Soil Moisture Prototype Processor Development (SMPPD)

PRELIMINARY REPORT FOR FORESTS

A LARGE SCALE APPROACH TO ESTIMATE L BAND EMISSION FROM FOREST COVERED SURFACES

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ACRONYMS
Preliminary Report for Forests

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1. INTRODUCTION

This document describes the approach adopted to estimate the emissivity of main forest categories, at L band, and for a range of incidence angles useful for SMOS. The selected procedure takes into account several different requirements.

- The description of the emission process should be physically sound;
- The outputs must be given in a simple way, suitable to be included in the general SM retrieval algorithm;
- The available inputs are necessarily limited and rough, due to the large scale of available information.

For each grid node, inputs derived by ECOCLIMAP are Leaf Area Index (LAI) and broad forest category. This information, in conjunction with allometric equations available in the literature and a large scale averaging process, provides geometrical variables required by a discrete RT model. The model, on its turn, predicts the emissivity for several values of soil moisture and incidence angles, at both polarizations. Finally, a simple parametrization gives equivalent values of optical depth and albedo as output.

The electromagnetic model developed at Tor Vergata University is adopted [1], [2]. It is based on a discrete approach. The forest is subdivided into three main components: soil, trunks and crown (Figure 1). Each component is described in geometrical and dielectric aspects. In summary, several inputs are required: soil moisture, soil roughness parameters, density and geometry of trunks, branches and leaves, permittivity of trunks, branches and leaves. Soil moisture is an independent variable. Realistic assumptions are made for soil roughness variables. Vegetation variables are derived by using the procedure described in Sections 2, 3 and 4.
Figure 1. Vegetation scheme used by model

ECOCLIMAP database is a basic source, from which LAI and forests species information are obtained. Information about density and geometry of trunks, branches and leaves is then derived. To obtain the input data required by the Tor Vergata model (TVM) it is necessary to use also a set of allometric equations [3], which link a simple parameter, such as the trunk diameter at breast height (Dbh), with dry biomass of the entire tree and its components: roots, branches, trunks and leaves. Some species treated in [3] are typical of North America, but other ones, such as pine, fir or oak, are much more common and present in many other countries of the world. Neither information contained in [3] nor ECOCLIMAP one are sufficient by themselves, but from a merge of both data sources it is possible to get a systematic description of many kinds of forests. In particular, allometric equations are used for a single tree, while LAI is used to estimate the number of trees per unit surface.

The modelling work may be subdivided into 3 main steps, which will be described in next Sections:

- Single tree description, using allometric equations for different forest kinds
- Averaging and merging with LAI information, in order to provide inputs to TVM
Running the TVM

The following forest species are considered:

- Needleleaf
- Deciduous broadleaf
- Evergreen broadleaf (including Tropical forests)
- Mixed forest
- Woodland
2. 2. SINGLE TREE DESCRIPTION

For a single tree belonging to a given forest species, the allometric equations of [3] provide several important variables as a function of Dbh. Figure 2 shows the trends of total dry biomass (in kg)

![Graph showing total biomass for various forest species](image)

**Figure 2: Total biomass for several kind of coniferous and Hardwood species [3]**

for different Softwood and Hardwood species. Since the sensitivity to soil moisture variations depends strongly on total biomass, the information of Figure 2 is of fundamental importance. Other important information contained in [3,4], regards the subdivision of total biomass. Indeed, another set of allometric equations allows us to assess how total biomass is subdivided into components. Figure 3 shows the percentages, with respect to total dry biomass, of stem (trunk), branches and foliage dry biomass, for both hardwood and softwood forest typologies.
The information content of Figure 3 is essential for TVM, because it uses a discrete approach to describe the electromagnetic interactions with single vegetation components.

However, the information contained in [3] is not sufficient to develop a complete growth routine, because all the available data are referred just to a single tree, whereas the model requires information about the entire forest, or a part of it. Indeed leaves, branches and stems densities are obtained by merging LAI information, available in ECOCLIMAP dataset, with allometric equations of [3], as it is shown in the next Section.
3. USING ECOCLIMAP LAI INFORMATION

The passage from “single tree” level to forest level requires two fundamental steps:

- To adopt a distribution of Dbh values within the considered forest plot.
- To establish a realistic correspondence between LAI and forest density

Within an extended forest plot, assuming a single Dbh value is not realistic. Therefore, a distribution is taken, in such a way as to have:

\[
N_p(Dbh_i) = N_{tot} \int_{dbh_i}^{dbh_{i+1}} f_{Ntr}(dbh_i) \cdot \delta(Dbh) \tag{1}
\]

where:

- \(N_{tot}\) is the total number of trees per unit of surface [ha^-1]
- \(f_{Ntr}\) is the selected distribution function for Dbh parameter
- \(N_{tr}(Dbh_i)\) is the number of trees per unit of surface with diameter included in the range \(Dbh_i - Dbh_{i+1}\) [ha^-1]

Typical distribution functions of Dbh are given in [5]. Figure 4 shows the trends for three common coniferous species: Douglas-fir, Ponderosa pine and Western white pine.

![Figure 4: Distribution function for three coniferous species [5]](image-url)
Other distributions are available in the literature for different species [5].

At this point, information about LAI and leaves dry biomass is used. The first step aims to link the LAI to leaves dry biomass (LDB) per unit of underlying surface. This is accomplished by fitting the measured data given in Cannel [6] (See Figure 5).

![Figure 5: Relation between LAI values and dry leaves for Hardwood and Softwood species](image)

A linear relationship between LAI and LDB is assumed. A regression analysis gives:

Hardwood : \( \text{LAI} = 1.4889 \times \text{LDB} \)  \( \text{(2)} \)

Softwood : \( \text{LAI} = 0.4314 \times \text{LDB} \)  \( \text{(3)} \)

By inversion of (2) and (3), the total forest LDB may be derived as a function of LAI. Once the forest LDB is known, a relationship with tree density may be established with the following considerations. A typical natural forest is composed of trees of different age and dimension, and this is represented by a distribution of Dbh. The range of Dbh values is subdivided into N discrete intervals. Therefore, the total LDB may be expressed as:

\[
\text{LDB} = \sum_{i=1}^{N} \text{LDB}_i = \sum_{i=1}^{N} \text{LDB}(\text{Dbh}_i) \cdot N_{\text{tr}}(\text{Dbh}_i) = \int_{\text{Dbh}_{\text{min}}}^{\text{Dbh}_{\text{max}}} f(N_{\text{tr}}(\text{Dbh})) \cdot \delta(\text{Dbh})
\]  \( \text{(4)} \)
where:

- **LDB_i** is the dry biomass (per unit of underlying surface) of leaves [t/ha], for all the trees with Dbh values within the i-th interval. Information about the total dry biomass of leaves for a single tree can be obtained from [3,4];
- **LDB(Dbhi)** is the dry biomass [t] due to the trees with Dbh values within the i-th interval;
- \( N_{tot} \int_{dbhi}^{dbhi+1} f_{N_{tot}}(Dbh) \cdot \delta(Dbh) \) represent the number of trees [ha^-1] with Dbh within the i-th interval (i.e. with diameter included in the range Dbhi - Dbhi+1).

At this point allometric equations giving total dry biomass of single trees and component subdivision, as a function of Dbh, are used. For this scope, it is important to have the maximum yearly value of LAI, corresponding to full leaf development, and derive LDB values corresponding to it from (2) and (3). For a given forest species, we have [3]:

\[
DB_{Tot} = e^{(b_0 + b_1 \ln(Dbhi))} \quad DB_x = DB_{Tot} e^{(a_0 - a_1/Dbhi)}
\]

(5)

\(DB_{Tot}\) is the total tree dry biomass, while \(DB_x\) is the component referred to leave, stems or branches.

\(b_0\) and \(b_1\) coefficients depend on tree species, whereas \(a_0\) and \(a_1\) depend also on the considered component.

Using these equations for each Dbh interval, the value of \(LDB(Dbhi)\), to be used in (4), is computed. Eq. (4) is then used to compute \(N_{tot}\) and, hence, absolute values of \(N_{av}(Dbhi)\).

In this way, dry biomass values for trunk, branch and leaf, may be converted from single tree values into values per unit of underlying surface.

Figure 6 shows examples of biomass components, computed as a function of LAI. Pine forest data are represented with continuous lines, whereas Douglas-fir data are in dotted lines.
Figure 6: Dry biomass components as a function of LAI for Douglas-fir and Pine forests.

Differences are appreciable.
Figure 7: Douglas – fir and Pine numbers of trees per hectar, for different values of LAI
4. GEOMETRICAL AND MOISTURE VARIABLES

The procedure described in the previous Sections gives the biomass of forest components (in [t/ha]) for each Dbh interval. Since the TVM needs geometrical dimensions and moistures as input, a suitable conversion procedure must be established. First of all, volumes of leaves, branches and trunks, per unit of underlying area, are computed.

Since vegetation is composed by water and dry matter, we can establish, for each tree component, connections among water component, dry and fresh matter:

\[ W_w = VM \cdot W \]
\[ W_D = (1 - VM) \cdot W \]
\[ W_w = \frac{VM}{1 - VM} W_D \]

(6)

where:

- **VM (Vegetation moisture)** is the fraction of water by weight (with respect to total fresh matter)
- **\( W_w \)** is the water weight [g/ha]
- **\( W_D \)** is the dry matter weight [g/ha]
- **\( W \)** is the fresh matter weight [g/ha]

For each component, the volume may be computed as:

\[ V = V_D + V_w = \frac{W_D}{\rho_D} + \frac{W_w}{\rho_w} = \left( \frac{1}{\rho_D} + \frac{1}{\rho_w - VM} \right) W_D + \left( \frac{1 - VM}{\rho_D} + \frac{VM}{\rho_w} \right) W \]

(7)
where:

- \( V \) and \( \rho \) are fresh matter volume \([\text{m}^3/\text{ha}]\) and effective density \([\text{g}/\text{m}^3]\)
- \( V_W \) and \( \rho_W \) are water volume \([\text{m}^3/\text{ha}]\) and density \([\text{g}/\text{m}^3]\)
- \( V_D \) and \( \rho_D \) are dry matter volume \([\text{m}^3/\text{ha}]\) and density \([\text{g}/\text{m}^3]\)

\[
W = \rho V \quad \Rightarrow \quad \rho = \frac{\rho_D \rho_W}{(1 - VM) \rho_W + \rho_D VM}
\]

(8)

Since the dry matter is given by \([3,4]\), we can obtain the fresh one and then the volumes by using the previous relations and assuming \( VM \) to be known. Typical values for dry matter density are 0.3 \(\text{g}/\text{m}^3\) for leaves and 0.4 \(\text{g}/\text{m}^3\) for branches and trunks, whereas the corresponding typical values of vegetation moisture are 50% and 60%, respectively.

![Figure 8: Stems Height versus Dbh values](image.png)
By the knowledge of stem volume, it is possible to estimate the stem height as a function of Dbh. Results for Douglas-fir and Pine are shown in Figure 8. An appreciable difference between two coniferous species is observed.

The overall branch volume may be obtained using the same procedure as for leaves, given by equations (6) – (8). A priori knowledge of $V_M$ will be supposed also in this case. The overall branch volume is subdivided into cylindrical branches of different diameters. To this aim, we assume the maximum branch diameter to be equal to Dbh/3 [7]. The following function is adopted to reproduce the branches diameter distribution [7]:

$$P(\beta) = A \cos^n \left( \frac{\pi}{2} \frac{(\beta - \beta_m)}{(\beta_0 - \beta_m)} \right) \quad \beta_1 \leq \beta \leq \beta_2$$

(9)

- $P(\beta)$ represents the density of probability of a random variable to be equal to $\beta$
- $\beta_m$ is the value of the random variable with highest probability of occurrence.
- $\beta_0$ is the value of the random variable with the lowest probability of occurrence.
- $\beta_1$ and $\beta_2$ define the function range.

The relative volume of branches within a diameter range is obtained by integrating the fit function (9) between two diameters, with the appropriate model parameters.

Figure 9 represents the branch diameter distribution functions for several Dbh values. In order to reproduce the natural curvature of branches, all branches are subdivided into elements 50 cm long, similarly to the approach adopted in [7]. For the time being, a random branch orientation distribution is adopted. This will be kept for smaller branches. Other distributions will be considered for larger branches and the effect on the overall emissivity will be evaluated.
As far as leaves are concerned, the model uses as input LAI and geometrical parameters, i.e. radius and thickness for broadleaf, radius and length for needleleaf. These parameters are available in [7,8,9] for various species. In order to include leaf effects, a monthly sampling of LAI should be sufficient.

In summary, the overall emissivity simulation algorithm is structured as indicated below:

**Inputs:**
- Soil parameters
- Forest main category,
- LAI,
- Leaf (needle) dimensions,
- Gravimetric moisture of trunks, branches, leaves
- Dry matter density of trunks, branches, leaves

For each Dbh value:
- Compute \( LDB(Dbh) \) and \( N_{tot} \) as a function of LAI using (1) -- (4)
- Compute trunk volume per unit area and trunk dimensions using (5) - (7) for trunks
- Compute branch volume per unit area using (5) – (7) for branches
- Establish maximum branch diameter as a function of Dbh and apply branch diameter distribution of Figure 8
- Compute leaf volume per unit area using (5) – (7) for leaves
- Use information about leaf dimensions and compute number of leaves per area
- Using TVM, compute scattering and absorption of all forest elements of the considered Dbh category

End for

Combine contributions from all Dbh categories

Compute overall emissivity
5. EMISSIVITY RESULTS

In this Section, preliminary simulation results are reported. For soil, height standard deviation and correlation length have been assumed to be equal to 1.5 cm and 5 cm, respectively. Simulations have been made at L band (1.4 GHz) and for V and H polarizations. Single emissivity and transmissivity components are also reported.

5.1 NEEDLELEAF

Figure 10 and Figure 11 show overall emissivity and single components trends vs. observation angle at V and H polarization, with a Volumetric Soil Moisture Content (SMC) equal to 10%.

Figure 10: V polarization emissivity vs observation angle for a SMC = 10%
The same trends, but for a SMC equal to 20%, are given in Figure 12 and Figure 13. Figures show a low contribution from trunks, although they contain most of the biomass (see Figure 3)
Figure 12: V polarization emissivity vs observation angle for a SMC = 20%

Figure 13: H polarization emissivity vs observation angle for a SMC = 20%
In order to describe completely the effects of single forest components, also transmissivity values are represented in Figure 14 and Figure 15. A stronger contribution to attenuation comes from branches, a weak contribution comes from needles and trunks contribution is even lower (i.e. trunk transmissivity is close to the unity).

![Figure 14: Transmissivity for V polarization vs observation angle](image)

**Figure 14: Transmissivity for V polarization vs observation angle**
Figure 15: Transmissivity for H polarization vs observation angle

Figure 16 and Figure 17 allow us to estimate the sensitivity with respect to soil moisture variations, which is a key issue for SMOS. The emissivity trends as a function of SMC are reported for angles of $25^\circ$ and $45^\circ$.

Figure 16: Emissivity at V and H polarization vs SMC for $\theta$ equal to $25^\circ$
As expected, the sensitivity is better for smaller angles, due to the lower value of attenuation, but some sensitivity is observed also at 45° and for the higher values of LAI.

5.2 HARDWOOD

Results obtained for Hardwood forests are shown in this Section. Figure 18 and Figure 19 show overall emissivity and single components trends vs. observation angle at V and H polarization, with a Volumetric Soil Moisture Content (SMC) equal to 10%.

**Figure 17: Emissivity at V and H polarization vs SMC for θ equal to 45°**
Figure 18: V polarization emissivity vs observation angle for a SMC = 10%

Figure 19: H polarization emissivity vs observation angle for a SMC = 10%
The same trends, but for a SMC equal to 20%, are given in Figure 20 and Figure 21. Similarly to Needleleaf forest case, contribution from trunks is low.

**Figure 20: V polarization emissivity vs observation angle for a SMC = 20%**
In order to describe completely the effects of single forest components, also transmissivities are represented in Figure 22 and Figure 23.
Figure 23: Transmissivity for H polarization vs observation angle

Figure 24 and Figure 25 represent the sensitivity with respect to soil moisture variations. The emissivity trends as a function of SMC are reported for angles of 25° and 45°.
Similarly to Needleleaf case, some sensitivity is observed also at 45° and for the higher values of LAI.
6. PARAMETRIZATION

Simulated emissivity values described in Section 5 have been used to obtain the equivalent values of albedo and optical depth as a function of LAI. This “parametrization” has been made following two steps.

- First of all, equations of ATBD for soil reflectivity have been considered. The constants $Q$, $N$ and $h$ have been fitted in order to represent the reflection properties computed by TVM for the rough soil assumed by us (i.e. with height standard deviation equal to 1.5 cm and correlation length equal to 5 cm). In order to have a statistically significant fitting, several SMC values, between 5% and 30% and several angles, between 5° and 55°, have been considered.

- Then, equations of ATBD for vegetation emissivity have been taken. For several values of LAI, brightness temperatures values predicted by ATBD formulas have been compared against values simulated by TVM for the same physical temperature. Using, again, several SMC values, between 5% and 30% and several angles, between 5° and 55°, the values of $\omega$ and $\tau$ producing the best fit have been computed.

Results of these computations provide the equivalent values of albedo and optical depth as a function of LAI. It must be remarked that the maximum yearly value of LAI, named LAI_max in ATBD, must be taken.

Three kinds of fitting have been done: V polarization, H polarization, both polarizations. Parametrization results obtained by using both polarizations are shown in Figure 26. Green lines show the trends of optical depth as a function of LAI. Blue lines represent albedo trends. As expected the trend of optical depth is almost linear. Also RMS values, in emissivity units, are reported.
Figure 26: Parametrization results for Hardwood and Softwood forests

Because of the quasi-linear trend of the optical depth and the small variation of the albedo, the parameters of a pair of relationships such as

\[
\tau = b' \text{LAI}_{\text{max}} + b'' \\
\omega = \text{cost}
\]

have been computed, by a fitting over results of the physical model.

Fitted values are:

**Hardwood**

- \( b' = 0.186 \)
- \( b'' = 0.001 \)
- \( \omega = 0.094 \)
Results indicate differences between Coniferous (Softwood) and Deciduous Broadleaf (Hardwood) forests not to be critical. Detailed allometric equations for other forest kinds are scarcely available. Therefore, we suggest to adopt the parameters indicated below.

- Mixed forests: adopt intermediate parameters between Coniferous and Deciduous Broadleaf:
  - $b' = 0.188$
  - $b'' = 0.003$
  - $\omega = 0.083$

- Evergreen Broadleaf: adopt the same parameters of Deciduous Broadleaf. Higher values of $\tau$, due to higher values of LAI_max, are expected.

- Woodland: adopt the same parameters of Deciduous Broadleaf. Lower values of $\tau$, due to lower values of LAI_max, are expected.