles per gram would be enough to cover three layers of water molecules around the sandy soil particle per gram (Jha 1982). An interesting feature of the wet stratification of sand-silt-stone appears at a cross-over beyond 45° when the reflectivity is enhanced significantly and comes closer to the maximum reflectivity shown by wet stratification of silt-sand-stone (figure 3). The cross-over has been checked and is found to exist. The probable physical interpretation of the cross-overs may be that, when two such curves are crossed at a particular angle, the reflection coefficient in both the cases at that angle is same and the sensors cannot identify the target characteristic at that particular angle. Therefore, whenever a sensor looks at the earth from the sky at a particular angle many absurd results are obtained. This problem is being solved by using two or more frequencies. Such cross-overs have been reported by other workers also (Shiue *et al* 1978).

The variation of reflectivity for vertical polarization shows a steadily decreasing trend with look angle because in this case the electric vector is parallel to the plane of incidence. This is rather remarkable because it involves the passage of a wave through the interface without the production of a reflected wave (for this the reader can see any elementary book of field theory). The reflectivity becomes minimum at the Brewster's angle and thereafter increases rather rapidly. For dry sample, the maximum reflectivity is shown by the stone-silt-sand combination and minimum value is shown by the sand-silt-stone stratification. Similar nature of variation has been shown by silt-metal plate-sand-stone and sand-metal plate-silt stone. The silt-sand-stone reflectivity gives cross-over at different angles. No such cross-overs are observed in the layer combination with metal plate because the depth of penetration of the signal used is inversely proportional to the conductivity of the target material as well as the frequency of the signal used. Thus higher the conductivity and frequency lower the depth of penetration. In this case when the target consists of silt-metal plate-sand stone, the signal only penetrates the silt layer and is reflected back from the metal surface. Hence the received power is greater compared to silt-sand-stone combination. The Brewster's angles are not well defined in dry samples and show a broad minimum in each case. In wet stratifications, the reflectivity increases considerably and the Brewster's angle becomes well defined. Theoretically, at the Brewster's angle, due to total transmission of electromagnetic wave in the second medium, the reflectivity should be zero, as shown in figure 6. But this is true only in the ideal condition. The earth medium is complex in nature and due to its complex electrical parameters reflectivity increases at Brewster's angle and instead of showing total attenuation, there is a minimum reflection of power. The three stratifications namely silt-sand-stone, sand-silt-stone and stone-silt-sand give Brewster's angles respectively 53, 50 and 54°. These angles give effective dielectric

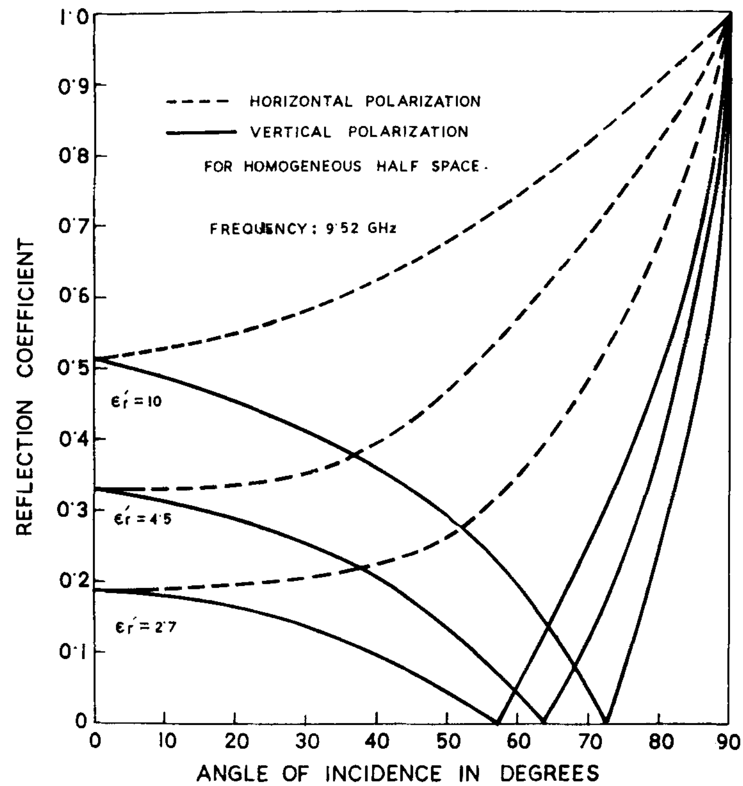

Figure 6. Angular variation of reflection coefficient for a plane wave incident on a semi-infinite media with $\varepsilon_r = 2·7$, 4·5, 10 and $\mu_r = 1$.

constant of the stratification. The stratifications affect the dielectric constant significantly at least in the case of sand and silt as upper surfaces. The general nature of reflectivity variation compares well with theoretical variation with look angle.

Using reflectivity variation with look angle, we have computed the corresponding emissivity and brightness temperature following (7) and (8). The emissivity variation of mocked-up model subsurface varies between 0·5 and 0·9. There is no direct comparison of measured data with reported results due to entirely different target combinations and certain climatic variations although these results agree with the reported result (Batlivala and Ulaby 1977). This variation is because of the rearrangement of stratified surfaces and moisture content in the layers. The frequency variation of emissivity for a particular target is comparatively less dominant as compared to changes in subsurface material composition, stratification thicknesses, and moisture content (Jha 1982). The brightness temperature for two polarizations changes significantly with look angle variations. The maximum brightness temperature is around 290°K for vertical polarization. The brightness temperature decreases by 25°K for moisture content of 15% by weight. In horizontal polarization, the brightness temperature is maximum at lower look angles and is higher for dry sample and decreases for the wet sample. The horizontal polarization at lower angles is more sensitive to moisture content and depicts a variation of 70°K for 15% moisture content by weight. This is quite understandable because of the bulk effect of the earth's surface which results in a cumulative radiation. The bulk effect has been crudely estimated by varying the thickness of the mocked-up layers. The comparison of results from actual surfaces and mocked-up surfaces may provide better insight in the interpretation of satellite data.

6. Conclusions

The laboratory measurements provide realistic signature of the mocked-up subsurface composition, stratification and moisture content, which is polarization dependent. Characteristic and systematic variations have been found in the measured reflectivity, and its corresponding brightness temperature values. The signature of known samples and their bulk effect are important in interpreting the satellite data and in obtaining physical parameters closer to the ground truths. The reliable and meaningful correlation of the measured data with satellite measured brightness temperature can be developed by carrying out extensive laboratory and field measurements using ground truths and the corresponding sky temperatures in various known conditions. Such a study would enable us to develop empirical relationships and correction factors which may prove very useful in interpreting the satellite data and obtain correct information about the earth's subsurface or ocean surface.

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