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André Chanzy and Jean-Pierre Wigneron

1 Introduction

The emission of microwave radiation from soil and vegetation is localised in a layer the depth of which depends on both the radiation characteristics (frequency, polarization, propagation direction), and the soil and vegetation properties (dielectric permittivity, geometry). The layer is generally heterogeneous and contains elements with various geometries and dielectric properties. The size of the elements is often comparable to the wavelength and therefore, complex types of volume scattering can occur. Moreover, the vegetation canopy is a dynamic system with rapidly changing properties according to diurnal (soil moisture and temperature) and seasonal (vegetation, soil surface roughness, temperature) cycles as well as to soil wetting/drying sequences. So, the microwave emission models from soil and vegetation must account for the following time dependent characteristics:

- the soil surface dielectric constant or the surface soil moisture combined with a model of soil dielectric constant,
- the soil surface roughness,
- the vegetation biomass and geometry
- the vegetation dielectric constant,
- the soil and vegetation temperature profiles.

Microwave emission models from soil and vegetation were mainly developed at low frequencies, i.e. at frequencies lower than 20 GHz. Two types of model can be distinguished: the physical models to understand the emission processes in relation to the soil and vegetation geometry, and the semi-empirical models dedicated to inversion studies. At higher frequencies, most of the emission models are based on semi-empirical approaches.

The scope of the following section is to present the general modelling framework for soil and vegetation cases. Then we present a brief presentation of the selected models. Soil and vegetation are presented separately, since they are accounted through specific models. However, to represent a soil covered by vegetation, it is necessary to combine a soil and a vegetation model.

2 Microwave emission from vegetation

2.1 Physical models

Coherent approach

In the coherent approach, wave equations are used to derive the bistatic scattering coefficients, which are integrated to compute the total reflectivity. The emissivity e_p at polarization p (= h or v) is then obtained using the energy conservation law:

$$e_p(\theta_0,\phi_0) = 1 - 1/4\pi \int_{4\pi} \left[\gamma_{pp}(\theta_0,\phi_0,\theta_1,\phi_1) + \gamma_{pq}(\theta_0,\phi_0,\theta_1,\phi_1)\right] d\Omega_1 \qquad (1)$$

where subscripts 0 and 1 stand for the incident and the reflected waves, θ is the incidence angle and ϕ the azimuth direction. Equation (1) is also referred to as the Peake Law. The bistatic scattering coefficients γ_{pq} and γ_{pp} can be computed with vegetation described either by a continuous medium (Stogryn, 1974, Fung and Fung, 1977, Fung and Ulaby, 1978, Tsang and Kong, 1981, Jin and Kong, 1984, Lee and Kong, 1985) or a discrete medium (Lang et al, 1983). The Peake law is interesting to bridge studies in the active and passive domains. However, it was developed to derive the surface emissivity. In case of vegetation, where transmission through the canopy may be important, the Peake Law must be used with care, since it is does not account for the thermal structure of the medium.

Incoherent approach

The incoherent approach is based on the radiation intensity. The radiative transfer equation can be written at v polarisation for the vegetation, which is divided into horizontal layers:

$$\mu \frac{dI_v(\mu,z)}{dz} = k_a \frac{2k_0T(z)}{\lambda^2} - k_e I_v(\mu,z) + k_e \int_{-1}^{+1} P(\mu,\mu')I_v(\mu',z)d\mu' \qquad (2)$$

where I_v is the specific intensity, λ the wavelength, k_a and k_e the absorption and the extinction coefficients, $\mu = \cos(\theta)$ and $P(\mu,\mu')$ is the phase function (In a fully polarimetric formulation, the phase function becomes a matrix, the specific intensity becomes the Stokes vector, and k_a and k_e become appropriate absorption and extinction vectors). The right side of Equation (2) is the sum of the emission term, the extinction and the scattering source. The phase function, k_a and k_e can be computed either for a continuous or discrete medium. When considering a continuous medium, the vegetation is described by statistical dielectric fluctuations. They are characterised by autocorrelation functions, usually parameterised by a horizontal and a vertical correlation length (Jin , 1989, Wigneron et al., 1993a).

With the discrete medium, the scatterers are determined by simple geometric elements (ellipsoid, cylinder, disc), which are characterized by their dimension and dielectric constant (Ferrazoli et al., 1992, Wigneron et al., 1993b, Ferrazoli and Guerriero, 1996). The different models using the discrete media approach differed by the resolution of the radiative transfer equation. Ferrazoli et al. 1992 computed the bistatic scattering coefficient using the matrix doubling method to combine the different layers in the vegetation canopy. Then they calculate the emissivity with the Peake law. Wigneron et al. 1993b numerically resolved the radiative transfer equation. The thermal emission of each layer is accounted for to allow the description of a given temperature profile on the microwave emission.

2.2 Simplified models

When the scattering source term is negligible (Kirdiashev et al., 1979), the solution of the radiative transfer equation (Equation 2) simplifies to:

$$T_{B_p} = (1 + L\Gamma_p)(1 - L)(1 - \omega)T_V + (1 - \Gamma_p)\, L\, T_S \qquad (3)$$

where:

T_v and T_s are the vegetation and soil effective temperature, respectively;
Γ_p is the soil reflectivity
ω is the single scattering albedo ($1-\omega = k_a/k_e$)
L is the canopy attenuation, given by :

$$L = \exp(-\tau/\mu) \quad (4)$$

where τ is the vegetation opacity, which depends on the extinction coefficient and the canopy height ($\tau = k_e \cdot H$).

The simplified expression of T_B is widely used (Mo et al., 1982, Kerr and Njoku, 1990, Wegmüller et al. 1994, Van de Griend and Owe 1994, Wigneron et al. 1995a, Van Oevelen 1999) for the estimation of surface parameters (soil moisture and vegetation). The elimination of the scattering source term is a strong hypothesis for frequencies above ~5-10 GHz. When limiting the scattering term to the forward direction (Delta-Eddington approximation), the radiative transfer equation takes the simplified formulation given above, with ω and τ replaced by ω^* and τ^*, given by:

$$\omega^* = (1-\alpha)\omega/(1-\alpha\omega) \quad (5)$$

$$\tau^* = (1-\alpha\omega)\tau \quad (6)$$

where α represents the fraction of the radiation intensity scattered along the incident direction. ω^* and τ^* are often estimated as ω and τ from experimental data (Pampaloni and Paloscia, 1986).

At low frequencies (<10 GHz), Jackson et al. (1982), Wang et al. (1990), Jackson and Schmugge (1991), Haboudane et al. (1996), and Chanzy et al. (1997a) further simplified the equation by assuming that ω is equal to 0 and $T_v=T_s$. Such a simplification leads to the following equation:

$$T_{Bp} = (1-L^2\Gamma_p)T_v \quad (7)$$

2.3 Dielectric constant of vegetation elements

Two models are generally used :

- The Debye-Cole dual dispersion dielectric model is valid over the 0.1-20 GHz range (Ulaby and El-Rayes, 1987). It accounts for the relaxation frequency of the bound water, which was determined experimentally.

- The semi-empirical formula of Mätzler (1994a) is valid over the 1-100 GHz range.

3 *Microwave emission from soil*

3.1 Physical emission models

For rough surface, soil emission models are based on the Peake law (Equation 1). In the soil case, the bistatic scattering coefficients are computed using Kirchhoff's approximations or using the small perturbation approach (Mo et al., 1987, Schiffer, 1987, Saatchi et al. 1994, Fung 1994, Laguerre 1995). As an extreme case, the soil emissivity can be derived for smooth soil from the Fresnel reflectivity. With all these approaches, the radiation emission below the surface is neglected. A difficulty arisen by surface models is then the determination of the soil dielectric constant and more specifically, the soil layer depth (hereafter referred to as sampling depth δ) over which the dielectric constant should be characterised.

The soil dielectric constant vertical profile can be accounted for in emission models from layered media. In such models, the soil is assumed to be smooth. Different approaches were developed. With the coherent models, the radiation intensity is computed from the electric field determined at the boundary of each layer. In the Wilheit model (Wilheit, 1978), the electric field is computed at each layer interface for an electromagnetic wave propagating through the soil. The fractional energy absorption f_i in each layer, the thermal weighting function, is then derived from the electric fields. The radiant flux is obtained by multiplying the weighting function by the average temperature of each layer. Wilheit (1978) found two sampling depths, one for temperature δ_T and one for the reflectivity δ_r. An alternate model is that of Njoku and Kong (1977); this model is based on the fluctuation-dissipation theorem. Comparative studies (Schmugge and Choudhury, (1981); Costes et al. (1994)) have shown that both models provide almost identical results.

Burke et al., (1979) proposed a model based on an incoherent approach. However, in their model, the moisture and temperature profiles contribute to the effective temperature calculation only, whereas the soil emissivity is solely determined by the soil dielectric constant in the surface layer.

Coherent and incoherent models can be easily combined to a mechanistic model of soil heat and mass flows in order to provide temporal variation of the soil microwave emission. Suresh Raju et al., (1995) have shown the importance of the diurnal cycles. Moreover, they found that diurnal cycles have an impact on the effective value of the sampling depth of the soil emission models.

3.2 Semi empirical emission models

Choudhury et al. (1979) proposed a simple model based on the smooth soil reflectivity (R_p) and the standard deviation of height (σ) to characterize the roughness :

$$r_p(\theta) = R_p \cdot \exp(-4k^2\sigma^2\cos^2\theta) \tag{8}$$

where r_p is the reflectivity of the rough surface at p polarisation (h or v). This formulation has a physical meaning since it represents the coherent reflectivity of the scattered radiation along the specular direction. Often the term $h = k^2\sigma^2$ is treated as a free parameter fitted to the experimental data independently at each frequency, incidence angle and polarisation. Wang and Choudhury (1981) proposed another reflectivity formulation, which includes the depolarisation of the radiometric signal associated with the surface roughness :

$$r_p(\theta) = \left[(1-Q)R_p + QR_q\right] \cdot \exp(-h\cos^2\theta) \tag{9}$$

Here h and Q are empirical parameters, and q is the polarization orthogonal to p. Wang and Choudhury (1981) showed that once h and Q are fitted, the model predicts properly the angular variations of the soil reflectivity. Wang et al. (1983) showed that for very rough soils the angular dependence in $\cos^2(\theta)$ should be replaced by 1. This leads to another formulation with an additional parameter where the exponential factor in (9) is modified by $\exp[-h \cdot \cos^n(\theta)]$ with n varying from 0 to 2.

We notice that this formulation is also applied to vegetated surfaces at high frequencies using appropriate parameters (Hewison and English, 2000, this issue). In their model, the spectral dependence of the reflectivity is represented by the Debye/Fresnel formulae.

Wegmüller and Mätzler (1999) proposed an empirical formula of the soil emissivity, derived from surface-based measurements at frequencies from 3 to 100 GHz. They related the emissivity at *h* and *v* polarization at a given incidence angle θ to the Fresnel reflectivity at θ (*h* polarization only), to a an empirical function of θ, polarization and surface roughness (σ).

3.3 Soil dielectric constant

At low frequencies, several semi-empirical or empirical models are available (Wang and Schmugge, 1980, Hallikainen et al., 1985, Dobson et al., 1985). The soil composition is accounted for through the granulometric fractions of clay and sand. They are used in empirical relations to estimate the fraction of water bound to the soil constituents. The frequency and temperature dependences are governed by the Debye equation applied to saline water. The validity of such models is limited to 18 GHz since most of the observations, required to parameterise the fraction of bounded water, were limited to that frequency range.

At higher frequencies (>20 GHz) there are only a few soil dielectric properties data sets (Ulaby et al., 1986, Calvet et al. 1995a, Frasch et al., 1998). England et al. (1992) proposed a simple approximate expression at SSM/I frequencies. Calvet et al. (1995a) presented experimental measurements from 23 to 90 GHz.

4 Selection of emission models

To build a model of microwave emission from vegetated surfaces, we have to combine several sub-models to represent :

- the radiative transfer in the canopy,
- the dielectric constant of vegetation elements,
- the soil emissivity,
- the dielectric constant of the soil surface,
- the surface effective temperature.

In the following sections, we present one or two possibilities for each sub model. The selection is made to provide a model that is the closest as possible to the physics as a research tool and a simpler model dedicated to the inversion applications.

The model developed by Wigneron (Wigneron et al. 1993b, Wigneron et al. 1995b) is selected for the physical representation of the vegetation emission. An incoherent approach is preferred since it allows to account for the thermal structure of the canopy. A discrete description of the vegetation medium is chosen in order to have measurable inputs. At the present time, this is not possible with the continuous medium approach. Indeed, the correlation lengths of the dielectric constant in the vegetation are minimally related to the geometrical description of the vegetation elements (Wigneron et al. 1993, Wigneron et al. 1995b, Calvet et al. 1995b, Calvet et al. 1996). To go further with the continuous approach, new experiments should be designed to establish the explicit relationships between the geometric vegetation parameters and the parameters of the continuous model, such as the correlation lengths of the vegetation dielectric constant.

The semi-empirical model given in Equation (3), hereafter referred to as ω–τ model, is widely used and therefore is selected as the simple model dedicated to the inversion applications.

For the soil emissivity, the available physical models have a narrow field of validity regarding the surface roughness conditions. Consequently, we only selected the h-Q semi empirical model (Equation 9).

For the dielectric constant we selected the most common models.

Finally, we present different approaches to estimate the microwave effective temperature.

4.1 Physical model of microwave emission from vegetation

The model of Wigneron ((Wigneron et al. 1993b, Wigneron et al. 1995b) solved the radiative transfer equation (2) in the vegetation canopy represented as a discrete medium.

Purpose of the model	To compute the brightness temperature (T_B) of vegetated surface.
Applications	Research studies on the microwave emission
Model variables	frequency (1-25 GHz)
Input parameters	- volume fraction of the vegetation (m^3/m^3) - canopy height (m) - dielectric constant of the vegetation - dimensions of the ellipsoids (m) (leaves) - probability density function of the leaf orientation (inclination, azimuth, rotation along foliar axis) - dimension of the cylinders (m) (stem, branches, trunk) - Probability density function of the cylinder orientation (inclination, azimuth) - Soil reflectivity - Soil effective Temperature (K) - Vegetation temperature (K) - Thermal gradient within the canopy (K/m) - Atmospheric downwelling radiation (K)
Output parameters	T_B at both polarizations (h and v) and at θi ($0<\theta i<\pi/2$)
Expected errors	≈15 K (Wigneron 1993, Wigneron et al. 1993b, 1995b).

4.2 Semi-empirical model of microwave emission from vegetation

The ω–τ model (Equation 3) is based on a simplified resolution of the radiative transfer equation (Equation 2) primarily proposed by Kirdiashev et al. (1979).

Purpose of the model	To compute the brightness temperature (T_B) of vegetated surfaces
Applications	Inversion for retrieving surface geophysical parameters: surface soil moisture, vegetation water content, surface temperature
Input parameters	- single scattering albedo (ω) at a given polarization and frequency - optical thickness (τ) at a given polarization and frequency - Soil reflectivity - Soil effective Temperature (K) - Vegetation temperature (K) - Atmospheric downwelling radiation (K)
Output parameters	T_B at θi $0<\theta i<60°$
Expected errors	≈5K over the range of soil moisture after fitting the vegetation parameters
Accuracy requirements	useful : T_B= 5K Adequate : T_B=3K

The determination of ω and τ is the key step for implementing the model. Studies reported in the literature focussed on the low frequencies (below 15 GHz) since they are more suitable for inversion studies. We will first report studies dealing with ω and τ determination at these frequencies and then give some indications to tackle the microwave emission at higher frequencies. As ω and τ are generally fitted parameters, we do not make the distinction between ω, τ and ω^*, τ^* (Equations 5 and 6).

Characterisation of the single-scattering albedo

In general ω is estimated from brightness measurements by a fitting process; ω is found to be small (<0.12) at low frequencies (<10 GHz) (Kerr and Wigneron, 1994, Van de Griend and Owe, 1994, Wigneron et al., 1995a, Wigneron et al., 1996). The spectral dependence of ω is not always clear. ω depends on the angle of incidence and polarization (Van de Griend and Owe, 1994, Wigneron et al., 1996) but such a dependence is often ignored (Kerr and Njoku, 1991, Wigneron et al. 1995a). Van de Griend and Owe, 1994 found that $\omega_H/\omega_V = 0.83$ over savannah. Results of ω are summarised in Table 1. The single-scattering albedo is also computed from k_a and k_e. Wigneron et al. (1995b) used a physical model (discrete model) to compute ω. The physical model accounts for the scattering sources and therefore the apparent ω in the ω–τ model can be different from ω defined rigorously in the physical model.

Characterisation of the opacity

The opacity τ can be physically determined from the imaginary part of the dielectric constant of saline water in the vegetation (ε''_{sw}):

$$\tau = A \ f\, W_c\, \varepsilon''_{sw} \qquad (10)$$

Where A is coefficient related to the plant structure, f the frequency, W_c the vegetation water content. This formulation is valid at low frequencies (below 10 GHz). Since the A coefficient is not always a well-known term, τ can be related to the canopy dielectric constant (Schmugge and Jackson, 1992).

$$\tau = 4\,\pi\,(H/\lambda)\ \mathrm{Im}(\varepsilon_{can}{}^{1/2}) \qquad (11)$$

where

$$\varepsilon_{can} = [1+vegf\,(\varepsilon_{veg}{}^{\beta}-1)]^{1/\beta} \qquad (12)$$

where *vegf* is the volume fraction of vegetation elements of the canopy. Best results are found for β=0.5, i.e. for the refractive mixing model. Another way to avoid the determination of A is followed by relating τ to the W_c through an empirical relationship:

$$\tau = b\, W_c \qquad (13)$$

where b is a coefficient which depends on plant structure; it is determined by experimental data sets. It appears to be strongly dependent on the frequency and in less extent on polarisation and angle of incidence. Furthermore b depends on temperature. At L band results converge within a rather small range of variation [0.1-0.15]. At higher frequencies, b values are variable, and there are no clear laws that help in sorting the results into vegetation classes. Therefore, b still needs to be estimated on a case by case basis. However, the τ dependence on polarisation, which can be explained by the canopy structure and the leaf geometrical description, is addressed e.g. in Ulaby and Wilson (1985), Van de Griend and Owe (1994), and Wigneron et al. (1995a).

The opacity τ can also be estimated by radiometric measurements. The idea is that the polarisation difference or the angular variations of T_B are linked to the amounts of vegetation. Thus, τ is related to T_B indices, which needs to be insensitive to soil moisture (Haboudane et al. 1996, Chanzy et al. 1997a, Wigneron et al. 1999). Such an approach should be validated with different types of vegetation, see e.g. the following field experiments: Chukhlantsev et al. (1989) for tomato fields at L Band, Mätzler (1990) for oat, Mätzler (1994b) for beech trees, both at frequencies from 5 to 94 GHz, and van de Griend et al. (1996) for wheat at 1.4 and 5 GHz.

Table 1: Published values of the single-scattering albedo (WC: vegetation water content in kg/m²)

Source Vegetation type	Vegetation description	Frequency (GHz)	Polarisation	Incidence Angle (°)	ω* , ω
Mo et al. 1982					
Soybean	WC=1.54	1.42	H and V	0-50	0.07
Soybean	WC=1.54	C Band	H and V	0-70	0.13
Corn	WC=0.66	1.42	H and V	0-50	0.04
Corn	WC=0.66	C Band	H and V	0-70	0.10
Grass	WC=1.34	1.42	H and V	0-50	0.04
Grass	WC=1.34	C Band	H and V	0-70	0.05
Ulaby et al. 1983					
Corn		1.4		0	0.04
Corn		1.4	H	40	0.13
Corn		5		0	0.05
Corn		5	H	40	0.05
Brunfeldt and Ulaby 1984					
Wheat	Mid season	2.7	H	>40	0.075
Wheat	Mid season	2.7	V	>40	0.118
Wheat	Mid season	5.1	H	>40	0.065
Wheat	Mid season	5.1	V	>40	0.081
Corn	Mid season	2.7	H	>40	0.049
Corn	Mid season	2.7	V	>40	0.082
Corn	Mid season	5.1	H	>40	0.092
Corn	Mid season	5.1	V	>40	0.085
Soybean	Mid season	2.7	H	>40	0.103
Soybean	Mid season	2.7	V	>40	0.124
Soybean	Mid season	5.1	H	>40	0.124
Soybean	Mid season	5.1	V	>40	0.127
Brunfeldt and Ulaby 1986					
Soybean	WC=2.3	2.7	H and V	0-50	0.05-0.1
Soybean	WC=2.3	5.1	H and V	0-50	<0.05
Pampaloni and Paloscia 1986					
Alfalfa	WC=1.6	9.7	H and V	0-50	0.05
Alfalfa	WC=1.6	37.5	H and V	0-50	0.05
Alfalfa	WC=0.5	9.7	H and V	0-50	0.04
Alfalfa	WC=0.5	37.5	H and V	0-50	0.03
Corn	WC=2.0	9.7	H and V	0-50	0.08
Corn	WC=2.0	37.5	H and V	0-50	0.03
Corn	WC=5.3	9.7	H and V	0-50	0.08
Corn	WC=5.3	37.5	H and V	0-50	0.06
Van de Griend and Owe 1994					
Shrub savannah		6.6	H	52	0.076
Shrub savannah		6.6	V	52	0.091
Wigneron et al. 1995a					
Wheat	WC=[0.5-2.5]	5	H and V	8-38	0.04
Soybean	WC=[0.2-1.5]	5	H and V	8-38	0.11
Wigneron et al. 1996					
Wheat	WC=[0.5-2.5]	5	H	8-58	0.065-0.05
Wheat	WC=[0.5-2.5]	5	V	8-58	0.07-0.115
Wheat	vegetative cycle	5	H	30-70	0.05-0.055
Wheat	vegetative cycle	5	V	30-70	0.07-0.09

Towards higher frequencies

To tackle the vegetation emission at frequencies higher than 20 GHz, few modelling studies are available. To our knowledge, only the studies of Pampaloni and Paloscia (1986) and Wegmüller et al. (1994) use the ω–τ model. From an analysis based on a geometric optics, the latter proposed to extend the use of Equation (10) up to 40 GHz to compute τ by multiplying the right term (Equation 10) by the leaf transmissivity. They also proposed a formulation for ω, but their results were far larger than the fitted values proposed by Pampaloni and Paloscia (1986), an indication that there exists a significant difference between ω and ω^*, see (5)-(6).

Physical approaches were used in Isaac et al. (1989) and Choudhury et al. (1990) up to 40 GHz. However their models were not really validated against controlled data.

One can benefit from available data bases. In a recent study, Prigent et al. (1997) proposed a set of computed emissivities derived from SSM/I observations over different surfaces in Europe and Africa. Measurements were made 36.5 GHz at different dates over savannah using an airborne radiometer during the Hapex-Sahel experiment (Chanzy et al., 1997a). Ground-based multi-frequency measurements were collected over different crops (Chanzy et al. 1999, Mätzler and Wiesmann, 1999). Choudhury (1993) and Prigent et al. (1997) noticed that the emissivity slowly varies with frequency. This means that interpolation can be done from the existing data set to estimate an emissivity at a required frequency.

4.3 Soil emission model

The selected model is the so-called h-Q model, the analytic form of which is given by Equation (9) (Wang and Choudhury, 1981).

Purpose of the model	To compute the soil reflectivity
Applications	Inversion for retrieving soil surface moisture offer the lower boundary condition in vegetation model
Input parameters	- surface roughness parameters h and Q - Soil dielectric constant within the sampling depth -exponent n
Output parameters	T_B at θ_i ($0<\theta_i<60°$)
Expected errors	≈5K over the range of soil moisture after fitting roughness parameters
Accuracy requirements	useful : T_B= 5K Adequate : T_B=3K

To implement the model, one needs to determine the sampling depth and the surface roughness parameters.

Sampling depth

For the sampling depth there is an agreement for the following depths (Wang, 1987, Suresh Raju et al., 1995): 2-5 cm, 1 cm and 0.5 cm for the L, C and X bands, respectively. These values correspond to about 0.1 wavelength. For extreme aridity, such as dry desert sand, the penetration depth can be much larger (on the order of 1 m) than the above values. Dielectric properties and penetration depth of dry Sahara sand were published by Mätzler (1998).

Surface roughness

As far as the surface parameters are concerned, there is no clear relation between h and Q and the surface roughness description (Wang et al. 1983, Chanzy et al. 1994, Haboudane et al.

1996). This is likely a consequence of the error propagation in the fitting algorithm and/or of the existing correlation between h and Q. However, Kerr and Njoku, 1990 proposed a formulation for Q which depends on the frequency f (in GHz) and the standard deviation of the surface height σ:

$$Q=0.35(1-\exp(-0.6\sigma^2 f) \tag{14}$$

4.4 Vegetation dielectric constant

Ulaby and El Rayes (1987) model:

Purpose of the model	To compute the dielectric constant of the vegetation elements within the 0.2-20 GHz range
Model variable	Frequency
Input parameters	- the gravimetric moisture of the vegetation (kg/kg) - the bulk density of the dry vegetation material (Kg/m^3) - the ionic conductivity of the free water solution - temperature
Output parameters	The dielectric constant (real and imaginary parts)
Expected errors	+/- 5% (Ulaby and el Rayes, 1987

Mätzler (1994a) model:

Purpose of the model	To compute the dielectric constant of the leaves within the 1-100 GHz range. This model is the only one available at f>20 GHz
Model variable	Frequency
Input parameters	-the gravimetric moisture of the vegetation (kg/kg) -temperature
Output parameters	The dielectric constant (real and imaginary parts)

4.5 Soil dielectric constant

The selected model is the Dobson et al. (1985) semi-empirical model:

Purpose of the model	To compute the dielectric constant of the soil in the 1.4-18 GHz range. This model accounts for bound and free water depending on soil type.
Model variable	Frequency
Input parameters	- Soil dry bulk density - Solid density - Soil salinity - sand fraction - clay fraction - Temperature
Output parameters	The soil dielectric constant (real and imaginary parts)
Expected error	≈1 for ε' =0.5 for ε'' (Dobson et al. 1985)

4.6 Effective temperature

The effective emission temperature (T_e) depends on the vertical temperature profiles of the soil and the canopy and a weighting function, which accounts for the contribution of each layer. To model the microwave emission, T_e is an important term to estimate since it can strongly vary (up to 50 K) during diurnal and/or annual climatic cycles.

The most common way is to use the skin temperature (T_s) delivered by thermal infrared sensors. However, the major drawbacks from these approaches are the availability of T_s at the time of the microwave observation (requirement of cloud free condition), the significance of T_s in comparison to T_e. Choudhury et al., (1982) have shown that T_s is poorly related to T_e at frequencies lower than 10 GHz.

For well watered surface, T_e is close to the air temperature (T_a) during the day and T_a is therefore a good estimator of T_e (Chanzy et al. 1997b). In dry condition, T_a remains a good estimator of T_e in the morning two hours after the beginning of the surface heating by solar radiation (Gaudin, 1994). In all cases T_a cannot be used to estimate T_e during the night period since the nocturnal surface cooling induces strong air temperature gradients near the surface which are also governed by the atmospheric conditions (humidity, cloudiness).

The major difficulties to estimate T_e come from the dry bare soils where the variations of T_e are the strongest. Choudhury et al., (1982) proposed a model based on T_s and a deep temperature T_d. Chanzy et al. (1997b) proposed a model to overcome the T_s availability problem by using either T_a or the microwave brightness temperature at X band and V polarisation, to estimate the near surface temperature.

T_e can also be estimated using a combination of T_B measurements. McFarland et al. (1990), Hiltbrunner and Mätzler (1994), Njoku (1994) proposed empirical algorithms based on multichannel measurements. Calvet et al. (1994), Calvet et al., (1996), Calvet and Jullien (1996) estimate T_e by an inversion of a microwave emission model using dual polarisation and multifrequency measurements.

5 Conclusions and recommendations

The effort in physical modelling of the microwave emission should be pursued. We need theoretical tools to understand what the contributions of the different surface elements are to the total microwave emission. Moreover, the future inversion algorithms (i.e. the algorithms developed to derive surface geophysical parameters from passive microwave observations) will be based on a microwave multi-configuration approach. We need models that simulate consistent sets of brightness temperatures at the different configurations of measurements in order to optimise the inversion algorithms.

Most of the studies were done at low frequencies (<20 GHz) or at 37GHz. The continuity of the microwave emission signature should be further analysed to estimate the microwave emission at the other frequencies, especially at the frequencies of atmospheric sounders.

The discrepancies between model and experimental results, the variability in the fitted model parameters may be due to measurement errors or due to inadequacies in the selected models. Efforts in statistical analysis should be made to evaluate errors of measurements, models, parameter calibration and inversion algorithms. Measurements accuracy requirements should be established from such analysis.

We need reference sets of data that reach the above measurement accuracy requirements. The accuracy of the existing data should be evaluated. Measurement quality must be the priority for the future measurement campaigns.

Scaling issues need to be developed. Due to the pixel size, complex mixed pixels will be the common data delivered by microwave radiometers aboard satellites. An effort should be done to take benefit from the multi-configuration possibilities (polarisation difference, angular variations, frequency signature) of the future microwave radiometers since the different radiometric measurements are delivered at the same scale and "orthogonal" information on the surface description may be retrieved from combination of measurements.

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