Two-Layer Canopy Reflectance Model
ACRMf User Guide

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Contents

Abstract

A directional multispectral homogeneous canopy reflectance (CR) model has been developed in the group of vegetation remote sensing at Tartu Observatory, Estonia. The early versions of the CR model by Nilson and Kuusk (1984, 1989) and Kuusk (1995a, 1996, 1994, 1995b) have been extended to a two-layer model (Kuusk, 2001). In order to apply the model for foests two clumping/regularity parameters are introduced. The model works in the spectral region 400-2400 nm, the spectral resolution is 1 nm. Any Sun and view directions are allowed. In the present version (ACRMf) the same code works both for direct and inverse problems. The following manual presents the Fortran-code of the model.

1 Introduction

Several vegetation canopies have a two-layer structure. In forests a moss or lichen layer is on ground surface under grass layer. In field crops a thin weed layer on ground under crop canopy is rather common. Both, optical and structural parameters of these two layers may be rather different and if we use homogeneous canopy reflectance (CR) models for the calculation of the directional reflectance of such canopies using mean (weighted mean) values of phytometrical and optical parameters we may have systematic errors in reflectance values. Below a simple two-layer CR model is described which could be used for the calculation of directional reflectance of such two-layer vegetation canopies. The model is an extension of the homogeneous multispectral CR model MSRM (Kuusk, 1994) and Markov chain CR model MCRM (Kuusk, 1995b). Like the MSRM and MCRM models, the new model accounts for nonlambertian soil reflectance, the specular reflection of direct Sun radiation on leaves, the hot spot effect, and a two-parameter leaf angle distribution (LAD). The mutual shading of leaves/needles in clumped canopies is accounted for by a (shoot-level) clumping parameter. Another clumping/regularity parameter considers the aggregating of foliage into tall crowns in forests.

The model works in the optical domain of radiation, 400-2400 nm, spectral resolution is 1 nm.

2 Description of the model

Vegetation canopy is supposed to consist of a main layer of vegetation, and a geometrically thin layer of vegetation on ground surface. Both vegetation layers are characterized with a similar set of phytometrical parameters: leaf area index (LAI), leaf angle distribution (LAD) parameters, leaf size, foliage clumping parameter, and biochemical parameters which control the optical properties of leaves. In the upper layer a clumping/regularity parameter is used to characterize the clustering of foliage into tree crowns in forests (Kuusk, 2015).

Canopy hemispherical-directional reflectance ρ is calculated as a sum of directional and diffuse components,

$$\rho = (S'_\lambda / Q_\lambda)\rho_1 + \rho_d \tag{1}$$

where ρ_1 is the single-scattering component of the bidirectional reflectance factor, ρ_d is the share of diffuse fluxes in hemispherical-directional reflectance factor, and S'_λ and Q_λ are the direct solar and total spectral irradiances in a horizontal plane above the plant canopy.

2.1 Single scattering of radiation

Single scattering of direct radiation from a two-layer canopy can be represented as the sum of three components

$$\rho_1 = \rho_1^{\mathrm{c1}} + \rho_1^{\mathrm{c2}} + \rho_1^{\mathrm{soil}}. \tag{2}$$

Here ρ_1^{c1} and ρ_1^{c2} are the components of single scattering from the lower and upper layer of vegetation, respectively, and ρ_1^{soil} is the component of single scattering from soil. The single scattering of the upper layer is calculated as in an one-layer canopy (Kuusk, 1991)

$$\rho_1^{\mathrm{c2}} = \frac{\Gamma^{(2)}(r_1, r_2) u_L^{(2)}}{\mu_1 \mu_2} \int_0^H Q^{(2)}(r_1, r_2, z) dz, \tag{3}$$

where $\Gamma^{(2)}(r_1, r_2)$ is the phase function in the upper layer, r_1 and r_2 are unit vectors in Sun and view directions, respectively, $u_L^{(2)}$ is the leaf area density (m^2/m^3) in the upper layer corrected for the shoot-level clumping, $u_L^{(2)} = \kappa^{(2)}\, u_0^{(2)}$, $u_0^{(2)}$ is the leaf area density in the upper layer given in the input file, $\kappa^{(2)}$ is the shoot-level clumping of foliage in the upper layer, $\mu_i = \cos(\theta_i)$, $\theta_i, i = 1, 2$ are the polar angles of vectors r_1 and r_2, $Q^{(2)}(r_1, r_2, z)$ is the bidirectional gap probability in the layer 2 (the upper layer) at level z, and H is the canopy height.

Single scattering in the lower layer is calculated as

$$\rho_1^{\mathrm{c1}} = \frac{\Gamma^{(1)}(r_1, r_2) u_L^{(1)}}{\mu_1 \mu_2}\, Q^{(2)}(r_1, r_2, H) \int_0^{H^{(1)}} Q^{(1)}(r_1, r_2, z) dz, \tag{4}$$

and single scattering from soil as

$$\rho_1^{\mathrm{soil}} = \rho_{\mathrm{soil}}(r_1, r_2) Q^{(0)}(r_1, r_2, H), \tag{5}$$

where $\rho_{\mathrm{soil}}(r_1, r_2)$ is the soil bidirectional reflectance factor, $Q^{(0)} = Q^{(1)}(r_1, r_2)\, Q^{(2)}(r_1, r_2)$, $Q^{(j)}(r_1, r_2) = p_1^{(j)} p_2^{(j)} C_{HS}^{(j)}(\gamma)$, and $H^{(1)}$ is the height of the lower layer. Here $p_i^{(j)}$ is the gap

probability in the layer j in direction r_i , $p_i^{(j)} = \exp(-u_L^{(j)} G_i^{(j)}/\mu_i)$, $G_i^{(j)} = c^{(j)}\, G_{0,i}^{(j)}$ is the effective Ross-Nilson G-function, the projection of a unit leaf area in direction r_i in the layer j (Ross and Nilson, 1968) corrected for the clumping/regularity of the foliage pattern by the respective parameter $c^{(j)}$. In the lower layer the parameter $c^{(1)}$ is kept constant, $c^{(1)} = 1$. In the upper layer the regularity parameter $c^{(2)}$ depends on zenith angle θ_i,

$$c_i^{(2)} = (c_0^{(2)} - 1)(1 - \mu_i) + 1\,, \tag{6}$$

$c_0^{(2)}$ is the parameter value in the zenith direction given in model input. The hot-spot correction is calculated for both layers in the similar manner, only the phytometrical parameters ($u_L^{(j)}$, $\kappa^{(j)}$, $s_L^{(j)}$, $G_i^{(j)}$) may be different,

$$C_{HS}^{(j)}(\gamma) = \exp[\sqrt{G_1^{(j)} G_2^{(j)}/(\mu_1\mu_2)}\, u_L^{(j)} (1 - \exp(-\xi^{(j)}))/\xi^{(j)}], \tag{7}$$

$\xi^{(j)} = \Delta/s_L^{(j)}$, $\Delta = \sqrt{1/\mu_1^2 + 1/\mu_2^2 - 2\cos\gamma/(\mu_1\mu_2)}$, $s_L^{(j)}$ is the leaf size parameter in the layer j, and γ is the angle between vectors r_1 and r_2.

Expressions for the single scattering in both layers are similar, except the bidirectional reflectance of the lower layer is multiplied to the bidirectional gap probability in the upper layer $Q^{(2)}(r_1, r_2, H)$. Equation (4) is an approximation, it is valid in the case of geometrically thin lower layer, $H^{(1)} << H$.

2.2 Diffuse fluxes

Diffuse fluxes in a single layer are calculated similar to the SAIL model (Verhoef, 1984). Four differential equations define four fluxes: vertical fluxes up E_+ and down E_-, a direct solar flux E_s, and a flux associated with the radiance in the direction of observation E_o,

$$\begin{aligned} dE_+/dz &= -a u_L E_+ + \sigma u_L E_- + s' u_L E_s \\ dE_-/dz &= -\sigma u_L E_+ + a u_L E_- - s u_L E_s \\ dE_s/dz &= k u_L E_s \\ dE_o/dz &= v u_L E_- + u u_L E_+ - K u_L E_o \end{aligned} \tag{8}$$

The SAIL coefficients a, σ, s', s, k, v, u, and K can be expressed using the G-function and leaf reflection and transmission coefficients ρ_L and τ_L, $k = G_1/\mu_1$, $K = G_2/\mu_2$, $\sigma = (\rho_L + \tau_L)/2 + (\rho_L - \tau_L)J/2$, $a = 1 - (\rho_L + \tau_L)/2 + (\rho_L - \tau_L)J/2$, $s = (\rho_L + \tau_L)k/2 - (\rho_L - \tau_L)J/2$, $s' = (\rho_L + \tau_L)k/2 + (\rho_L - \tau_L)J/2$, $v = (\rho_L + \tau_L)K/2 + (\rho_L - \tau_L)J/2$,

Table 1: Scattering operators of the leaf layer

Definition	Boundary conditions			
$r_{dd} = E_+(0)/E_-(0)$	$E_s(0) = 0,$	$E_+(-1) = 0,$	$E_-(0) = D_\lambda$	
$t_{dd} = E_-(-1)/E_-(0)$	$E_s(0) = 0,$	$E_+(-1) = 0,$	$E_-(0) = D_\lambda$	
$r_{sd} = E_+(0)/E_s(0)$	$E_s(0) = S'_\lambda,$	$E_+(-1) = 0,$	$E_-(0) = 0$	
$t_{sd} = E_-(-1)/E_s(0)$	$E_s(0) = S'_\lambda,$	$E_+(-1) = 0,$	$E_-(0) = 0$	
$r_{do} = E_o(0)/E_-(0)$	$E_s(0) = 0,$	$E_+(-1) = 0,$	$E_-(0) = D_\lambda$	
$t_{do} = E_o^-(-1)/E_-(0)$	$E_s(0) = 0,$	$E_+(-1) = 0,$	$E_-(0) = D_\lambda,$	$E_o^-(0) = 0$
$r_{so} = E_o(0)/E_s(0)$	$E_s(0) = S'_\lambda,$	$E_+(-1) = 0,$	$E_-(0) = 0,$	$E_o(-1) = 0$

$u = (\rho_L + \tau_L)/2 - (\rho_L - \tau_L)J/2$, z is the vertical coordinate, $z = 0$ at the top of the canopy and $z = -1$ on the ground. J is an integral function, $J = (1/2\pi) \int_{2\pi} g_L(r_L)\mu_L^2 dr_L$, where $g_L(r_L)$ is the distribution density of leaf normals r_L. Equations (8) can be solved analytically, the general solutions for E_+, E_- and E_s are given e.g. in (Bunnik, 1978).

A series of reflection and transmission coefficients (operators) is introduced for the calculation of the diffuse component ρ_d for a single layer,

$$\rho_d = \rho_d^{\text{plants}} + \rho_d^{\text{soil}}, \tag{9}$$

where

$$\begin{aligned} \rho_d^{\text{plants}} &= \text{SQ}\, r_{so} + (1 - \text{SQ})\, r_{do} + \\ &+ [\text{SQ}\,(p_1\, r_{sd}^{\text{soil}} + t_{sd}\, r_{dd}^{\text{soil}}) + (1 - \text{SQ})\, t_{dd}\, r_{dd}^{\text{soil}}]\, t_{do} \,/\, (1 - r_{dd}\, r_{dd}^{\text{soil}}) \end{aligned} \tag{10}$$

and

$$\rho_d^{\text{soil}} = [\text{SQ}\,(p_1\, r_{sd}^{\text{soil}}\, r_{dd} + t_{sd}) + (1 - \text{SQ})\, t_{dd}]\, r_{ds}^{\text{soil}}\, p_2 \,/\, (1 - r_{dd}\, r_{dd}^{\text{soil}}) \tag{11}$$

Here $\text{SQ} = S'_\lambda/Q_\lambda$ is the share of direct flux in the total irradiance, $p_i = p(r_i)$ is the gap probability in direction r_i, r_{sd}^{soil} is the soil directional-hemispherical reflectance, r_{ds}^{soil} is the soil hemispherical-directional reflectance, and r_{dd}^{soil} is the soil hemispherical-hemispherical reflectance. The scattering operators of the leaf layer $r_{so}, r_{do}, t_{do}, t_{sd}$, and t_{dd} are defined in Table 1 where $D_\lambda = Q_\lambda - S'_\lambda$ is the diffuse flux from the sky. Equation (10) sums together radiances of diffuse fluxes scattered in the view direction. The factor $1/(1 - r_{dd} r_{dd}^{\text{soil}})$ accounts for the multiple scattering of diffuse fluxes between the leaf layer and soil (Sobolev, 1956).

In order to define the forward scattering operator t_{do} an additional differential equation should

be added to the set of equations (8),

$$dE_o^-/dz = -uu_L E_- - vu_L E_+ + Ku_L E_o^-, \tag{7a}$$

where E_o^- is a diffuse flux which is associated opposite to the view vector r_2. In Eq. (10) and Table 1 the validity of reciprocity relations is supposed i.e. the scattering operators for a direction r_i are equal to those in the opposite direction.

In a two-layer canopy the diffuse components $\rho_d^{\rm plants}$ and $\rho_d^{\rm soil}$ are also computed with equations (10) and (11) where the scattering operators for the composite leaf layer are calculated using the adding method (Sobolev, 1956) and scattering operators of component layers as defined in Table 1.

2.3 Leaf optics

Leaf optics models PROSPECT (Jacquemoud and Baret, 1990) or LIBERTY (Dawson et al., 1998) can be used for the calculation of leaf reflectance and transmittance. Both these models are modified so that the number of leaf constituents and names of files of their extinction spectra are listed in the input file. Extinction spectra of the models PROSPECT2 (Jacquemoud et al., 1996), PROSPECT3 (Fourty and Baret, 1998), and LIBERTY (Dawson et al., 1998) are available.

If compared with the PROSPECT model, the LIBERTY model has two additional parameters: average internal cell diameter and intercellular air space determinant (Dawson et al., 1998).

In the model input, the biochemical parameters are expressed as a fraction of the dry matter of leaves/needles. Using the described set of biophysical parameters, the whole spectrum of leaf reflectance and transmittance in the spectral range 400-2400 nm is calculated with the spectral resolution of 1 nm.

2.4 Sky radiation

The wavelength-dependent relative share of direct and diffuse flux in incoming radiation is needed, Eq. (1). Here the results by McCartney (1978a) and McCartney and Unsworth (1978b) are used (Kuusk, 1994),

$$D_\lambda/Q_\lambda = a_0(\lambda) + \gamma(\lambda)\tau(\lambda), \tag{12}$$

where $\tau(\lambda) = \beta \cdot \lambda^{-\kappa}$, $\kappa \approx 1.4$, and β is the Ångström turbidity factor. Functions $a_0(\lambda)$ and $\gamma(\lambda)$ are given by McCartney (1978a) and are tabulated in the model.

3 Inversion of the model

Inversion of the model can be performed similar to Goel and Strebel (1983) or Kuusk (1991): a merit function is built, which has its minimum value when the best fit of measured and calculated reflectance data is reached. This way the complicated task of the solution of an array of non-linear equations for the estimation of model parameters is reduced to a more simple problem of the search of an extremum of a multidimensional function. In the merit function constraints are used in order to avoid the non-physical values of input parameters, and uncertainties of reflectance data and an expert estimate of parameter values are accounted for (Kimes et al., 2000),

$$F(X) = \sum_{j=1}^{m} \left(\frac{\rho_j^* - \rho_j}{\epsilon_j} \right)^2 + \sum_{i=1}^{n} \left[(x_i - x_{i,b})^4 \, w_i^2 + \left(\frac{x_i - x_{e,i}}{dx_i} \right)^2 \right] . \tag{13}$$

Here $X = (x_{27}, x_{28}, ..., x_{70})$ is the vector of model input parameters, m is the number of the measured reflectance values ρ_j^*, ρ_j is the model reflectance value, ϵ_j is the error of the measured reflectance value ρ_j^*, x_i is a model parameter and $x_{i,b}$ its value on the boundary of the given region; w_i is a weight, $w_i = 0$ in the given region $x_i \in [x_{i,min}, x_{i,max}]$ and $w_i =$ const else, $x_{e,i}$ is the expert estimate of the parameter x_i, and dx_i is a tolerance for the parameter x_i which controls the sensitivity of the merit function on the expert estimate. The component numbers start from 27 in order to be congruent to the component numbers of the forest reflectance model FRT (Kuusk and Nilson, 2002). If the concentration of some leaf component is subject to the estimation, then water should be the first leaf component. The sum of concentrations of other components is forced to be equal to 100% in the inversion.

There is an option to use only absolute differences $(\rho_j^* - \rho_j)^2$ in the merit function.

In the inversion, the redundancy of data can be effectively used, i.e. the number of reflectance values inverted may be more than the number of model parameters subject to estimation. Anyway, as the number of model parameters is large, most of the model parameters should be fixed at 'best guess' values, and only a few parameters can be estimated simultaneously.

4 Conclusion

The model can be used for the interpretation of multispectral and/or multiangular remote sensing data in the wide range of Sun and view angles in the whole optical domain 400-2400 nm. The proposed version of the model seems to be a good tool for different sensitivity analyses, e.g. an analysis of the dependence of BRDF, in particular near the hot spot, on the canopy optical and structural variables.

The same computer code can be used both for direct and inversion modeling.

The model is coded in Fortran. The computational aspects of the model are detailed in the following appendices:

- General description of the computer code
- Example of inputs and outputs
- Complete description of the subroutines

Acknowledgments

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Appendix

A General description of the computer code

A rough flowchart of the computer code is in Fig. 1, and the full call-tree in Fig. 2.

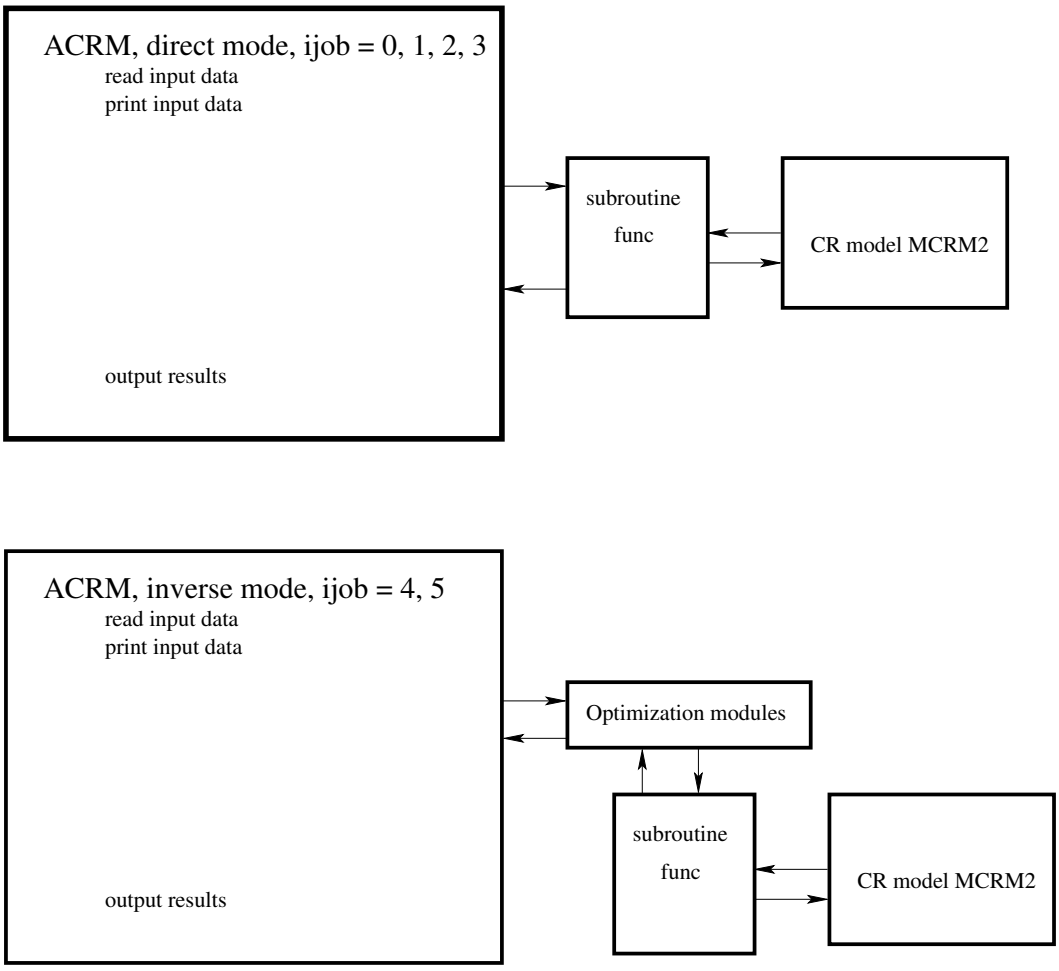

Figure 1: Flowchart of the computer code.

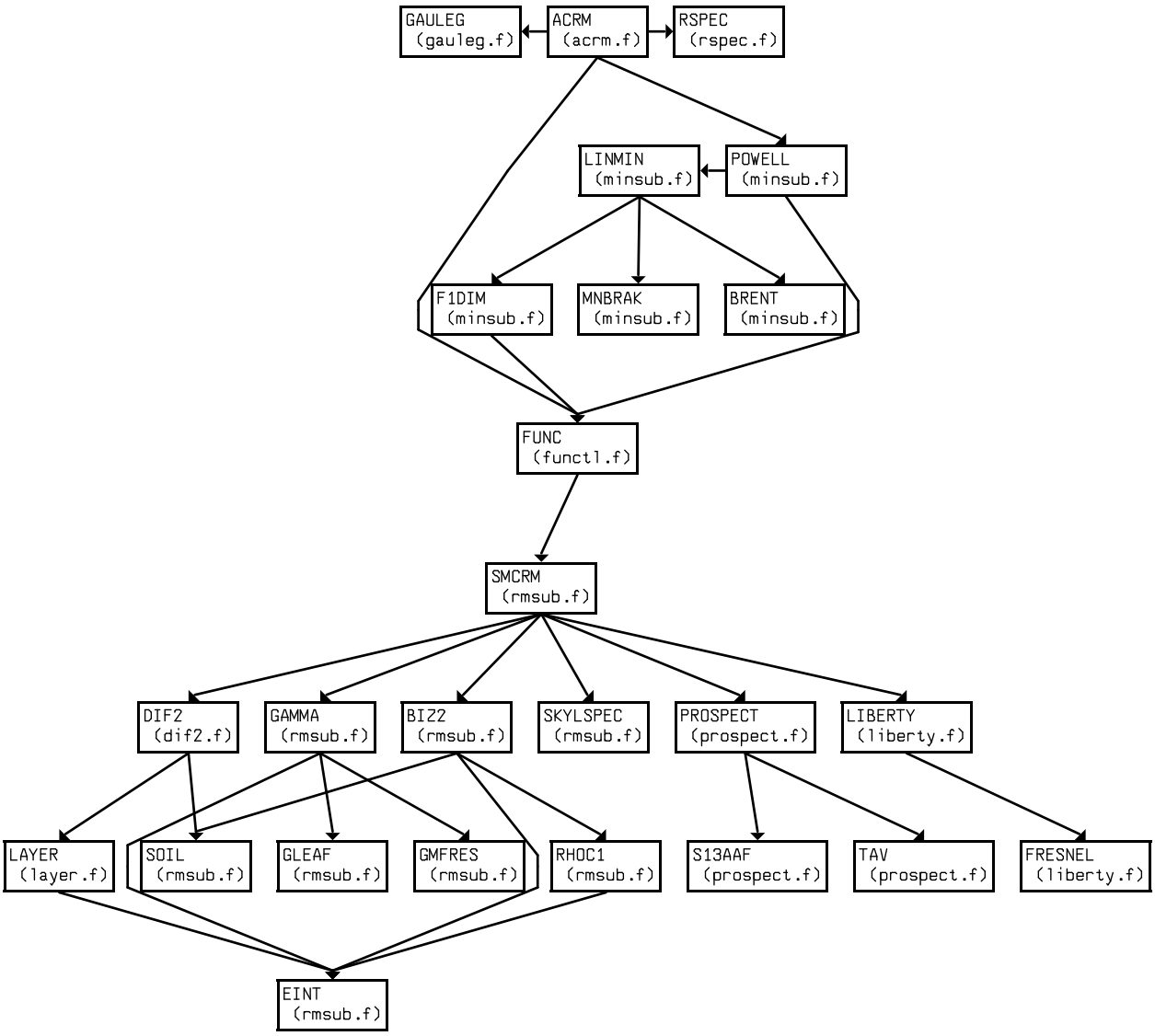

Figure 2: The call-tree of the computer code.

B The usage

The model is distributed as a compressed tar-archive of source texts, sample input and output files. It is recommended to create a separate directory for the model. Move the archive acrmf??????.tar.gz to this directory, extract the files and make

tar -xzvf acrmf??????.tar.gz
make acrmf or make all

make clean removes object files,
make distclean removes object files and executables.

If you don't use the gfortran compiler then you should modify the makefile.

To run the code type on the commandline

./acrmf inputfile outputfile

If you do not give input and output files on commandline then you will be asked for the filenames.

Program acrmf calculates in direct mode canopy reflectance. There are options to perform calculations in various modes:

- a single run for given Sun and view angles and fixed wavelength
- reflectance spectrum for given view and Sun angles in the given range of wavelengths or for a list of spectral bands
- angular distribution of reflectance at given azimuth (relative to the Sun azimuth) for a given Sun zenith angle in the range of view polar angles 0 .. 80°.

Any view and Sun angle is allowed, however, do not use polar angles very close to 90°.

There are several input files required: a file of canopy parameters and files of absorption spectra for the leaf optics model.

The same code is used for the inversion: any input parameter of the model and/or any number of model parameters can be estimated. An additional flow control file *flow.dat* is required for the model inversion.

B.1 The input file of canopy parameters

The same input file can be used both for the direct and inverse modes. In direct mode the unnecessary parameters may be missing.

The input parameter $ijob$ controls which task will be run:

ijob	task
0	single run, Sun and view angles, and wavelength fixed to the first value of the respective parameter in the input file
1	calculate spectrum, Sun and view angles fixed
2	calculate angular distribution for theta = -80 .. 80°, Sun zenith, azimuth and wavelength fixed
3	n_sun Sun zenith angles, view angles and wavelength fixed
4	inversion of the model, the initial guess, the recommended range of parameters, and errors of the reflectance values are accounted for in the merit function
5	inversion of the model, absolute differences in the merit function

ijob = 1
The spectral range is determined by the wavelength of the first spectral band, the wavelength increment dwl, and the number of spectral bands. The valid range of wavelengths is 400 - 2400 nm, spectral resolution 1 nm. The spectrum step is given by an input parameter dwl, if $dwl \leq 0$ then the list of wavelengths should be given.

ijob = 2
Program calculates the angular distribution of canopy reflectance in the range -80 .. 80° at a given azimuth (relative to the principal plane) and given increment in the view nadir angle. Negative polar angles correspond to the backscattering (hot-spot side), and positive polar angles - to the forward scattering.

ijob = 3
Program calculates the canopy reflectance at the given view direction for n_sun Sun zenith angles.

ijob = 4
The code is run in inverse mode, n parameters of the model which are listed in the key vector $ll(n)$ are estimated by minimizing the merit function $F(X)$, Eq. (13).

ijob = 5
As $ijob = 4$, except absolute differences are accounted for in the merit function $F(X)$, i.e. $\epsilon = 1$ in Eq. (13).

Structure of the input file of canopy parameters

A sample input file of canopy parameters is printed in the page 15. Colons are used to mark comments, information after a colon is not used by the computer program. Below the sample input file is commented linewise. The row of the input file is printed in bold. As the number of lines is not constant - it depends on the number of leaf components - the lines in comments are not numbered.

A sample input file

```
 'Järvselja Pine'                                  : data set name
*** files of refractive index and McCartney functions for sky flux ***
'refrind.dat' 'angstr.dat'
x0      xmin      xmax      dx                                                  i
2.9     1.        5.        .3        : LAI2, upper layer                       29
.1      .02       .4        .05       : sl2 - HS-parameter                      30
0.6     0.4       1.2       .3        : clmp2 - foliage clumping parameter      31
1.2     1.        2.        .3        : szz - the regularity parameter          32
2.0     .0        4.5       .5        : eln2 - -ln(1 - eps2)                    33
88.     0.        90.       20.       : thm2 - modal leaf angle                 34
.9      .6        1.3       .2        : n_ratio2                                35
160.    80.       180.      30.       : SLW2(g/m^2)                             36
'prospect'                              : leaf optics model, upper layer
4                                       : # of leaf components
137.    130.      320.      50.   'waterb.dat'      : c1, % of SLW, comp.1      37
.305    .2        .7        .2    'chlorp3.dat'     : c2, % of SLW, comp.2      38
98.0    50.       99.       30.   'drymatter.dat'   : c3, % of SLW, comp.3      39
.038    .0        1.        .1    'anthocyanins.dat' : c4, % of SLW, comp.4     40
1.624   1.4       2.6       .5        : N2 (PROSPECT)                           49
1.064   .01       1.8       .3        : LAI1, lower layer                       50
.15     .02       .4        .05       : sl1 HS-parameter                        51
1.      .4        1.        .2        : clmp1 - foliage clumping parameter      52
2.      .0        4.5       .5        : eln1 - -ln(1 - eps)                     53
0.      0.        90.       20.       : thm1 - modal leaf angle                 54
1.2     .6        1.3       .2        : n_ratio1                                55
78.54   80.       180.      30.       : SLW1(g/m^2)                             56
'prospect'                              : leaf optics model, lower layer
5                                       : # of leaf components
134.    130.      320.      50.   'waterb.dat'      : c1, % of SLW, comp.1      57
.425    .3        .8        .2    'chlorp3.dat'     : c2, % of SLW, comp.2      58
.733    .3        .8        .2    'anthocyanins.dat'   : c3, % of SLW, comp.3   59
98.3    94.       99.8      20.   'drymatter.dat'   : c4, % of SLW, comp.4      60
.5      .0002     4.        .1    'cellp3.dat' : c5, % of SLW, comp.4           61
1.05    1.0       1.3       .1        : N1 (PROSPECT)                           69
'price.dat'       45.                 : file of Price' vectors, th*
.217    .05       .4        .07       : s1 - soil parameters                    70
-.05    -.1       .1        .02       : s2                                      71
.0      -.05      .05       .02       : s3                                      72
.0      -.04      .04       .02       : s4                                      73
1       : *ijob*: 0-single, 1-spectrum, 2-ad, 3-n_sun, 4,5-inversion (4-relat., 5-abs. differences)
1       6         -5.                 : # of Sun angles, spectral channels, spectrum step
38.  50.                              : Sun zeniths
.18  .24                              : b_Ångström
486.  571.  650.  838.  1677.  2217.  : spectral channels (Landsat TM)
0.      2.        0.                  : view nadir angle, its increment, and azimuth angle
'powell'                              : name of the optimization subroutine
5000    10        100       100       : nfmax, itmax, itbr, nbrak
1.E-9   1.E-7     1.E-13    1.E-8     : zeps, tolbr, tiny, ftolp
1.      .5        2.        .2        : alpha, beta, gamma, dx
3       20.       f                   : n, at, lig - which initial guess
27  67  68                            : ll(i)
6                 : nref - # of reflectance data for the inversion
486.        .0481       .0084       0.          0.          38.         .10
572.        .0633       .0095       0.          0.          38.         .10
661.        .0863       .0127       0.          0.          38.         .10
838.        .1601       .0116       0.          0.          38.         .10
1677.       .3066       .0209       0.          0.          38.         .10
2217.       .2475       .0218       0.          0.          38.         .10
************************************************************
lambda      reflectance delta_rho   th_o        phi         th_s        b_Angs
```

'Järvselja Pine' : data set name
***** files of refractive index and McCartney functions for sky flux ***** – a comment line
'refrind.dat' 'angstr.dat'
x0 xmin xmax dx i - a comment

Starting from the next row there are four parameter values in each line. Only the first value (*x0*) is required for the direct problem, x_min and x_max are the boundary values of the parameter in the inversion run. The fourth column, dx, is the tolerance of the parameter in the inversion, Eq. (13). The first value (*x0*) serves as an initial guess and as an expert estimate $x_{e,j}$, Eq. (13) of the parameter value in the inversion. There is the parameter number in the vector of parameters in the last column. The parameter numbers start from 29 for the compatibility to the forest model FRT12. Only the first column (*x0*) is needed in the direct mode ($ijob$ = 0, 1, 2, 3)

2.9	**1.**	**5.**	**.3**	: LAI2, upper layer
.1	**.02**	**.4**	**.05**	: sl2 - HS-parameter
0.6	**0.**	**2.**	**.3**	: clmp2 - foliage clumping parameter
1.2	**1.**	**2.**	**.3**	: szz - the regularity parameter
2.0	**.0**	**4.5**	**.5**	: eln2 - -ln(1 - eps2)
88.	**0.**	**90.**	**20.**	: thm2 - modal leaf angle
.9	**.6**	**1.3**	**.2**	: n_ratio2

Refraction index of the leaf surface wax is calculated from the tabulated value by multiplying to this coefficient.

160.	**80.**	**180.**	**30.**	: SLW2(g/m^2)

'prospect' : leaf optics model, options are 'prospect' and 'liberty'.
4 : # of leaf components n_{comp}

In the next n_{comp} lines the percent concentration of the component and the file name of the component absorption spectrum for every component is listed. Despite in the direct mode only the first parameter $x(0)$ is used, the filename must be at the fifth position in the line. The components 37-46 of the vector of parameters are reserved for the leaf biochemical constituents - the upper layer, and components 57-66 - the lower layer of ground vegetation, so the maximum number of leaf biochemical components is 10. The components 47 and 48, and 67 and 68 of the vector of parameters are the LIBERTY parameters cell diameter and amount of inter-cell air, for the upper and lower layer of vegetation, respectively.

4					: # of leaf components
137.	**130.**	**320.**	**50.**	**'waterb.dat'**	: c1, % of SLW, comp.1
.305	**.2**	**.7**	**.2**	**'chlorp3.dat'**	: c2, % of SLW, comp.2
98.0	**50.**	**99.**	**30.**	**'drymatter.dat'**	: c3, % of SLW, comp.3
.038	**.0**	**1.**	**.1**	**'anthocyanins.dat'**	: c4, % of SLW, comp.4
1.624	**1.4**	**2.6**	**.5**		: N2 (PROSPECT)
1.064	**.01**	**1.8**	**.3**		: LAI1, lower layer
.15	**.02**	**.4**	**.05**		: sl1 - HS-parameter
1.	**.4**	**1.**	**.2**		: clmp1 - foliage clumping parameter
2.	**.0**	**4.5**	**.5**		: eln1 - -ln(1 - eps)

0.	**0.**	**90.**	**20.**		: thm1 - modal leaf angle
1.2	**.6**	**1.3**	**.2**		: n_ratio1
78.54	**80.**	**180.**	**30.**		: SLW1(g/m^2)
'prospect'					: leaf optics model, lower layer
5		: # of leaf components n_{comp}			
134.	**130.**	**320.**	**50.**	**'waterb.dat'**	: c1, % of SLW, comp.1
.425	**.3**	**.8**	**.2**	**'chlorp3.dat'**	: c2, % of SLW, comp.2
.733	**.3**	**.8**	**.2**	**'anthocyanins.dat'**	: c3, % of SLW, comp.3
98.3	**94.**	**99.8**	**20.**	**'drymatter.dat'**	: c4, % of SLW, comp.4
.5	**.0002**	**4.**	**.1**	**'cellp3.dat'**	: c5, % of SLW, comp.5
1.05	**1.**	**1.3**	**.1**		: N1 (PROSPECT)
'price.dat'	**45.**				: file of Price' vectors, th*
.217	**.05**	**.4**	**.07**		: s1 - soil parameters
-.05	**-.1**	**.1**	**.02**		: s2
.0	**-.05**	**.05**	**.02**		: s3
.0	**-.04**	**.04**	**.02**		: s4

1 : *ijob*: 0-single, 1-spectrum, 2-ad, 3-n_sun, 4,5-inversion (4-relat., 5-abs. differences)

The job control parameter $ijob$
0 - calculate a single value of canopy reflectance
1 - calculate reflectance spectrum for the given Sun and view angles
2 - calculate reflectance angular distribution at given azimuth
3 - calculate CR for several Sun zenith angles
4 - inversion of the ACRM model, relative differences in the merit function
5 - inversion of the ACRM model, absolute differences in the merit function

2 **6** **-5.** : # of Sun angles, spectral channels, spectrum step
Number of Sun angles and spectral channels; the spectrum step $d\lambda$.
If $d\lambda < 0$ then give the list of spectral channels on the next line
otherway, the spectrum has the fixed increment and only the first wavelength is read

38. 50. : Sun zeniths
.18 .24 : b_Ångström
486. 572. 661. 838. 1677. 2217. : spectral channels
0. **2.** **0.** : view nadir angle, its increment, and azimuth angle.
In case of b_Ångström < 0 there is no diffuse sky flux, $D_\lambda/Q_\lambda = 0$.
The azimuth angle is counted from the principal plane.

The next group of parameters are optimization parameters. The only working option for the optimization subroutine is 'powell'.

'powell'				: name of the optimization subroutine
5000	**10**	**100**	**100**	: nfmax, itmax, itbr, nbrak

$nfmax$ – the max number of calculations of merit function
$itmax$ – the max number of iterations
$itbr$ – the max number of iterations in the subroutine brent
$nbrak$ – number of iterations in the subroutine mnbracket

1.E-9	**1.E-7**	**1.E-13**	**1.E-8**	: zeps, tolbr, tiny, ftolp
1.	**.5**	**2.**	**.2**	: alpha, beta, gamma, dx

3 **20.** **f** : n, at, lig - which initial guess
n - the number of model parameters subject to inversion
at - penalty – the weight w_i, Eq. (13), at = 20. is ok!
lig is a logical parameter,
lig = t (.true.) – parameters will be read from a temporary file
(results of the previous iteration)
lig = f (.false.) – parameters will be read from the input file
In the first run take lig = f (.false.)
27 67 68 : ll(i)
The key vector $ll(n)$, here the numbers of free model parameters
which are subject to estimation are listed.
6 : nref - # of reflectance data for the inversion

The next lines are the reflectance values for inversion.

486.	**.0481**	**.0084**	**0**	**0**	**38.**	**.10**
572.	**.0633**	**.0095**	**0**	**0**	**38.**	**.10**
661.	**.0863**	**.0127**	**0**	**0**	**38.**	**.10**
838.	**.1601**	**.0116**	**0**	**0**	**38.**	**.10**
1677.	**.3066**	**.0209**	**0**	**0**	**38.**	**.10**
2217.	**.2475**	**.0218**	**0**	**0**	**38.**	**.10**
lambda	rho	stdev	th_view	phi	th_sun	b_Angs

B.2 The flow control file *flow.dat*

The inversion procedure is iterative. If in given number of iterations the minimum of the merit function is found, $ier = 1$, then the program prints output and stops. Otherway ($ier \neq 1$), the flow control parameter $next$ is read from the flow control file *flow.dat*. The meaning of this parameter is:

1 - continue
7 - stop

A sample file *flow.dat*

1 : continue
1 : continue
1 : continue
7 : stop

C A sample output file

```
#
#   Reflectance of a two-layer canopy by A. Kuusk, ACRMf_12.2012
#
##  Input parameters:     Järvselja Pine
##  ijob =   1  - the reflectance spectrum
#
#   Files of refractive index,
#   of McCartney functions for sky fluxes,
#   and of Price' vectors:
#   refrind.dat         angstr.dat          soil.dat
#   The sun zenith of soil reflectance    45.0
#
# ***                    Upper layer    Lower layer
#   LAI                       2.900        1.064
#   leaf relat. size          0.100        0.150
#   clmp                      0.600        1.000
#   szz                       1.200
#   eln                       2.000        2.000
#   thm                      88.000        0.000
#   n_ratio                   0.900        1.200
#   SLW                     160.000       78.540
#   Leaf models:           prospect     prospect
#   # of leaf components:         4            5
#      waterb.dat         waterb.dat
#   c1, % of SLW             137.000      134.236
#      chlorp3.dat        chlorp3.dat
#   c2, % of SLW                0.305        0.425
#      drymatter.dat      anthocyanins.dat
#   c3, % of SLW               98.000        0.733
#      anthocyanins.dat   drymatter.dat
#   c4, % of SLW                0.038       98.343
#                         cellp3.dat
#   c5, % of SLW                0.000        0.500
#   leaf struct. par.          1.6240       1.0500
#   s1_soil                    2.0373
#   s2                         0.0000
#   s3                         0.0000
#   s4                         0.0000
#         Sun zenith(s)      44.0
#         b_Ångström        0.060
#
#
# *** Results:
#
# Sun zenith, deg    44.0
# View zenith and azimuth, deg     0.0     0.0
#
# lmbda, nm; refl; rc1; rcd; rs1; rsd; S'/Q
#
 489.1    0.0261    0.0212    0.0080    0.0046    0.0006    0.6773
 549.7    0.0747    0.0605    0.0240    0.0056    0.0015    0.7441
 629.1    0.0458    0.0355    0.0090    0.0072    0.0011    0.8352
 671.9    0.0276    0.0184    0.0031    0.0086    0.0007    0.8792
 703.4    0.0931    0.0676    0.0200    0.0099    0.0029    0.9062
 738.5    0.2844    0.1449    0.1266    0.0112    0.0123    0.9318
 777.2    0.3463    0.1568    0.1678    0.0124    0.0174    0.9517
 890.8    0.3816    0.1596    0.1866    0.0157    0.0246    0.9718
```

D Description of the subroutines

D.1 Subroutines of general use

Subroutines

gauleg - quadrature knots and weights for numerical integrations
rspec - reads tabulated spectra
function *func*

In the direct mode the function *func* organizes the data exchange between subroutines and the main program.

In the inverse mode the function *func* checks that the model parameters are in the allowed range, organizes the data exchange between subroutines and the main program, and computes the merit function.

D.2 Leaf optics models

D.2.1 PROSPECT

Leaf optics model by Jacquemoud and Baret (1990).

prospect
tav
s13aaf

D.2.2 LIBERTY

Leaf optics model by Dawson et al. (1998).

liberty
fresnel

D.3 CR model MCRM2

Subroutines

smcrm - root of the model
biz2 - single scattering by plants and soil
rhoc1 - single scattering from leaves
gamma - phase function and G-function
layer - diffuse reflection and transmission of a layer of leaves
gleaf - elliptical LAD
gmfres - Fresnel' reflection
soil - soil reflectance
skylspec - diffuse/total ratio of incoming flux

D.4 Optimization modules

The Powell's method (Press et al., 1992), Algorithm 10.5 is used for the minimization of the merit function Eq. (16). The corresponding subroutines are

powell
linmin
mnbrak
function brent

References

Dawson, T.P., Curran, P.J., and Plummer, S.E. LIBERTY - modeling the effects of leaf biochemical concentration on reflectance spectra. Remote Sens. Environ. 1998; 65:50-60.

Jacquemoud, S., and Baret, F. PROSPECT: A model of leaf optical properties spectra. Remote Sens. Environ. 1990; 34:75-91.

Press, W.H., Teukolsky, S.A., Vetterling, W.T., and Flannery, B.P., 1992. Numerical Recipes in FORTRAN. The Art of Scientific Computing. Cambridge University Press, Cambridge. 963 pp.