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Investigating the correlation between radar backscatter and in situ soil property measurements

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ABSTRACT

Utilizing remote sensing techniques to extract soil properties can facilitate several engineering applications for large-scale monitoring and modeling purposes such as earthen levees monitoring, landslide mapping, and off-road mobility modeling. This study presents results of statistical analyses to investigate potential correlations between multiple polarization radar backscatter and various physical soil properties. The study was conducted on an approximately 3 km long section of earthen levees along the lower Mississippi river as part of the development of remote levee monitoring methods. Polarimetric synthetic aperture radar imagery from UAVSAR was used along with an extensive set of in situ soil properties. The following properties were analyzed from the top 30–50 cm of soil: texture (sand and clay fraction), penetration resistance (sleeve friction and cone tip resistance), saturated hydraulic conductivity, field capacity, permanent wilting point, and porosity. The results showed some correlation between the cross-polarized (HV) radar backscatter coefficients and most of these properties. A few soil properties, like clay fraction, showed similar but weaker correlations with the co-polarized channels (HH and VV). The correlations between the soil properties and radar backscatter were analyzed separately for the river side and land side of the levee. It was found that the magnitude and direction of the correlation for most of the soil properties noticeably differed between the river and the land sides. The findings of this study can be a good starting point for scattering modelers in a pursuit of better models for radar scattering at cross polarizations which would include more diverse set of soil parameters.

1. Introduction

Several monitoring and modeling applications including agriculture, mining, and civil engineering as well as military tactics require knowledge of soil properties over a large area. Earthen levees monitoring, regional landslide modeling and off-road mobility assessment are some example applications. The ability to employ remote sensing techniques to estimate such properties can enable large areas to be surveyed economically. While direct measurements of many soil properties may not be possible solely by remote sensing techniques, knowledge of possible relationships between these soil properties and remote observables could allow estimates of their range to be mapped, and when combined with limited in situ measurements may reduce uncertainty in such maps. Therefore, exploring the relationship between what can be mapped by remote sensing methods and in situ soil properties will be of value.

Past studies relating remote sensing data to in situ soil properties have primarily focused on soil moisture, surface roughness and texture. Ulaby et al. (1978, 1979) investigated the relationships of microwave backscatter and surface roughness, soil moisture, and soil texture for bare soil as well as vegetation covered soil. They also studied the impacts of incidence angle and microwave frequency on such relationships. Bindlish and Barros (2001) incorporated a vegetation parameter into a radar backscatter model for soil moisture estimation. Santanello et al. (2007) estimated surface soil moisture and hydraulic conductivity for troop and vehicle mobility using L and C bands SAR. Thoma et al. (2008) presented a protocol to decide on the appropriate scale at which to retrieve soil moisture from high resolution radar data. Anderson and Croft (2009) extensively reviewed remote sensing methods including active and passive microwave and optical imaging to monitor soil moisture and surface roughness. Zribi et al. (2012) showed that TerraSAR-X backscatter and clay fraction had a linear relationship

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in their study area. Flores et al. (2012, 2014) explored the possibility of soil moisture estimation from L-band radar for military mobility applications. Lowe et al. (2013) used a radar system to identify clandestine graves in various soil property scenarios. Han et al. (2014) used passive microwave simulations to estimate soil moisture, sand and clay fraction, organic density, saturated hydraulic conductivity, and surface energy flux with assimilation models. Liu et al. (2013) and Santanello et al. (2007) used SAR to estimate soil properties, but they both also used ancillary data to estimate soil moisture which then enabled the separation of soil texture effects on backscatter from moisture (and thus dielectric) effects.

Studying the possible relationships among soil properties can enable us to utilize remote sensing methods to indirectly estimate soil properties other than the soil moisture and surface roughness. Clapp and Hornberger (1978) showed that soil moisture characteristics could be modeled reasonably well with soil texture. Elbanna and Witney (1987) modeled cone penetration resistance with clay fraction and soil moisture. Pan et al. (2012) reported that soil moisture was closely related to soil texture, bulk density, and air dried water content. Ayers and Bowen (1987) estimated soil density using cone penetration resistance and soil moisture profile. Vaz et al. (2011) tried to find the best regression model among known models with in situ cone penetration resistance, soil moisture, soil bulk density, and soil texture. Vaz et al. (2013) found that normalized water content and soil bulk density were effective to reduce regression model variation from soil texture and organic matter content.

A motivating question for our investigation was: What can be learned about soil properties from a single SAR image without ancillary data related directly to soil moisture? Put another way: Is there significant correlation between the radar backscatter and soil texture and other properties? Furthermore, the soil properties are measured to depths at which the L-band radar penetration is low to non-existent. Any correlation found would thus rely on the related correlation between the deeper soil and that nearer the surface. Such correlation is expected to be stronger in constructed soil environments where the soils are fairly homogenous.

We have found no studies which have investigated any direct or indirect relationship between radar backscatter data and more extensive sets of soil physical properties such as penetration resistance and hydraulic conductivity. The main objective of this study was to statistically explore possible relationships between radar backscatter and several soil physical properties. Typically, land microwave radar scattering models rely on surface roughness parameters and dielectric constant of soil, which in its turn, is related to the soil texture and soil moisture. This study attempts to go beyond this limited set of parameters and establish a relationship between backscatter and other parameters less known to the radar community but important in the fields of engineering geology, geotechnical engineering, and agricultural engineering, among others. The findings of this study can be used to create or improve models of radar backscatter that could then be potentially used for estimation of more diverse set of soil parameters.

2. Materials and methods

Three polarization channels (i.e., HH, HV and VV) of an airborne Synthetic Aperture Radar (SAR), the NASA JPL's Uninhabited Aerial Vehicle Synthetic Aperture Radar (UAVSAR) (Rosen et al., 2006) and eight in situ soil physical properties were considered in the statistical analyses. The UAVSAR data product used for this study is the projected multi-looked data, having a spatial resolution of 5.5 m. The soil properties which were examined include penetration resistance parameters (sleeve friction q_s and cone tip resistance q_c), clay fraction, sand fraction, saturated hydraulic conductivity (K_{sat}) and porosity (n). Field capacity (f_c), and permanent wilting point (pwp) were measured in terms of volumetric percentage (%v).

2.1. Study area

Fig. 1 shows the study area which was used in this paper. As shown, the study area is an approximately 3 km long portion of the levee system on the east side of the Mississippi river, north of Vicksburg, Mississippi, USA. Recently, Aanstoos et al. (2012) obtained polarimetric synthetic aperture radar (PolSAR) imagery and also measured several in situ soil properties on earthen levees in this study area as part of the development of remote levee monitoring methods. Sehat et al. (2014) analyzed these in situ soil data to detect differences in soil properties in the vicinity of slump slides versus non-slide areas as determined by an automatic SAR image classification.

The study area (Fig. 1) used in this investigation is a portion of a constructed earthen levee system, and as such is relatively homogeneous—by design—in terms of soil properties, topography, and surface vegetation. This homogeneity allows us to consider the extent of correlation between long-wave (L-band) radar backscatter and slowly changing soil properties without explicitly accounting for the amount of soil moisture present at the time of the radar acquisition. This assumption is further supported by the observation that the range of spatial and temporal variability of soil moisture over this area is relatively narrow.

In situ soil properties and airborne radar data were obtained as part of a study applying SAR to the problem of monitoring earthen levees (Aanstoos et al., 2012). Over the course of that project, it was observed that analysis of the radar image not only detected surface anomalies such as slump slides resulting from slope instability, but also highlighted some areas that had not slid at the time of the radar image but later did show unstable slope characteristics (Sehat et al., 2014). This led to our speculation that deeper subsurface soil characteristics, at least in this specific and fairly homogeneous environment, might be detectable in the radar profiles.

2.2. Field investigation

Several in situ soil properties were measured from Sept. 13 to Sept. 29, 2010. A detailed description of how this data was collected can be found in Sehat et al. (2014), and a summary is presented here for completeness. C3 Consulting, LLC made in situ soil measurements over the entire study area. A hydraulic push system drove a miniaturized cone penetrometer (Fig. 2) into the ground to measure various soil properties. The miniaturized cone penetrometer integrates moisture, resistivity and compaction sensors that simultaneously collect data in one centimeter increments of depth for moisture content, resistivity to electricity flow and soil compactness, respectively.

2.3. In situ soil property measurements

Cone penetrometer locations are shown in Fig. 3. A total of 106 testing locations were uniformity selected over the study area. Further, to supplement the soil texture properties and validate the data obtained by the cone penetrometer, seven core samples were taken. The data were then integrated to estimate the soil property value in a depth layer at each sampling location. This layer excluded the top 7 cm of the soil to avoid anthropogenic effects, then extended down to the first horizon break line of the soil profile which varied from 30 cm to 50 cm below the surface. In this study, sleeve friction (q_s), cone tip resistance (q_c), saturated hydraulic conductivity (K_{sat}), soil texture (sand and clay fractions), field capacity (f_c), permanent wilting point (pwp), and porosity (n) were analyzed.