Microwave Dielectric Properties of Soil and Vegetation and Their Estimation from Spaceborne Radar

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Abstract - This paper is largely tutorial in nature and provides an overview of the microwave dielectric properties of certain natural terrestrial media (soils and vegetation) and recent results in estimating these properties remotely from airborne and orbital synthetic aperture radar (SAR). Sections present (1) instrumentation for laboratory and *in situ* measurement of the relative dielectric constant, (2) a synopsis of laboratory measurements, (3) examples of *in situ* measurements, (4) the relationship between dielectric properties and radar backscatter, and (5) a summary of recent progress in estimation of surface dielectric properties from SAR observations.

1.0 Introduction

The dielectric resonance of both pure and saline water lies in the microwave portion of the spectrum, and the relative dielectric constant of liquid water can be 1 to 2 orders of magnitude greater than anhydrous terrestrial media. Hence, the microwave dielectric constant is very sensitive to water content and can be highly diagnostic of other system attributes. There are secondary dependencies of the dielectric constant on dry density, chemical composition and the temperature of tile. medium.

Because of the near-transpartincy of the atmosphere, the. potentials of active. radars (scatterometers and imagers) and passive radiometers have been (and continue to be) explored for earth observation. The emission and scattering behaviors of a medium are controlled by Iwo sets of factors: (1) the geometrical properties describing boundary conditions and (2) dielectric properties. Most theoretical developments have concerned description of the, forward problem, that is solving for scattering and emission as functions of media properties, whereas the inverse problem is of greatest interest to the application of remote sensing techniques and has received less attention to date. The key in the inverse problem is often to decouple the geometric (structural) effects of the medium from the dielectric effects cm the measured signal.

2.0 Instrumentation for Dielectric Measurements

Several methods may be used to measure dielectric properties of natural media and include transmission, reflection, and resonance techniques. The development of automatic network analyzers and sweep frequency measurement techniques has lead to the development of faster measurement techniques. Emphasis is place.d on techniques specifically suitable for vegetation and soil media. Most transmission techniques utilize either a wave.guide or a free-space system. The amplitude and phase of the transmission coefficient through a substance of unknown dielectric constant is measured and an iterative procedure is used to express the unknown dielectric constant in terms of the propagation constant of the dielectric filled sample holder. Full details of the procedure are given in [1].

Reflection techniques utilize slotted line or coaxial probe systems. These methods measure the magnitude and phase of the reflection coefficient at the end of a transmission line and relate it to the dielectric constant of the medium placed at the end of the transmission line. Broadhurst [2] utilized a slotted line system in which he measured dielectric constant by relating it to the admittance of a coaxial transmission line with the material specimen occupying some of the space between the coaxial conductors. The measurement of the admittance of a coaxial line is equivalent [o the measurement of reflection coefficient at the same plane of reference Open-ended coaxial lines have been used successfully by many researchers [3-5]. This approach applies a standard reflection coefficient measurement system with the probe tip in contact with the dielectric sample acting as the termination load.

Resonant cavities may also be applied to measure dielectric constant in (he. filled-cavity approach, the dielectric constant of a material is determined by the shift in the resonant frequency and the quality factor of a resonant cavity [6]. Although theoretically (his technique is straightforward 10 apply. from a practical standpoint it may be very difficult to completely fill the resonant cavity with the solid dielectric material (e.g. Vegetation) without some air pockets remaining. This complicates the inference of the dielectric constant of the material.

The par[ially-filled cavity technique, also known as the perturbation technique, makes use of small changes in the cavity's resonant frequency attainable by proper selection of the sample size. The derivation is based on the assumption that either the sample size or its dielectric constant is small enough that the field structure inside the cavity is not substantially changed by inst.) tion of the sample. The shape of the sample is also an important factor in determining the appropiate formula to be used. Spheres, discs, and needles are the most commonly used shapes.

Various techniques have been applied for *in situ* characterization of the dielectric properties of vegetation canopies. For measurement of vegetation dielectric constant, the waveguide and filled cavity techniques are not suitable because it is not possible to avoid air gaps between the vegetation sample and the measurement assembly. Also, it is impossible to achieve the smooth surface required of the sample for free-space. system measurements. Slotted line and partially filled cavity measurements always suffer from inaccuracies in thickness measurements of the sample. Soil and vegetation dielectric properties are typically monitored using time domain reflectometry or coaxial probe systems..

A field portable dielectric probe (PDP) has been developed and marketed by Applied Microwave corporation [7] and has proven very useful in many remote sensing studies in which microwave dielectric properties of vegetation and soil must be characterized. The PDP has proven useful in characterizing dielectric properties in a number of studies [8-10] However it is an inefficient instrument for purposes of studies involving, more intense analyses of the temporal response of physiologic and dielectric properties of vegetation. Consequently, a design effort was undertaken in order to facilitate the measurement scheme necessary to carry out experiments that involve continuous long-term monitoring of canopy dielectric properties [1]]. The dielectric monitoring system developed for this application incorporates [hr. PDP unit with a switching network and data logger assembly that permits autonomous monitoring of dielectric constant in a near-continuous fashion.

3.0 Laboratory Measurements of Dielectric Constant

The average dielectric properties of the soil medium depend upon bulk soil characteristics, such as moisture, density, par(icle-size distribution, mineralogy and fluid chemistry. Soil is commonly considered to be a four component system consisting of soil solids, air and water in turn consisting of 'bulk' and 'bound' phases.

A number of studies [12,13] have reported on the dielectric properties of rocks mostly as functions of composition (mineralogy) and bulk density (i.e, the mass to volume ratio of powdered specimens). A reflection technique using an open-end coaxial probe was used to measure the relative. permittivity of 80 terrestrial rock samples over the range from 0.5 - 18 Ghz [13]. The dielectric ioss factor of these same rocks was measured using resonant cavity techniques at five frequencies from 1.6 - 16 GHz. The real part of the permittivity was found to be independent of frequency. The effects of the specific density of rock were found to account for approximately 50% of the variance. between rock samples using a geometric mean fromulation. An additional 28% of the variance was found to be related to differences in bulk chemical composition of the samples that are related to mineralogy. The loss tangent was always small and found todccl-case. with frcqucncyandval) by mineral class: carbonate or silicate (subdivided into volcanic, plutonic and sedimentary) and also the bulk chemical composition . Dielectric loss was found to be poorly correlated with rock density.

The microwave dielectric properties of bulk soils were examined in the laboratory by a number of investigators in the 1970s [14, 15]. Theoretical dielectric mixing formulations treating a two-component system of soil and water could not account for all of the observed effects. As a consequence, relatively simple empirical models were developed relating the dielectric behavior to readily measured bulk soil physical properties such as density and particle size distribution [1, 17-19]. In addition, more complex semi-empirical and theoretical mixing models incorporating up to four-components (soil, air, bulk water and bound water) were developed [19]. These provide better agreement with observations but are more complicated and can require knowledge of additional soil properties such as cation exchange capacity, salinity and specific surface. These studies show that the soil dielectric properties are primarily controlled by moisture content, bulk density, texture and clay mineralogy. No studies have reported on the effects of the organic content of soils.

Similar laboratory studies have performed on the dielectric properties of vegetation as functions of density, moisture content and temperature and used to generate fairly simple expressions to estimate vegetation dielectric properties from 1 .18 GHz via a dual-dispersion model that uses a sucrose solution to model the behavior of 'bound' plant fluids [20]. The model has been found to work well for many plant materials and the results compare favorably to *in situ* observations.

4.0 *In situ* Measurement of Dielectric Constant

In situ measurements of dielectric properties have been made as a component of a number of recent remote sensing investigations. The EOS Synergism Study examined the temporal variability of the optical reflectance and microwave backscatter caused by diurnal change in canopy properties of interest to ecosystem modelers [21]. The experiment was designed specifically to address diurnal changes in canopy water status, including water potential and vegetation water content, that relate to canopy transpiration. As part of the synergism study, an L-band (1.2 GHz) field portable dielectric probe. was used to obtain measurements of the dielectric constant of the vegetation and soil. Diurnal observations were made of the soil surface, the main tree stems, the bark and the higher order green stems. The most dramatic diurnal changes in dielectric constant were found in the main stems and the soil surface. The diurnal behavior observed in the dielectric of the soil surface is explained by irrigation and subsequent drying processes. To quantify behavior of the vegetation dielectric constant, a single tree was instrumented to monitor the time dependence of ε in the main stem (trunk) at several selected heights. Probe tip depth increments were selected to obtain a depth profile at depths of 1 cm, 2 cm, 4 cm, and 7.5 cm for a 15 cm diameter trunk.

The time dependence of ε_r was found to be greatest at the 2 cm depth (nominally in the hydroactive xylem tissue) and to vary by an order of magnitude over a 24 hour period. There was little diurnal variation observed in the bark and the diurnal variation decreased with increasing depth into the main stem. The drop in the trunk dielectric constant in the afternoon occurs coincidentally with the drop (to greater negative values) in xylem water potential. Following that, the rise in dielectric constant in the late afternoon and evening nearly coincides with the rise in water potential.

In March 1988, a campaign was carried out at the Bonanza Creek Experimental Forest (BCEF) near Fairbanks, Alaska, in order to examine the seasonal transitions in boreal forest with synthetic aperture radar (SAR) **[10]**. As part of that campaign, a PDP was used to measure L-band dielectric properties in white spruce, black spruce and balsam poplar trees. Data were collected as a function of depth into the tree trunks on two dates with air temperatures of 2°C and -14°C. The freezing of the liquid water within the trunks caused the dielectric constant of the trunks to drop from 35 to below 5 for the species measured.

To develop a better understanding of the relationship between vegetation dielectric constant and vegetation physiologic activity, a number of field exercises have been performed using the single and multi-channel dielectric monitoring systems in concert with xylem sap flux and microclimate sensors that allow for characterization of the. hydraulic response of the vegetation. During 1994, several stands at the Boreal Ecosystem-Atmosphere Study (BOREAS) in Canada were instrumented with this equipment throughout much of the growing season [22, 23]. Mean xylem dielectric constant showed a decrease with higher vapor pressure deficit and sap flux density but the trend was not significant. Individual trees varied widely in trend and diurnal amplitude of xylem dielectric constant changes. Similar **results were observed** in previous studies in Alaska [24].

5.0 Radar Backscatter Response to Dielectric Constant

Results of field measurements carried out with dielectric and hydrologic monitoring equipment have shown that a link exists between canopy water status and dielectric constant. Thus, since dielectric constant is sensitive to changes in the canopy water status, and since radar is sensitive to dielectric constant, then it should be possible to couple radar backscatter to canopy water status *via* the dielectric constant. This would greatly improve our ability to estimate canopy carbon, water and energy budgets using remote sensing techniques.

A three. day series of scatterometer observations of a walnut orchard was obtained during the August 1987 EOS Synergism Study [9]. As part of the analysis of those measurements, the vegetation dielectric constant measurements and corresponding soil and branch dielectric measurements were used as input to the MIMICS radiative transfer model [25]. The model successfully predicts the level of the measured backscatter along with the decreasing trend in backscatter observed over the three day period. Furthermore, MIMICS predicts the 1-2 dB dip seen in σ^ovv anri σ^ohv in the early afternoon each day.

5.0 Retrieval of Dielectric Constant from Backscatter Measurements

Recently, a constellation of earth-orbiting synthetic aperture radars has been put into place (i.e., ERS- *1/2*, JERS- 1 and Radarsat), and research interest has begun to focus on the inverse problem and the development and demonstration of applications. One such area of application is the estimation of soil moisture via its dependence on **the.** dielectric properties of soil. The critical part is to deconvolve the effects of geometric attributes (the soil surface roughness) and the effects of any overlying vegetation from the dielectric effects. All of these SAR systems are single polarization and frequency systems, so multiple channels of information arc. not available to estimate these three. sets of parameters. However, on the basis of single frequency polarimetric data, an empirical approach was developed to estimate both moisture (via the dielectric) and roughness by using polarization ratios [26] for bare soil (non-vegtetated conditions. This approach was modified to usc only hh and vv polarizations and applied to airborne polarimetric SAR data and SIR-C data obtained at L-band over a watershed in Oklahoma [27]. in applying the inversion algorithm in the image domain for a time series of data, the results show the spatial pattern of the dry-down sequence over a large area after saturating rains. The technique did not work very well for vegetated conditions. A diffc.rent inversion algorithm that also uses polarization ratios at I.-band (hh and vv) was dcvc.lope.d using empirical coefficients applied to a simplified first order solution to the integral equation method [28]; this algorithm solves for dielectric constant and two roughness parameters. his approach has aiso been tested using the same data from Oklahoma. The strengths and weaknesses of the two approaches are compared by Wang [29]. All approaches solve for dielectric constant and then infer soil moisture using an empirical model along with some assumptions about properties. At present, there arc no algorithms that opperate well for soils cove.rcct with vegetation (other than short grass).

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