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POLSCAT

UCL POLARIMETRIC RADIATIVE TRANSFER MODEL

USER MANUAL

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Contents

1 Introduction

A polarimetric radiative transfer model, has been developed at UCL and implemented into a computer programme, for the simulation of polarimetric radar, or SAR, observation of rough soils, vegetated areas and forested areas. It can be applied to a number of land scenes, including : cultivations, low vegetation, bush, savannah, forests composed of coniferous or decideous trees. It is a fully polarimetric model, based on the radiative transfer assumption. It allows to compute the complete Mueller matrix from which the backscattering coefficients in various polarisations, or the complete polarimetric signature, can be obtained.

A summary of the model is provided in section 2 and some basic relationships in radar polarimetry are recalled in section 3. This will allow the user to make an efficient use of the model. In section 4, a detailed description is provided of all required input parameters. This is followed by an example of input file. Finally, explanations are provided on the execution of the programme, and on the output data.

The user should be aware that the validity of the results produced by the model will be highly dependent on the completeness, accuracy and validity of the input data. Obtaining all data required to properly modelise complex targets such as vegetated soil or forests, is probably the most challenging task.

2 Summary of the UCL polarimetric radiative transfer model

A polarimetric radiative transfer model was previously developed for forested areas but applied only to coniferous forests [11]. The model has been extended to any kind of forest and to low vegetation covers, such as savanna [6]. It starts from existing scattering models for plates and cylinders and for the soil, that have been carefully reviewed and updated. The forest is represented by three superposed layers : ground, trunks and canopy. For low vegetation, only two layers are considered : ground and vegetation cover.

The model developed at UCL provides more flexibility than other available models : it includes size distributions, it accounts for the reciprocity effect, it allows vertical distributions within the canopy and provides a more precise description of the vegetation components. It is a fully polarimetric radiative transfer model that accounts for the enhancement effect. It allows to calculate the complete scattered Stokes vector, and therefore the complete polarimetric response of a distributed target. The various scattering mechanisms considered are (see figure1) : the direct canopy contribution **DC**, the canopy ground contribution **CG**, the ground canopy ground contribution **GCG**, the trunk ground contribution **TG**, the direct ground contribution **DG**, and the dubble canopy contribution **DC2** (double bounce within the canopy). However, since this last mechanism requires a very long computation time and provides in the most cases a rather low contribution, it is not yet included in the programme (and it is not represneted in figure 1).

For the soil, we have implemented the so-called Integral Equation Method (IEM) developed by Fung and colleagues [3]. The surface scattering model requires as input : the geometric properties of the surface (rms height and slopes), and the electric properties of the soil, i.e. the permittivity, directly related to soil moisture and water salinity.

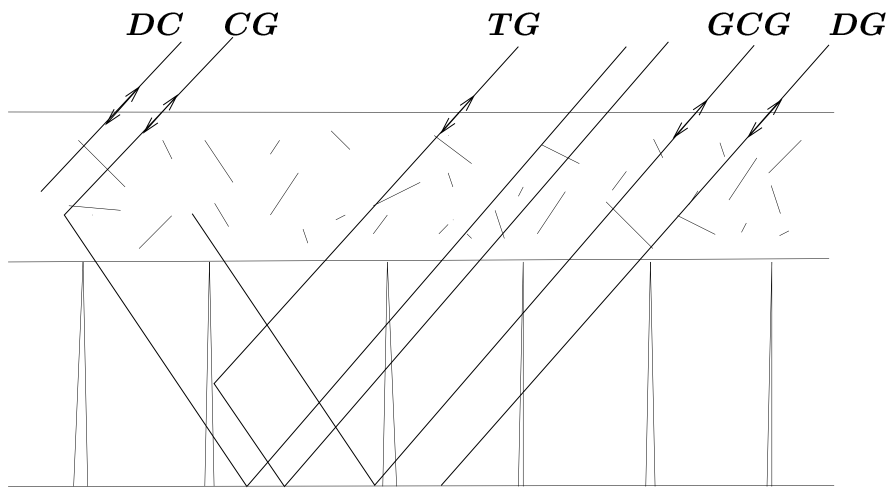

Figure 1: First order contributions for the radiative transfer approach. The symbols, taken from the litterature have the following meaning : ***DC*** for "Direct Crown backscattering", ***GCG*** for "Ground Crown Ground backscattering", ***CG*** for "Crown Ground backscattering", ***TG*** for "Trunk Ground backscattering" and ***DG*** for "Direct Ground backscattering".

Our volume electromagnetic scattering model is based on the radiative transfer theory. It is a polarimetric approach and handles concrete objects such as branches, leaves and trunks. The theory is based on the fundamental assumption that the scattering processes from the various constituents are incoherent, and that consequently powers (and more generally Stokes parameters) add up. However caution has been taken to handle properly particular situations of backscattering enhancement, related to double bounce cases. The canopy is represented by a distribution of branches and leaves, or needles, with random dimensions and orientations. The branches are modelised by circular cylinders, the leaves by circular or elongated flat dielectric plates, and the needles by thin circular cylinders. The trunks are modelised either by dielectric circular cylinders or by dielectric circular cones, with a distribution of inclination angles with respect to the vertical.

3 Basic relationships for radar polarimetry

A polarimetric radar provides a complete information on the observed target, by measuring the backscattered signal in amplitude and phase for two orthogonal polarisations. The target is described by a so-called *Mueller matrix*. Two equivalent formulations are in use. One is known as the Mueller matrix, the other is the modified Mueller matrix, depending on the definition of the Stokes vector. A summary of basic radar polarimetry can be found in Guissard [5] and more details are provided in the textbook by Ulaby and Elachi [14].

Let an incident field $\vec{E}^i$ fall on a target. A scattered field $\vec{E}^s$ is generated and the two fields are related together by the diffraction matrix of the target. Let $\vec{E}^i$ be represented by two orthogonal components 1 and 2 in a plane perpendicular to the incident direction $\hat{\imath}$ (Jones vector), and similarly for $\vec{E}^s$ with respect to the scattering direction $\hat{s}$; $\hat{\imath}$ and $\hat{s}$ are unit vectors. We can write

$$\begin{pmatrix} E_1^s \\ E_2^s \end{pmatrix} = \begin{pmatrix} f_{11} & f_{12} \\ f_{21} & f_{22} \end{pmatrix} \begin{pmatrix} E_1^i \\ E_2^i \end{pmatrix} \tag{1}$$

where the elements f_{ij} depend on the characteristics of the target, on the directions $\hat{\imath}$ and $\hat{s}$, and on the distance r to the observer. This transformation matrix for a plane wave is called the *Jones matrix* by the optical community [9]. In the following and in the program *polscat*, the subscripts 1 and 2 will correspond respectively to horizontal H and vertical V polarisations.

In most practical situations one is interested in the far field. In that case, the scattered wave has the general behavior of a spherical wave and it is convenient to extract the factor

$$G(r) = \exp(-jkr) \,/\, kr \tag{2}$$

and to write [18]

$$\begin{pmatrix} E_1^s \\ E_2^s \end{pmatrix} = G(r) \begin{pmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{pmatrix} \begin{pmatrix} E_1^i \\ E_2^i \end{pmatrix} \tag{3}$$

where

$$\mathbf{S} = \begin{pmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{pmatrix} \tag{4}$$

is the scattering matrix, also sometimes called the *Sinclair matrix*. Note that we are using the radioelectrician convention for the propagating wave, i.e. a $\exp(+j\omega t)$ factor is assumed. With this convention the complex permittivity has a *negative* imaginary part.

In the form (3), the scattering matrix is nondimensional and independent of the distance r. Various normalisations of $\mathbf{S}$ are found in the literature, as for example ([7, chapter 2], [2, p.34], [10])

$$\frac{\exp(-jkr)}{r} \;\text{(a)} \quad \text{or} \quad \frac{\exp(-jkr)}{jkr} \;\text{(b)} \quad \text{or} \quad \frac{\exp(-jkr)}{(\sqrt{4\pi})r} \;\text{(c)} \tag{5}$$

With the definition (2), the elements of $\mathbf{S}$ are dimensionless and no extra phase shift is introduced that is not related to the target contribution. Note that the program *polscat* has been written using the definition (5.a).

The *Stokes vector* is a four elements vector which contains the information on the power density and the polarisation of an electromagnetic wave. It is defined by the following column matrix

$$\mathbf{J} = \begin{pmatrix} I \\ Q \\ U \\ V \end{pmatrix} = \begin{pmatrix} \langle E_1 E_1^* \rangle + \langle E_2 E_2^* \rangle \\ \langle E_1 E_1^* \rangle - \langle E_2 E_2^* \rangle \\ 2\,\Re\,\langle E_1 E_2^* \rangle \\ -\,2\,\Im\,\langle E_1 E_2^* \rangle \end{pmatrix} \tag{6}$$

Another form called the *modified Stokes vector* is also of frequent use and is defined as

$$\mathbf{J}_m = \begin{pmatrix} I_1 \\ I_2 \\ U \\ V \end{pmatrix} = \begin{pmatrix} \langle E_1 E_1^* \rangle \\ \langle E_2 E_2^* \rangle \\ 2\,\Re\,\langle E_1 E_2^* \rangle \\ -\,2\,\Im\,\langle E_1 E_2^* \rangle \end{pmatrix} \tag{7}$$

Only the first two elements are different. In the Stokes vector they are equal to the total power (within a constant factor) and to the difference of powers in the two polarisations. In the modified Stokes vector they are equal to the powers in the two polarisations.

The Stokes vector $\mathbf{J}$ and the modified Stokes vector $\mathbf{J}_m$ are related by the *permutation matrix* $\mathbf{P}_{12}$

$$\mathbf{J} \;=\; \mathbf{P}_{12}\,\mathbf{J}_m; \qquad \text{with} \qquad \mathbf{P}_{12} \;=\; \begin{pmatrix} 1 & 1 & 0 & 0 \\ 1 & -1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}. \tag{8}$$

Conversely we have

$$\mathbf{J}_m \;=\; \mathbf{P}_{12}^{-1}\,\mathbf{J}; \qquad \text{with} \qquad \mathbf{P}_{12}^{-1} \;=\; \begin{pmatrix} 0.5 & 0.5 & 0 & 0 \\ 0.5 & -0.5 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}. \tag{9}$$

When the wave is scattered by a target, the scattered Stokes vector $\mathbf{J}^s$, or the scattered modified Stokes vector $\mathbf{J}^s_m$, is given in terms of the incident vector $\mathbf{J}^i$, or $\mathbf{J}^i_m$, by

$$\mathbf{J}^s_{(m)} \;=\; \mathbf{M}_{(m)}\,\mathbf{J}^i_{(m)} \tag{10}$$

where $\mathbf{M}$ is the Mueller matrix, and $\mathbf{M}_m$ is the modified Mueller matrix.

Using the scattering or *Sinclair* matrix $\mathbf{S}$, the Mueller matrix is expressed in terms of $\mathbf{W}$, the direct product of $\mathbf{S}$ and $\mathbf{S}^*$, as follows [5]

$$\mathbf{M} = \mathbf{R}\,\mathbf{W}\,\mathbf{R}^{-1} \tag{11}$$

with

$$\mathbf{R} \;=\; \begin{pmatrix} 1 & 0 & 0 & 1 \\ 1 & 0 & 0 & -1 \\ 0 & 1 & 1 & 0 \\ 0 & j & -j & 1 \end{pmatrix} \tag{12}$$

and

$$\mathbf{W} \;=\; \mathbf{S} \otimes \mathbf{S}^* \;=\; \begin{pmatrix} S_{11}S_{11}^* & S_{11}S_{12}^* & S_{12}S_{11}^* & S_{12}S_{12}^* \\ S_{11}S_{21}^* & S_{11}S_{22}^* & S_{12}S_{21}^* & S_{12}S_{22}^* \\ S_{21}S_{11}^* & S_{21}S_{12}^* & S_{22}S_{11}^* & S_{22}S_{12}^* \\ S_{21}S_{21}^* & S_{21}S_{22}^* & S_{22}S_{21}^* & S_{22}S_{22}^* \end{pmatrix} \tag{13}$$

In order to get the explicit form of the modified Mueller matrix $\mathbf{M}_m$, one first expresses (10) in terms of $\mathbf{J}_m$ giving

$$\mathbf{P}_{12}\,\mathbf{J}^s_m \;=\; \mathbf{M}\,\mathbf{P}_{12}\,\mathbf{J}^i_m$$

and we get the modified Mueller matrix as

$$\mathbf{M}_m \;=\; \mathbf{P}_{12}^{-1}\,\mathbf{M}\,\mathbf{P}_{12}; \tag{14}$$

Using the expression (11) of $\mathbf{M}$, we have

$$\mathbf{M}_m \;=\; \mathbf{P}_{12}^{-1}\,\mathbf{R}\,\mathbf{W}\,\mathbf{R}^{-1}\,\mathbf{P}_{12} \;=\; \mathbf{R}_m\,\mathbf{W}\,\mathbf{R}_m^{-1} \tag{15}$$

with

$$\mathbf{R}_m = \mathbf{P}_{12}^{-1}\,\mathbf{R} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 1 & 1 & 0 \\ 0 & j & -j & 1 \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 0.5 & -0.5j \\ 0 & 0 & 0.5 & 0.5j \\ 0 & 1 & 0 & 0 \end{pmatrix}^{-1} . \tag{16}$$

Replacing (16) into (15) finally yields $\mathbf{M}_m$

$$\mathbf{M}_m = \begin{pmatrix} |S_{11}|^2 & |S_{12}|^2 & \Re(S_{11}S_{12}^*) & \Im(S_{11}S_{12}^*) \\ |S_{21}|^2 & |S_{22}|^2 & \Re(S_{21}S_{22}^*) & \Im(S_{21}S_{22}^*) \\ 2\Re(S_{11}S_{21}^*) & 2\Re(S_{12}S_{22}^*) & \Re(S_{11}S_{22}^* + S_{12}S_{21}^*) & \Im(S_{11}S_{22}^* + S_{21}S_{12}^*) \\ -2\Im(S_{11}S_{21}^*) & -2\Im(S_{12}S_{22}^*) & -\Im(S_{11}S_{22}^* + S_{12}S_{21}^*) & \Re(S_{11}S_{22}^* - S_{12}S_{21}^* \end{pmatrix} \tag{17}$$

For a random target, all products of the form $S_{mn}S_{pq}^*$ must be replaced by their average values $< S_{mn}S_{pq}^* >$.

We note that the four elements of the upper left corner in the modified Mueller matrix are directly proportional to the four backscattering coefficients σ_{pq} ($p = H, V$; $q = H, V$), given that the subscripts $(1, 2)$ of the scattering matrix $\mathbf{S}$ correspond to horizontal and vertical polarisation respectively. With the definition (5.a) of the Green's function, we have

$$\sigma_{pq} = 4\,\pi\,|S_{pq}|^2 \tag{18}$$

or expressed in decibels

$$\sigma_{pq}\,(\mathrm{dB}) = 10\,log10(4\,\pi\,|S_{pq}|^2) \tag{19}$$

As the electromagnetic wave is propagating within a lossy and scattering medium, it is attenuated. The corresponding attenuation of the Stokes vector is given by the extinction matrix $\kappa_{\mathbf{e}}$. Its expression can be found in [14, p.140], where however the optician convention is used, which is based on the $\exp(-i\omega t)$ time factor. With the radioelectrician convention and the Green's function (5.a), we have

$$\kappa_{\mathbf{e}} = -\frac{2\,\pi}{k} \begin{pmatrix} 2\Im(S_{11}) & 0 & \Im(S_{12}) & \Re(S_{12}) \\ 0 & 2\Im(S_{22}) & \Im(S_{21}) & -\Re(S_{21}) \\ 2\Im(S_{21}) & 2\Im(S_{12}) & \Im(S_{11}+S_{22}) & -\Re(S_{11}-S_{22}) \\ -2\Re(S_{21}) & 2\Re(S_{12}) & \Re(S_{11}-S_{22}) & \Im(S_{11}+S_{22}) \end{pmatrix} \tag{20}$$

The *Kennaugh matrix* $\mathbf{K}$ is the tool for the calculation of the radar received power for any specified polarisations at emission and reception [5]. It is related to the Mueller matrix $\mathbf{M}$ by

$$\mathbf{K} = \mathbf{U}_4 \times \mathbf{M} \tag{21}$$

where

$$\mathbf{U}_4 = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix} . \tag{22}$$

The Kennaugh matrix has the following properties [5] :

1) it is symmetric,

2) the diagonal elements satisfy the condition

$$K_{11} \;=\; K_{22} \;+\; K_{33} \;+\; K_{44} \tag{23}$$

The Kennaugh matrix allows to obtain the *polarimetric signatures*, which display the radar response as a function of the radar polarisations. The normalized transmitted Stokes vector can be represented as

$$\mathbf{J}_t(\chi_t,\psi_t) \;=\; \begin{pmatrix} 1 \\ Q_t \\ U_t \\ V_t \end{pmatrix} \;=\; \begin{pmatrix} 1 \\ \cos 2\chi_t \cos 2\psi_t \\ \cos 2\chi_t \sin 2\psi_t \\ \sin 2\chi_t \end{pmatrix} \tag{24}$$

where χ is the *ellipticity angle* related to the polarisation ellipse axis ratio by $\tan\chi = b/a$ (with a the large axis and b the small axis), and ψ is the *orientation angle* of the ellipse, giving the great axis inclination. The normalized Stokes vector in the receiving mode has the same form with the subscript t replaced by r. The expression of the received power in the backscattering situation, assuming a unit value for the transmitted electric field and the (5.a) Green's function is

$$\langle P_r \rangle \;=\; 0.5\,\frac{1}{r^2}\,F\,\tilde{\mathbf{J}}_{\mathbf{r}}\,\langle \mathbf{K} \rangle\,\mathbf{J}_{\mathbf{t}} \tag{25}$$

where r is the distance from the radar to the target, the tilde means the transposed matrix and F is a radar dependent factor. It is given by

$$F \;=\; \frac{\lambda^2}{8\pi\eta}\,Ga(\theta,\phi) \tag{26}$$

where $\lambda = 2\pi/k$ is the wavelength, η is free space characteristic impedance, Ga is the antenna gain in the direction specified by the elevation θ and the azimuth ϕ.

In order to reduce the number of independent variables, polarisation signatures are usually given for identical polarisations (copolar case) or for orthogonal polarisations (crosspolar case), when transmiting and receiving respectively. The orthogonal Stokes vector at reception is given by

$$\mathbf{J}_r(\chi_r,\psi_r) \;=\; \begin{pmatrix} 1 \\ Q_r \\ U_r \\ V_r \end{pmatrix} \;=\; \begin{pmatrix} 1 \\ -Q_t \\ -U_t \\ -V_t \end{pmatrix} \tag{27}$$

Examples of polarimetric signatures are provided for trihedral and dihedral corner reflectors in figure 2, where the relative received power is drawn as a function of the angles χ and ψ. The line $\chi = 0$ corresponds to linear polarisation with any inclination ψ. The trihedral backscattered wave for linear polarisation has the same polarisation as the incident wave and therefore leads to a maximum response in the copolar case and to no response in the crosspolar case. The lines $\chi = \pm 45°$ correspond to circular polarisations (right- or left-handed). The trihedral maintains the rotation direction of the electric field leading to maximum response of the radar in the crosspolar case and no response in the copolar case. The behavior of the

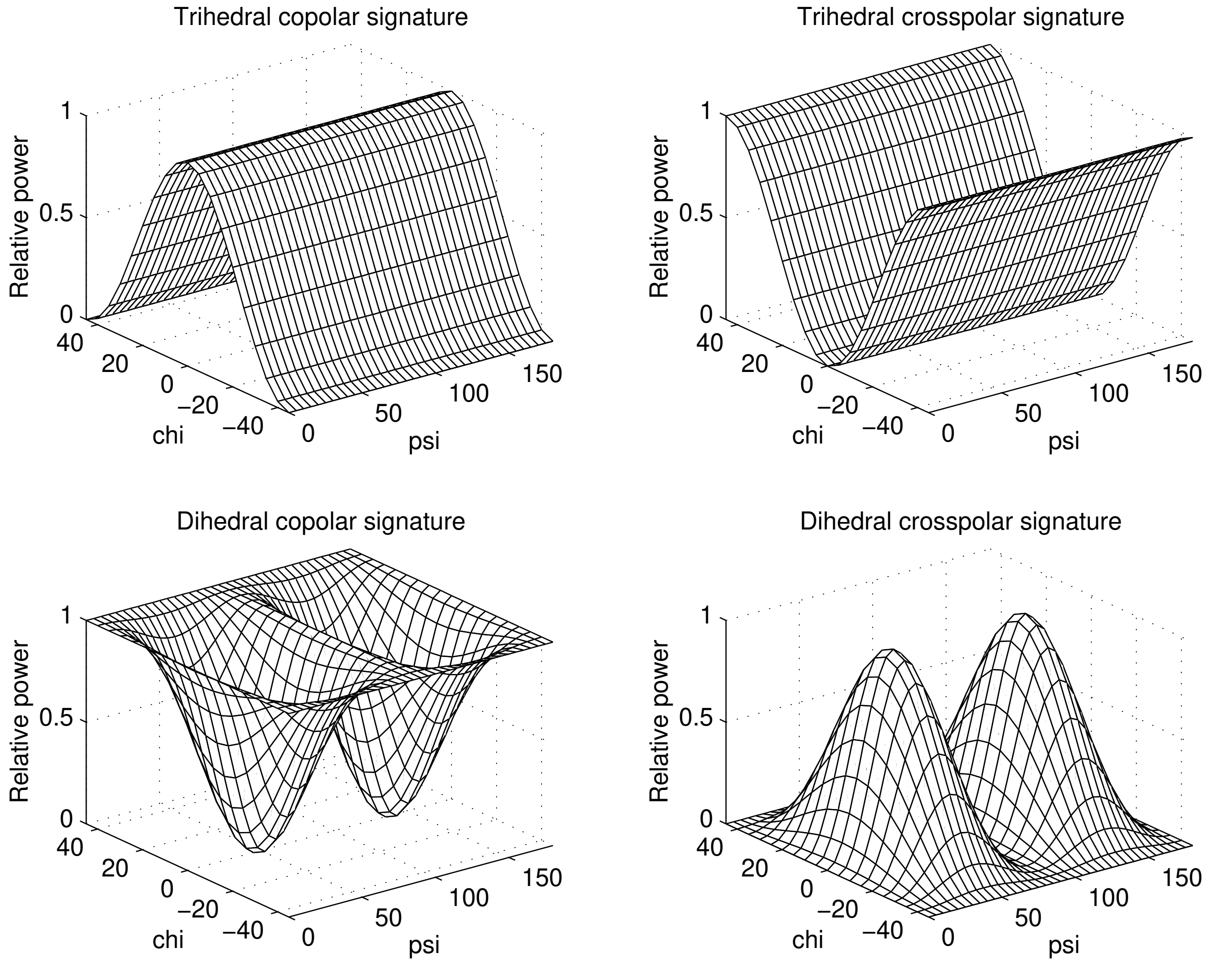

Figure 2: Polarimetric signatures of trihedral (upper) and dihedral (lower) corner reflectors

dihedral is completely different leading to maximum response in the copolar case to circular polarisations, as well as for vertical and horizontal linear polarisations. More details about polarimetric signatures can be found in [5].

Another interesting approach for the analysis of polarimetric radar data is based on the notion of target vector [1, 5]. A simple target vector $\mathbf{b}$ can be constructed simply by the enumeration of the elements of the scattering matrix $\mathbf{S}$, as follows (the superscript T stands for the transposed vector)

$$\mathbf{b} = \begin{pmatrix} S_{11} & S_{12} & S_{21} & S_{22} \end{pmatrix}^T \tag{28}$$

Then a target covariance matrix $\mathbf{C}$ can be defined as follows

$$\mathbf{C} = \mathbf{b}\,\tilde{\mathbf{b}}^* = \begin{pmatrix} S_{11}S_{11}^* & S_{11}S_{12}^* & S_{11}S_{21}^* & S_{11}S_{22}^* \\ S_{12}S_{11}^* & S_{12}S_{12}^* & S_{12}S_{21}^* & S_{12}S_{22}^* \\ S_{21}S_{11}^* & S_{21}S_{12}^* & S_{21}S_{21}^* & S_{21}S_{22}^* \\ S_{22}S_{11}^* & S_{22}S_{12}^* & S_{22}S_{21}^* & S_{22}S_{22}^* \end{pmatrix} \tag{29}$$

Note that the structure of the matrix $\mathbf{C}$ is different from that of the matrix $\mathbf{W}$ defined in (13). We cannot find $\mathbf{C}$ by simple transformations, such as interchanges of the lines and columns of $\mathbf{W}$. For a random target, the *target covariance matrix* $\mathbf{C}$ is defined as the ensemble average

$$\mathbf{C} = \langle \mathbf{b}\,\tilde{\mathbf{b}}^* \rangle \tag{30}$$

with elements $\langle S_{ij}S_{kl}^* \rangle$. The unique relationship between $\mathbf{S}$ and $\mathbf{C}$ is lost, as was previously the case for the Mueller matrix $\mathbf{M}$.

The following correlation coefficients can be extracted from the covariance matrix C. The norm and argument of the copolar correlation are

$$\begin{aligned} \rho_c &= \sqrt{Re\left(\frac{C_{14}C_{14}^*}{C_{11}C_{44}}\right)} = \frac{|\langle S_{HH}S_{VV}^* \rangle|}{\sqrt{\langle |S_{HH}|^2\rangle \langle |S_{VV}|^2\rangle}} \\ \phi_c &= \arctan\frac{\Im(C_{14})}{\Re(C_{14})} = \arctan\frac{\Im\langle S_{HH}S_{VV}^*\rangle}{\Re\langle S_{HH}S_{VV}^*\rangle} \end{aligned} \tag{31}$$

The norms of the crosspolar correlations are

$$\begin{aligned} \rho_{c1} &= \sqrt{Re\left(\frac{C_{13}C_{13}^*}{C_{11}C_{33}}\right)} = \frac{|\langle S_{HH}S_{VH}^* \rangle|}{\sqrt{\langle |S_{HH}|^2\rangle \langle |S_{VH}|^2\rangle}} \\ \rho_{c2} &= \sqrt{Re\left(\frac{C_{24}C_{24}^*}{C_{22}C_{44}}\right)} = \frac{|\langle S_{VV}S_{HV}^* \rangle|}{\sqrt{\langle |S_{VV}|^2\rangle \langle |S_{HV}|^2\rangle}} \end{aligned} \tag{32}$$

The main output file of *polscat* contains the modified Mueller matrix, the scattering coefficients in dB and the co- and cross-polar correlations.

4 Input Parameters and input files

In this section a description is provided of all the input parameters required for the UCL Polarimetric Radiative Transfer Software. This is completed in some cases by indications on how these input data are interpreted in the software.

Two files must be prepared by the user : a comment file, with the extension *.read*, and a data file, with the extension *.data*. The comment file contains all the explanations required in order to introduce the input parameters, and numbered lines where the letters and numerical values must be placed. The data file is the file used by the software. It has the form of a table with the same numbered lines as in the comment file and with all letters and numerical values on each line.

The user should first complete the comment file. It is then an easy task to complete the table of the data file. Here follows a detailed description of the comment file. It is composed of four parts : the general data, the characteristics of the canopy, the characteristics of the trunks and the characteristics of the soil. An example of comment file and of the corresponding data file is given in the next sections.

In the present version of the implemented programme, it is assumed that the canopy (leaves and branches) and the soil are symmetric in azimuth. The trunks however can have a non-zero average tilting angle. For the modelisation of forests, all component classes should be used. For the modelisation of low vegetation, use should be made of the leaves class, while the stalks are modelised either by one branch class or by the trunks class.

4.1 General data

1)-4) The following parameters are introduced : temperature, frequency(s), incidence angle(s) θ_{i_0}, azimuth angle(s) ϕ_{i_0}

The incidence and azimuth angles, θ_{i0}, ϕ_{i0}, define the direction from the radar to the ground target. These angles are converted into the program to the angles θ_i, ϕ_i, defining the incidence direction unit vector $\hat{\imath}$ which is pointing from the radar to the target. All angles are defined in a standard spherical reference frame, with the OZ axis pointing vertically upward.

4.2 Characterisation of the canopy, composed of leaves and three kinds of branches (tertiary, secondary and primary)

5.1) Distribution of leaves and branches within the canopy.

5.1.1) Density of each canopy component
Enter one of three letters : $< C >, < M >$ or $< T >$ according to the choice of input, expressed as a number per cubic meter, or a number per square meter. $< C >$ stands for Crest, $< M >$ for Mean and $< T >$ for Total. The latter is expressed per square meters.
Then enter the density of leaves $< N_f >$, of tertiary branches $< N_{b3} >$, of secondary branches $< N_{b2} >$, and of primary branches $< N_{b1} >$.

5.1.2) Leaves and branches orientation

The azimuth angular distributions are assumed uniform. For the elevation, a choice is proposed between five distributions $p(\theta)$, denoted respectively as :
$<S>, <H>, <V>, <I>, <G>$
For the first four, just enter a letter. The last one $<G>$ is a Gaussian that requires the average elevation, the rms elevation and the window width. The angle θ, as used within the code, represents the orientation of the leaves *normal* or the branches *principal axis*, defined with respect to the vertical. It is defined in the following interval : $0 \leq \theta \leq \pi$. However, for the leaves the input elevation is the angle θ_p of the leaves plane with respect to the vertical. This angle is converted to the normal elevation θ within the program.

a) Case of leaves. The selection is done by the choice of the appropriate entry letter : $<S>, <V>, <H>, <I>$ or $<G>$. For the Gaussian case $<G>$, also enter the average plane elevation (elevation of the leave main axis) $\overline{\theta_p}$, the rms elevation σ and the *window* width (optional).

Choice	**Model**	**Orientation** of the leaves *plane*	**Formulation** with respect to the leaves *normal*
$<S>$	Spherical	isotropic	$p(\theta) = \frac{1}{4\pi}\sin(\theta)$
$<H>$	Planophilic	horizontally oriented *plane*	$p(\theta) = \begin{cases} \frac{\lvert\sin(2\theta)\rvert}{8\pi} & \text{if } 0 \leq \theta \leq \pi/2 \\ 0 & \text{otherwise} \end{cases}$
$<V>$	Erectophilic	vertically oriented *plane*	$p(\theta) = \frac{\sin^2(\theta)}{\pi^2}$
$<I>$	Plagiophilic	*plane* oriented at 45 °	$p(\theta) = \begin{cases} \frac{2\cdot\lvert\cos(\theta)\rvert\sin^2(\theta)}{3\pi} & \text{if } 0 \leq \theta \leq \pi/2 \\ 0 & \text{otherwise} \end{cases}$
$<G>$	Gaussian	*plane* oriented at the angle with the following mean, rms value $(\overline{\theta}_p, \sigma)$	$p(\theta) = \frac{G(\theta,\overline{\theta},\sigma)\sin(\theta)}{\int_0^\pi G(\theta,\overline{\theta},\sigma)\sin(\theta)d\theta}$ *with* $\overline{\theta} = \begin{cases} \overline{\theta}_p + \pi/2 & \text{if } 0 \leq \overline{\theta}_p < \pi/2 \\ \overline{\theta}_p - \pi/2 & \text{if } \pi/2 \leq \overline{\theta}_p \leq \pi \end{cases}$

where $G(\theta, \overline{\theta}, \sigma) = \begin{cases} e^{-\frac{(\theta-\overline{\theta})^2}{2\sigma^2}} & \text{if } \overline{\theta} - \frac{Window}{2} \leq \theta \leq \overline{\theta} + \frac{Window}{2} \\ 0 & \text{otherwise} \end{cases}$

b) Case of branches : the orientation is determined by the axis of the branches

Choice	Model	Orientation	Formulation
$< S >$	Spherical	isotropic branches	$p(\theta) = \frac{1}{4\pi}\sin(\theta)$
$< V >$	Vertical	vertically oriented *branches*	$p(\theta) = \begin{cases} \frac{\lvert\sin(2\theta)\rvert}{8\pi} & \text{if } 0 \le \theta \le \pi/2 \\ 0 & \text{otherwise} \end{cases}$
$< H >$	Horizontal	horizontally oriented *branches*	$p(\theta) = \frac{\sin^2(\theta)}{\pi^2}$
$< I >$	Inclined	*branches* oriented at 45 °	$p(\theta) = \begin{cases} \frac{2\cdot\lvert\cos(\theta)\rvert\sin^2(\theta)}{3\pi} & \text{if } 0 \le \theta \le \pi/2 \\ 0 & \text{otherwise} \end{cases}$
$< G >$	Gaussian	*branches* oriented at the angle with the following mean, rms value $(\overline{\theta}, \sigma)$	$p(\theta) = \frac{G(\theta,\overline{\theta},\sigma)\sin(\theta)}{\int_0^\pi G(\theta,\overline{\theta},\sigma)\sin(\theta)d\theta}$

The selection is done by the choice of the appropriate entry letter : $< S >$, $< V >$, $< H >$, $< I >$ or $< G >$. For the Gaussian case $< G >$, also enter the average elevation $mu = \overline{\theta}$, the rms elevation σ and the *window* width, expressed as a fraction x of σ (optional).

Remark 4.1 *The Gaussian distribution is truncated at the angles $\theta = mu - x\sigma$ and $\theta = mu + x\sigma$, or at $\theta = 0$ and π, whichever is the lowest. As a consequence of the truncation, the resulting average and rms elevations may differ slightly from the input values.*

Remark 4.2 *The orientation integration is based on a Romberg iterative procedure, that stops as soon as a specified accuracy is reached. Therefore the discretization is done by the programme, with no interaction with the user.*

5.1.3 Vertical Distribution

This entry describes the vertical distribution of mixed leaves and branches density within the canopy. It is normalized with respect to the crest density of each canopy component $\left(N_f, N_{b1}, N_{b2}, N_{b3}\left[\frac{\#}{m^3}\right]\right)$. A choice is provided between a uniform $< L >$ and an assymetrical trapezoidal distribution $< T >$. The number of discretization steps for the vertical integration is specified within the programme.

Choice	Distribution	Parameters	Formulation
$< L >$	Uniform (linear)	Heights : h_{inf}, h_{sup}	$p(h) = \begin{cases} 1 & \text{if } h_{inf} \leq h \leq h_{sup} \\ 0 & \text{otherwise} \end{cases}$
$< T >$	Asymmetrical trapezoidal distribution superposed on a constant value P	h_{inf}, h_{sup}, $Z_1, Z_2, P[\%]$	$p(h) = \begin{cases} 1 & \text{if } C(h) \\ p_1(h) & \text{if } C_1(h) \\ p_2(h) & \text{if } C_2(h) \\ 0 & \text{otherwise} \end{cases}$

where

$$\begin{aligned} C(h) &= Z_1 \leq h \leq Z_2 \\ C_1(h) &= h_{inf} \leq h < Z_1 \\ C_2(h) &= Z_2 < h \leq h_{sup} \end{aligned}$$

$$\begin{aligned} p_1(h) &= \frac{(1 - \frac{P}{100})(h - h_{inf})}{Z_1 - h_{inf}} + \frac{P}{100} \\ p_2(h) &= \frac{(1 - \frac{P}{100})(h - h_{sup})}{Z_2 - h_{sup}} + \frac{P}{100} \end{aligned}$$

5.2) Geometric characteristics of the leaves

5.2.1) Shape and mean dimensions of leaves

A choice is proposed between three shapes : circular, elliptical, and rectangular, by the selection of the appropriate code $< Cir >, < Ell >, < Rec >$ respectively.

a) Circular shape $< Cir >$: enter the mean diameter $\overline{d}$. From this the program computes the *equivalent radius* :

$$\overline{r}_c = \overline{d}/2$$

The axial ratio of circular leaves is set to $x_{ab_c} = 1$.

b) Elliptic shape $< Ell >$: enter the mean major ($\overline{a}_e$) and mean minor ($\overline{b}_e$) axis. The program computes the *equivalent radius* :

$$\overline{r}_e = \frac{1}{2}\sqrt{\overline{a}_e \overline{b}_e}$$

The axial ratio of elliptical leaves is computed as $x_{ab_e} = \overline{a}_e / \overline{b}_e$.

Remark 4.3 *In the elliptical case, the* equivalent radius *is computed so that the area S of the equivalent circle is equal to the ellipse area :*

$$S = \pi \overline{r}_e^2 = \frac{\pi}{4} \overline{a}_e \overline{b}_e$$

c) Rectangular shape $< Rec >$: enter the mean large ($\overline{a}_r$) and mean small ($\overline{b}_r$) sides. The program computes the *equivalent radius* :

$$\overline{r}_r = \sqrt{\frac{\overline{a}_r \overline{b}_r}{\pi}}$$

The axial ratio of rectangular leaves is computed as $x_{ab_r} = \overline{a}_r / \overline{b}_r$.

Remark 4.4 *In the rectangular case, the equivalent radius is computed so that the area S of the equivalent circle is equal to the rectangle area*

$$S = \pi \overline{r}_e^2 = \overline{a}_r \overline{b}_r$$

5.2.2) Distribution of dimension :

A choice is provided between four distributions : uniform (or linear) $< L >$, Gaussian $< G >$, exponential $< E >$ and lognormal $< X >$.
A numerical distribution $< N >$ is also foreseen, but not yet implemented.

The axis or side ratio remains constant. The distribution is specified with respect to the diameter (in the case $< Cir >$) or the largest dimension (in the cases of $< Ell >$ and $< Rec >$).

The following parameters are introduced in the input file :

- uniform distribution : distribution width (cm),
- Gaussian distribution : standard deviation (cm) and window width (cm),
- exponential distribution : minimum and maximum dimensions (cm),
- lognormal distribution : standard deviation (cm), minimum and maximum dimensions (cm).

In each case, the number of steps for the radius integration must be specified in the input file.

The program works with the *equivalent radius* and the axial ratio. The input data are transformed by the program to the corresponding data for the equivalent radius.

This transformation is made according to the following rules :

Shape of leaves	**Input parameter**	*axialratio* x_{ab}	**Equivalent radius**
Cir	$\overline{d}$	1	$\overline{r}_c = \overline{d}/2$
Ell	$\overline{a}_e, \overline{b}_e,$	$\overline{a}_e/\overline{b}_e$	$\overline{r}_e = \overline{a}_e/\sqrt{4 \cdot x_{ab_e}}$
Rec	$\overline{a}_r, \overline{b}_r,$	$\overline{a}_r/\overline{b}_r$	$\overline{r}_r = \overline{a}_r/\sqrt{\pi \cdot x_{ab_r}}$

Then the program computes the constant M by wich the input distribution parameters must be multiplied to give the corresponding parameters with respect to the equivalent radius.

$---$	**Cir**	**Ell**	**Rec**
Constant M	$1/2$	$1/\sqrt{4 \cdot x_{ab_e}}$	$1/\sqrt{\pi \cdot x_{ab_e}}$

The distributions of equivalent radius are :

Choice	**Model**	**Equivalent parameters**	**Formulation** of *non normalised*$^{(*)}$ distributions ; $r_0 \leq r \leq r_{max}$
$< L >$	Uniform	$\overline{r}, \Delta r$ $r_0 = \overline{r} - \Delta r/2$ $r_{max} = \overline{r} + \Delta r/2$	$p(r) = 1$
$< G >$	Gaussian	$\overline{r}, \sigma, x_\sigma$ $r_0 = \overline{r} - x_\sigma/2$ $r_{max} = \overline{r} + x_\sigma/2$	$p(r) = e^{-\frac{(r-\overline{r})^2}{2\sigma^2}}$
$< E >$	Exponential	$\overline{r}, r_0, r_{max}$ $\sigma = \overline{r} - r_0$	$p(r) = e^{-\frac{(r-\overline{r})}{\sigma}}$
$< X >$	Log-normal	$\overline{r}, r_0, r_{max}, \sigma$	$p(r) = \frac{1}{r} e^{-\frac{[\ln(r/r_{max})-\overline{r}_x]^2}{2\sigma_x^2}}$ where $\sigma_x^2 = \ln[(\sigma/\overline{r})^2 + 1]$ $\overline{r}_x = \ln(\overline{r}/r_{max}) - \frac{1}{2}\sigma_x^2$

Remark 4.5 $^{(*)}$ *The normalisation is introduced after the dimension integrations have been performed.*

The Gaussian distribution is truncated at the window width, the exponential distribution at the maximum dimension and the lognormal distribution at the minimum and maximum dimensions. As a consequence of the truncations, the resulting average and rms values may differ slightly from the input values.

5.2.3) Thickness distributions : A uniform distribution $< L >$ (see uniform model) is foreseen, but not yet implemented. The existing program computes only for one value, the mean thickness.

5.2.4) Specification of the electromagnetic scattering model : a manual choice is provided between four models denoted by the symbols $< e >, < f >, < i >, < j >$. An automatic choice $< a >$ is also available. The models are listed in the next table :

Choice	**Model**	**Formulation**
$< e >$	Physical Optics (PO)	LeVine et al. [16]
$< f >$	Thin disk Physical Optics (TPO)	Willis et al. [17]
$< i >$	Resistive Sheet model	Senior et al. [12]
$< j >$	Gen. Rayleigh-Gans model (GRG) (circular disk only)	Karam et al. [8]
$< a >$	model $< f >$ else model $< e >$	if $flagval < 0.1$ where $flagval = \lvert\sqrt{\varepsilon_r}\rvert k \cdot t$ $^{(*)}$

Remark 4.6 $^{(*)}$ *In this expression, ϵ_r is the relative permittivity, k is the free space wavenumber and t is the leave thickness.*

5.2.5) Electrical characteristics of the leaves .

The leaves relative permittivy, required for the scattering model, is either introduced directly, or is calculated from the gravimetric or volumetric moisture and the salinity, as indicated in the table below. Thus a choice is proposed between : Gravimetric moisture $< G >$, Volumetric moisture $< V >$ or Permittivity $< P >$. In the first two cases the permittivity is calculated with the model of Ulaby et al. [15] *part II : dual dispersion model* and [13].

Choice	**Input**	**Computed**
$< P >$	ϵ_r	—
$< G >$	Gravimetric moisture Salinity	ϵ_r
$< V >$	Volumetric moisture Salinity	ϵ_r

5.(3-4-5)) Tertiary, secondary and primary branches parameters

The description of the branches follows a scheme similar to that for the leaves, with the exception that all branches are assumed to be circular cylinders. Thus there is no shape description.

5.(3-4-5).1) Branches scattering models

The choice is provided between the following models :
- Rayleigh approximation for very thin cylinders $< p >$ [14, chap.3].
- Generalized Rayleigh-Gans approximation (GRG) for thin cylinders $< q >$ [8].
- Infinitely long cylinder for very long cylinders $< r >$ [8].
- Physical optics (PO) for long and thick cylinders $< o >$ [4].

An automatic choice is also provided between $< q >$, $< r >$ and $< o >$.

5.(3-4-5).2) Diameter distribution.

A choice is proposed between uniform $< L >$, Gausian $< G >$, exponential $< E >$ and lognormal $< X >$ distributions (cf. 5.2.2)

5.(3-4-5).3) Length.

It is assumed that the length is a linear function of the diameter $L = a * d + b$
Thus two parameters must be entered : a and b.

5.(3-4-5).4) Relative permittivity.

Here also, the choice is proposed between the permittivity $< P >$, the gravimetric moisture $< G >$ or the volumetric moisture $< V >$

4.3 Characteristics of trunks

6.1) Trunks density

The trunks density is specified as the number of trunks per square meter.

6.2) Trunks models

The lower diameter of the trunks is specified as the *diameter at breast height* or DBH (1.5 m above ground). A double choice of models is proposed, first between cylindrical or conical shaped trunks, and then between several electromagnetic models.

For cylindrical trunks, the following models are available :

- generalized Rayleigh-Gans approximation (GRG) for thin cylinders $< q >$ [8],
- infinitely long cylinder model for very long cylinders $< r >$ [8],
- the physical optics model (PO) for long and thick cylinders $< o >$ [4].

An automatic choice $< n >$ is also provided.

For conical trunks, the choice is provided between :

- a linearly decreasing diameter from DBH to zero diameter at the top $< s >$,
- a linear decreasing diameter from DBH to a specified diameter at the top $< v >$,
- a circular paraboloid approximation $< u >$.

In this case, the trunk is modelised as a set of superposed cylinders of decreasing radius and the infinitely long cylinder model is used for each section.

6.3) Distribution of trunks diameter.

A choice is proposed between uniform $< L >$, Gausian $< G >$, exponential $< E >$ and lognormal $< X >$ distributions (cf. 5.2.2).

6.4) Trunks heigth.

As for the branches, a linear relationship is assumed between the heigth and the diameter, in the form $H = a * d + b$. The two coefficients a and b must be entered.

6.5) Tilting distribution.

The trunks tilting distribution is more general that the leaves and branches orientation distributions. It can be anisotropic : the mean tilting may have non zero values. Two distributions around the vertical are available : uniform (linear) $< L >$ and Gaussian $< G >$. It is assumed that the average tilting azimuth angle is $\phi = 0$, or that the trunks with average tilting lies in the XOZ plane.

The linear distribution requires as inputs : the mean tilting and the distribution width.

The Gaussian distribution requires the mean tilting, the standard deviation and the total window width (this last parameter is optional).

6.6) Relative permittivity.

The same choice is provided as for leaves and branches between permittivity $< P >$, gravimetric moisture $< G >$ and volumetric moisture $< V >$ (cf. 5.(3-4-5).4).

4.4 Characteristics of soil

The soil is described by its surface roughness and electrical properties. The surface roughness is described by the vertical displacement rms value and correlation function. The electrical properties are specified either by the permittivity, or by the soil composition, moisture and salinity, from which the permittivity is computed.

7.1) Soil roughness

A choice is foreseen between an isotropic Gaussian correlation function (input $< LG >$) or an anisotropic correlation function (input $< LE >$), as described in the table.

Choice	**Input**
$< LG >$	$\rightarrow$ rms roughness (cm) $\rightarrow$ Correlation length (cm)
$< LE >$	$\rightarrow$ rms roughness (cm) $\rightarrow$ Two correlation lengths (cm)

Remark 4.7 *The choice $< LE >$ is not yet implemented into the program.*

7.2) Relative permittivity.

The choice is provided between the permittivity $< P >$, the gravimetric moisture $< G >$ or the volumetric moisture $< V >$. The required parameters are specified in the table below.

Choice	**Input**	**Computed**
$< P >$	ϵ_r	—
$< G >$	Gravimetric moisture Salinity Sand concentration Clay concentration	ϵ_r
$< V >$	Volumetric moisture Salinity Sand concentration Clay concentration	ϵ_r

5 Example of comment file : *Example.read*

```
DATE : 06/09/2000

INPUT PARAMETERS  :

GENERAL REMARKS

!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!

- Model variables not used (n.u.) in the program
  should be set to 0.0 in the input file <name>.data

!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!

- All Gaussians used in the program to define the orientation of leaves,
  branches or trunks are computed in the window of total width x*sigma.
  In the absence of his definition (value 0.0 in lines 10-13), x is set
  automatically in the program in the subroutine dataradar -> donnees.f
  to the value x=4.6526
  From the value of x the program computes the percentage of
  the Gaussian distributions truncation.
  For example for x = 4.6526, the Gaussians are truncated at 2%.

- Numerical distributions are foreseen
  (!! but not yet implemented !!)
  for the dimensions of leaves, branches and trunks.
  These distributions are represented by the number of elements with a given
  dimension. The numbers of points of each numerical distribution
  is defined in the file <name>.data when <N> is selected.
  The numerical distribution is given in "Numerical_pdf.data"
  as a table, in the following order :

  -> Leaves dimension :
     - diameter, large axis or side
     - number of elements for each dimension

  -> Tertiary branches diameter distribution :
     - diameter
     - number of elements for each diameter

  -> Secondary branches diameter distribution :
     - diameter
     - number of elements for each diameter

  -> Primary branches diameter distribution :
```

```
     - diameter
     - number of elements for each diameter

  -> Trunks diameter distribution :
     - diameter
     - number of elements for each diameter


  This order should be respected, even if not all numerical
  distributions are used
---------------------------------------------------------------------

COMMENT FILE Example.read
==========================

         GENERAL DATA (LINES 1-8)
         ========================

Line 1: Datafile name : Example.data

        1) TEMPERATURE (Celsius) :
        ---------------------------
Line 2: 22.0

        2) FREQUENCY (GHz) :
        ---------------------------

        Number of different frequencies (maximum 10)
Line 3:    1

        Frequency values
Line 4:   5.3

        3) INCIDENCE ANGLE (degree, with respect to the vertical):
        --------------------------------------------------------------

        Number of incidence angles (maximum 10)
Line 5:    1

        Incidence angle values
Line 6:   30.0

        4) AZIMUTH ANGLE (degree) :
        ----------------------------

        Number of different azimuth angles (maximum 10)
```

```
Line 7:   1

        Values of azimuth angles
Line 8:  0.0

====================================================================
        5) CHARACTERISTICS OF CANOPY
        =================================

        5.1) GENERAL PARAMETERS OF CANOPY (LINES 9-17) :
        ..................................

        5.1.1) Choice of density : <C> = peak,
               <M> = average or  <T> = total

               +  Values of densities
               (in #/m3 if C or M  ----------- in #/m2 if T)
     ----------------------------------------------------------------
              Leaves (Nf), Tertiary branches  (Nb3),
            + Secondary branches  (Nb2), Primary branches  (Nb1)
     ----------------------------------------------------------------
              Nf              Nb3                Nb2           Nb1
Line 9: T    1670.0          10.5               0.15         0.0087

         5.1.2) Orientation of the leaves plane (principal axis)
                and of the branches principal axis :

                All orientation distributions are defined in the interval
                (0-pi)in elevation (theta), and in (0-2pi) in azimuth (phi)
                They are uniform in azimuth, with the exception of the trunks.

                    Leaves orientation    Branches orientation

                <S>=  Spherical              Spherical
                <H>=  Planophilic            Horizontal
                <V>=  Erectophilic           Vertical
                <I>=  Plagiophilic           Inclined at 45 degree
                <G>=  Gaussian               Gaussian

                If the orientation is Gaussian, enter mu and sigma in degree,
                and possibly the total window width, relative to sigma ;
                else SET 0.0 IN THE INPUT FILE !
                (if x = 0.0 the window is set to the value 4.6526*sigma)
        ---------------------------------------------------------------
                        Orientation      mu       sigma       x
                                      (degree)  (degree)  (degree/degree)
```

```
Line 10 Leaves               :  V           0.0       0.0          0.0
Line 11 Tertiary branches    :  S           0.0       0.0          0.0
Line 12 Secondary branches   :  I           0.0       0.0          0.0
Line 13 Primary branches     :  H           0.0       0.0          0.0

         5.1.3) Vertical distributions :
                levels are defined from bottom of canopy
                ("0" is the lowest level of the canopy)

                <L> = Constant     : enter lower and upper level
                <T> = Trapezoidal  : this distribution can be asymmetrical
                                     and superposed on a constant value
                                     (pedestal)
        In the trapezoidal case, enter the following values :

        - Lower level (m)
        - Upper level (m)
        - Z1 : lower intermediary value (m)
        - Z2 : upper intermediary value (m)
        - P  : relative value of pedestal in  %
               with respect to maximum  density

        If the distribution is constant, the values Z1, Z2 and P are not
        used and must be set at 0.0.
        ---------------------------------------------------------------
                              Kind  Lower   Upper    Z1    Z2      P
                                     (m)     (m)    (m)   (m)     (%)

Line 14 Leaves              :    T    4.0    10.0    6.5   7.5    0.0
Line 15 Tertiary branches   :    T    5.0    10.0    7.0   8.0    0.0
Line 16 Secondary branches  :    T    0.0     5.0    2.0   3.0   10.0
Line 17 Primary branches    :    T    0.0     5.0    2.0   3.0    0.0

=======================================================================
        5.2) LEAVES PARAMETERS (LINES 20-22) :
         .............................


        5.2.1) Shape and mean dimensions of the leaves :

          <Cir>    : Circular, in this case enter only mean diameter (in cm)
                     (second entry is not used)

          <Ell>    : Elliptical, in this case enter :
                     a) Mean large axis (in cm)
```

```
                 b) Mean small axis (in cm)

       <Rec>    : Rectangular, in this case enter :
                 a) Mean large side (in cm)
                 b) Mean small side (in cm)

     -------------------------------------------------

       Shape     diameter / large axis/side      small axis/side
                           (cm)                        (cm)
Line 18:  Cir              4.0                         0.0
```

```
     5.2.2) Distribution of dimension

            Note : the axis or side ratio remains constant.
                   The distribution is specified with respect to
                   the diameter or the largest dimension.

            <L> : Linear, enter the following parameters :

                  a) First parameter  : distribution width (cm)
                  b) Second parameter : (n.u.)
                  c) Third parameter  : (n.u.)
                  d) Number of steps

            <G> : Gaussian, enter the following parameters :
                  a) First parameter  : standard deviation (cm)
                  b) Second parameter : window width       (cm)
                  c) Third parameter  : (n.u.)
                  d) Number of steps

            <E> : Exponential, enter the following parameters :

                  a) First parameter  : minimum dimension  (cm)
                  b) Second parameter : maximum dimension  (cm)
                  c) Third parameter  : (n.u.)
                  d) Number of steps

            <X> : Log-normal, enter the following parameters :

                  a) First parameter  : standard deviation (cm)
                  b) Second parameter : minimum dimension  (cm)
                  c) Third parameter  : maximum dimension  (cm)
                  d) Number of steps
```

```
        <N> : Numerical distribution defined in the file
              "Numerical_pdf.data" at "Leaves dimension".
              Enter the following parameters :

              a) First parameter  : (n.u.)
              b) Second parameter : (n.u.)
              c) Third parameter  : (n.u.)
              d) Number of steps in numerical distribution

              (the number of steps must correspond to the
               number of discrete distribution values)

--------------------------------------------------

  Kind     1-st param.   2-nd param.   3-rd param.    number of steps
              (cm)          (cm)          (cm)

Line 19:   L          2.0          0.0          0.0              5


5.2.3) Thickness distribution :

        <L> : Linear : uniform distribution :

              a) Mean thickness     (mm)
              b) Distribution width (mm)
              c) Number of steps

---------------------------------------------------

  Kind     Mean       Width        Number of steps
           (mm)       (mm)

Line 20:   L       2.0        2.0              1

!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!

       Note : the thickness distribution is not yet implemented.
              The program uses the mean thickness and proceeds to the
              integration with one step.

!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!

----------------------------------------------------

5.2.4) Leaves Models :
```

```
        <e>    : Physical Optics (PO)
        <f>    : Thin disk Physical Optics (TPO)
        <i>    : Resistive sheet
        <j>    : Generalized Rayleigh-Gans model (GRG) (only for circular leaves)
        <a>    : automatic choice in function of
                 flagval=|sqrt(Eps_r1)|*k*t

                 -> <f> if flagval<0.1
                 -> <e> else

        ----------------------
Line 21:    i


        5.2.5) Enter relative permittivity Er or moisture to compute Er.
               Choice between :

                 <P> : Permittivity Er, in this case enter :
                       a) First parameter  : Real part of Er
                       b) Second parameter : Imaginary part of Er

                 <G> : Gravimetric moisture, in this case enter :
                       a)  First parameter  : Gravimetric moisture (%)
                       b)  Second parameter : Salinity (#/thousand)


                 <V> : Volumetric moisture, in this case enter :
                       a)  First parameter  : Volumetric moisture (%)
                       b)  Second parameter : Salinity (#/thousand)

        ----------------------------------------------------------------

               Choice     1-st parameter     2-nd parameter
                            (%)               (#/thousand)

Line 22:         G          70.0                11.0

========================================================================

        5.3) Tertiary branches parameters (LINES 23-26)
            ..............................................................

        5.3.1) Branches Models :

        <p>    : Very thin cylinder - Rayleigh approximation
```

```
<q>    : Thin cylinder - GRG approximation
<r>    : Very long cylinder - infinitely long cylinder
<o>    : Long cylinder - physical optics
<n>    : automatic choice in function of
         k*r and flagval=|sqrt(Eps_r)|*k*r

         -> <q> if flagval<0.4
         -> <r> if flagval>=0.4 and k*r<10
         -> <o> else

-----------------------
```

```
Line 23:        n

        5.3.2)  Diameter distribution (in cm) :


                <L> : Linear, enter the following parameters :

                      a) Mean diameter                              (cm)
                      b) First parameter  : distribution width      (cm)
                      c) Second parameter : (n.u.)
                      d) Third parameter  : (n.u.)
                      e) Number of steps

                <G> : Gaussian, enter the following parameters :

                      a) Mean diameter                              (cm)
                      b) First parameter  :  standard deviation     (cm)
                      c) Second parameter :  window width           (cm)
                      d) Third parameter  : (n.u.)
                      e) Number of steps

                <E> : Exponential, enter the following parameters :

                      a) Mean diameter                              (cm)
                      b) First parameter  : minimum diameter        (cm)
                      c) Second parameter : maximum dimension       (cm)
                      d) Third parameter  : (n.u.)
                      e) Number of steps

                <X> : Log-normal, enter the following parameters :

                      a) Mean diameter                              (cm)
                      b) First parameter  : standard deviation      (cm)
                      c) Second parameter : minimum dimension       (cm)
                      d) Third parameter  : maximum dimension       (cm)
```

```
          e) Number of steps

      <N> : Numerical distribution defined in the file
            "Numerical_pdf.data" at
            "Tertiary branches diameter distribution"
            Enter the following parameters :

            a) Mean             : (n.u.)
            b) First parameter  : (n.u.)
            c) Second parameter : (n.u.)
            d) Third parameter  : (n.u.)
            e) Number of steps in numerical distribution

            (the number of steps must correspond to the
            number of discrete distribution values)

      --------------------------------------

       Kind     Mean    1-st param.   2-nd param.   3-rd param.  Nbr of steps
                (cm)       (cm)          (cm)          (cm)

Line 24:  E      1.9        1.0           3.0           0.0            5


      5.3.3) Length as a function of diameter L = a*d + b
             (L and b in cm) :

      ------------------------------------------------------------------
                 a              b
Line 25:        50.0           0.0

      5.3.4) Enter relative permittivity Er or moisture to compute Er.
             Choice between :

               <P> : Permittivity Er, in this case enter :
                     a) First parameter  : Real part of Er
                     b) Second parameter : Imaginary part of Er

               <G> : Gravimetric moisture, in this case enter :
                     a)  First parameter  : Gravimetric moisture (%)
                     b)  Second parameter : Salinity (#/thousand)


               <V> : Volumetric moisture, in this case enter :
                     a)  First parameter  : Volumetric moisture (%)
                     b)  Second parameter : Salinity (#/thousand)
```

```
        ----------------------------------------------------------------

              Choice     1-st parameter     2-nd parameter
                              (%)            (#/thousand)

Line 26:        G          65.0               14.0

==============================================================================

       5.4) Secondary branches parameters (LINES 27-30) :
            .............................................................

        5.4.1) Branches Models :

        <p>    : Very thin cylinder - Rayleigh approximation
        <q>    : Thin cylinder - GRG approximation
        <r>    : Very long cylinder - infinitely long cylinder
        <o>    : Long cylinder - physical optics
        <n>    : automatic choice in function of
                 k*r and flagval=|sqrt(Eps_r)|*k*r

                 -> <q> if flagval<0.4
                 -> <r> if flagval>=0.4 and k*r<10
                 -> <o> else

        -----------------------
Line 27:        n

        5.4.2)  Diameter distribution (in cm) :

                <L> : Linear, enter the following parameters :

                      a) Mean diameter                          (cm)
                      b) First parameter  : distribution width  (cm)
                      c) Second parameter : (n.u.)
                      d) Third parameter  : (n.u.)
                      e) Number of steps

                <G> : Gaussian, enter the following parameters :

                      a) Mean diameter                          (cm)
                      b) First parameter  :  standard deviation (cm)
                      c) Second parameter :  window width       (cm)
                      d) Third parameter  : (n.u.)
                      e) Number of steps
```

```
<E> : Exponential, enter the following parameters :

      a) Mean diameter                              (cm)
      b) First parameter  : minimum diameter        (cm)
      c) Second parameter : maximum dimension       (cm)
      d) Third parameter  : (n.u.)
      e) Number of steps

<X> : Log-normal, enter the following parameters :

      a) Mean diameter                              (cm)
      b) First parameter  : standard deviation      (cm)
      c) Second parameter : minimum dimension       (cm)
      d) Third parameter  : maximum dimension       (cm)
      e) Number of steps

<N> : Numerical distribution defined in the file
      "Numerical_pdf.data" at
      "Secondary branches diameter distribution".
      Enter following parameters :

      a) Mean             : (n.u.)
      b) First parameter  : (n.u.)
      c) Second parameter : (n.u.)
      d) Third parameter  : (n.u.)
      e) Number of steps in numerical distribution

      (the number of steps must correspond to the
      number of discrete distribution values)
```

```
        -----------------------------------------------------------
         Kind     Mean    1-st param.   2-nd param.   3-rd param.  Nbr of steps
                  (cm)       (cm)          (cm)          (cm)

Line 28:   L      10.0      10.0           0.0           0.0            5
```

```
        5.4.3) Length as a function of diameter L = a*d + b
               (L and b in cm) :

        ------------------------------------------------------------------

                  a              b
Line 29:         80.0           0.0
```

```
5.4.4) Enter relative permittivity Er or moisture to compute Er.
       Choice between :

         <P> : Permittivity Er, in this case enter :
               a) First parameter  : Real part of Er
               b) Second parameter : Imaginary part of Er

         <G> : Gravimetric moisture, in this case enter :
               a)  First parameter  : Gravimetric moisture (%)
               b)  Second parameter : Salinity (#/thousand)


         <V> : Volumetric moisture, in this case enter :
               a)  First parameter  : Volumetric moisture (%)
               b)  Second parameter : Salinity (#/thousand)

-----------------------------------------------------------------

       Choice     1-st parameter     2-nd parameter
                     (%)             (#/thousand)

Line 30:         G          65.0               14.0

=============================================================================

       5.5) Primary branches parameters (LINES 31-34) :
            ..............................................................

        5.5.1) Branches Models :

        <p>    : Very thin cylinder - Rayleigh approximation
        <q>    : Thin cylinder - GRG approximation
        <r>    : Very long cylinder - infinitely long cylinder
        <o>    : Long cylinder - physical optics
        <n>    : automatic choice in function of
                 k*r and flagval=|sqrt(Eps_r)|*k*r

                 -> <q> if flagval<0.4
                 -> <r> if flagval>=0.4 and k*r<10
                 -> <o> else

        -----------------------
Line 31:        n

        5.5.2)  Diameter distribution (in cm) :
```

```
<L> : Linear, enter the following parameters :

      a) Mean diameter                            (cm)
      b) First parameter  : distribution width    (cm)
      c) Second parameter : (n.u.)
      d) Third parameter  : (n.u.)
      e) Number of steps

<G> : Gaussian, enter the following parameters :

      a) Mean diameter                            (cm)
      b) First parameter  :  standard deviation   (cm)
      c) Second parameter :  window width         (cm)
      d) Third parameter  : (n.u.)
      e) Number of steps

<E> : Exponential, enter the following parameters :

      a) Mean diameter                            (cm)
      b) First parameter  : minimum diameter      (cm)
      c) Second parameter : maximum dimension     (cm)
      d) Third parameter  : (n.u.)
      e) Number of steps

<X> : Log-normal, enter the following parameters :

      a) Mean diameter                            (cm)
      b) First parameter  : standard deviation    (cm)
      c) Second parameter : minimum dimension     (cm)
      d) Third parameter  : maximum dimension     (cm)
      e) Number of steps

<N> : Numerical distribution defined in the file
      "Numerical_pdf.data" at
      "Primary branches diameter distribution".
      Enter the following parameters :

      a) Mean             : (n.u.)
      b) First parameter  : (n.u.)
      c) Second parameter : (n.u.)
      d) Third parameter  : (n.u.)
      e) Number of steps in numerical distribution

      (the number of steps must correspond to the
      number of discrete distribution values)
```

```
        -------------------------------------
         Kind      Mean    1-st param.   2-nd param.  3-rd param.   Nbr of steps
                   (cm)       (cm)         (cm)          (cm)

Line 32:   E      26.4       3.4            70            0.0            5


        5.5.3) Length as a function of diameter L = a*d + b
               (L and b in cm) :

        -----------------------------------------------------------------

                   a              b
Line 33:         10.5            960.0

        5.5.4) Enter relative permittivity Er or moisture to compute Er.
               Choice between :

                 <P> : Permittivity Er, in this case enter :
                       a) First parameter  : Real part of Er
                       b) Second parameter : Imaginary part of Er

                 <G> : Gravimetric moisture, in this case enter :
                       a)  First parameter  : Gravimetric moisture (%)
                       b)  Second parameter : Salinity (#/thousand)


                 <V> : Volumetric moisture, in this case enter :
                       a)  First parameter  : Volumetric moisture (%)
                       b)  Second parameter : Salinity (#/thousand)

        ----------------------------------------------------------------

               Choice     1-st parameter     2-nd parameter
                              (%)             (#/thousand)

Line 34:         G            58.0               14.0

============================================================================

        6) Trunks parameters (LINES 35-39) :
        ========================================

        6.1) Trunks density (#/m2) :
        ............................
```

```
Line 35:     2.72E-2


        6.2) Trunks model and mean diameter of trunks.
             Lower diameter is specified as DBH or
             "diameter at breast height" (1.5 m)
             .........................................

        Choice between :

         ->  6.2.1) Cylindrical trunks models

         <q>    : Thin cylinder - GRG approximation
         <r>    : Very long cylinder - infinitely long cylinder
         <o>    : Long cylinder - physical optics
         <n>    : automatic choice in function of
                  k*r and flagval=|sqrt(Eps_r)|*k*r

                 -> <q> if flagval<0.4
                 -> <r> if flagval>=0.4 and k*r<10
                 -> <o> else
         ------------------------------------------
          enter :
                 a) Mean DBH             (cm)
                 b) (n.u.)

        OR

         -> 6.2.1) Conically shaped trunks

        <s>    : Linear decreasing cone from DBH to 0 cm at top, enter:
                 a) Mean DBH             (cm)
                 b) (n.u.)

        <v>    : Linear decreasing cone from DBH to diameter at top, enter:
                 a) Mean DBH             (cm)
                 b) Mean diameter at top (cm)

        <u>    : Circular paraboloid approximation, enter:
                 a) Mean DBH             (cm)
                 b) (n.u.)

         ------------------------------------------
```

	Model	DBH (cm)	Diameter at top (cm)
Line 36:	r	44.9	0.0

6.3) Distribution of trunks diameter
....

Note (for the model <v>) : The distribution is specified with respect to the DBH (cm)
The ratio between top diameter and DBH remains constant

<L> : Linear, enter the following parameters :

a) First parameter : distribution width (cm)
b) Second parameter : (n.u.)
c) Third parameter : (n.u.)
d) Number of steps

<G> : Gaussian, enter the following parameters :
a) First parameter : standard deviation (cm)
b) Second parameter : window width   (cm)
c) Third parameter : (n.u.)
d) Number of steps

<E> : Exponential, enter the following parameters :

a) First parameter : minimum dimension (cm)
b) Second parameter : maximum dimension (cm)
c) Third parameter : (n.u.)
d) Number of steps

<X> : Log-normal, enter the following parameters :

a) First parameter : standard deviation (cm)
b) Second parameter : minimum dimension (cm)
c) Third parameter : maximum dimension (cm)
d) Number of steps

<N> : Numerical distribution defined in the file "Numerical_pdf.data" at "Trunks diameter distribution".
Enter the following parameters :

a) First parameter : (n.u.)

```
                 b) Second parameter : (n.u.)
                 c) Third parameter  : (n.u.)
                 d) Number of steps in numerical distribution

                 (the number of steps must correspond to the
                  number of discrete distribution values)

        -------------------------------------------------

          Kind     1-st param.   2-nd param.   3-rd param.    number of steps
                      (cm)          (cm)          (cm)

Line 37:   E           23.6         63.9               0.0                5


        6.4) Height as a function of trunks diameter H = a*d + b
             (b and H expressed in cm)

        ----------------------------------------------
            a        b
Line 38:   39.5     139.5


        6.5)  Tilting distribution with respect to the vertical (degree) :
        ...................................................................

                <L> : Linear, enter the following parameters :

                      a) Mean tilting                          (degree)
                      b) First parameter  : distribution width (degree)
                      c) Second parameter : (n.u)

                <G> : Gaussian, enter the following parameters :

                      a) Mean tilting                           (degree)
                      b) First parameter  : standard deviation  (degree)
                      c) Second parameter : total window width (degree/degree),
                                 relative to the value of sigma
                                 (if x = 0.0 the window is set
                                 to the value 4.6526*sigma)


         Note: it is assumed that the mean tilting is in the plane phi=0

        --------------------------------------
```

```
           Kind      Mean    1-st parameter  2-nd parameter
                  (degree)     (degree)     (degree/degree)

Line 39:    G       0.0         10.0            0.0


        6.6) Enter relative permittivity Er or moisture to compute Er,
             choice between :
        ...............................................................

                 <P> : Permittivity Er, in this case enter :
                       a) First parameter  : Real part of Er
                       b) Second parameter : Imaginary part of Er

                 <G> : Gravimetric moisture, in this case enter :
                       a)  First parameter  : Gravimetric moisture (%)
                       b)  Second parameter : Salinity (#/thousand)


                 <V> : Volumetric moisture, in this case enter :
                       a)  First parameter  : Volumetric moisture (%)
                       b)  Second parameter : Salinity (#/thousand)

        -----------------------------------------------------------------

              Choice     1-st parameter     2-nd parameter
                              (%)           (#/thousand)
Line 40:        G           55.0               7.0

=============================================================================

        7) Soil parameters (LINES 41-42) :
        ====================================

        7.1) Enter soil parameters :
        ..................................................

                <LG> : Gaussian function. Enter :

                       a) First parameter   : rms roughness
                       b) Second parameter  : correlation length (cm)
                       c) Third parameter   : (n.u)

                <LE> :  Other function. Enter :

                       a) First parameter   : rms roughness
```

```
                b) Second parameter  : 1st correlation length (cm)
                c) Third parameter   : 2d correlation length (cm)

        --------------------------------------------------------------------

               Choice       Roughness       2-nd           3-rd
                                          parameter      parameter

Line 41:        LG             2.0           15.0           0.0

!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!

       Note : The choice of <LE> is not yet implemented in the program.

!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!

        7.2) Enter relative permittivity Er or moisture to compute Er,
             choice between :
        ...................................................................

                  <P> : Permittivity Er, in this case enter :
                        a) First parameter  : Real part of Er
                        b) Second parameter : Imaginary part of Er
                        c) Third parameter  : n.u.

                  <G> : Gravimetric moisture, in this case enter :
                        a) First parameter  : Gravimetric moisture (%)
                        b) Second parameter : Salinity (#/thousand)
                        c) Third parameter  : Sand concentration (%)
                        d) Fourth parameter : Clay concentration (%)

                  <V> : Volumetric moisture, in this case enter :
                        a) First parameter  : Volumetric moisture (%)
                        b) Second parameter : Salinity (#/thousand)
                        c) Third parameter  : Sand concentration (%)
                        d) Fourth parameter : Clay concentration (%)

        -----------------------------------------------------------------
               Choice       1-st          2-nd          3-rd        4-th
                          parameter     parameter     parameter   parameter

Line 42:         G          35.0           5.0          80.0         5.0


 --------============== END OF DATA  ===================------------
```

6 Example of data file : *Example.data*

```
Example.data
22.0
1
5.3
1
30.0
1
0.0
T          1670.0       10.5        0.15        0.0087
V          0.0          0.0         0.0
S          0.0          0.0         0.0
I          0.0          0.0         0.0
H          0.0          0.0         0.0
T          4.00         10.00       6.5         7.5         0.0
T          5.00         10.00       7.0         8.0         0.0
T          0.00         5.00        2.0         3.0         10.0
T          0.00         5.00        2.0         3.0         0.0
Cir        4.0          0.0
L          2.0          0.0         0.0         5
L          2.0          2.0          1
i
G          70.0         11.0
n
E          1.9          1.0         3.0         0.0          5
50.0       0.0
G          65.0         14.0
n
L          10.0         10.0        0.0         0.0          5
80.0       0.0
G          65.0         14.0
n
E          26.4          3.4        70.0        0.0          5
10.5       960.0
G          58.0         14.0
2.72E-2
r          44.9         0.0
E          23.6         63.9        0.0         5
39.5       139.5
G          0.0          10.0        0.0
G          55.0         7.0
LG         2.0          15.0        0.0
G          35.0         5.0         80.0        5.0
```

7 Programme execution

In order to run the programme, the following files must stand in the working directory :
- the input file *name.data*
- the executable *polscat**

The programme is started with the command *polscat*. Several questions appear :
- do you want to compute all the mechanisms ?
- if the answer is no, what mechanisms do you want ?
- a confirmation of your choice.
- the name of the input file ?
- a confirmation of your input file choice.

Then the programme starts.

At the end of the computation, the following files will have been produced :
- *name.res*
- *name.details*
- *Input.data*

The file *name.res* contains the main results, while the file *name.details* contains other informations. Detailed explanations are given in the next section. The file *Input.data* contains the name of the last input file, for the case the user wants to use it again in the next computation.

8 Output data

In this section, we provide a description of the available output data and of the way they are organised.

8.1 Description of the files

The programme *polscat* is organised in such a way that computations can be performed for several frequencies and several radar look directions, i.e. several incidence angles θ and several azimuth angles ϕ. The maximum number is 10. If the input file has the name *Example.data*, two output files will be produced for each set of frequency, incidence angle and azimuth angle. For each case, the output files will have the names *Example_XXX_YY_ZZZ.res* and *Example_XXX_YY_ZZZ.details*, where XXX stands for the frequency in GHz (for instance 530 for 5.30 GHz), YY stands for the incidence angle, and ZZ for the azimuth angle (YY and ZZZ are integers). The main results are put in the file *name.res* while the file *name.details* contains auxiliary results.

The main output file *name.res* has the form of a table with four columns and a variable number of lines. An example of output file is given below. When starting the programme, the user has the choice of the mechanisms he wants to compute. The output file will contains a first line with four numbers : frequency, incidence angle, azimuth angle and temperature. Then follows a set of data, with subsets of 8 lines each. Each subset corresponds to a particular mechanism, with a corresponding number, defined as follows :

1 = CG (canopy-ground)
2 = DC (direct canopy)
3 = TG (trunk-ground)
4 = GCG (ground-canopy-ground)
5 = DG (direct ground)
6 = Total

The double bounce in canopy mechanism (DC2) is not yet effective : therefore no results appear for that mechanism.

The results for each mechanisms contains the following :

- first line : contains the number corresponding to the mechanism, followed by three zeros (in order to complete the line),
- lines two to five : contains the modified Mueller matrix,
- line six : contains the σ° in dB in the following order : HH, VV, HV, VH.
- line seven : contains the copolar correlation norm and phase, and the two crosspolar correlations (as defined in (32) and (33)).
- line height : contains the four attenuations (in dB) computed from the four diagonal elements of the extinction matrix (20).

An example of the main output file is given in the next section.

The second output file *name.details* contains some of the input data, serving as a check. It also contains quantities of interest for applications : total leaves area, leaf area index (LAI), volume of leaves, volume of the three branches classes, and volume of the trunks. Values of the permittivities for the various components are displayed, which is an interesting ouput if the moisture is introduced as input. Finally peak values of scattering (without attenuation) and of attenuation (on a vertical path) are also displayed for each class of components, and for each mechanism for which the computation has been asked by the user.

8.2 Example of output file *Example_530_30_000.res*

Here is an example of the ouput file XXXX.res, corresponding to the input file Example.data.

```
   5.300    30.000     0.000    22.000
1             0             0             0
 0.45269E-04   0.34785E-05   0.33550E-09  -0.36186E-10
 0.34785E-05   0.13445E-04   0.29564E-09   0.28306E-10
-0.67100E-09  -0.59128E-09  -0.64890E-05  -0.30577E-05
-0.72372E-10   0.56612E-10   0.30577E-05   0.46810E-06
  -32.44986    -37.72229    -43.59395    -43.59394
 0.17393E+00   0.45446E+02   0.26891E-04   0.43428E-04
   10.27321     10.38359     10.32840     10.32840
2             0             0             0
 0.91164E-02   0.22522E-03  -0.53504E-06   0.64974E-10
 0.22522E-03   0.90420E-02   0.52170E-06  -0.68938E-10
 0.10721E-05  -0.10454E-05  -0.88595E-02  -0.22267E-04
 0.12905E-09  -0.12916E-09   0.22267E-04  -0.84090E-02
   -9.40967     -9.44524    -25.48185    -25.48185
 0.95100E+00   0.14776E+00   0.37409E-03   0.36628E-03
   10.23798     10.34829     10.29316     10.29316
3             0             0             0
 0.12077E-04   0.11813E-10   0.76051E-13  -0.85249E-14
 0.11813E-10   0.19930E-05  -0.29722E-13  -0.89584E-14
-0.15210E-12   0.59445E-13   0.48229E-05   0.89643E-06
-0.17050E-13  -0.17917E-13  -0.89643E-06   0.48230E-05
  -38.18822    -46.01281    -98.28446    -98.28446
 0.99988E+00  -0.16947E+03   0.64070E-05   0.63979E-05
    0.82561      0.83854      0.83208      0.83208
4             0             0             0
 0.22149E-07   0.93575E-08   0.28484E-10   0.43110E-12
 0.93575E-08   0.13506E-07  -0.22284E-10  -0.33726E-12
-0.56965E-10   0.44565E-10  -0.85318E-08  -0.71845E-10
 0.86213E-12  -0.67446E-12   0.71845E-10   0.10183E-07
  -65.55442    -67.70256    -69.29630    -69.29630
 0.47919E-01   0.17503E+03   0.19787E-02   0.19823E-02
   10.27321     10.38359     10.32840     10.32840
5             0             0             0
 0.30059E-05   0.00000E+00   0.00000E+00   0.00000E+00
 0.00000E+00   0.23889E-05   0.00000E+00   0.00000E+00
 0.00000E+00   0.00000E+00  -0.26788E-05  -0.41781E-07
 0.00000E+00   0.00000E+00   0.41781E-07  -0.26788E-05
  -44.22817    -45.22585  -1000.00000  -1000.00000
 0.99979E+00   0.89355E+00   0.00000E+00   0.00000E+00
   10.27321     10.38359     10.32840     10.32840
6             0             0             0
 0.91768E-02   0.22871E-03  -0.53468E-06   0.29210E-10
 0.22871E-03   0.90599E-02   0.52197E-06  -0.40978E-10
 0.10713E-05  -0.10459E-05  -0.88638E-02  -0.24470E-04
 0.57527E-10  -0.73239E-10   0.24470E-04  -0.84064E-02
   -9.38100     -9.43668    -25.41511    -25.41511
 0.94703E+00   0.16237E+00   0.36976E-03   0.36331E-03
   10.27321     10.38359     10.32840     10.32840
```

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