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SCIENCE DIRECT®
Remote Sensing of Environment 96 (2005) 119–134
Remote Sensing of Environment
www.elsevier.com/locate/rse

Ground-penetrating radar measurement of crop and surface water content dynamics

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Received 29 February 2004; received in revised form 4 November 2004; accepted 9 January 2005

Abstract

Ground-penetrating radar (GPR) with a suspended 1 GHz horn antenna was deployed for measurement of soil water contents and crop canopy properties over bare and electrically terminating surfaces. Surface reflection (SR) and signal propagation times (PT) were used to independently determine dielectric permittivity and water content of soil and canopy. Measured surface reflection coefficients progressively decreased with increasing canopy biomass according to Beer-Lambert type relationships. In contrast, PT measurements remained unaffected by canopy, and hence provided an accurate account of soil water content dynamics. Immediately after canopy removal, SR-based soil water content measurements were in close agreement with PT values. Canopy dielectric properties were inferred from canopy water contents ($\varepsilon_{c\text{-}CWC}$) and canopy propagation times ($\varepsilon_{c\text{-}CPT}$). Distinct canopy reflections were correlated with key canopy biophysical parameters. The study demonstrates the usefulness of a horn antenna GPR for characterization of vegetation canopy scattering, and for subcanopy water content measurements within a well-defined footprint, thereby offering a potential for calibration and verification of radar data collected from air- and spaceborne platforms.

Keywords: Ground penetrating radar; Vegetation canopy scattering; Soil water content measurement

1. Introduction

Remote measurement of soil water content and plant cover is becoming a key component for accurate climate modeling, flood prediction, large-scale water balance, land use, and agricultural management. Vegetation cover of large tracts of the Earth's surface presents a challenge to interpretation of radar-based soil water content determination (Ulaby et al., 1996). Numerous studies of crop canopies and sub-canopy water content by radar remote sensing have employed frequency domain measurement via synthetic aperture radar (SAR) and scatterometer at a variety of frequencies, polarizations and incidence angles (Attema & Ulaby, 1978; Brown et al., 2003; Dobson & Ulaby, 1986a,b; Du et al., 2000; Inoue et al., 2002; Moran et al., 1998; Paloscia, 2002; Stiles & Sarabandi, 2000; Stiles et al., 2000; Toure et al., 1994; Ulaby, 1975; Ulaby et al., 1975, 1996, 1990; Wigneron et al., 1999).

Many of these studies utilized frequency domain radar signatures which combined vegetation canopy, soil surface, and subsurface contributions into single values, and relied on modeling for separation of these frequency- and polarization-dependent contributions. A notable exception is a recent study by Brown et al. (2003) that used a ground-based SAR system at C- and X-bands to image wheat canopies in the laboratory and the field at a variety of incidence angles. A cursory review of published results shows that higher frequency measurements are more influenced by vegetation cover and are less sensitive to subsurface conditions than those at lower frequencies. Present models of vegetation scattering tend to be either very simplistic, treating the canopy as if it were a uniform cloud of water droplets (Attema & Ulaby, 1978; Dobson &

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doi:10.1016/j.rse.2005.01.018

Ulaby, 1986b), or employ complicated radiative transfer or phase-coherent models (Ferrazzoli & Guerriero, 1994; Karam et al., 1992; Macelloni et al., 2001; Marliani et al., 2002; Stiles & Sarabandi, 2000; Ulaby et al., 1996) which require numerous biophysical and soil parameters, hence limiting their applicability for routine use.

Multi-frequency and polarization measurements utilizing AIRSAR, SIR-C, EMISAR, and other radar sensors have provided for a wealth of information from campaigns over agricultural sites, showing that radar backscatter from vegetation canopies are functions of canopy phenology, type, and radar frequency and polarization (Basili et al., 1994; Brown et al., 2003; De Matthaeis et al., 1994; Dobson & Ulaby, 1986a; Du et al., 2000; Ferrazzoli & Guerriero, 1994; Ferrazzoli et al., 1997; Inoue et al., 2002; Lee et al., 2001; Lemoine et al., 1994; Moran et al., 1998; Paloscia, 2002; Skriver et al., 1999; Ulaby et al., 1996). Defoliation measurements of corn canopy at 5.1 GHz and varying incidence angles by Dobson and Ulaby (1986a) show that beneath $\theta = 15°$, radar was insensitive to canopy, but above this backscatter was dominated by vertical components such as stalks and cobs, with losses being attributed to leaves. Since lower frequency measurements such as P-band at ~0.4 GHz have greater penetration into vegetation than those at L-band (~1.24 GHz) or C-band (5.3 GHz), different frequencies are influenced by different parts of the canopy (Macelloni et al., 2001; Paloscia, 2002). Radar studies of rice paddies by Inoue et al. (2002) show that different frequencies and polarizations were sensitive to different canopy and crop parameters, with higher frequency measurements sensitive to grain yield and seed head weights, while C-band was more sensitive to *LAI* and total fresh biomass in the L-band. Paloscia (2002) and Macelloni et al. (2001) showed that at different frequencies different types of crops had different responses, with both narrow-leaved (wheat, colza, and alfalfa) and broad-leaved plants (corn, sorghum, and sunflower), showing opposite responses at C-band, almost no sensitivity to narrow-leaved biomass at L-band, as opposed to broad-leaved species, which show increases in backscatter with biomass, and at P-band, where biomass shows weak effects on radar backscatter from all crop canopy types. The studies showed that radar backscatter values decreased with increase in biomass for narrow-leaved crops, but had increases with biomass for broad-leaved plants. Radar leaf area index (LAI) estimates by Paloscia (2002) also show that beneath a minimal LAI value, radar is insensitive to canopy until that threshold is crossed. Brown et al. (2003) used a ground based SAR system to profile the wheat canopy structure. This study determined that wheat canopy backscatter was caused by two or three layers within the canopy, with greater influence of canopy on higher frequency X-band than on C-band.

Ground-penetrating radar (GPR) has been employed in recent years for measurement of subsurface and surface water contents, and measurements from vegetation canopy (Chanzy et al., 1996; Huisman et al., 2001; Lambot et al., 2004a,b; Serbin & Or, 2003, 2004). Serbin and Or (2003, 2004) demonstrated that GPR equipped with a suspended horn antenna provided continuous record of soil water content, using both surface reflection magnitude (SR) and propagation time (PT) measurements over a well-defined measurement footprint. They further showed that SR measurements were influenced by canopy biomass.

The objectives of this research were (1) to quantify effects of vegetation canopy on subcanopy water content measurements using simple, easily measured parameters, and (2) to observe dynamics and characteristics of plant canopy development using GPR with a suspended horn antenna. Radar estimated and physically measured canopy parameters will then be used to compare modeled and measured radar measurements. Lastly, we will describe how this method can be used for future studies of canopy and subcanopy measurements.

2. Theoretical considerations

2.1. Soil dielectric properties

The dielectric properties of soils in the microwave region are functions of volumetric water content (Or & Wraith, 1999), measurement frequency f (Debye, 1929; Hasted, 1973), mineralogy (von Hippel, 1954), particle size, shape and orientation to the imposed EM field (Jones & Friedman, 1999) surface area, bulk density, temperature, and salt content. The dielectric permittivities of soil solid and gaseous phases are assumed to remain constant with frequency for the entire microwave region.

Under natural conditions, the most dynamic factor in soils is water content, which greatly influences dielectric permittivity due to the large disparity between dielectric permittivity (ε_r) of water ($\varepsilon_r = 81$) and soil minerals ($\varepsilon_r = 3 \sim 8$). Soil water may be decomposed into free and bound water, where bound water refers to the first few molecular water layers near solid surfaces that are rotationally hindered by surface forces (Bockris et al., 1966). The dielectric permittivity of bound water is typically in the range of 6–30 for the first and second molecular layers, respectively, and is temperature dependent (Bockris et al., 1966; Dobson et al., 1985; Jones & Or, 2002; Or & Wraith, 1999; Serbin, 2001; Serbin & Or, 2003, 2004).

Several models are available for relating measured bulk dielectric permittivity to water content, amongst them the relationships of Topp et al. (1980) for mineral soils, and those of Schaap et al. (1997) and da Silva et al. (1998) for organic soils.

2.2. Reflection and transmission of electromagnetic radiation at dielectric boundaries

At an interface between two media of differing dielectric and magnetic properties, an incident EM wave may be