WORKING PAPER 341

REMOTE SENSING OF SOIL MOISTURE (3): PASSIVE AND ACTIVE MICROWAVE SYSTEMS

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WORKING PAPER
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Abstract

Estimates of the moisture content of near-surface soils can be made from remotely sensed data collected from aircraft and spacecraft. Techniques which make use of data gathered at microwave frequencies are reviewed in this context. Remote sensing of soil moisture in the microwave portion of the electromagnetic spectrum is subdivided into two distinct sections. These are termed 'passive' and 'active'. Passive systems measure the naturally emitted terrestrial radiation while active (radar) systems are based on the backscatter from a pulse of transmitted radiation. Attempts to establish operational parameters for routine measurement of soil moisture are reviewed.

June 1982

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Achnowledgement

The author is very grateful to Dr J. Hogg for his advice, help and encouragement throughout the period of this study.

Remote Sensing of Soil Moisture.

(1). General Introduction

There is a growing need for frequent and accurate estimates of the moisture content of surface soils. This need may be identified at various levels ranging from local and regional scales to a national scale. It is felt most keenly by scientists working within the hydrological, agricultural and meteorological sciences. In these, estimates of soil moisture are crucial for modelling and planning of natural resources. For example, agricultural scientists might use estimates of soil moisture to predict crop growth and yields whilst hydrologists may use such estimates for managing water supply based on integrated models for watershed planning. It is not surprising, therefore, to find that the estimation of soil moisture has provided a focus for research for many scientists in recent years.

Conventional techniques of measuring the moisture content of surface soils suffer from two major limitations. The first of these relates to the physical disturbance of the soil by the measurement technique itself. For example, the gravimetric techniques express soil moisture as the volumetric water content of a sample of soil taken from a site. During the process of measurement, the water regime of the soil is disturbed.This tends to give rise to large errors in measurement and to limit the usefulness of the method, especially if one is attempting to monitor changes in soil moisture over a long period of time. More advanced techniques based on neutron scattering, gamma ray attenuation or electric current flow within the soil, are subject to the same limitation although they generally avoid the need to take samples from the soil body (McKim et. al. 1980).

The second limitation relates to the high density of sampling points needed to obtain accurate estimates of soil moisture over large areas using conventional techniques. An adequate sampling density is rarely achieved because of the high cost of field observations. Estimates of soil moisture content over large areas are therefore limited in accuracy due to the large interpolations which have to to be made between points. These may leave out many important features such as pockets of saturated soil (Elkington, 1979).

The measurement of soil moisture from space or airborne platforms offers a solution to these problems. Remote sensing techniques have a good potential for providing timely and comprehensive areal coverage with few of the problems of limited accessibility or sampling density of the more traditional methods of soil moisture measurement.

Several techniques have been devised for the purpose of extracting soil moisture information from remote sensor data. These fall into three broad categories based on the region of the electromagnetic spectrum within which they operate. These are:

(1) The visible and reflective infrared waveband (0.38um-3.0um).

(2) The thermal infrared waveband(3.0um-15.0um).

(3) The microwave waveband (0.3 to 300 cm).

This paper deals with the remote sensing of soil moisture within the microwave portion of the electromagnetic spectrum. A brief outline of the physical principles together with a review of the literature dealing with soil moisture estimation at these wavelengths is given. Complementary papers dealing with the remote sensing of soil moisture in the other two wavebands are also available.

(2). Microwave Remote Sensing

Introduction.

Remote sensing of soil moisture in the microwave portion of the electromagnetic spectrum (c. 0.1 cms to 100 cms) is subdivided into two distinct sections. These are termed passive and active, referring respectively to the measurement of naturally emitted terrestial radiation and the use of radar systems at microwave frequencies. Passive systems thus make use of radiometers similar to those used at thermal infra-red wavelengths. Active systems are based on a variety of instruments (scatterometers, altimeters, imaging radar etc.). The operational physics of these instruments is only briefly mentioned here. Attention is given to the interaction between microwave radiaton, from whatever source, and soil moisture. Attempts to establish operational parameters with a view to routine measurement of soil moisture are reviewed.

(3). Passive Microwave Systems.

Microwave radiation occurs at the tapering end of the terrestial radiation spectrum (see Figure 1). Compared to reflected visible or emitted thermal infra-red radiation, its radiant power is low. Passive microwave radiometers (which may be scanning or non-scanning) are thus required to be highly sensitive in order to detect signals with a radiant power ranging from 10^{-11} to 10^{-20} W. (Reeves, 1975). Compensating for this however is the relative freedom of these longer wavelengths from attenuation by the atmosphere (Jackson et. al., 1981). The radiance of the microwave emission from a soil surface is given by the product of the soil temperature (T) and soil emissivity ($\mathcal{E}$). This product is referred to as the brightness temperature T(b).

(1) $$B = \mathcal{E}.T$$

The signal received by the radiometer is also influenced by its path through the atmosphere which both attenuates the ground emitted radiation and adds a radiant component of its own (B.atm.) either directly or through reflectance from the ground surface. Equation 1 is thus modified to give the radiance recdived at the radiometer aperture.

(2) $$B = \tau \left[(1-\mathcal{E}).B_{atm} + \mathcal{E}.T_{soil} \right] + B_{atm}$$

where τ is the atmospheric transmission (Schmugge et. al. 1980).

The emissivity of a substance is defined as the ratio of its emitted radiation to that of a perfect 'black-body' radiator. Unlike emissivity values of earth surface features at thermal infra-red wavelengths, those at microwave wavelengths may differ greatly from unity. In a typical scene variations in the brightness temperature are often dominated by variations in emissivity which may range over as much as one order of magnitude (Reeves, 1975). This range of variation thus overwhelms any variation in temperature in the same scene. Although the latter can still introduce significant errors if not acounted for (Hardy, 1980), thermal microwave emission from soils is dominated by factors which influence their emissivity.

Microwave radiation from soils is generated within the soil volume. 'Surface' emissivity is therefore only an approximation to the 'body' emissivity of a soil (Buettner and Kern, 1965). The amount of energy generated at any point within the volume of the soil depends on its dielectric properties and temperature at that point (Schmugge et. al., 1980). The soil s' dielectric properties are essentially dependent on soil moisture and, more indirectly, upon soil texture (Schmugge, 1980). Successive layers within the depth profile, each with varying soil moisture, texture and temperature contributes to the microwave emission. Factors such as surface roughness and vegetative cover also modify the resultant brightness temperature. The brightness temperature as measured by the radiometer is therefore an integral representation of characteristics of the vegetative cover, surface properties and the soil depth profile.

The radiative transfer between these various components must be modelled to achieve an understanding of the relative importance of each. Consider a soil volume as shown in Figure 1 where the Brightness radiation B(z) is changed to B(z+dz) over the incremental distance dz in direction z. When travelling through a medium, radiation may be transmitted directly or attenuated (absorbed and scattered) and subsequently re-emitted. The proportion of radiation transmitted, absorbed or scattered is dependent on the properties of the medium. If the soil volume in Figure 2 has an absorptance of (a) and a scattering coefficient α_{sc}, then the change in transmitted radiation over dz is given by;

(3) $$dB = (a . J_a + \alpha_{sc} . J_{sc}) dz + B(z)(a + \alpha_{sc}) dz$$

where J_a and J_{sc}. are source functions which respectively account for thermal emission and scattering in direction z. For solid bodies such as soil the scattering process is negligible when compared to absorption. Thus (3) simplifies to;

(4) $$dB = (a . J_a + a . B(z)) . dz$$

The source function for thermal emission for microwaves is given by equation 1. Making this substitution, and integrating

4 over the complete depth of soil gives the formal expression for radiative transfer of microwave energy.

$$B = \mathcal{E} \int_{-\infty}^{0} T(z).\, a(z) \exp\left[-\int_{z}^{0} a(z')\, dz'\right] dz \qquad (5)$$

where T(z) is the temperature profile and a(z) is the absorptivity as a function of depth (z). An increase in moisture content increases the absorptance and the dielectric constant of the soil both of which decrease the emissivity of the soil (Figure 2). This gives microwave radiometry a good potential for the remote sensing of soil moisture

Equation 5 holds if the thermal microwave emissivity of soil ($\mathcal{E}$) is a slowly varying function of depth (z) over distances comparable to a wavelength in the soil profile. Discontinuities often occur in the soil moisture profile with depth . These may be due to a sub-surface water table or to rapid drying of the surface layer caused by an unusually high evaporative demand. In any case, they will tend to dominate the radiative transfer process since a water surface has a low emissivity and a high reflectivity. These discontinuities are accentuated when longer wavelengths are used since the rapidity of change increases relative to the wavelength. Furthermore depth penetration is greater and so by implication is the probability of encountering a discontinuity. For wavelengths above 21 cm therefore a stratified model of the soil profile is more useful than the continuously varying medium assumed in equation 5. Several authors have described such models. Njoku and Kong (1977) used a numerical finite difference approximation to the radiative transfer equation (5). This consisted of finite layers with homogeneous dielectric and thermal properties. This approach is only fruitful if the layers are not arbitrarily defined solely for the purposes of computation . Unfortunately a corollary of this is that a large amount of data about the soil is required together with some information about the distribution of moisture within the soil. This, however, defeats the whole object of the exercise of remote sensing.

To avoid the problems posed by deterministic modelling of the radiative transfer process, more empirical relationships have been established between thermal microwave emission,its wavelength and polarisation and earth suface properties such as soil moisture, surface temperature, vegetation, surface roughness, topography, etc. The relationship between depth resolution, wavelength, and soil moisture was established in this fashion by Cihlar and Ulaby (1975) (see Figure 3). The depth of soil contributing to microwave emission is thus not only dependent on the wavelength of emission, but also on the moisture content of the soil. The latter tends to decrease the 'skin' depth owing to its greater absorbing properties. Vegetation tends to attenuate the emission from the soil as well as contributing a microwave component of its own. The effect of a canopy is minimised by use of the longer wavelengths (Shutko and Chukhlantsev, 1982) (see Figure 4)

As the emitted radiation passes from the soil volume into the atmosphere, its distribution is determined by the surface properties. The small scale roughness of the ground, which may include the vegetative canopy for longer wavelengths, can mask variations in emissivity brought about by soil moisture change (Schmugge,1980). Scattering by a rough surface is characterised by the scattering coefficient, which relates the magnitude of the power scattered in the direction (θ_s , ϕ_s) with polarisation Ps to the power incident on the surface from the direction (θ_i , ϕ_i) with polarisation Po (the radiant power may be horizontally or vertically polarised). For a specific wavelength the scattering coefficient σ^o is given by:

(6) $$\sigma^o = \sigma^o (\theta_i , \phi_i ; \theta_s , \phi_s ; P_i , P_s)$$

This coefficient is analogous to the bi-directional reflectance function which is used to uniquely characterise the reflectance properties of surfaces at visible wavelengths. By applying Kirchoff's law to scattering by rough surfaces (i.e. the sum of the ratios of the reflected, emitted (or absorbed) and transmitted power to the total power incident at one point must equal unity), the following expression is obtained for the polarised emissivity of a surface from the direction (θ_o ; ϕ_o) (after Ulaby, 1981):

(7) $$\mathcal{E} (\theta_o , \phi_o , P_o) = \frac{1}{4\pi \cos \theta_o} \cdot \int \left[\sigma^o (P_o , P_o) + \sigma^o (P_o , P_s) \right] d\Omega_s$$

Idealised models of perfectly rough (Lambertian) and perfectly smooth surfaces form the extreme points of a range of possible behaviour. For a perfectly smooth surface, the scattering coefficient is zero and the emissivity is simply the complement of the reflectance (ρ) for a specific polarisation. That is:

$$\varepsilon(\theta_o, \phi_o; P_o) = 1 - \rho(\theta_o, \phi_o; P_o) \quad (8)$$

The effect of surface roughness is to decrease reflectivity (and hence increase emissivity) and to cause cross-polarisation to occur (i.e $\sigma^o(h,v)$ is non-zero). For a Lambertian surface, the emissivity is independent of both polarisation and direction (see Figure 5) and is simply related to the dielectric properties of the scattering medium (Ulaby et. al., 1981). For surfaces which lie between the extremes of a perfectly diffusing and a perfectly specular surface, the polarisation of the emitted radiation is dependent both on the geometrical and on the electrical properties of the surface. Choudbury et. al. (1979) defined the following expression which relates the change in emissivity ($\Delta\varepsilon$) from a smooth surface with reflectance (ρ_o) to a change in roughness defined by the root mean square height h.

$$\Delta\varepsilon = \rho_o(1 - \exp.(-h)) \quad (9)$$

For dry fields, $\rho_o < 0.1$ and the overall change is small. For wet fields, $\rho_o = 0.4$ at microwave frequencies and so the change is proportionately much greater.

Newton (1979) established the relationship between viewing angle, polarisation, and microwave brightness temperature. Although the vertically polarised brightness temperature increased with viewing angle at the expense of the horizontally polarised brightness temperature, the average value of these two remained constant for angles up to 40° (Figure 6). This large degree of independence from viewing angle gives passive microwave radiometry a good advantage over alternative remote sensing systems. Measurements made in the thermal infra-red or reflected visible wavelengths, for example, often have to be corrected for the distorting effects of topography on the data.

(4). Active (Radar) systems.

Like much of the technology used in remote sensing, RADAR (RAdio Detection And Ranging) systems were originally developed for military purposes. Civilian uses of radar have burgeoned in number since the war and research work continues to add new applications to a long list (Browning 1980; de Loor 1980; Reeves 1975). This variety is due to the inherent flexibility of radar systems: they may be installed on land, on ships, on aircraft or spacecraft and, under normal conditions, are independent of time of day or year and the vagaries of the weather. A large literature exists which deals with the use of radar for the purposes of soil moisture estimation. The principles of radar operation are well understood and most of the research work in this area is geared towards devising a reliable system for the routine measurement of soil moisture.

There are several types of radar system used in remote sensing. These fall into three categories viz. altimeters, imaging radars, and scatterometers. Altimeters, as the name suggests, measure the height of an aircraft or spacecraft above the ground. Satellite altimeters have a measurement accuracy in the order of 10 cm. (Ulaby, et. al. 1981). Experimental projects based on the Skylab and Seasat satellites showed that this high degree of resolution offers a valuable potential for measuring the height of sea waves (Cracknell 1981).

Imaging radars provide information about the backscattering properties of the earth's surface in a visual form. The most common imaging radar system is described by the acronym SLAR (Side Looking Airborne Radar) which provides continuous strip images in a direction perpendicular to the the flight direction of the aircraft. Microwave energy sent out in the form of frequency modulated pulses is proportionately converted into light energy and recorded on photographic film as a function of distance along and perpendicular to the aircraft track. If the backscattered pulses are used to create the image without pre-processing, then the resolution of the image in the across track direction is dependent on the width of the beam. Since this increases with distance from the aircraft, the resolution also deteriorates with distance from the aircraft. This type of system is termed 'real aperture' radar. 'Synthetic aperture' radar systems make use of the doppler shift between transmitted and received signals to make across track resolution effectively independent of distance from the aircraft (Ulaby et. al. 1981; Reeves 1975). Because of this advantage, together with general improvements in the quality of the data, synthetic aperture systems are most commonly used in imaging radar.

Scatterometers are non-imaging radars which are most frequently used in research and development work. They may be used in the initial design of an imaging radar or in the analysis of relationships between the backscatter response and the properties of a target. Most of the work concerning the relationships between soil moisture and microwave radar has been done using scatterometer instruments. This remainder of this section is thus concerned with these relationships.

(4.1) Soil Moisture and Radar Backscatter

As in the terrestrial emission of microwave energy, the backscatter of a radar pulse from terrain is dependent upon its geometrical and electrical properties (Batilava and Ulaby, 1977). The response of terrain to 'illumination' by microwave radar is usually expressed in terms of the scattering coefficient σ^{o} of the surface. The measured value of σ^{o} is equated with the normalised ratio between the transmitted (Pt) and the received (backscattered) (Pr) power:

(10) $$P_r = \left(\frac{P_t .\ G_t .\ G_r .\ \lambda^2 .\ A}{(4\pi)^3 .\ R^4} \right) \sigma^{o}$$

The transmitted power (Pt) and antenna gain for transmitted and received signals (Gt and Gr) are known system parameters whilst A (the area contributing to the backscatter) is effectively constant for synthetic aperture radar. The range distance R is calculated from the time lag between transmitted and received signals.

The basic operation of a radar system is shown in Figure 8. Most correlation exercises which link earth surface features to their response to microwave radar make use of the backscatter coefficient. The magnitude of this varies with surface characteristics (large and small scale roughness, vegetation), the sensor parameters (incidence angle, polarisation, wavelength etc.) and the dielectric properties of the soil. The dielectric properties of soil are dependent on soil moisture and indirectly dependent upon texture through its effect on soil moisture (Schmugge et. al., 1974). Many investigators have sought to establish the optimum operating system for the estimation of soil moisture by radar. To do this, a compromise must be reached between the various factors involved. The distorting effects of a vegetation canopy and surface roughness, for example, can be minimised by using longer wavelengths (e.g. above 25 cm). However, the sensitivity of radar backscatter to incidence angle (and hence slope angle) also increases with wavelength (Figure 9). Ulaby et. al. (1976, 1978, 1979), in a series of papers based on truck mounted scatterometer experiments, attempted to establish the optimum operational parameters for remote sensing of soil moisture. They considered 'target' characteristics such as soil texture, vegetation and surface roughness together with sensor parameters such as wavelength, polarisation and incidence angle. They concluded that the best overall linear correlation between σ^{o} and soil moisture occurred at a frequency of 75 GHz (i.e. at a wavelength of 6.3 cm , 'C' band), at a 10 degree incidence angle using HH polarisation (i.e. the antenna transmits and receives for horizontal polarisation only). Jackson et. al. (1981) confirmed these results for aircraft mounted scatterometers.

A vegetative canopy both attenuates the response from the soil whilst at the same time adding a backscattered component of its own. The latter is so dominant at shorter wavelengths that direct identification of crop type and estimation of crop parameters such as leaf area index, biomass, etc. can be made from backscattered data alone (Brakke, *et. al*. 1980; de Loor 1980; Ulaby, *et. al*. 1980; Kim, *et. al*. 1981). Useful estimates of soil moisture can still be obtained, however, using the same operational parameters as outlined for the bare soil case (Ulaby, *et. al*. 1979). But to avoid any major backscatter from vegetation, a wavelength longer than the average roughness parameter of the canopy must be used (Meier, 1981)

Like vegetation, non-uniform topography can be characterised by its effect on the backscatter of microwave radar (Reeves, 1975). Unlike vegetation, its effects become dominant at longer wavelengths. Thus the sensitivity of active microwave systems to the variations in incidence angle presented by uneven topography may be overcome by using the shorter wavelengths (e.g. in the 'C' band) (Batilava and Ulaby, 1977). This is only effective, however, for slopes of less than 5-10° (Jackson , Chang *et. al*. 1981). An alternative approach is to normalise the correlation between the backscatter coefficient and slope angle. Meier (1981) did this with the aid of a digital terrain model of a small catchment area (Figure 10). The distance of a point above or below the regression line indicates its soil moisture value. This technique gave a soil moisture estimate with a degree of accuracy of about 10 percent. It is therefore a blunt tool for many applications except where only relative values of soil moisture are required. It also requires a large amount of data processing to establish the regression line between incidence angle and backscatter.

(5). General Discussion

Remote sensing from airborne and space platforms has several important advantages over alternative means of resource evaluation which are based on interpolation between point samples. The ability of remote sensing systems to make quick and frequent inventories of earth resources over large areas is their most attractive feature. These inventories fall into two categories (Hardy, 1980):

(a) The surveying of relatively static earth surface features such as lithology, soil type and topography;

(b) The survey and subsequent monitoring of more dynamic phenomena such as weather systems, soil moisture or vegetation.

Many properties of the earth's surface (such as vegetative cover) may be arbitrarily placed in either category. Soil moisture content, however, is firmly embedded in the latter group of highly dynamic phenomena. Although an initial survey may be able to determine how much moisture a soil can hold between field capacity and wilting point, it s soil moisture status at any point in time can only be ascertained through frequent monitoring.

The decision to use remotely sensed data an alternative to regional estimates of soil moisture from precipitation and potential evaporation data is an economic one (Hardy, 1980). However, the more technological problem of devisng a remote sensing system that works has still to be solved. As yet there is no fully operational method for calculating soil moisture over a large area from remotely sensed data, although there are several candidates. With this in mind, the physical principles of remote sensing in the visible and reflective waveband have been reviewed above.

In order to depict the spatial variations of soil moisture, remotely sensed data are organised into resolution cells. These represent the smallest area in a scene which can be considered as a unit. The dimensions of a resolution cell define the smallest angular or linear sep ration which can occur between two distinct points in, for example, a Landsat image. The value attributed to a cell is the aggregated response of it s constituents. The problem then arises as to the physical meaning of this aggregated response. The discrimination between two objects in a Landsat image, for example, is based on the difference between their 'spectral signatures'. The spectral signature attributed to each resolution cell is made up of the reflectance properties of each of it s constituents. Because of this, the spectral signature of a heterogenous ground area may not be representative of any of it s constituents.

For thermal infra-red and passive microwave remote sensing, a similar problem is encountered with respect to the meaning of surface temperature. For a truely homogenous and flat ground surface at thermal equilibrium, the surface temperature is well defined, if not easily measured (Becker, 1980). The surface temperature of an undulating and heterogeneous surface with a vegetation canopy is much more ambiguous. Each element within the canopy (stems, leaves and ground surface) contributes to the radiative flux and these contributions vary over time and space. Often some kind of weighting system is used. Smith et. al.(1981), for example, weighted the radiometric temperature of the lowest (of three) layers of a forest canopy most heavily. This ambiguity makes 'ground truth' measurement of surface temperature difficult. This point can be generalised to all remote sensing systems. That is, to enable a check to be made on the accuracy of remotely sensed data, the ground data collection must be organised to take into account the size of the resolution cell involved and it s aggregating properties (Hardy, 1980b).

Because of their nature, remote sensing techniques are most sensitive to the upper few centimetres of the soil. The extent of penetration into the profile varies with the method used. The visible albedo, for example, is only related to the soil moisture content of a very thin surface layer (less than 0.2 cm. thick) (Idso et. al. 1974). Skin penetration by microwave radar varies both with soil moisture and with wavelength (Figure 4.4) but with the most widely used systems (4.7 GHz., HH, 10° incidence angle), it has been found to be representative of a soil depth of up to 15 cm (Jackson et. al., 1981) Again it is only the aggregated value of soil moisture over this limited depth profile which contributes to the emitted radiation, reflectance or backscattering properties of a soil. Knowledge of the form of the depth profile may possibly be obtained by radar systems through the use of a number of different microwave frequencies each with a different depth penetration.

A practical assessment of the two microwave systems must balance the cost and complexity of active systems against the relative simplicity but low resolution of passive systems. Radiometric data are preferred in hilly areas because of their lower sensitivity to variations in incidence angle. Thus, in Great Britain passive systems may be a useful tool for monitoring soil moisture in rugged catchment areas with a view to flood forecasting. The small size of drainage basins in Great Britain, however, together with the poor resolution of current radiometers (tens of metres for aircraft, kilometres for satellite platforms) limits their use in this context. Radar systems, on the other hand, are extremely sensitive to variations in incidence angle and their usefulness outside vast uniform areas such as the wheat belt of Northern America has still to be assessed. Despite this, active microwave systems are rapidly emerging from the research and development stage into full maturity as an operational technique . Most of the research in this area continues to be involved in establishing optimum parameters for the routine measurement of soil moisture (Ulaby et. al., 1978; 1979; Jackson, Chang et. al., 1981). Several authors have described ways of linking estimates of soil moisture from microwave radar to more general hydrological models (Jackson et. al. 1981, Bernard et. al., 1981). These are however only schematic in nature and an integrated hydrological model using remotely sensed data has still to be developed.

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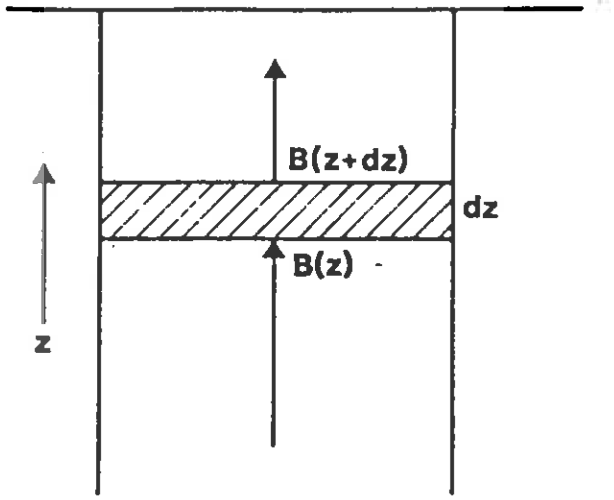

FIG. 1. RADIATION TRANSFER ACROSS AN INFINITESIMAL DISTANCE WITHIN THE SOIL VOLUME

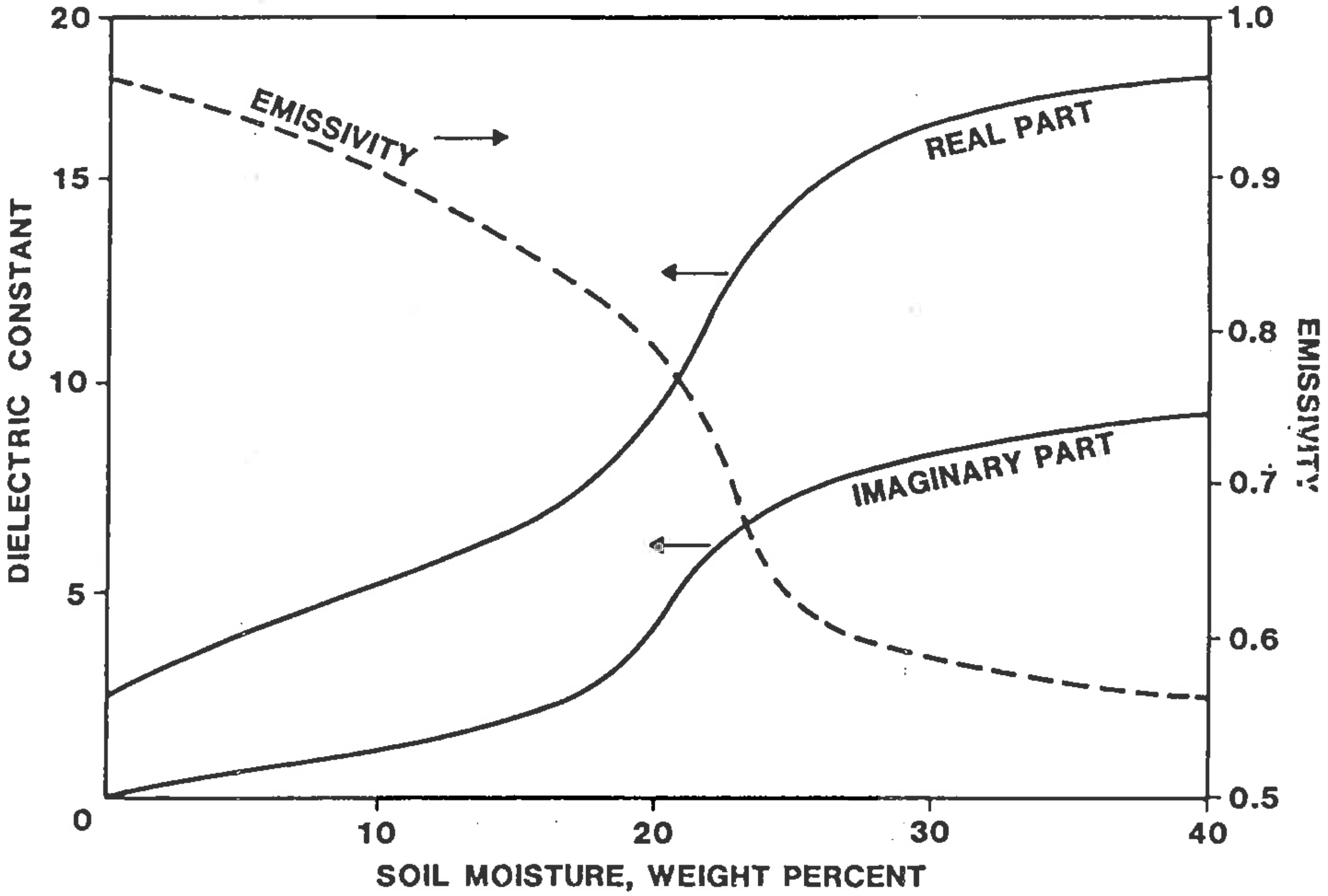

FIG. 2. THE DIELECTRIC CONSTRAINTS OF SILTY CLAY LOAM SOIL (1.55CM LAYER) AND ITS EMISSIVITY PLOTTED AGAINST SOIL MOISTURE CONTENT

(AFTER SCHMUGGE, 1974)

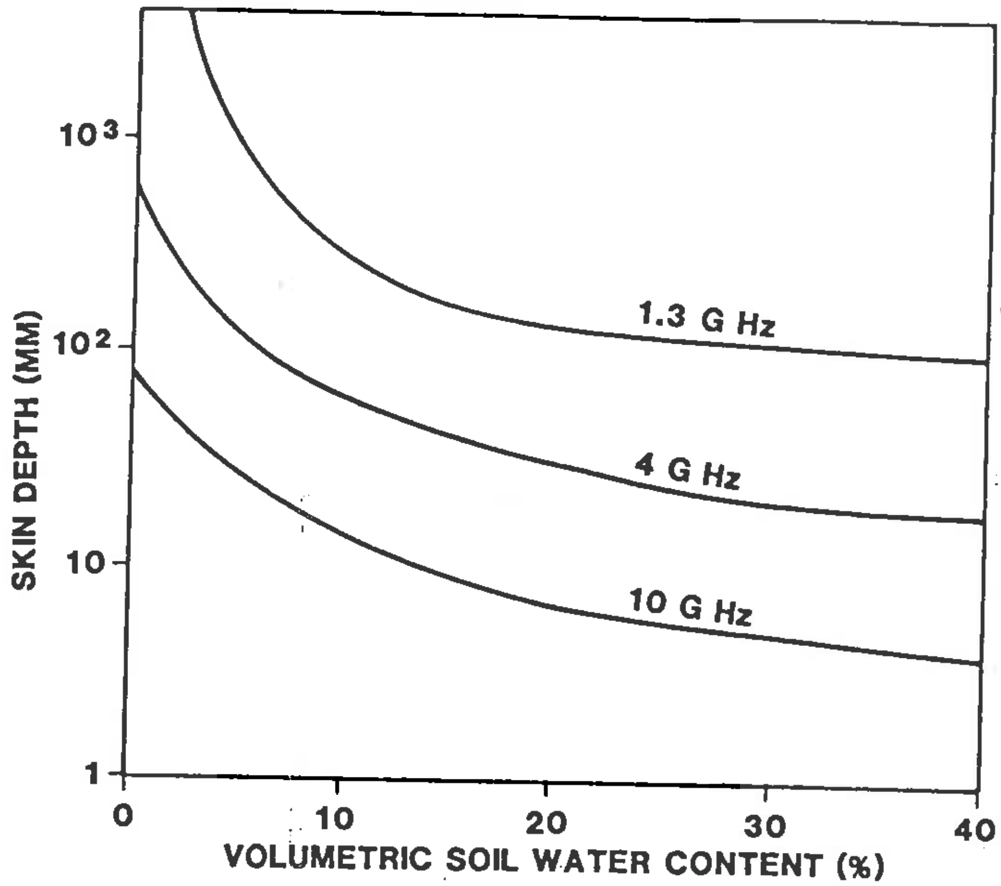

FIG. 3. SKIN DEPTH PENETRATION OF A SOIL WITH VARIABLE MOISTURE CONTENT FOR DIFFERENT FREQUENCIES (AFTER CIHLAR AND ULABY 197

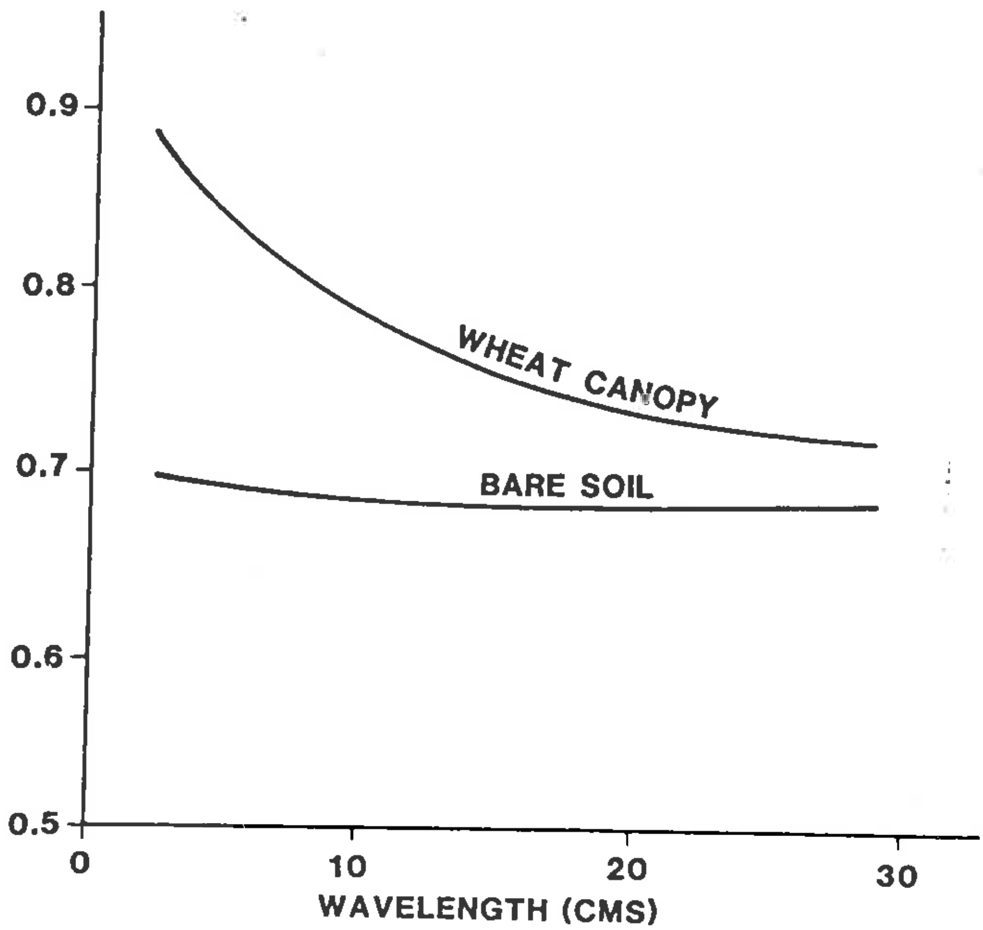

FIG.4. EMISSIVITY SPECTRUMS FOR BARE SOIL AND FOR A WHEAT CANOPY

(SHUTKO AND CHUKHLANTSEV, 1982)

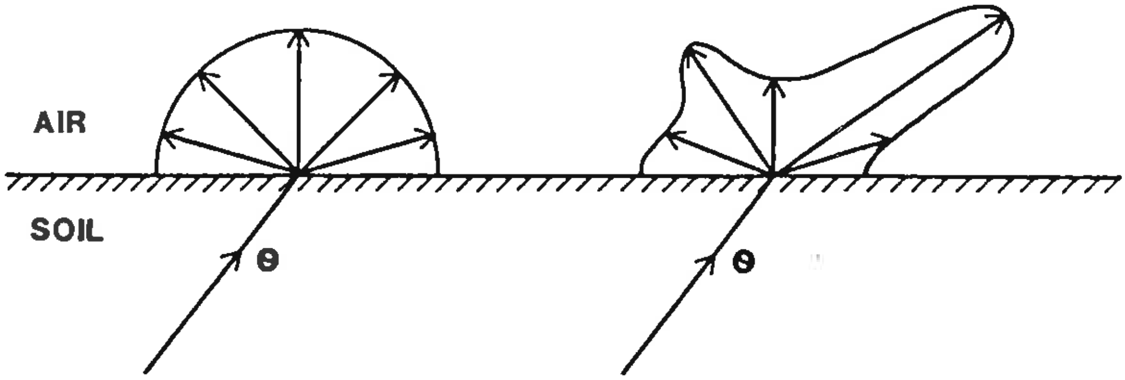

FIG. 5. ROUGH SURFACE EMISSION (a) ACROSS A PERFECTLY DIFFUSING SURFACE AND (b) ANISOTROPIC PATTERN OF EMITTED RADIATION

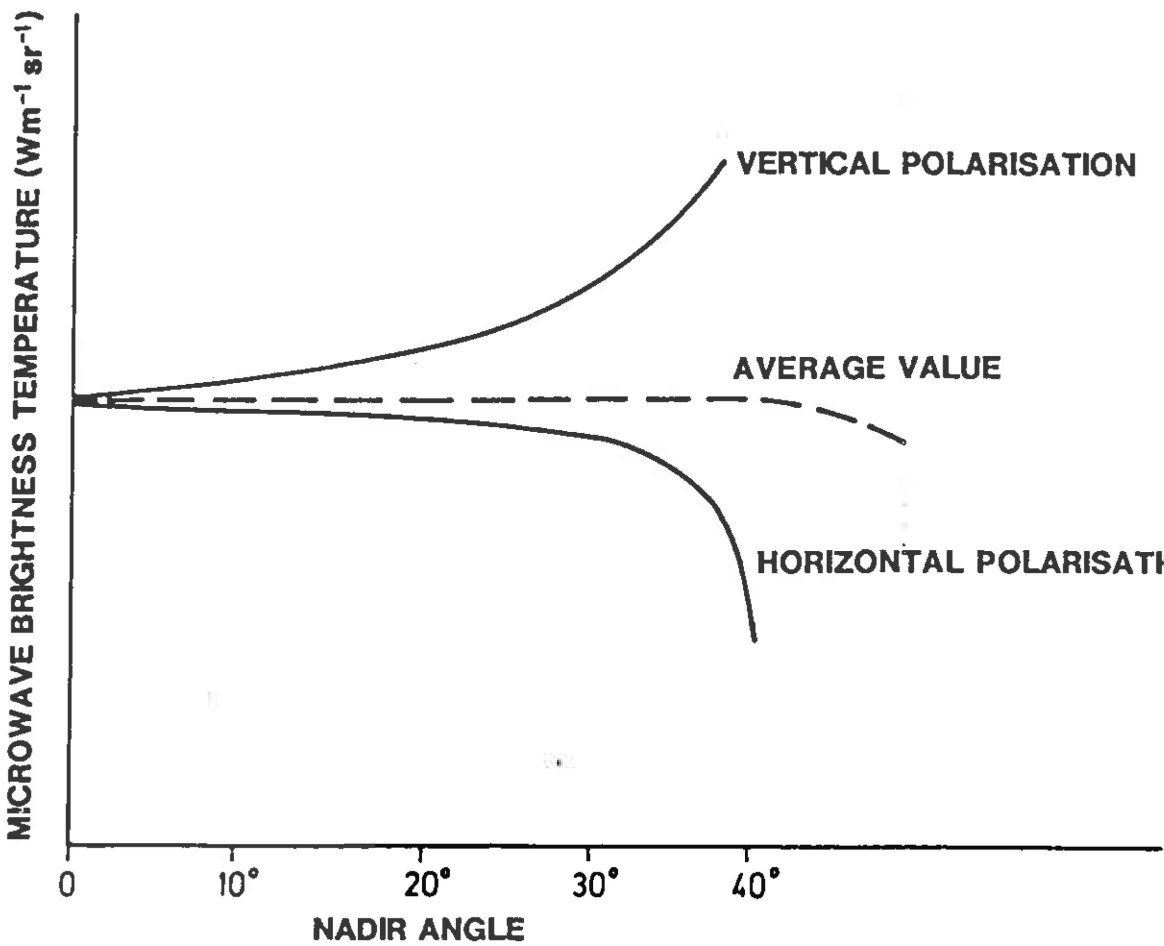

FIG. 6. RELATIONSHIP BETWEEN NADIR (VIEWING) ANGLE BRIGHTNESS TEMPERATURE AND POLARISATION

(REPRODUCED FROM SCHMUGGE ET. AL. 1980, AFTER NEWTON 1979)

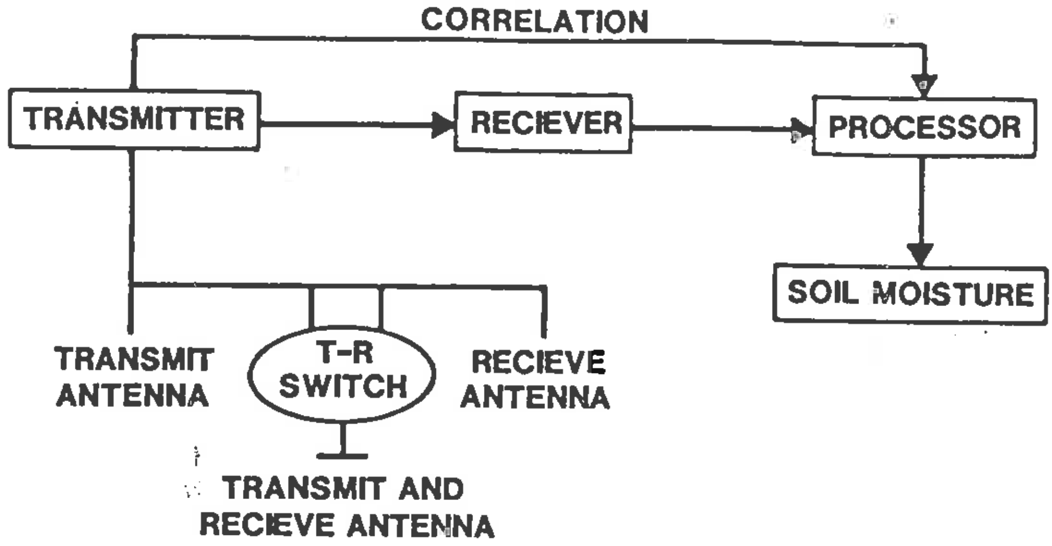

FIG. 7. THE BASIC ELEMENTS OF A RODAR SYSTEM

(AFTER VLABY ET. AL. 1981)

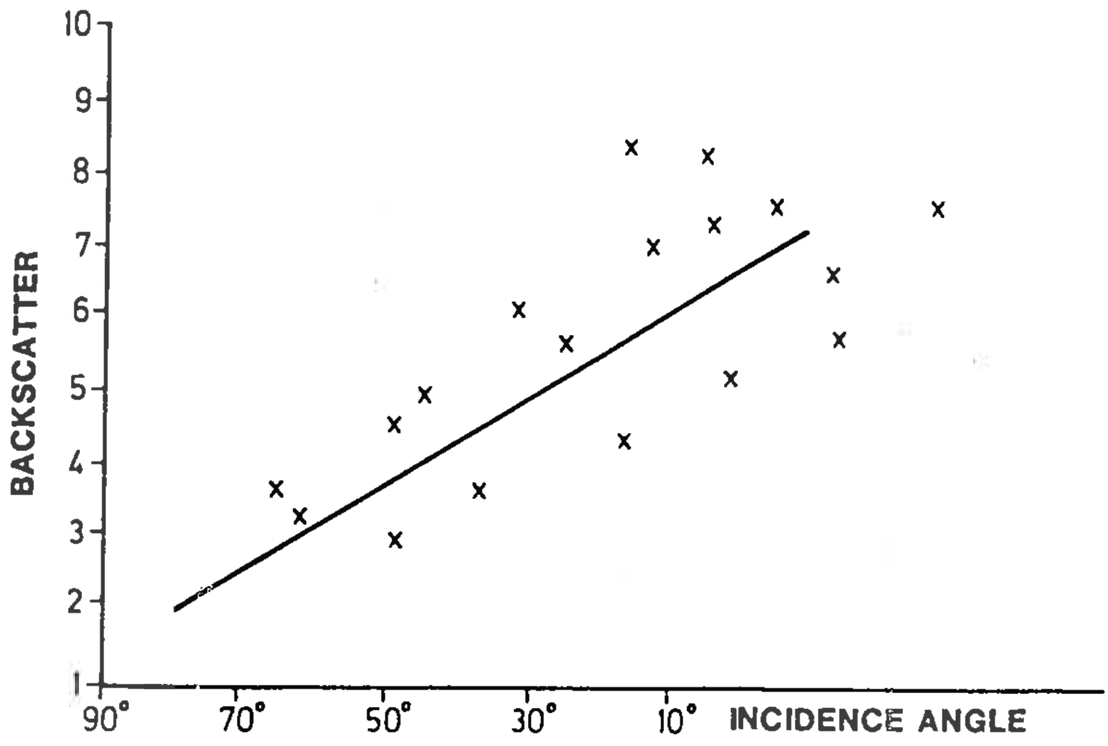

FIG. 8. CORRELATION BETWEEN BACKSCATTER SIGNAL AND INCIDENCE ANGLE

(AFTER MEIER, 1981)

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