PROGRESS IN PASSIVE MICROWAVE REMOTE SENSING OF VEGETATION

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INTRODUCTION

The sensitivity of microwave emission to biomass and biophysical properties of crops and forests has been proved in several experimental and theoretical studies. Experimental investigations on microwave emission from crops carried out since early 1980s by using ground based and airborne sensors demonstrated that useful information on vegetation covered soils can be obtained by combining brightness temperatures, measured at two or more microwave frequencies and polarizations. At the lower frequencies of microwave band (around 1-3 GHz), and for small incidence angles, emission from a vegetation-covered soil is mostly influenced by soil moisture, whereas, at higher frequencies, the contribution from vegetation to the radiation is significant and the emission can be related to vegetation type and plant water content. More recently microwave radiometers on satellites, such as the recently launched AMSR-E have shown a great potential in global monitoring of natural vegetation, and a significant improvement is expected by the enhanced performances of the new generation sensors such as the planned SMOS and HYDROS. In the same time of experimental activities theoretical models were developed to interpret the observed relations between radiometer observations and vegetation and soil parameters. These models included semi-empirical approaches based on regressions obtained from radiometer observations and on the simple single scattering continuous medium radiative transfer theory as well as more sophisticated physical models based on calculating electromagnetic fields on vegetation constituents assuming either single or multiple scattering. This paper offers a review of recent achievements in both experimental and theoretical research in this field.

EXPERIMENTAL RESULTS

A significant amount of experimental data related to microwave emission from vegetated surfaces has been collected in field experiments with the use of ground based and airborne sensors, and on a global scale with satellite radiometers. Quantitative experimental relationships between brightness temperature measured between 1 and 36 GHz, and biomass parameters were obtained for several crop and forest types [1]. From these results it has been shown that, although bare and vegetated soils generally show different values of brightness temperature, more information can be obtained by combining multifrequency dual polarized microwave data and by adding information taken in the thermal infrared band. Of particular interest was found to be the Polarization Index which is maximum on bare soil and decreases as vegetation grows [2]. A significant work has been recently carried out in the framework of SMOS program [3] mostly aiming at evaluating the effects of canopy cover on soil moisture measurements. For example: the effect of grapevines on the emission and on the soil moisture retrieval, have been exploited by, in the SMOS REFLEX experiment [4]. The L-band anisotropy in 1.4-GHz brightness induced by a field corn vegetation canopy was been investigated in [5]. It was found that both polarizations of brightness are isotropic in azimuth during most of the growing season. Whereas, when the canopy is senescent, the brightness is a strong function of row direction.

Investigations on the spectral characteristics of forests were performed for the purpose of evaluating the potential of multi-frequency radiometry in separating forest types, estimating woody biomass, and identifying the differences between the summer and winter features of trees. Measurements carried out on several sites in Finland since 1991 by using a multi frequency airborne radiometer showed the brightness temperature increases with stem volume at all frequencies [6]. Airborne measurements covering a frequency range between 1.4 and 37 GHz carried out in Italy by IFAc-CNR on broadleaved and coniferous forests in winter and summer, pointed out the potential of the high frequency data in separating forest types, whereas the highest sensitivity to woody volume (WV) was obtained at L-band [7, 8]. A similar trend between L-band emission and WV was obtained in [9, 10]. Multi-frequency observations carried out on Les Landes showed a rather fast saturation of emissivity as a function of tree age at all frequencies [11]. High frequency (24-157 GHz) near-nadir emissivity spectra of deciduous and coniferous forests, collected in winter and summer in Sweden, showed only small differences between the two categories [12]. Measurements from spaceborne radiometers (SMMR, SMM/I, AMSR-E) confirmed on a worldwide scale the usefulness of multifrequency dual polarized data in monitoring vegetation cover [13 -15]. Indeed, despite the coarse ground resolution, microwave radiometry from satellite offers a unique opportunity to probe forests at a global scale. The analysis of temporal variations of the microwave polarization difference measured with the SMM/I over the Sahel showed a minimum near the peak of green biomass [16].

RADIOMETRY MODELS

Several models, mostly based on radiative transfer theory, have been developed to interpret remote sensing data and to be used in the retrieval algorithms. Many approaches for the retrieval of soil and vegetation parameters from low frequency (L-band) measurements make use of the so-called ω-τ model [e.g. 17, 18] that relies on two vegetation parameters: the optical depth τ and the single-scattering albedo ω. The dependence of optical depth and single scattering albedo at L-band on crop and observation (incidence angle and polarization) parameters was investigated in [19] for several crop types (corn, soybean, wheat, grass, and alfalfa). For a certain vegetation type and frequency, optical depth has usually been directly related to the vegetation water content (in kilograms per square meter). However, a reanalysis of the frequency dependence of the linear relationship between vegetation optical depth and vegetation water content conducted in [20] confirmed that, when a large frequency domain is considered, the b-factor is inversely proportional to the power of the wavelength as already observed in [18]. In a further study [21] the optical depth was derived from the microwave polarization difference index and the dielectric constant of the soil.

More sophisticated models exploited the relationship between electromagnetic radiations and vegetation parameters [e.g. 22-25]. Temperature profiles within the canopies are among those parameters. The profiles influence both radiation sources within vegetation canopies [25], and dielectric properties of vegetation components [26] and hence electromagnetic radiations. On the other hand, atmospheric turbulence drives heat and momentum fluxes that in turn drive temperature profiles within the vegetation canopies.

A model, recently developed in [27], has been integrated with a canopy turbulence model [28] to relate the response of microwave radiometers over the canopy to the atmospheric turbulence driving temperature profiles within the canopy. The model is based on a semi-analytic solution for the stochastic radiative transfer equations. The stochastic radiative transfer equations are considered to account for gaps within the canopy, and the semi-analytic solution is used to account for multiply scattered radiations. The canopy turbulence model uses localized near-field Lagrangian theory in formulating temperature profiles within the canopy. It also uses a physically based one-dimensional analytical model in describing the influence of canopy structure and density upon the wind vertical velocity variance, and the within-canopy far field diffusivity.

The brightness temperature data used for validating the radiometry model were acquired over a corn canopy by a radiometer mounted on a rotating hydraulic boom. The radiometer, which operated at 10 GHz, acquired both vertical and horizontal brightness temperature data over the angle range of 10^o to 60^o. The brightness temperature data were acquired over several days during the growth cycle of the corn crop. For each day the air, the leaf, and the soil temperature profiles were measured every 20 minutes and were acquired simultaneously with the brightness temperature data. For the same days, measurements were made for plant height, stalk diameter, plant water content, leaf area index, number of leaves per plant, and gravimetric soil moisture.

In adapting the corn ground truth as an input for the radiometry model, the corn canopy was treated as a layer of dielectric elliptic discs and finite cylinders above a rough interface representing the leaves, the stalks, and the soil surface respectively. The discs and the cylinders were distributed within spherical spatial cells with average height equal to the layer height. The Eulerian angles of orientation were used to describe orientation of the leaves and the stalks [29]. Both leaves and stalks were assumed to be uniformly oriented in the azimuth direction. The third angle of orientation was equated to zero. This had no impact on the stalks because of their circular symmetry. The soil surface was taken to be a Gaussian rough surface with an rms of 3.5 cm and a correlation length of 10 cm. The soil bulk density is equated to $1.29 g/cm^3$. The soil temperature and moisture are assumed to be uniform with values equal to the corresponding values averaged over a soil depth of 3 cm [27].

Model simulations were found to be in good agreement with the brightness temperature data collected at different incidence angles over the corn crop. Thus, model results were further compared with two radiometry models based on the conventional radiative transfer. The first model treated the canopy as a continuous random medium. The second model accounted for gaps through applying the linear spectrum-mixing model [30]. The comparison showed that both the latter models overestimated the corn canopy brightness temperature, and pointed out the merit of the new model. The canopy turbulence model was then employed in investigating impacts of turbulence parameters (the canopy temperature at air-canopy interface, the soil heat flux, the friction velocity/horizontal wind speed, and the foliage-canopy temperature difference) on the foliage temperature profiles. Furthermore, the radiometry model was integrated with the turbulence model and used to investigate impacts of the foregoing turbulence parameters on the canopy brightness temperature, and hence on radiometers' response. This showed that both vertical and horizontal brightness temperatures were equally affected by the turbulence parameters. This is because the turbulence parameters affect the foliage temperature profiles that in turn affect both the level of the radiation sources within the canopy, and dielectric constants of canopy constituents. Since the canopy was taken to be uniform in the azimuth direction, the radiation sources, and dielectric constant properties contributed equally to the vertical and horizontal brightness temperatures. In addition, maximum impact of the turbulence parameters occurs near nadir incidence and decrease as the incident angle increases due to the longer paths traveled by the radiations within the canopy. Accordingly, to reduce the influence of the atmospheric turbulence on the response microwave radiometers in the presence of a vegetation canopy; the radiometers should operate at angles far from nadir incidence.

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