Using Microwave Radar for Soil Moisture Inversion Under Soybean Canopies

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ABSTRACT

The successful radar mapping of soil moisture under vegetation canopies would be a boon to agriculture, global climate change studies, water resource management and other areas. Toward this end, a series of polarimetric radar measurements of soybeans over the entire growing season of 1996 were made at L- and C-band at the Long Term Ecological Research site at the Kellogg Biological Station, Hickory Corners, MI. The radar data obtained has been successfully modeled with a simplified radiative transfer expression, including the dependence of the VV, HH, and cross-polarized backscattering coefficients on the angle of incidence, vegetation water mass, vegetation height, and volumetric soil moisture. In addition, a simple inversion model based on the forward model has been obtained which yields vegetation water mass and volumetric soil moisture for select polarization and frequency combinations.

DESCRIPTION OF MEASUREMENTS

During the summer of 1996, an extensive set of radar measurements were conducted at the Long-Term Ecological Research site of the Kellogg Biological Station in Hickory Corners, MI, for the purpose of developing algorithms which would relate the soil moisture content of agricultural fields to the microwave radar backscatter of those fields. Three primary types of crops were chosen for measurement: corn, which represents agricultural fields in which a stem or stalk is a dominant feature at microwave frequencies, and soybeans and alfalfa, which represent agricultural fields which lack a dominant stem. In addition, measurements were also made of a field which has lain fallow for many years and is now populated with many native species. This report is restricted to the analysis of the soybean data.

Target characteristics

Soybean measurements commenced on 20 Jun 1996 and were completed on 26 Oct 1996, after the harvest for the season. During this period, the vegetation fresh biomass ranged from negligible, during the early summer and post-harvest, to a maximum of 1.337 kg/m² on 30 Aug.

The volumetric soil moisture ranged from 0.036 cc/cc on 5 Sep to a maximum of 0.249 cc/cc on 28 Sep. Despite a relatively wet spring and fall, western Michigan was plagued with a drought in the midst of the summer, resulting in lower biomass values than normal for the region.

Radar characteristics and techniques

Polarimetric radar measurements were made at 1.25 GHz (L-band) and 5.4 GHz (C-band). The choice of frequencies was based on previous observations that the L-band response was sensitive to both the soil moisture and biomass of vegetated surfaces, and the C-band response was largely dependent only on the biomass, and the hope that together, unequivocal inversion of measurements for soil moisture would be possible. The angle of incidence was restricted to 45° from nadir in order to reduce the volume of the required dataset to an obtainable size. This is an angle at which radar backscatter is sensitive to the primary ground parameters of soil moisture and biomass, and also is amenable to SAR deployment for large scale observations.

Special care was taken to reduce the effect of the agricultural row structure on the radar backscatter. Anomalous scattering is observed parallel and perpendicular to the row directions, with relatively smooth transition halfway between these two extremes [1, 2]. Therefore, the platform on which the antennas were mounted was translated adjacent to the fields, and the antennas were always azimuthally oriented at 45° with respect to the row direction and at a range of 12 m to the ground. To reduce fading, the number of independent samples was kept to at least 205 at L-band and 157 at C-band for each measurement.

The Single Target Calibration Technique [3] was used to correct raw radar data to differential radar cross sections. Calibrations were performed prior to any measurements (but only after the system had stabilized), and again after the measurements for the day were completed. Calibration precision is estimated at ±0.5 dB for co-polarized backscatter, ±1.0 dB for cross-polarized backscatter. A season-long systematic bias appears to be present in the data, but its presence does not affect the conclusions about the accuracy with which a radar sensor can invert soil moisture. This bias remains under investigation.

A CLOUD MODEL FOR BACKSCATTERING

The scattering mechanisms of the agricultural canopies are modeled as a cloud of water vapor over a rough ground [4]. This model is similar to the Michigan Microwave Canopy Scattering (MIMICS) model [5], developed for predicting backscatter from forests. The model for the rough ground backscattering component is an empirical model for bare rough ground as derived by Oh et al.[6]. Various interaction terms between the ground and the canopy “cloud” are included.

The model predicts the scattering to depend on the values of
the area density of the vegetation water mass, the volumetric soil moisture, the soil rms surface height. This model also contains a number of free parameters, describing the strength of the various scattering and extinction mechanisms. These free parameters were chosen to provide the best fit of the model to the measured backscatter.

With the model coefficients found, the polarizations and polarization ratios are found which have the largest sensitivity to biomass while insensitive to soil moisture, as well as the opposite. The polarization ratio with the largest sensitivity to biomass is the C-band HV to C-band VV ratio, and the model predictions as well as the data used to derive the model coefficients are shown in Fig. 1.

The polarization ratio with the largest sensitivity to soil moisture while relatively insensitive to biomass is the L-band HV to C-band HV ratio. It is shown in Fig. 2. It is important to note that the data itself has more sensitivity to the soil moisture, especially at low moistures, than is predicted by the model derived from the data.

**INVERSION APPROACH**

Inverting the derived model for vegetation water mass and the soil moisture is not straightforward. The models serve to justify the following simplifying assumptions. First, the C-band cross-polarization to VV-polarization ratio is linear (on a log-log scale) and independent of the soil moisture. That is, the functional dependence of this polarization ratio is of the form

\[
\frac{\sigma_{HV}^0}{\sigma_{VV}^0}(\text{C-band}) = b_1 m_w^{b_2}
\]

Second, the L-band cross-polarization to C-band cross-polarization ratio is similarly dependent on both the soil moisture and vegetation water mass:

\[
\frac{\sigma_{HV}^0(L\text{-band})}{\sigma_{HV}^0(C\text{-band})} = b_3 m_v^{b_4} m_w^{b_5}
\]

The coefficients are readily found from a regression on the data. It must be pointed out that while the soil moisture data has been measured simultaneously with each radar measurement, the vegetation data was measured more sparsely in time, necessitating an interpolation between measured values to produce an estimated vegetation water mass for each radar measurement. The parameters which produce the best fit to the data are

\[
b_1 = 0.2766 \quad (3)
\]

\[
b_2 = 0.3404 \quad (4)
\]

\[
b_3 = 2.4036 \quad (5)
\]

\[
b_4 = 0.7127 \quad (6)
\]

\[
b_5 = -0.0003 \quad (7)
\]

The very small value of \(b_5\) indicates that the ratio of the L-band and C-band cross-polarizations is not sensitive to vegetation water mass, despite the indications of the forward model. Fig. 3 shows the values of the vegetation water mass (measured and interpolated) against the inversion of (1). Fig. 4 shows the values of the measured soil moisture against the inversion of (2), except that the dependence on biomass has been neglected (ie. \(b_5 = 0\)).

**CONCLUSIONS**

From a careful, season-long sequence of measurements of the radar backscatter from a soybean canopy, an algorithm for inverting soil moisture and vegetation water mass from L-band
and C-band radar backscatter have been developed. A simple model which treats the soybean canopy as a cloud has been developed, but this model does not predict the dynamic range of the radar observations. A second, purely empirical model has also been developed from observations that the ratio of the C-band cross-polarized backscatter to the C-band co-polarized scatter is sensitive to vegetation water mass but largely independent of soil moisture, and that the ratio of the L-band cross-polarized backscatter to the C-band cross-polarized backscatter is sensitive to soil moisture but not the vegetation water mass.

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REFERENCES


