ESTIMATION OF BARE SOIL EVAPORATION USING MULTIFREQUENCY AIRBORNE SAR

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Abstract

The optimal radar parameters to estimate soil moisture indicated by past research are C-band, H polarization at steep incidence angles (10 to 20 degrees). Although these parameters minimize effects of roughness and vegetation, the spatial application of space and airborne radar are limited to the near range of the swath. Aiming at the development of algorithms to broaden the range of useful data, an experiment was conducted with NASA/JPL airborne radar polarimeter (P, L and C Bands) in September 1989 in an agricultural area near Fresno, California. There were two flights six days apart; ground measurements of soil moisture and surface roughness were taken on both flight dates in eight different fields.

Based on first order surface backscattering models, a physically based algorithm for retrieval of soil moisture and surface roughness has been developed. It has been shown that the co-polarization ratio is sensitive to soil moisture but not to soil roughness at high incidence angles (38 to 60 degrees).

The derived soil moisture was used to drive a two-layer heat and energy flux model in order to estimate evaporation from bare soils. The estimated values of evaporation for a two-week period are realistic. As the model incorporates time variations in both soil moisture and surface temperature, it could be used in conjunction with values of those parameters periodically estimated using SAR and infrared imagery, providing estimates of bare soil evaporation.

Introduction

Estimates of soil moisture are of great importance in numerous environmental studies, including hydrology, meteorology, and agriculture. Soil moisture information is not widely used in resource monitoring or prediction because it is difficult and costly to obtain on a routine basis over large areas. Measurements of radar backscattering from agricultural fields using ground-level (Ulaby et al. 1986; Engman & Wang 1987) indicate that the backscattering coefficient is highly modulated by soil moisture content up to 5 to 10 cm bellow the surface, and that the optimal radar parameters for estimating soil moisture are C-band, incidence angle of 10 to 20 degrees, and HH polarization.

Since roughness and vegetation do affect radar backscatter, any practical application of radar must be able to account for all three of these target features. At small incidence angles , surface roughness effects on the received radar signature are minimized. Results of many investigators have shown considerable variability in the relationship between soil moisture and radar backscatering for different sites, and a large range in suggested optimal incidence angles for soil moisture monitoring. Algorithms that do not require fitting to site specific conditions are needed. They should also tale advantage of the wider swaths provided from space based radar. Then, a major objective of this study is to develop and evaluate an algorithm to estimate bare soil moisture using far-range SAR data. A second major objective is to couple radar derived soil moisture with a two-layer model to estimate soil evaporation and keep track of time changes in soil water availability.

Description of the experiment

An experiment was conducted in September 1989 with the NASA/JPL airborne imaging radar polarimeter in an agricultural area near Fresno, California. There were two flights six days apart (Sept 8 and 14). Most of the fields were either bare or covered with mature cotton plants. Crops in the remaining fields included alfalfa, corn, lettuce, vineyards, and orchards.

Ground measurements of soil moisture and surface roughness were taken on both flight dates in eight of the bare fields. Soil samples were obtained for three depths: 0 to 5 cm, 5 to 10 cm, and 10 to 15 cm, and soil moisture was determined gravimetrically. The volumetric soil moisture for the sampled dry fields varied between 3 and 9 %, corresponding to real dielectric constants of 3 to 5.5 for C and L bands. The measured fields all fell within the near range of the radar swath; because the focus of this analysis is the far range, the dielectric constants for other bare dry fields in the far range were assumed to be in the same range. This assumption is felt to be valid because the fields are flat and essentially uniform in soil texture. None of them had been irrigated for at least several weeks; under conditions of high temperatures, low humidity, and no rainfall, the fields approach a fairly constant and homogeneous surface moisture condition until winter rains or irrigation begin. Eight large bare dry fields were selected. Five corner reflectors were deployed during the two flights allowing for full calibration.

Surface roughness was estimated using photographs of a gridded panel, oriented both paralel and perpendicular to rows in furrowed fields. Photographs were digitized and the correlation length and standard deviation of the surface height were determined. For the flat fields, the standard deviation of the surface height was whitin 1 cm and the correlation distance varied from 3 to 19 cm, depending on the starting point. The condition of stationarity was not observed, so that extrapolation from the field measurements to the pixel level could not be done.

Hourly meteorological data available for a meteorogical station neaby the selected fields were used as the atmospheric forcing for a two-reservor energy and water flux model that imports regional estimates of remotely sensed soil moisture. The soils are classified as clays, clay loams and loams. Soil texture drives the hydraulic properties of the soil.

Radar-derived dielectric constant algorithms and results

The interaction between electromagnetic waves and bare soil can be approximately described as a surface scattering problem. The scattering of electromagnetic waves by rough surface shave been studied for many years, but no exact closed-form solutions have been obtained. Numerical techniques can be used to compute the exact solution, but in general these techniques are computationally prohibitive and are used only in evaluating the accuracy and range of validity of approximate models (Chen & Fung, 1988). When dealing with practical applications, simpler approximate models are often used. Although valid only within a limited range of roughness surface parameters, these models can still be used quite effectively in many situations. Two types of surface scattering models are often used in soil backscattering simulation, depending on surface roughness conditions.

- The small perturbation method assumes that variations in surface height are small relative to the wavelength and the surface slope is small.
- The physical optics model (Kirchhoff model under scalar approximation) is given by the sum of the coherent part σ_{cp}, non coherent part σ_{np}, and the term due to surface slope σ_{sp}. The approximation is valid when the radius of curvature is large and the rms surface slope is small relative to the wavelength.

Detailed explanations and validity conditions for these models can be found in Ulaby et al. (1986). Algorithms used to derive dielectric constant based on surface scattering mechanisms are described in Shi et al. (1991). The table bellow shows the inversion results for four of the eight bare dry fields focused. The algorithm-derived dielectric constant range agrees well with the in situ measurements of 3 to 5.5 in the far range.

Field Number	5	6	7	8
Incedence angle	39.1^{o}	44.5^{o}	47.9^{o}	50.0^{o}
Dielectric constant	3.14	2.97	2.89	2.83

Table1. Estimated dielectric constants for test fields.

Since the algorithm only accounts for surface scattering , the volume-scattering contribution or even a small error introduced by calibration or signal noise can result in a miss-estimation of the surface dielectric constant.

Parameterization of soil heat and water vertical movements

Soil surface temperature and soil water content in the surface layer may be estimated from radar and infrared radiometry (See for example Soares et al. 1988). Parameterization to estimate those variables uses the two-layer soil description of Deardorff (1978). Two systems of equations are employed: The first one describes the water flow; the second one describes the heat flow, which in turn is coupled to water flow by dependence of the thermal properties on the soil water content.

Heat flow equations

The parameterization used here is based on a particular solution of the heat flow equations and assumes that the daily atmospheric forcing is siusoidal (Bhumralkar 1975). It leads to the following equations:

$$\frac{\partial Ts}{\partial t} = \frac{C_1}{C_g d_1} - \frac{C_2}{\tau_1}(T_s - T_2) \qquad (1)$$

$$\frac{\partial T_2}{\partial t} = -\frac{H_a}{C_g d_2} \qquad (2)$$

Where: T_S is the surface skin temperature; T_2 soil temperature of the deep layer (Fig 1); Ha is the heat flux from the soil to the atmosphere; $C_1 = (2\pi)^{1/2}$; $C_2 = 2\pi$; C_g is the soil heat capacityin layers 1 and 2; $d_1 = (DT_{g1}\tau_1)^{1/2}$;where τ_1=24 hours, and DT_{g1} is the thermal diffusivity in layer 1; and $d2 = (365 DT_{g2})^{1/2}$,where DT_{g2} is the thermal diffusivity of layer 2. C_g, d_1, and d_2 depend on W_g and W_2, the soil moisture in the first layer (0-10 cm) and the second layer (10-120 cm).

Water flow equations

Again, following Deardorff (1978), the soil is described as a double layer where the exchange between the two layers is decribed by a diffusivity type of feedback relationship (Soares et al. 1988). The surface layer, assumed to extend from the surface to 10 cm below, has a volumetric water content (Wg) which corresponds to the radar measurement. The temperature Tg of this lkayer is assumed equal to the soil surface temparature Ts. The second layer has a water content W2, its temperature is T2 and its thickness Z2 is 120 cm. The flow eqyations are then:

$$\frac{\partial Wg}{\partial t} = -\frac{Eg}{Z1} + C_{w2}(W_2 - W_g) \qquad (3)$$

$$\frac{\partial W2}{\partial t} = -\frac{Eg}{Z2} \qquad (4)$$

where: Eg is the evaporation flux at the soil surface; Z_1 and Z_2 are thicknesses of the two layers and C_{W2} is the pseudidiffusivity (Soares et al. 1988, Bernard et al. 1986), which depend on W_2 and W_g.

Relation to atmospheric forcing

The soil and the atmosphere are linked through heat (*Ha*) and mass (*Eg*) transfers at the boundary. The energy budget at the interface is written:

$$Ha = -Rn + Hs + LEg \qquad (5)$$

where Ha, Rn, Hs and LEg are soil heat flux, net radiation, sensible heat flux and latent heat flux.

The sensible heat flux and the latent heat flux are calculated by classical formulas based on a Ohm's law type of exchange, in which the transfer coeficients are calculated using the formula of Businger et al. (1971). For evaporation a corrective term α is applied to account for the drying of the soil surface. It is calculated as follows:

$$\alpha = \min(1, \frac{E\lim}{Epot}) \qquad (6)$$

$$E\lim = a\exp(bWg^2)\frac{Ws}{Ws - Wg} \qquad (7)$$

Where E_{lim} represents a limiting evaporation derived from the equation for soil water movement; a, b and Ws, which is the soil moisture at saturation,are soil related constants (For details, the reader is reffered to Soares et al. 1988).

Application to the data

The inversion of the surface scattering model provided soil moisture from a multiparametric SAR. Calculated values match *in situ* measurements . The two-layer model that uses radar-derived soil moisture as input is able to simulate the response of Wg to a given atmospheric demand. The model depends on few parameters that can be inferred by comparing the model outputs with the remote measurements. While running the model for a two weeks period including the SAR flight dates, assumption of a fairly constant soil surface moisture (dry), both temporally and spatially, seems to be quite realistic. In addition, the soil thermal and hydraulic properties for clay and clay loam soils are well known and are assumed to be valid for the test site.

Figure 1 is a schematic representation of the model inputs and outputs together with the necessary functional parameters. As the atmospheric demand (U_a, T_a, q_a, R_n) is measured in a site within the SAR swath, the model is able to calculate the outputs provided that the soil thermal and hydraulic properties are known and the initial values describing the state variables at time t=0 (W_g, T_g, W_2, T_2) have been set.

The initial value of Wg is set to 0.06 cm3/cm3 on September 4, based on assumptions stated previously. T_g (0) is set assuming that, soon after sunrise, the heat flux from the soil to the atmosphere (H_s) is zero. T_2 *is taken as the mean air temperature during the preceding days.* W_2 is roughly estimated from measures taken at 15 cm into the soil and general knowledge of the soil hydraulic behavior, with no water inputs in the previous several weeks. The other unknown soil parameters may be approximated from the knowledge of the soil properties (b=44.0 and W_{sat}=0.38).

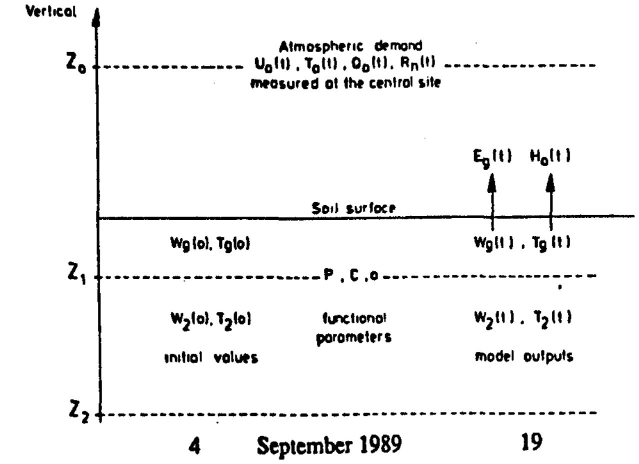

Figure 1. Schematic representation and time evolution of the model.

Figure 2 presents a typical daily distribution of the net radiation (Rn) in latent heat flux (Eg), sensible heat flux (Hs) and soil heat flux (Ha). The soil evaporation took about 5% of the available energy for the two-weeks window and the soil surface moisture remained practically constant (ranging only from 6.0% to 5.7%) matching the SAR derived values for the two flights. The daily total evaporation never exceeded 0.3 mm while the potential evapotranspiration measured was most frequently over 5 mm, which is in good agreement with the three-stage drying process described in Rosenberg et al. (1983).

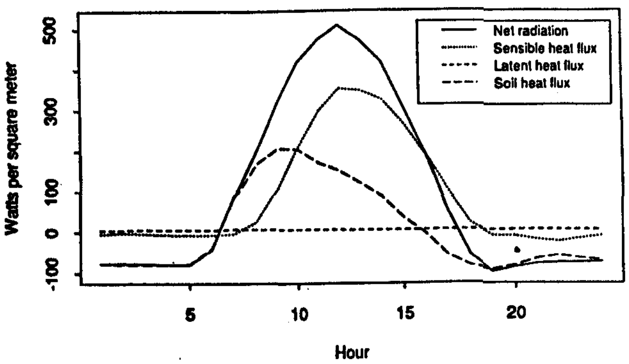

Figure 2. Model-derived outputs for Net Radiation and Heat fluxes for September 8.

Finally, a comparison between estimated net radiation and independent measurements at the meteorological station is presented in Figure 3, for September 8. The same agreement exists for the entire time period. Rn depends on soil surface temperature, soil albedo (well known for the dry clay soils dominant in the test site), and emissivity; the parameterization is therefore sufficient to describe both water and temperature time dependence.

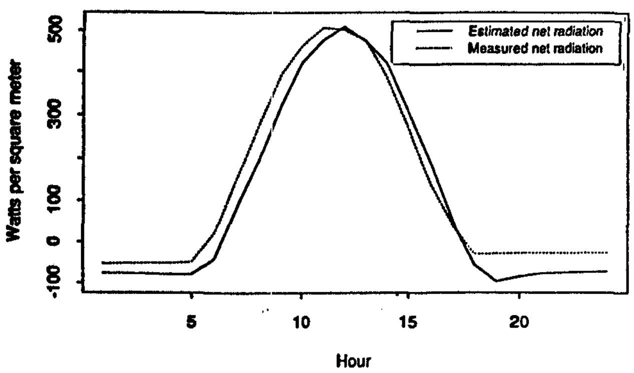

Figure 3. Modeled and measured Net Radiation, September 8, 1989.

Conclusion

This paper shows that for homogeneous areas soil moisture can be derived from SAR measurements, so that the use of microwave remote sensing can give realistic estimates of energy fluxes, if coupled to a simple two-layer model representing the soil. The model simulates Wg using classical meteorological data, provided that some of the soil thermal and hydraulic properties are known. Only four parameters are necessary: mean water content, thermal conductivity and diffusivity and soil resistance to evaporation. The may be derived if a minimal number of measured values of Wg and Tg are available together with independent measurements of energy flux to compare with the estimated values. The estimated evaporation has been shown to be realistic and in good agreement with drying stage theory in which the transfer of water in the soil is in the vapor form. Another very useful product is a parameter defined as the mean water content of soil (W_2) as estimated by remote sensing. It describes the hydraulic state of the soil unsaturated zone and is of primary importance for atmospheric mesoscale models and hydrologic models.

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