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Influence of incidence angle on detecting flooded forests using C-HH synthetic aperture radar data

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ABSTRACT

Hydrology is the single most important abiotic factor in the formation and functioning of a wetland. Many limitations still exist to accurately characterizing wetland hydrology over large spatial extents, especially in forested wetlands. Imaging radar has emerged as a viable tool for wetland flood mapping, although the limitations of radar data remain uncertain. The influence of incidence angle on the ability to detect flooding in different forest types was examined using C-HH Radarsat-1 data (23.5°, 27.5°, 33.5°, 39.0°, 43.5°, and 47.0°) during the leaf-off and leaf-on seasons. The ability to detect flooding under leaf-on conditions varied much more according to incidence angle while forest type (open canopy tupelo-cypress, tupelo-cypress, and bottomland hardwood) had a greater effect during the leaf-off season. When all forest types were considered together, backscatter generally decreased with increasing incidence angle under all conditions (2.45 dB between 23.5° and 47.0° flooded, leaf-off; 2.28 dB between 23.5° and 47.0° not flooded, leaf-off; 0.62 between 23.5° and 43.5° flooded, leaf-on; 1.73 dB between 23.5° and 43.5° not flooded, leaf-on; slope was not constant between incidence angles), but the distinction between flooded and non-flooded areas did not decline sharply with incidence angle. Differentiation of flooded and non-flooded forests was similar during the leaf-off and leaf-on seasons. The ability to detect inundation under forest canopies was less than expected at smaller incidence angles and greater than expected at larger incidence angles, based on the results of previous studies. Use of a wider range of incidence angles during the entire year increases the temporal resolution of imagery which may, in turn, enhance mapping of inundation beneath forest canopies.

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1. Introduction

Wetland hydropattern – spatial and temporal variations in inundation and soil saturation – is the primary factor controlling the formation of wetlands and is a major driver of ecosystems processes within wetlands. Small changes in water regime can cause large changes in wetland characteristics and functions (e.g., Mitsch & Gosselink, 2000). Although the importance of hydropattern is widely understood, analysis of inundation patterns across landscapes remains limited by the unavailability of *in situ* data due to the excessive expense needed to collect accurate ground-based information and the difficulty of modeling hydrology in areas of subtle topography (Hess et al., 1990, Townsend & Walsh 1998; Tiner, 1999). Current literature states that the hydrological sciences are limited by a lack of data (Engman, 1996; Conly and Van der Kamp, 2001; Mendoza et al., 2003; Price, 2005), especially long-term data at broad spatial scales. Remote sensing offers the potential to overcome such limitations, but traditional optical remote sensing methods are ineffective during times of the year when the ground is obscured by vegetation.

Imaging radar has emerged as a viable alternative to *in situ* data collection and temporally limited optical data for monitoring inundation in wetland ecosystems (Bourgeau-Chavez et al., 2005; Hess et al., 1990; Hess et al., 1995; Imhoff et al., 1987; Kasischke et al., 2003; Krohn et al., 1983; Ormsby et al., 1985; Townsend & Walsh 1998; Wang et al., 1995). However, the utility of synthetic aperture radar (SAR) data for this purpose has not been fully explored, and important questions remain regarding sensor and environmental conditions that may limit the ability of SAR to detect flooding beneath forest canopies. Specifically, incidence angle (the angle between the radar signal and an imaginary line perpendicular to the Earth's surface) can affect the utility of SAR data for monitoring inundation primarily due to interactions with the intervening canopy. Although the incidence angle effect has been modeled (Enheta & Elachi, 1982; McDonald et al., 1990; Richards et al., 1987; Wang et al., 1995) and some studies have been conducted (Ford & Casey 1988; Töyrä et al., 2001; Kandus et al., 2001), empirical evaluation is still limited. The objective of this paper is to determine the influence of incidence angle on the ability of C-HH SAR data to detect flooding under forest canopies. Radarsat-1 (C-HH) SAR data, collected at different incidence angles under leaf-on and leaf-off conditions, were evaluated

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in a study region where these data have already been used to effectively map flooded forests (Townsend 2001).

2. Background

The potential of SAR data to benefit forested wetland research is substantial because of the sensitivity of microwave energy to the presence or absence of standing water and its ability to penetrate forest canopies, even during the leaf-on period (Hall 1996; Kasischke et al., 1997; Kasischke & Bourgeau-Chavez 1997; Rao et al., 1999). Because the analytical methods for interpretation are relatively new compared to optical remote sensing, research has been ongoing to fully develop the capabilities of imaging radars.

SARs are active sensors, using different wavelengths of microwave radiation and often transmitting and receiving that energy in different planes relative to the direction that the energy is traveling. Although a number of past studies have used L-band (15.0–30.0 cm wavelengths) data to study flooding beneath forest canopies (Hess et al., 1995; Krohn et al., 1983; Place, 1985; Pope et al., 1997; Townsend & Walsh 1998), there was a gap in the availability of L-band satellite data between 1998 (Japan Earth Resources Satellite) and 2006 (Phased Array Type L-band Synthetic Aperture Radar). This led researchers to assess the suitability of C-band (4.0–7.5 cm wavelengths) SAR data for forested wetland hydrology research. As more studies concluded that C-HH data could be used to accurately detect flooding beneath the forest canopy under certain conditions (Costa 2004; Townsend and Walsh 1998; Townsend, 2000), the need to fully define the limitations of these data increased.

Radar energy is typically transmitted at angles incident to the Earth's surface ranging from ~10° to ~65°, where small angles (closer to nadir) are considered steep incidence angles and larger angles are termed shallow. Many studies concluded that smaller incidence angles were preferable for distinguishing flooded from non-flooded forests (Bourgeau-Chavez et al., 2001; Ford & Casey 1988; Hess et al., 1990; Richards et al., 1987; Töyrä et al., 2001; Wang et al., 1995). Others have not shown incidence angle to affect the ability of SAR data to detect flooding beneath vegetation (Imhoff et al., 1986; Ormsby et al., 1985). Hess et al. (1990) concluded that the role of incidence angle in the ability of SAR to detect flooding beneath forest canopies should be further explored.

A simple model can be used to describe the interaction of microwave energy, transmitted by a SAR sensor towards the Earth's surface, with different elements that comprise the scattering surface. Forests are conceptualized as having three layers: The canopy layer, the trunk layer, and the ground layer, where total backscatter coefficient from a forest (σ°) is described as (Kasischke and Bourgeau-Chavez 1997; Townsend 2002; Fig. 1):

$$\sigma^o = \sigma^o_c + \tau^2_c\tau^2_t(\sigma^o_t + \sigma^o_s + \sigma^o_d + \sigma^o_m) \quad (1)$$

where

- σ°_c backscatter coefficient of the crown layer of smaller woody branches and foliage,
- τ_c transmissivity of the crown layer,
- τ_t transmissivity of the trunk layer,
- σ°_t backscatter coefficient of the trunk layer,
- σ°_s backscatter coefficient of the surface layer,
- σ°_d double-bounce between the trunk and the surface layers, and
- σ°_m multi-path scattering between the ground and canopy layers.

Due to the size (usually 5–6 cm) of the microwave wavelength in relation to the size of smaller woody branches and foliage, C-band SAR total backscatter coefficient (σ°) is primarily influenced by scattering caused by the crown layer (σ°_c). However, in flooded forests double-bounce (σ°_d) and multi-path scattering (σ°_m) can have a sizable effect on total backscatter coefficient when the transmissivity of the crown (τ_c) and trunk (τ_t) layers is sufficiently high. In addition to greatly increasing double-bounce (σ°_d) and multi-path scattering (σ°_m), inundation beneath the forest canopy also eliminates surface scattering (σ°_s). Because of large increases in total backscatter coefficient (σ°) caused by inundation, flooded forests often have much higher total backscatter coefficient (σ°) than non-flooded forests. In non-flooded forests, increases in soil moisture raise surface backscatter coefficient (σ°_s) and multi-path scattering (σ°_m). However, the increase in double-bounce (σ°_d) and multi-path scattering (σ°_m) that flooding causes is much higher than the increase caused by higher soil moisture levels (Wang et al., 1995). Increases in canopy foliage leaf area index (LAI) during the warmer months decrease the transmissivity of the crown layer (τ_c), and thus decrease the amount of microwave energy reaching the forest floor. Therefore, an increase in foliage should reduce the ability to detect flooded forests using SAR data. More detailed explanations of microwave scattering from forests are found in Dobson et al. (1995) and Wang et al. (1995).

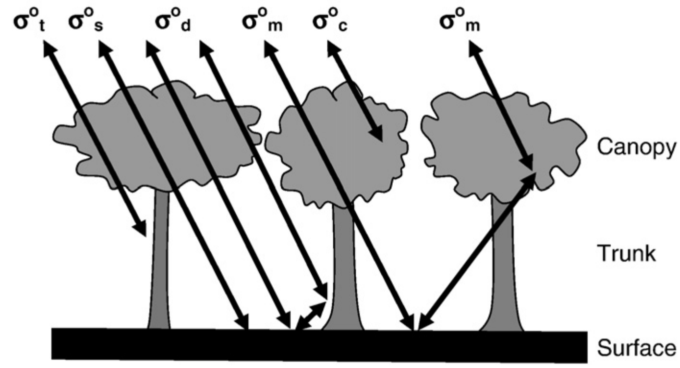

Fig. 1. Conceptual drawing of the major sources of backscatter from forests (σ°_c = backscatter coefficient of the crown layer of smaller woody branches and foliage; τ_c = transmissivity of the crown layer; τ_t = transmissivity of the trunk layer; σ°_t = backscatter coefficient of the trunk layer; σ°_s = backscatter coefficient of the surface layer; σ°_d = double-bounce between the trunk and the surface layers; and σ°_m = multi-path scattering between the ground and canopy layers; adapted from Kasischke & Bourgeau-Chavez, 1997).

The influence of incidence angle on backscatter varies according to forest structure (i.e., basal area, canopy height, canopy depth, and branching qualities) and ground layer characteristics, including surface roughness, soil moisture, and the presence/absence of standing water (Hess et al., 1990; Rauste, 1990). Much like forests are described as having specific spectral signatures using optical remote sensing, forests have distinct angular signatures (backscatter coefficient as a function of incidence angle) when imaged at multiple incidence angles (Rauste, 1990). Microwave energy that is transmitted by SARs operating at larger (shallower) incidence angles interacts more with the canopy, thus decreasing transmissivity in the crown layer (τ_c), but increasing the ability of the radar to estimate canopy characteristics (Kandus et al., 2001; Magagi et al., 2002; Rauste, 1990; Sun & Simonett, 1988). In contrast, microwave energy transmitted at smaller (steeper) incidence angles takes a shorter route through the canopy, increasing transmissivity in the crown layer (τ_c) and leaving more energy to interact with the trunk and ground layers.

Backscatter is expected to vary with incidence angle in flooded and non-flooded forests, under leaf-on and leaf-off conditions. The longer path length at shallow incidence angles generally increases attenuation in the canopy and therefore decreases backscatter coefficient originating from the ground surface (Hess et al., 1990; Kandus et al., 2001; Magagi et al., 2002; Rauste, 1990; Sun & Simonett, 1988). Backscatter from flooded and non-flooded sites should decrease with increasing incidence angle due to lower transmissivity in the crown and trunk layers. It is hypothesized, however, that the decrease will be greater for