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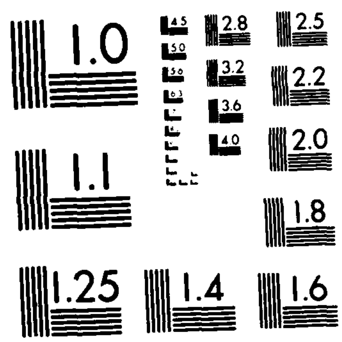

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The purpose of this research is to determine the microwave dielectric behavior of soil through: (a) experimental measurements and (b) the development of theoretical models. To this end, dielectric measurements were made using waveguide and free-space transmission systems over the 1-2 GHz and the 4-18 GHz bands over a wide range of moisture for several soil types. The measured data were then used to (a) test existing theoretical models, (b) develop a new physical soil model, and (c) develop semi-empirical models.

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MICROWAVE DIELECTRIC CONSTANT DEPENDENCE ON SOIL TENSION

Fawwaz T. Ulaby

Final Report TR 545-5

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TABLE OF CONTENTS

1.0 INTRODUCTION

This report covers the research activities performed in support of Grant No. DAAG29-81-0142, covering the period between 8-12-81 to 8-11-83. The purpose of the research is to determine the microwave dielectric behavior of soil through: (a) experimental measurements and (b) the development of theoretical models. To this end, dielectric measurements were made using waveguide and free-space transmission systems over the 1-2 GHz and the 4-18 GHz bands over a wide range of moisture for several soil types. The measured data were then used to (a) test existing theoretical models, (b) develop a new physical soil model, and (c) develop semi-empirical models.

2.0 SUMMARY OF RESULTS

The following results were realized:

(1) The complex dielectric constant was measured for the following conditions:
   - (a) five soil types extending from sandy loam to silty clay,
   - (b) 1-2 GHz and 4-18 GHz,
   - (c) soil moisture range extending from oven dry to saturation,
   - (d) physical temperature extending from -30°C to +23°C.

(2) The dependence of the dielectric constant was evaluated for the following parameters:
   - (a) frequency,
   - (b) textural composition,
   - (c) bulk density,
   - (d) volumetric moisture content,
   - (e) soil salinity, and
   - (f) temperature.

(3) A detailed physical soils model was combined with a dielectric mixing model to model the dielectric behavior as a function of the six variables listed in (2).

(4) A semi-empirical model was developed defining the complex dielectric constant of soil in terms of: (a) frequency, (b) sand fraction, (c) clay fraction, (d) temperature, (e) bulk density, and (d) soil moisture content.

3.0 LIST OF PUBLICATIONS

1. "Microwave Dielectric Behavior of Wet Soil, Part I: Experimental Observations at 1.4 and 5 GHz," (Ulaby, Wu, Hallikainen, and Dobson), accepted for publication in IEEE Trans. on Geoscience and Remote Sensing. (Also RSL TR 545-1)

2. "Microwave Dielectric Behavior of Wet Soil Part II: Four-Component Dielectric Mixing Model," (Dobson, Ulaby, El-Rayes, and Hallikainen), accepted for publication in IEEE Trans. on Geoscience and Remote Sensing. (Also RSL TR 545-2)

3. "Dielectric Measurements of Soils in the 1.4-18 GHz Frequency Range," (Ulaby, Hallikainen, Wu, Dobson, and El-Rayes), National Radio Science Meeting (URSI Commission F), University of Colorado, Boulder, Colorado, January 5-7, 1983.

4. "Dielectric Behavior of Wet Soils Between 1.4 GHz and 18 GHz," (Hallikainen, Ulaby, Wu, Dobson, and El-Rayes), IEEE International Geoscience and Remote Sensing Symposium (IGARSS '83) San Francisco, California, August 31 - September 2, 1983.

5. "A Reexamination of Soil Textural Effects on Microwave Emission and Backscattering," (Dobson, Kouyate, and Ulaby), IEEE International Geoscience and Remote Sensing Symposium (IGARSS '83) San Francisco, California, August 31 - September 2, 1983.

6. "A Free-Space System for Dielectric Measurements in the 3-18 GHz Frequency Range," (Hallikainen and Ulaby), RSL TR 545-3, University of Kansas Center for Research, Inc., March 1983.

7. "Dielectric Behavior of Soils and Snow at Microwave Frequencies," (Hallikainen, Ulaby, Abdelrazik, Wu, Dobson, and El-Rayes), Proc. XI National Convention on Radio Science, Otaniemi, Finland, October 19-20, 1983.

4.0 PERSONNEL SUPPORTED

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5.0 ABSTRACTS OF PUBLICATIONS

(See Attached)

(Accepted for publication in IEEE Trans. on Geoscience and Remote Sensing)

MICROWAVE DIELECTRIC BEHAVIOR OF WET SOIL,

PART I: EXPERIMENTAL OBSERVATIONS AT 1.4 AND 5 GHz

F. T. Ulaby, L. Wu, M. Hallikainen, and M. C. Dobson

ABSTRACT

This is the first paper in a three-part sequence that evaluates the microwave dielectric behavior of soil-water mixtures as a function of water content and soil textural composition. Part I presents the results of dielectric constant measurements conducted for five different soil types at 1.4 GHz and for seven different soil types at 5.0 GHz. At each frequency, a polynominal was generated for the real part of the relative dielectric constant ε' as a function of the volumetric moisture content m_v and the percent sand and clay contents of the soil. A similar polynominal also was generated for the imaginary part ε''. In Part II, a dielectric model is developed on the basis of a physical soils model and evaluated against the measured 1.4 and 5 GHz data. Part III examines the dielectric behavior in the 4-18 GHz region.

(Accepted for publication in IEEE Trans. on Geoscience and Remote Sensing)

MICROWAVE DIELECTRIC BEHAVIOR OF WET SOIL
PART II: FOUR-COMPONENT DIELECTRIC MIXING MODEL

by M. C. Dobson, F. T. Ulaby, M. El-Rayes, and M. Hallikainen
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ABSTRACT

This paper is the second in a series that evaluates the microwave dielectric behavior of soil-water mixtures as a function of water content and soil textural composition. Part II develops a dielectric mixing model that accounts explicitly for the presence of a hydration layer of bound water adjacent to hydrophilic soil particle surfaces. The soil solution is differentiated into (1) a bound, ice-like component and (2) a bulk solution component, by a physical soil model dependent upon either soil particle size distribution or soil specific surface area. The four-component dielectric mixing model treats the soil-water system as a host medium consisting of dry soil solids with randomly distributed and oriented disc-shaped inclusions of bound water, bulk water, and air; it also treats the bulk-water component as being temperature- and salinity-dependent. The performance of the dielectric mixing model is evaluated as a function of soil moisture and texture using dielectric measurements of five soils ranging from sandy loam to silty clay (as described in Part I) at frequencies of 1.4 GHz and 5.0 GHz.

As a first-order approximation, the mixing model accurately predicts the measured dielectric response at both frequencies by either of two approaches, neither of which requires adjustable parameters. Both approaches incorporate the Stern/Gouy double-layer theory to calculate the effective conductive loss of the bulk-water component from

the soil's cation exchange capacity, specific surface, and salinity, and both also assume the bound water to be only a single monolayer thick (3Å) with ice-like dielectric properties ε_{WS} = (3.15, j0). The first approach apportions the soil solution into bound- and bulk-water volume fractions based upon a pore distribution model dependent upon measured soil particle size distribution, while the second approach accomplishes the same objective via a plate model which assumes that the clay mineral fraction dominates soil behavior and requires measurement of a soil's specific surface. Although the models account for most of the observed soil textural effects on dielectric constant at frequencies of 1.4 GHz and 5.0 GHz, not all of the frequency effects are satisfactorily explained. It is concluded that the bound-water layer may be thicker than 3Å and that the bound water may be more accurately described as a dielectric characterized by a distinctive relaxation near 1 GHz.

(National Radio Science Meeting (URSI Commission F) University of Colorado, Boulder, CO)

DIELECTRIC MEASUREMENTS OF SOILS IN THE 1.4 - 18 GHz FREQUENCY RANGE

F. T. Ulaby, M. Hallikainen, L. Wu, C. Dobson, M. El-Rayes, Remote Sensing Laboratory, University of Kansas Center for Research, Inc., Lawrence, Kansas 66045

An experimental program has been started to determine the dielectric behavior of soil-water mixtures in the microwave region. The experimental data will be used to develop a dielectric soil model, based on the physical characteristics of soils. Measurements at room temperature have been conducted between 1.4 GHz and 18 GHz on several soil types as a function of water content. In addition, preliminary measurements of frozen soils have been made in the 3-18 GHz region. This paper will present the experimental results and conclusions from the data.

A waveguide transmission method was employed at 1.4 GHz and in the 4-6 GHz range. Five different soil types, ranging from sandy loam to silty clay, were measured in both frequency ranges. In the 4-6 GHz region, two additional silt loam soils were measured. All measurements were conducted at room temperature as a function of water content. Polynomial expressions were generated for ε' and ε'' at 1.4 GHz and 5 GHz. The expressions depend on the water content and the fractions of sand and clay components of a soil in percent by weight. The linear correlation coefficients between the polynomial expressions and the experimental data are better than 0.99 for both ε' and ε''.

A free-space transmission system was constructed to cover the 3-18 GHz range. The system was tested against the waveguide method at 6 GHz, and the results were found to be in excellent agreement for both ε' and ε''. In the 3-18 GHz range, the same five soils, mentioned above were measured. In addition, pure sand, pure silt and silt with 10% of montmorillonite (clay) by weight, were measured. Preliminary measurements of frozen soils were made at temperatures between -10° C and -25° C. Polynomial expressions for ε' and ε'' up to 18 GHz are under development.

(IEEE International Geoscience
and Remote Sensing Symposium
IGARSS'83, San Francisco, CA)

DIELECTRIC BEHAVIOR OF WET SOILS BETWEEN 1.4 GHz AND 18 GHz

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and M. El-Rayes
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ABSTRACT

Dielectric measurements were conducted at room temperature for several soil types at 11 frequencies extending between 1.4 GHz and 18 GHz. Additionally, measurements were made for frozen soils over the 3 - 18 GHz range. The data were used to generate empirical expressions relating the real and imaginary parts of the soil dielectric constant to the volumetric moisture contents and to the sand and clay components of the soil. Additionally, the data were used to develop a four-component dielectric mixing model (air, soil particles, bound water, and free water) that incorporates the effects of soil salinity and particle size distribution.

(IEEE International Geoscience and Remote Sensing Symposium (IGARSS'83) San Francisco, CA)

A REEXAMINATION OF SOIL TEXTURAL EFFECTS ON MICROWAVE EMISSION AND BACKSCATTERING

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ABSTRACT

Measurements of the dielectric properties of moist soils at microwave frequencies made recently by the University of Kansas have brought into question the validity of percent of field capacity as an independent soil-moisture indicator. It was previously thought that this term was independent of soil textural effects with regard to microwave emission and backscattering; however, the dielectric data strongly suggest that earlier conclusions based upon measurements with both radar scatterometers and microwave radiometers are the spurious result of a relationship between soil bulk density and water retention at field capacity.

In this research, candidate soil moisture indicators (gravimetric, volumetric, and percent of field capacity) were tested for their capacity to reduce the divergence in dielectric behavior between soil textures at frequencies of 1.4 and 5.0 GHz. The most congruent dielectric behavior between soil textures is found to occur when soil moisture is expressed on a volumetric basis (which is proportional to the number of water dipoles per unit volume). In contrast to expectations from earlier field investigations, the use of percent of field capacity was shown to overcompensate for dielectric differences between soils, and can actually increase divergence.

This study shows that an inadequate characterization of soil bulk density in the field combined with a dependence of bulk density on water retention at field capacity (as controlled by soil structure) provides the most probable explanation for the earlier, misleading conclusions. It is recommended that increased attention be given to accurate mensuration of bulk density in future field experimentation, especially for soils high in clay content where near-surface bulk density is not independent of moisture content.

(Remote Sensing Laboratory Technical Report 545-3)

A FREE-SPACE SYSTEM FOR DIELECTRIC MEASUREMENTS IN THE 3-18 GHz FREQUENCY RANGE

by

Martti Hallikainen and Fawwaz T. Ulaby

ABSTRACT

A free-space system is designed to make wideband dielectric measurements of soils. Special attention is paid to minimizing the sample size, eliminating the nonlinearities of the system, and obtaining a reasonable accuracy over the 3-18 GHz frequency range. Frozen soil samples can be measured at room temperature by using sample holders made of a thermally insulating material. The results of numerous test measurements are included in the report.

U.R.S.I. XI Radiotieteen päivät 1983

DIELECTRIC BEHAVIOR OF SOILS AND SNOW AT MICROWAVE FREQUENCIES

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Abstract

Dielectric measurements were conducted for soil samples at eleven frequencies extending from 1.4 GHz to 18 GHz, and for snow samples at eight frequencies between 4 GHz and 18 GHz. The soil measurements were made at room temperature for moisture contents extending from oven-dry to saturated. The liquid water content of snow samples varied from 0 % to 13 % by volume. The two data sets were used to develop and/or evaluate several empirical and theoretical mixing models.

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