Remote sensing subroutines in crop growth simulation models
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Remote sensing sub-routines in crop growth simulation models

B.A.M. Bouman

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Preface

This report documents the implementation of optical and radar remote sensing models as Fortran subroutines to be used in crop growth simulation models. The models and software described in this report are (partly) a follow-up on the integration of remote sensing models and crop growth models as operationalized in SBFLEVO and WWFLEVO in 1992 (Bouman, 1992b). The work described in this document was co-funded by the European Space Agency (ESA/ESTEC) under contract number ESA AO/1-2832/94/NL/NB.
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Samenvatting

Dit rapport beschrijft de implementatie van optische en radar remote-sensing modellen in de vorm van Fortran-routinetjes, en de koppeling hiervan met simulatiemodellen van gewasgroei die beschreven zijn in Fortran Simulation Environment (FSE), versie 2.1. Gekoppelde remote-sensing - gewasgroemodellen kunnen gebruikt worden voor het volgen van actuele gewasgroei en -ontwikkeling, oogstvoorspelling, optimalisatie van remote-sensing opname tijdstippen en de interpretatie van remote-sensing beelden. De optische remote-sensing routines zijn gebaseerd op de modellen EXTRAD en CLAIR, en op empirische relaties tussen Leaf Area Index (LAI) en de vegetatie-index WDMI. De radar remote-sensing routines zijn gebaseerd op het één- en twee-lagige Cloud-model. Om de remote-sensing routines heen zijn 'interfaces' gebouwd, die vanuit gewasgroemodellen aangeroepen kunnen worden, en die berekeningen uitvoeren op variabelen die nodig zijn in de remote-sensing routines. Deze interfaces zijn eveneens in FSE 2.1 geprogrammeerd, en zijn geïmplementeerd in FSE-SUCROS-modellen voor suikerbieten, tarwe en aardappelen. Het laatste hoofdstuk van dit rapport leest zich als een gebruikershandleiding voor de ontwikkelde remote-sensing subroutines en voor de interfaces naar de gewasgroemodellen. De appendices bevatten een verklaring van de variabelen, complete listings van de programma-code, en een voorbeeld invoer data file.

Summary

This report describes the implementation of optical and radar remote sensing models as Fortran subroutines, and their linkage with crop growth simulation models that are written in the Fortran Simulation Environment (FSE), version 2.1. Integrated remote sensing - crop growth models can be used for monitoring crop growth and development, yield forecasting, optimisation of the timing of remote sensing observations and the interpretation of remote sensing data. The optical remote sensing routines are based on the models EXTRAD and CLAIR, and on empirical relationships between Leaf Area Index (LAI) and the Vegetation Index WDMI. The radar remote sensing routines are based on the one- and two-layer Cloud model. The remote sensing routines are incorporated in so-called 'interfaces', subroutines that can be called from crop growth models and that take care of computations on variables that are needed in the remote sensing routines. The interfaces are also written in FSE 2.1, and have been implemented in FSE-SUCROS models for sugar beet, wheat and potato. The last chapter of this report is structured as user manual of the developed remote sensing subroutines and interfaces to the crop growth simulation models. The appendices give an explanation of the variables, a complete listings of the source code of the software and an example input data file.
1 Introduction

This report describes the implementation of optical and radar remote sensing models as Fortran subroutines that can be linked with crop growth simulation models written in the Fortran Simulation Environment (FSE), version 2.1 (van Kraalingen, 1995). Integrated remote sensing - crop growth models are useful in agricultural research and in various types of application: (i) to derive optimum time-frames for remote sensing observations for crop type discrimination by comparing simulated time trends of remote sensing signals from different crop types, (ii) to increase the accuracy of crop growth monitoring and yield forecasting by calibrating simulated remote sensing signals on observed remote sensing signals, (ii) to aid the interpretation of observed remote sensing signals over agricultural areas, and (iv) to supply 'ground-truth' (i.e. crop information) for calibration of remote sensing models. Examples of application are found in Bouman (1992c, 1995) and Clevers et al. (1994).

The integration of remote sensing modules with crop growth models was done in three steps. First, the remote sensing models were written as 'straightforward' FORTRAN77 subroutines that can be used in any Fortran software program. Next, an interface was developed that forms the bridge between crop growth simulation models and the remote sensing subroutines. Third, this interface was 'operationsalized' in FSE-SUCROS crop growth models for sugar beet, wheat and potato. This report describes extensively steps one and two, and gives a (summary) example of step three. The models and software described in this report are (partly) a follow-up on the integration of remote sensing models and crop growth models as operationialized in SBFLEVO and WWFLEVO in 1992 (Bouman, 1992b). Major improvements with respect to SBFLEVO and WWFLEVO are that (i) the quality of the software (Fortran code) has been improved (e.g. structured programming, boundary checks on input data), (ii) the subroutines are made more 'generic' (i.e. simply adaptable to other crops by changing model parameter values in external files), (iii) that the subroutines are written in FSE 2.1 which is the current standard Fortran programming environment for crop growth models at AB-DLO. FSE consists of a main program, weather data and utilities for performing specific tasks such as retrieving weather data from file (the WEATHER system), writing output in the form of tables or graphs, and time control. FSE is flexible, user-friendly, enables easy input of parameters and initial state values, and has the capability to perform model reruns on these values. A complete explanation of FSE 2.1 is given by van Kraalingen (1995).

To read this report, no in-depth knowledge on crop growth processes is needed. A basic familiarity with the main processes, and the way these are modelled in crop growth simulation models of 'The School of de Wit' (Bouman et al., 1996) is, however, helpful (see e.g. van Keulen & Wolf, 1986; Penning de Vries et al., 1989). Chapter 6, that describes the interface of the remote sensing models with crop growth simulation models, assumes a basic knowledge of the Fortran Simulation Environment (van Kraalingen, 1995). In Chapter 2, some introductory remarks on the general theory of optical and radar remote sensing are given, but the reader is referred to text books on the topic for in-depth understanding (e.g. Schanda, 1986; Ulaby et al., 1981; 1982; 1986). The remote sensing models that are used for integration with crop growth models are briefly described with reference to original publications in Chapter 3. Chapter 4 suggests default values of model input parameters, and gives some literature references to find other values. Chapter 5 explains how the scientific models described in Chapter 3 were implemented in Fortran subroutines. Chapter 6 explains how these Fortran
routines were built in interfaces for crop growth models, and Chapter 7 indicates how these interfaces were actually linked with crop growth simulation models. The Appendices give respectively a variable name listing, the source code of the optical and radar backscatter routines, and an example remote sensing input file.
2 Remote sensing

Remote sensing is the measurement of electromagnetic (EM) radiation that is reflected or emitted from objects at the surface of the earth (such as field crops). Reflected EM waves may have been emitted by the sun (e.g. optical remote sensing) or by artificial sources (e.g. laser, radar). EM waves emitted by earth surfaces are measured in the thermal infra-red and passive microwave regions of the EM spectrum. This report addresses optical and radar remote sensing.

Remote sensing measurements can be made from a variety of platforms, e.g. ground-based, aircraft or satellite. The remote sensing models described in this report calculate remote sensing signals (optical reflectance, radar backscatter) at the top of a vegetation canopy. For comparison of the calculated signals with measured remote sensing signals from aircraft or satellite, the atmospheric transmission of the EM waves to the observation platform has to be taken into account for optical systems. This atmospheric correction makes part of the data processing chain of (optical) remote sensing observations, and is not addressed in this report. Microwaves as used in radar remote sensing are unhindered by the atmosphere, and no atmospheric correction is needed.

2.1 Optical remote sensing

Optical remote sensing is the measurement of solar radiation that is reflected from the surface (objects) of the earth. The spectrum is generally divided into the blue (0.4-0.5 μm), green (0.5-0.6 μm) and red (0.6-0.7 μm) visible wavelength bands, and the near infra-red (0.7-1.3 μm) and middle infra-red (1.3-3.0 μm) wavelength bands. The optical reflectance of crops is determined by the interaction of solar radiation with the crop canopy. From the late sixties, this interaction process has been extensively studied and the interaction of optical radiation with vegetation canopies is relatively well understood. By experimentation and well validated interaction models, crop canopy reflectance has been shown to be related to various crop parameters, the soil background, conditions of illumination and the geometry of observation (Suits 1972; Goudriaan 1977; Bunnik 1978; Verhoeef, 1984; Den Dulk, 1989; Kuusk and Nilson, 1989). For crop studies, relationships between optical reflectance and crop characteristics are most interesting, and so-called Vegetation Indices (VI) have been developed to minimize the 'disturbing' effects of variation in soil background, illumination conditions and observation geometry. Much used VIs are the near infra-red/red ratio (IR/R ; first used by Jordan, 1969), the Normalized Difference Vegetation Index, NDVI (developed as 'VI' by Rouse et al., 1973), and the Weighted Difference Vegetation Index, WDV1 (Clevers, 1988; 1989), Table 1. From a comparative analysis, the WDV1 gave the most stable relationships with measures of light interception by the canopy, namely Leaf Area index and percentage ground cover (Bouman, 1992a), and is therefore used in this report. In the calculation of WDV1 (Equation 3, Table 1), the constant c is calculated as the ratio of infra-red reflectance of the bare soil background over the red reflectance of the bare soil background. This ratio is best determined from measurements on bare soil just before crop emergence.
Table 1. Equations of some much used Vegetation Indices (VI) from optical reflectance characteristics.

<table>
<thead>
<tr>
<th>IR/R Ratio</th>
<th>NDVI</th>
<th>WDVI</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\frac{r_{ir}}{r_r}$ (Eq. 1)</td>
<td>$r_{ir} - r_r$ (Eq. 2)</td>
<td>$r_{ir} - cr_r$ (Eq. 3)</td>
</tr>
<tr>
<td>$r_{ir} + r_r$</td>
<td>$c = \frac{r_{ir,s}}{r_{r,s}}$</td>
<td></td>
</tr>
</tbody>
</table>

In Equations 1 to 3: $r$ is (nadir, i.e. in the vertical direction) canopy reflectance (%), with suffixes $ir$ and $r$ indicating infra-red and red part of the spectrum; and suffix $s$ indicating reflection of the bare soil. (Note that instead of red reflectance, green reflectance can also be used, e.g. Bouman et al., 1992).

2.2 Radar remote sensing

A radar system consists of a transmitter in which EM microwaves of a certain wavelength (usually between 1 and 30 cm) are generated, and an antenna for spatial distribution of the generated radiation. After reflection in a backward direction by an object on the earth's surface, the microwaves are received by the antenna and detected on the radar receiver: radar backscatter. The radar backscatter of an object is expressed by its radar cross-section, which may be defined as its microwave reflective power in the direction of the source. In this report, the radar backscatter is expressed as $g$: the radar cross-section of the target per unit projected area of the cross-section of the radar beam ($m^2/m^2$). The relationship between $g$ and $s^0$ (the Normalised Radar Cross Section NRCS, which is the radar cross-section per unit area illuminated by the antenna) is:

$$\gamma = \frac{s^0}{\cos \theta}$$

(Eq. 4)

where $\gamma$ is the angle of incidence, defined as the angle between the incident radar beam and the vertical. Furthermore, as a standard, $g$ is expressed in dB:

$$\gamma (\text{dB}) = 10 \log(\gamma (m^2/m^2))$$

(Eq. 5)

Microwaves that are used in radar remote sensing are relatively unhindered by atmospheric conditions. Wavelengths longer than 3 cm are hardly affected by clouds and wavelengths longer than 10 cm are very little attenuated by rain (Goodman, 1980).

The radar backscatter of crops depends on the properties of the incident microwaves, and on those of the canopy and the underlying soil. Properties of microwaves are frequency (or wavelength), state of polarization and angle of incidence. Generally used frequency bands for remote sensing are L-band (1.2 GHz = 24 cm), S-band (3.2 GHz = 9.4 cm), C-band (5.3 GHz = 5.7 cm), X-band (9.5 GHz = 3.1 cm), Ku1-band (13.7 GHz = 2.2 cm) and Ku2-band (17.3 GHz = 1.7 cm). States of polarization are denoted by a combination of two letters: VV, HH, HV and VH. In these abbreviations, the first
letter stands for the polarization of the transmitted wave, the second for that of the received wave; 'V' denotes vertical and 'H' horizontal. [The special case of radar polarimetry will not be considered here]. Angle of incidence of a radar beam can vary between about 10° - 80°.

In microwave scattering theory, a crop canopy can be considered as a dielectric mixture of discrete inclusions (e.g. leaves and stems) distributed in a host material of air (Ulaby & Jedlicka, 1984). Detailed physical models generally describe the scattering strength and the microwave attenuation through canopies from the dielectric constant, the volume fraction and the geometry of the various types of inclusions (e.g. Eom & Fung, 1986; Karam & Fung, 1988; Ulaby et al., 1990). However, unlike in the optical region, such detailed models still do not describe reality sufficiently well and model simulations do not explain radar backscatter measurements for many crop types (Bouman & Hoekman, 1993; Rijckenberg, 1994). Moreover, many of the input parameters can not be successfully related to measurable physical properties of the crop. Another class of simple physical models has been developed that treat the canopy as a collection of water droplets, e.g. the 'Cloud' model (Attema and Ulaby, 1978; Hoekman et al., 1982). This model has proven to give satisfactory descriptions of radar backscatter of agricultural crops based on measurable physical inputs. The Cloud model, therefore, was selected for the integration with crop growth simulation models (see Chapters 3-5).
3 Scientific model descriptions

3.1 Optical

The EXTRAD (EXTinction of RADiation) model developed by Goudriaan (1977) is used to calculate optical reflectance from crop canopies. Two 'descriptions' are used to calculate specifically the WDU (Weighted Difference Vegetation Index, see Table 1) from crop canopies: the CLAIR (meta)model, and a set of empirical relations.

3.1.1 EXTRAD

EXTRAD was developed by Goudriaan (1977) to calculate the (solar) radiation profile in crop canopies. A simplified version of EXTRAD is used in photosynthesis subroutines of the crop growth model SUCROS to compute the extinction of photosynthetically active radiation (\(> 0.4-0.7 \mu m\) wavelength). The original, more detailed model was used here to calculate the directional reflectance from crop canopies at wavelengths up to the near infra-red region.

In EXTRAD, the canopy is subdivided into a number of horizontal infinitely extended layers. The leaves in these layers are assumed to have Lambertian scattering properties, and to have a uniform azimuthal distribution. The angle distribution of the leaves is described by nine inclination intervals from 10° each. The radiation profile in the canopy is then calculated with a relaxation method. The canopy reflectance in a given direction (in our study: nadir) is computed from the total radiance leaving the top layer of the canopy in that direction. The input for the model are crop parameters (LAI, leaf scattering coefficient (\(\sigma\)), leaf angle distribution function (F)), soil parameters (hemispherical soil reflection coefficient (\(\rho\))), and illumination parameters (solar elevation angle (\(\beta\)), and fraction diffuse sky radiation (\(f\)). In principle, each parameter can be physically measured. Because a constant value is used as input for the reflection coefficient of bare soil, the influence of top soil (\(> 0-1 cm\)) moisture content on the reflectance of a crop-soil system is not modelled.

Because of the relative complexity of the model, readers are referred to Goudriaan (1977) for detailed information on the scientific background.

3.1.2 CLAIR

The simple model CLAIR relates the WDU to LAI of the canopy via an exponential extinction equation (Clevers, 1988, 1989):

\[
WDV = \left(1 - e^{(-bL)}\right) / \beta \quad (\%) \quad (Eq. 6)
\]

where \(b\) = the inverse of the asymptotic value of WDU at infinite \(L\) (\(\%^{-1}\)), \(k\) = extinction coefficient (\(\cdot\)); \(L\) = Leaf Area Index (LAI) (\(\cdot\)). Model driving variable is \(L\); model parameters (to be found by fitting the model to observations) are \(b\) and \(k\).
3.1.3 Empirical relationship WDVI

Simple linear relationships were established between WDVI and LAI (Bouman et al., 1992):

$$WDVI = \beta (L + \alpha) \% \quad \text{(Eq. 7)}$$

where $\alpha =$ regression coefficient (-); $\beta =$ regression coefficient (different from the one used in Equation 6), (%); $L =$ Leaf Area Index (LAI) (-). Model driving variable is $L$; model parameters (to be found by fitting the model to observations) are $\alpha$ and $\beta$.

3.2 Radar

The Cloud model (Attema and Ulaby, 1978) explains radar backscatter of crops on the basis of one equation with the amount of water in the canopy and the moisture content in the underlying top soil as driving variables. Effects of canopy and soil surface structure are accounted for by the model constants that need to be empirically derived from time series of observations:

$$\gamma = C_g (1 - e^{-\frac{D W}{\cos \theta}}) + G_q e^{-\frac{D K + D W}{\cos \theta}} \quad \text{(m}^2\text{m}^{-2})$$

where: $g =$ radar cross section ($m^2/m^2$), $W =$ crop water per unit soil surface ($kg/m^2$), $m =$ volumetric moisture content of top soil (%), $q =$ incidence angle (°), $D =$ coefficient of attenuation per unit of crop water ($m^2/kg$), $K =$ moisture coefficient of top soil per volumetric moisture content (-), $C_g =$ backscattering coefficient of an optically thick vegetation cover ($m^2/m^2$), $G_q =$ backscattering coefficient of dry soil ($m^2/m^2$). Model driving variables are $W$ and $m$; model parameters (to be found by fitting the model to observations) are $C_q$, $G_q$, $D$ and $K$.

This equation was found to give good results for crops with a canopy structure that was relatively homogeneous in the aerial distribution of its constituting elements (e.g. leaves, stems), such as sugar beet and potato. For cereals (e.g. wheat, barley, oats) with a distinct layering of its constituting elements (e.g. the layer of ears or plumes above the layer of 'vegetative' matter consisting of leaves and stems), a two-layer Cloud model was found to give improved results (for X-band data), (Hoekman et al., 1982):

$$\gamma = C_2 (1 - e^{-\frac{D_2 W_2}{\cos \theta}}) +$$

$$C_1 (1 - e^{-\frac{D_1 W_1}{\cos \theta}}) e^{-\frac{D_2 W_2 + D_1 W_1}{\cos \theta}}$$

$$G_2 e^{\frac{m K}{e^{-\frac{D_2 W_2 + D_1 W_1}{\cos \theta}}}}$$

where the symbols have the same meaning as above, with the suffix 1 to denote the vegetative layer of the canopy and 2 to denote the ear-layer (for wheat, barley; plumes for oats) of the canopy. Model driving variables are $W_1$, $W_2$ and $m$; model parameters (to be found by fitting the model to observations) are $C_1$, $C_2$, $G_q$, $D_1$, $D_2$ and $K$.

Originally, the Cloud model was developed for high frequency bands, namely the X-band; readers are referred to the publication of Attema & Ulaby (1978) for model assumptions and boundary conditions. In this report, the Cloud model will be used for $C_1$, $L$- and X-band (Paragraph 4.4).
4  Model parameter values

The remote sensing models described in Chapter 3 have been parameterized by a number of authors on data sets that differ in system configuration (e.g. wavelength band, incidence angle, state of polarization, platform type), crop type and soil background. In this report, some model parameters are presented that are taken from literature and that are derived from own observations. Parameter values are given for sugar beet, potato and wheat under Dutch conditions. Parameter values for the Cloud model are given for X-band (because of the extensive observations of the Dutch ROVE (Radar Observation VEgetation) team in 1975-1981), and for the configurations of the current ERS (European Remote sensing Satellite) and JERS (Japanese Remote sensing Satellite) radar satellites. The remote sensing models have been implemented in such a way in Fortran subroutines and functions that all model parameter values are read from external data files (Chapter 7). This way, the implemented models are generic, and model parameter values can easily be selected or adapted according to own insights and requirements.

4.1  Optical

4.1.1  EXTRAD

The EXTRAD model needs values for the scatter coefficients of the leaves, \( \sigma \), and for the hemispherical reflectance of the bare soil, \( \rho \). The following parameter values were derived from calibration of the model on hand-held reflectance measurements acquired during the Agriscatt 1987-1988 campaign in farmers fields in Southern Flevoland (Bouman, 1992b), Table 2a.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Sugar beet</th>
<th>Potato</th>
<th>Wheat</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \sigma ) green (548 nm)</td>
<td>-</td>
<td>0.294</td>
<td>0.331</td>
<td>0.341</td>
</tr>
<tr>
<td>( \sigma ) red (650 nm)</td>
<td>-</td>
<td>0.079</td>
<td>0.120</td>
<td>0.123</td>
</tr>
<tr>
<td>( \sigma ) infra-red (823 nm)</td>
<td>-</td>
<td>0.974</td>
<td>0.981</td>
<td>0.960</td>
</tr>
<tr>
<td>( \rho ) green (548 nm)</td>
<td>-</td>
<td>0.146</td>
<td>0.143</td>
<td>0.134</td>
</tr>
<tr>
<td>( \rho ) red (650 nm)</td>
<td>-</td>
<td>0.166</td>
<td>0.163</td>
<td>0.145</td>
</tr>
<tr>
<td>( \rho ) infra-red (823 nm)</td>
<td>-</td>
<td>0.199</td>
<td>0.172</td>
<td>0.174</td>
</tr>
</tbody>
</table>

Table 2a.  Parameter values of the leaf scatter coefficient \( \sigma \) and of the soil hemispherical reflection coefficient \( \rho \) of the EXTRAD model.

The leaf scatter coefficients \( \sigma \) of Table 2a are crop type specific, but derived from a data set that included various cultivars. Since values for \( \sigma \) were derived by fitting EXTRAD to measurements of whole crops during the growing season, these values do not only represent leaves but include other canopy elements, such as stems and ears, as well. The reflection coefficients of the soil apply to the soil type of South Flevoland where the observations were made.

The values of the other EXTRAD model parameters (leaf angle distribution function, solar height and fraction diffuse sky radiation) can be set by the user according to the condition of
application. Examples for leaf angle distributions are given in Table 2b. These values were calculated for (hypothetical) leaf angle distributions using the equations given by Bunnik (1978). Solar height can vary from nearly 0° to nearly 90°. Fraction diffuse sky radiation can vary from 0.2 for a standard clear sky to 0.8 for a standard overcast sky.

Table 2b. Possible values for hypothetical leaf angle distributions (F) for EXTRAD, calculated using the equations given by Bunnik (1978). The leaf angle classes are given as angles with the horizontal plane.

<table>
<thead>
<tr>
<th>Distribution function</th>
<th>Uniform</th>
<th>Spherical</th>
<th>Erectophile</th>
<th>Planophile</th>
<th>Plagiophile</th>
<th>Extremophile</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$2\pi$</td>
<td>$\sin\theta$</td>
<td>$\frac{2(1-\cos\theta)}{\pi}$</td>
<td>$\frac{2(1+\cos\theta)}{\pi}$</td>
<td>$\frac{2(1-\cos4\theta)}{\pi}$</td>
<td>$\frac{2(1+\cos4\theta)}{\pi}$</td>
</tr>
</tbody>
</table>

Classes:

<table>
<thead>
<tr>
<th>0 -10</th>
<th>0.111</th>
<th>0.015</th>
<th>0.002</th>
<th>0.220</th>
<th>0.009</th>
<th>0.213</th>
</tr>
</thead>
<tbody>
<tr>
<td>10-20</td>
<td>0.111</td>
<td>0.045</td>
<td>0.023</td>
<td>0.207</td>
<td>0.057</td>
<td>0.166</td>
</tr>
<tr>
<td>20-30</td>
<td>0.111</td>
<td>0.074</td>
<td>0.033</td>
<td>0.182</td>
<td>0.130</td>
<td>0.092</td>
</tr>
<tr>
<td>30-40</td>
<td>0.111</td>
<td>0.100</td>
<td>0.073</td>
<td>0.149</td>
<td>0.195</td>
<td>0.028</td>
</tr>
<tr>
<td>40-50</td>
<td>0.111</td>
<td>0.123</td>
<td>0.111</td>
<td>0.220</td>
<td>0.222</td>
<td></td>
</tr>
<tr>
<td>50-60</td>
<td>0.111</td>
<td>0.143</td>
<td>0.149</td>
<td>0.073</td>
<td>0.195</td>
<td>0.028</td>
</tr>
<tr>
<td>60-70</td>
<td>0.111</td>
<td>0.158</td>
<td>0.182</td>
<td>0.033</td>
<td>0.130</td>
<td>0.092</td>
</tr>
<tr>
<td>70-80</td>
<td>0.111</td>
<td>0.168</td>
<td>0.207</td>
<td>0.023</td>
<td>0.057</td>
<td>0.166</td>
</tr>
<tr>
<td>80-90</td>
<td>0.111</td>
<td>0.174</td>
<td>0.220</td>
<td>0.002</td>
<td>0.009</td>
<td>0.213</td>
</tr>
</tbody>
</table>

4.1.2 CLAIR

Parameter values of the CLAIR model have been presented by Bouman et al., 1992, Table 3. These values were derived from a large data set of 10 years of field observations that were gathered on different locations in The Netherlands, and that spanned a range of cultivars, treatments, soil types, soil moisture regimes, and growing conditions from severely stressed to near-potential growth. The CLAIR model was based on WDMI calculated from near infra-red (823 nm) and green (548 nm), instead of red, reflectance values (Equation 3, Table 1).

Table 3. Parameter values of b and k of the CLAIR model (Equation 6).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Sugar beet</th>
<th>Potato</th>
<th>Wheat</th>
</tr>
</thead>
<tbody>
<tr>
<td>b</td>
<td>%⁻¹</td>
<td>0.02056</td>
<td>0.0194</td>
<td>0.02128</td>
</tr>
<tr>
<td>k</td>
<td></td>
<td>0.485</td>
<td>0.588</td>
<td>0.400</td>
</tr>
</tbody>
</table>

The CLAIR model parameter values of Table 3 are crop type specific, but applicable for a wide variety of cultivars, soil backgrounds and growing conditions.
4.1.3 Empirical relationship WDV1

Empirical relationships between WDV1 and LAI were derived from the same data set that was used to parameterize the CLAIR model (see above, Paragraph 4.1.2), (Bouman et al., 1992). It was found that linear line segments were well able to describe the relationship between WDV1 and LAI for potato and wheat (better description of the data set than the CLAIR model). For sugar beet, no linear equations were derived since the relationship between WDV1 and LAI was sufficiently accurately described by the CLAIR model. The empirical relationships for potato and wheat are based on WDV1 calculated from near infra-red (823 nm) and green (548 nm), instead of red, reflectance values (Equation 3, Table 1).

Table 4. Coefficients of regression a and b for the relationship between WDV1 and LAI:

<table>
<thead>
<tr>
<th>Crop</th>
<th>LAI range</th>
<th>a (-)</th>
<th>b (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Potato</td>
<td>0 - 0.89</td>
<td>0</td>
<td>20.83</td>
</tr>
<tr>
<td></td>
<td>&gt; 0.89</td>
<td>0.87</td>
<td>10.99</td>
</tr>
<tr>
<td>Wheat</td>
<td>0 - 0.60</td>
<td>0</td>
<td>20.13</td>
</tr>
<tr>
<td></td>
<td>0.60 - 4.06</td>
<td>1.00</td>
<td>7.54</td>
</tr>
<tr>
<td></td>
<td>&gt; 4.06</td>
<td>10.37</td>
<td>2.65</td>
</tr>
</tbody>
</table>

The regression coefficients of Table 4 are crop type specific, but applicable for a wide variety of cultivars, soil backgrounds and growing conditions.

4.2 Radar

The Cloud model has been calibrated by various authors for agricultural crops in Dutch conditions on radar observations from different campaigns, using platforms that vary from ground-based trailers to aircraft and satellite. The model parameters were found to vary among campaigns, years, test sites and calibration method/algorithms used. These differences can be explained by various reasons. First, the observed radar backscatter data that were used to calibrate the model were not always comparable among campaigns. For instance the DUTSCAT data from the Agriscatt 1988 campaign were somewhat higher than other airborne observations in similar frequency bands (Bouman & Hoekman, 1993). Second, some data sets missed observations in important periods of the growing season so that Cloud parameters could only be determined with high standard deviation (again, DUTSCAT observations in Agriscatt 1988). Third, the Cloud model does not take variation in canopy structure into account. It can be expected that variation in canopy structure of crops among locations and over the years (due to, for instance, differences among cultivars or weather conditions) results in different Cloud model parameters. Fourth, using the same data set, different calibration algorithms produced different Cloud parameter values. It is outside the scope of this report to give an exhaustive overview of Cloud model parameters that have been reported by different authors. Instead, some parameter values are suggested that were found to give satisfactory comparisons with observed data from the author’s point of view (with reference to other publications with different parameter values). Since the Cloud model has been implemented in the simulation
software in a generic way, model parameter values can easily be adapted according to own insights and requirements of the user.

4.2.1 X-band

For the X-band, Cloud model parameters at VV polarization are given for sugar beet and potato (one-layer model) and for wheat (two-layer model) in Table 5 as derived by van Kasteren from the ground-based data set collected by the ROVE team in 1980 (Bouman, 1987). Parameter values derived from ROVE measurements in 1979 were presented by Hoekman (1981); parameter values for beet in 1980 were also calculated by Rijckenberg & van Leeuwen (1994). Parameter values derived from airborne DUTSCAT measurements in X-band from the Agriscatt 1988 campaign were calculated for sugar beet and wheat by van Leeuwen (presented in Bouman, 1992b; p. 32)

Table 5a, b. X-band cloud model parameters for sugar beet (cv Monohil), potato (cv Bintje) and winter wheat (cv Okapi), derived from ground-based radar backscatter observations at VV polarization, at test farm De Schreef near Dronten, 1980. Source: Bouman, 1992b.
Units: a: $C_\theta$ and $G_\theta$: m$^2$ m$^{-2}$; b: $D$: m$^2$ kg$^{-1}$; $K$: %$^{-1}$. (see Equations 8 and 9).

<table>
<thead>
<tr>
<th>a</th>
<th>$C_\theta$</th>
<th>$G_\theta$</th>
<th>$10^\circ$</th>
<th>$20^\circ$</th>
<th>$30^\circ$</th>
<th>$40^\circ$</th>
<th>$50^\circ$</th>
<th>$60^\circ$</th>
<th>$70^\circ$</th>
<th>$75^\circ$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beet</td>
<td>&amp; 0.1060 &amp; 1.190 &amp; 1.200 &amp; 1.150 &amp; 1.170 &amp; 1.150 &amp; 0.980 &amp; 0.930</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Potato</td>
<td>&amp; 0.525 &amp; 0.174 &amp; 0.120 &amp; 0.095 &amp; 0.076 &amp; 0.065 &amp; 0.055 &amp; 0.042</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wheat</td>
<td>&amp; 0.870 &amp; 0.710 &amp; 0.630 &amp; 0.560 &amp; 0.490 &amp; 0.440 &amp; 0.320 &amp; 0.300</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>&amp; 0.214 &amp; 0.195 &amp; 0.170 &amp; 0.151 &amp; 0.135 &amp; 0.117 &amp; 0.093 &amp; 0.071</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>&amp; 0.101 &amp; 0.048 &amp; 0.039 &amp; 0.040 &amp; 0.054 &amp; 0.79 &amp; 0.130 &amp; 0.172</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>&amp; 0.344 &amp; 0.326 &amp; 0.088 &amp; 0.057 &amp; 0.019 &amp; 0.010 &amp; 0.012 &amp; 0.009</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>b</th>
<th>$D$</th>
<th>$D1$</th>
<th>$DD$</th>
<th>$C1$</th>
<th>$K$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beet</td>
<td>0.46</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.06</td>
</tr>
<tr>
<td>Potato</td>
<td>1.02</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.06</td>
</tr>
<tr>
<td>Wheat</td>
<td>-</td>
<td>1.153</td>
<td>2.057</td>
<td>0.185</td>
<td>0.06</td>
</tr>
</tbody>
</table>
4.2.2 C-band (ERS configuration)

Cloud model parameters were derived from ERS-1 data obtained over Flevoland in 1992-1994. The ERS-1 SAR operates in the C-band, at 23° incidence angle, and at VV polarization. Table 6 presents Cloud model parameters derived by Bouman on radar backscatter data that were averaged over the whole test site of South Flevoland, for beet, potato and wheat. For all three crops, the one-layer Cloud model gave accurate descriptions of observed (average) radar backscatter.

Rijckenberg & van Leeuwen (1994) calculated Cloud parameters for sugar beet for the ERS configuration from airborne DUTSCAT data collected in the Agriscatt 1988 campaign, from airborne NASA JPL SAR data collected in the MacEurope campaign 1991, and from ERS-1 data collected in 1992. Parameter values derived from airborne DUTSCAT measurements in C-band during Agriscatt 1988 were also calculated by van Leeuwen for sugar beet and wheat (presented in Bouman, 1992b; p. 32)

Table 6. Cloud model parameters derived for sugar beet, potato and wheat, derived from ERS observations over South Flevoland in 1992-1994. The parameter values were derived from average backscatter data over all fields (per crop type) found in the images of South Flevoland, and therefore span a range of cultivars. For sugar beet, the percentage variance accounted for was 36%, for potato 39%. For sugar beet and potato, the standard errors of estimate of the parameter values are given behind brackets; for wheat, the fitting algorithm did not fully converge and no standard errors were supplied, and no % variance accounted for was calculated. (See also Equation 8).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Sugar beet</th>
<th>Potato</th>
<th>Wheat</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_\theta$</td>
<td>m$^2$ m$^{-2}$</td>
<td>0.2717</td>
<td>0.3416</td>
<td>0.005</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(0.0365)</td>
<td>(0.0359)</td>
<td>(-)</td>
</tr>
<tr>
<td>$D$</td>
<td>m$^2$ kg$^{-1}$</td>
<td>0.1678</td>
<td>0.398</td>
<td>0.200</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(0.0946)</td>
<td>(0.188)</td>
<td>(-)</td>
</tr>
<tr>
<td>$G_\theta$</td>
<td>m$^2$ m$^{-2}$</td>
<td>0.0122</td>
<td>0.0483</td>
<td>0.045</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(0.0152)</td>
<td>(0.0294)</td>
<td>(-)</td>
</tr>
<tr>
<td>$K$</td>
<td>%$^{-1}$</td>
<td>0.1251</td>
<td>0.0834</td>
<td>0.078</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(0.0495)</td>
<td>(0.0308)</td>
<td>(-)</td>
</tr>
</tbody>
</table>

4.2.3 L-band (JERS configuration)

Cloud model parameters were determined for sugar beet, potato and wheat for the JERS-1 configuration (i.e. L-band, 35° incidence angle, HH polarization) from airborne DUTSCAT measurements over Southern Flevoland during the Agriscatt 1988 campaign. The parameter values presented in Table 7 are modified values from data calculated by van Leeuwen for sugar beet and wheat (presented in Bouman, 1992b; p. 32), and supplemented for potato. For sugar beet and potato, the one-layer Cloud model was parameterized, for wheat the two-layer Cloud model.

Table 7. Cloud model parameters for sugar beet, potato and wheat, for the JERS configuration derived from airborne DUTSCAT observations at 40° incidence angle over South Flevoland in the Agriscatt 1988 campaign (see also Equations 8 and 9).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Sugar beet</th>
<th>Potato</th>
<th>Wheat</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_\theta$</td>
<td>m² m⁻²</td>
<td>0.11424</td>
<td>0.1972</td>
<td>-</td>
</tr>
<tr>
<td>$C1$</td>
<td>m² m⁻²</td>
<td>-</td>
<td>-</td>
<td>0.0486</td>
</tr>
<tr>
<td>$C2_\theta$</td>
<td>m² m⁻²</td>
<td>-</td>
<td>-</td>
<td>0.0676</td>
</tr>
<tr>
<td>$D$</td>
<td>m² kg⁻¹</td>
<td>1.1025</td>
<td>0.574</td>
<td>-</td>
</tr>
<tr>
<td>$D1$</td>
<td>m² kg⁻¹</td>
<td>-</td>
<td>-</td>
<td>0.2678</td>
</tr>
<tr>
<td>$D2$</td>
<td>m² kg⁻¹</td>
<td>-</td>
<td>-</td>
<td>2.0789</td>
</tr>
<tr>
<td>$G_\theta$</td>
<td>m² m⁻²</td>
<td>0.00070</td>
<td>0.00185</td>
<td>0.0022</td>
</tr>
<tr>
<td>$K$</td>
<td>%⁻¹</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
</tr>
</tbody>
</table>
5 Model implementation

The remote sensing models for optical reflectance, WDMI and radar backscatter have been implemented in separate subroutines and functions in Fortran code (Table 8).

<table>
<thead>
<tr>
<th>Scientific model name</th>
<th>Fortran name</th>
<th>Subroutine or function</th>
</tr>
</thead>
<tbody>
<tr>
<td>EXTRAD</td>
<td>EXTRAD</td>
<td>subroutine</td>
</tr>
<tr>
<td>CLAIR</td>
<td>CLAIR</td>
<td>function</td>
</tr>
<tr>
<td>Empirical WDMI relations</td>
<td>EMPWHE (wheat), EMPPOT (potato)</td>
<td>function</td>
</tr>
<tr>
<td>Cloud one-layer</td>
<td>CLOUD1</td>
<td>subroutine</td>
</tr>
<tr>
<td>Cloud two-layer</td>
<td>CLOUD2</td>
<td>subroutine</td>
</tr>
</tbody>
</table>

The subroutines and functions are straightforward standard FORTRAN77 and do not follow any specific FSE rules. They can be used as subroutines in any Fortran program for the calculation of remote sensing signals. For incorporation in crop growth models, special interfaces were written in FSE (see Chapter 6). Subroutine input data (driving variables and model parameters) need to be available in the 'calling' program, and passed-on to the subroutines/ functions. The model output data are passed back to the calling program from the subroutines/ functions. The variable names used in the subroutines and functions are listed and explained in Appendix I; the subroutines and functions themselves are given in Appendices II and III. Except for the 'Empirical WDMI relations', all subroutines and functions are 'generic', i.e. they are non-crop type specific. Because all model parameters are external input, the subroutines/functions can be applied to any crop type by adaptation of their values.

5.1 Optical

5.1.1 EXTRAD

SUBROUTINE EXTRAD (RHOS, SCAT, BETA, F, INF, LAI, FRDIF_T, NAR, RHOM)

Table 9 explains the argument list of the subroutine, and gives the relationship between the names of the model variables and parameters as used in the scientific model description, and the names as used in the Fortran subroutine.

EXTRAD calculates optical reflectance in single wavelength bands. By repeated calls to the subroutine using input values for \( r \) and \( s \) for different wavelength bands, optical reflectance \( (r \) and \( r_s) \) can be computed for the wavelength bands that are needed for the calculation of Vegetation Indices (see Paragraph 6.1)
Table 9. Explanation of the argument list of EXTRAD: main variable and parameter names, the corresponding symbols used in the scientific model descriptions, units, and indications of the data type: IV = Input variable (driving variable), IP = Parameter (input model parameter), OV = Output Variable.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Model abbreviation</th>
<th>Explanation</th>
<th>Units</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>r</td>
<td>RHOS</td>
<td>hemispherical soil reflectance</td>
<td>-</td>
<td>IP</td>
</tr>
<tr>
<td>s</td>
<td>SCAT</td>
<td>scatter coefficient leaf</td>
<td>-</td>
<td>IP</td>
</tr>
<tr>
<td>b</td>
<td>BETA</td>
<td>solar height</td>
<td>degree</td>
<td>IP</td>
</tr>
<tr>
<td>F</td>
<td>F</td>
<td>leaf angle distribution factor</td>
<td>-</td>
<td>IP</td>
</tr>
<tr>
<td>-</td>
<td>INF</td>
<td>array length</td>
<td>-</td>
<td>IP</td>
</tr>
<tr>
<td>L</td>
<td>LAI</td>
<td>Leaf Area Index</td>
<td>-</td>
<td>IV</td>
</tr>
<tr>
<td>f</td>
<td>FRDIF_T</td>
<td>instantaneous fraction diffuse radiation</td>
<td>-</td>
<td>IP</td>
</tr>
<tr>
<td>r</td>
<td>NAR</td>
<td>nadir crop reflectance</td>
<td>%</td>
<td>OV</td>
</tr>
<tr>
<td>r_s</td>
<td>RHOM</td>
<td>nadir soil reflectance</td>
<td>%</td>
<td>OV</td>
</tr>
</tbody>
</table>

The formulation of the process equations in the EXTRAD subroutine can be found in Appendix II. Because of the complexity of the model, it is not further explained here and readers are referred to Goudriaan (1977) for more details.

As part of the quality check of the subroutine, values of input data are checked on their boundary conditions before execution of the process equations (Table 10).

Table 10. Boundary conditions of input parameter and variable values tested in EXTRAD subroutine.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Model abbreviation</th>
<th>Explanation</th>
<th>Minimum</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>L</td>
<td>LAI</td>
<td>Leaf Area Index</td>
<td>0</td>
<td>10</td>
</tr>
<tr>
<td>r</td>
<td>RHOS</td>
<td>hemispherical soil reflectance</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>s</td>
<td>SCAT</td>
<td>scatter coefficient leaf</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>b</td>
<td>BETA</td>
<td>solar height</td>
<td>0</td>
<td>90</td>
</tr>
<tr>
<td>f</td>
<td>FRDIF_T</td>
<td>instantaneous fraction diffuse radiation</td>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>

When input values exceed the tested boundary conditions, the model run is stopped with an appropriate warning to the screen (using a call to the ERROR subroutine, see FSE 2.1 manual; van Kraalingen, 1995). Most boundary conditions are dictated by physical impossibilities (e.g. negative values of Leaf Area Index can not occur). The upper limit for Leaf Area Index is set rather arbitrarily, to 10. This value is chosen because agricultural crops rarely have LAI values that exceed 10. The reason to set an upper limit on LAI is that its magnitude is related to the declared length of arrays in the subroutine, and because model calculations with high values of LAI take very high computing time (because of the many iterations over leaf layers involved). The boundary conditions of Table 10 are implemented in the subroutine as follows:
* Checks on impossible values input data:
  IF (LAI.LT.0.) CALL ERROR ('EXTRAD', 'LAI smaller than 0')
  IF (RHOS.LE.0.) CALL ERROR ('EXTRAD', 'RHOS less/equal 0')
  IF (RHOS.GT.1.) CALL ERROR ('EXTRAD', 'RHOS greater than 1')
  IF (SCAT.LT.0.) CALL ERROR ('EXTRAD', 'SCAT less than 0')
  IF (SCAT.GT.1.) CALL ERROR ('EXTRAD', 'SCAT greater than 1')
  IF (BETA.LT.0.) CALL ERROR ('EXTRAD', 'BETA less than 0')
  IF (BETA.GT.90.0) CALL ERROR ('EXTRAD', 'BETA greater than 90')
  IF (FRDIRF_T.LT.0.) CALL ERROR ('EXTRAD', 'FRDIRF_T less than 0')
  IF (FRDIRF_T.GT.1.) CALL ERROR ('EXTRAD', 'FRDIRF_T greater than 1')

* Special check on maximum LAI i.r.t. declared array lengths:
  IF (LAI.GT.10.) CALL ERROR ('EXTRAD', 'LAI larger than 10')

As other part of the software quality check, a continuity test was performed by changing the values of input parameters with small increments and studying the course of output variables. The current implementation of the model in Fortran results in discontinuities in simulated reflectance as function of Leaf Area Index (LAI). This discontinuity results from the solution chosen to iterate the calculation of radiation flux over a fixed number of layers per LAI layer (Goudriaan, 1977). The result is that discrete changes in calculated reflectance take place at each 0.01 increment in LAI, whereas calculated reflectance is stable between subsequent LAI increments of 0.01. This effect is especially noticeable at near-infrared wavelengths at LAI values below 5, and at visible wavelengths at LAI values smaller than 2, see Figure 1. Consequently, when the subroutine EXTRAD is run as subroutine together with a crop growth simulation model (via the interface REFLEX, see Paragraph 6.1), some discontinuities may be present in the time curve of simulated reflectance values and Vegetation Indices, whereas the time curve of simulated LAI is smooth, see Figure 2. This problem of discontinuity will be solved in next versions of the subroutine EXTRAD.

Figure 1. Nadir reflectance (green, red and infrared) as function of Leaf Area Index, calculated with the Subroutine EXTRAD.
Figure 2. Simulated time curve of Leaf Area Index (2a) and Weighted Difference Vegetation Index (2b), using the EXTRAD subroutine in the SUCROS-Wheat crop growth simulation model.
5.1.2 CLAIR

REAL FUNCTION CLAIR(KCLAIR, BCLAIR, LAI)

Table 11 explains the argument list of the function, and gives the relationship between the names of the model variables and parameters as used in the scientific model description, and the names as used in the Fortran function.

Table 11. Explanation of the argument list of CLAIR: main variable and parameter names, the corresponding symbols used in the scientific model description, units, and indications of the data type: IV = Input variable (driving variable), IP = Parameter (input model parameter), OV = Output Variable.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Model abbreviation</th>
<th>Explanation</th>
<th>Units</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>k</td>
<td>KCLAIR</td>
<td>extinction coefficient</td>
<td>-</td>
<td>IP</td>
</tr>
<tr>
<td>b</td>
<td>BCLAIR</td>
<td>inverse of asymptotic value WDMI at infinite L</td>
<td>%⁻¹</td>
<td>IP</td>
</tr>
<tr>
<td>L</td>
<td>LAI</td>
<td>Leaf Area Index</td>
<td>-</td>
<td>IV</td>
</tr>
<tr>
<td>WDMI</td>
<td>CLAIR*</td>
<td>WDMI</td>
<td>%</td>
<td>OV*</td>
</tr>
</tbody>
</table>

*: Note that CLAIR is a Fortran function, with the output variable name the same as the function name.

Equation 6 of the CLAIR model is implemented in the Fortran function as follows:

CLAIR = (1.0 - EXP(-KCLAIR*LAI))/BCLAIR

The only boundary condition on model input data checked is that LAI values cannot be less than 0:

IF (LAI.LT.0.) CALL ERROR ("CLAIR",'LAI smaller than 0')

5.1.3 Empirical relationships WDMI: EMPWHE and EMPPOT

REAL FUNCTION EMPWHE(LAI)
REAL FUNCTION EMPPOT(LAI)

The empirical relations (Eq. 7) that relate WDMI to LAI are implemented in two crop-type specific functions: EMPWHE for wheat and EMPPOT for potato. The coefficients of the linear relations between WDMI and LAI are 'hard-coded' in these functions. Therefore, unlike the other subroutines and functions presented in this report, these functions are not generic. Note that for sugar beet, no linear relationships were found between WDMI and LAI, and therefore there is no function of this type for sugar beet.
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Model abbreviation</th>
<th>Explanation</th>
<th>Units</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>L</td>
<td>LAI</td>
<td>Leaf Area Index</td>
<td>-</td>
<td>IV</td>
</tr>
<tr>
<td>WDVI</td>
<td>EMPWHE*</td>
<td>WDVI</td>
<td>%</td>
<td>OV*</td>
</tr>
<tr>
<td></td>
<td>EMPPOT*</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*: Note that EMPWHE and EMPPOT are Fortran functions, with the output variable name the same as the function name. The linear equations are implemented as follows:

**EMPWHE (wheat):**

```fortran
IF (LAI.LT.0.) THEN
   CALL ERROR ('EMPWHE', 'LAI smaller than 0')
ELSE IF (LAI.GE.0..AND.LAI.LE.0.6) THEN
   EMPWHE = 20.13683*LAI
ELSE IF (LAI.GT.0.6..AND.LAI.LE.4.06) THEN
   EMPWHE = 7.540142*LAI+7.558019
ELSE IF (LAI.GT.4.06) THEN
   EMPWHE = 2.6453*LAI+27.431
END IF
```

**EMPPOT (potato):**

```fortran
IF (LAI .GT. 0.89) THEN
   EMPPOT=10.989*(LAI+0.867)
ELSE
   EMPPOT=20.83*LAI
ENDIF
```

The hard-coded coefficients were derived from literature (see Paragraph 4.1.3).

As in the CLAIR function, the only boundary condition on model input data checked is that LAI values cannot be less than 0 (see above).

### 5.2 Radar

#### 5.2.1 Cloud one-layer

```fortran
SUBROUTINE CLOUD1(PLWCR0, MCSoil, NOINCA, ANGLE, GS, KS, DCR0, CCR0, RBGAM, RBSOIL)
```

Table 13 explains the argument list of the subroutine, and gives the relationship between the names of the model variables and parameters as used in the scientific model description, and the names as used in the Fortran subroutine.
Table 13. Explanation of the argument list of CLOUD1: main variable and parameter names, the corresponding symbols used in the scientific model description, units, and indications of the data type: IV = Input variable (driving variable), IP = Parameter (input model parameter), OV = Output Variable.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Model abbreviation</th>
<th>Explanation</th>
<th>Units</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>W</td>
<td>PLWCRO</td>
<td>plant water amount in canopy</td>
<td>kg m(^{-2})</td>
<td>IV</td>
</tr>
<tr>
<td>m</td>
<td>MCSOIL</td>
<td>volumetric moisture content top soil</td>
<td>%</td>
<td>IV</td>
</tr>
<tr>
<td>-</td>
<td>NOINCA</td>
<td>number of incidence angles (array)</td>
<td>-</td>
<td>IP</td>
</tr>
<tr>
<td>θ</td>
<td>ANGLE</td>
<td>incidence angle (array)</td>
<td>degree</td>
<td>IP</td>
</tr>
<tr>
<td>Gθ</td>
<td>GS</td>
<td>backscattering of dry soil (array)</td>
<td>m(^2) m(^{-2})</td>
<td>IP</td>
</tr>
<tr>
<td>k</td>
<td>KS</td>
<td>moisture coefficient of top soil</td>
<td>%(^{-1})</td>
<td>IP</td>
</tr>
<tr>
<td>D</td>
<td>DCROP</td>
<td>coefficient of attenuation of canopy</td>
<td>m(^2) kg(^{-1})</td>
<td>IP</td>
</tr>
<tr>
<td>Cθ</td>
<td>CCROP</td>
<td>backscattering coefficient of canopy (array)</td>
<td>m(^2) m(^{-2})</td>
<td>IP</td>
</tr>
<tr>
<td>gθ</td>
<td>RBGAM</td>
<td>radar backscatter (gamma), (array)</td>
<td>dB</td>
<td>OV</td>
</tr>
<tr>
<td>-</td>
<td>RBSOIL</td>
<td>radar backscatter contribution soil, (array)</td>
<td>dB</td>
<td>OV</td>
</tr>
</tbody>
</table>

CLOUD1 calculates radar backscatter for a specific crop type for a number of incidence angles simultaneously, for one specific state of polarization and frequency. The values of the model parameters relate to crop type, state of polarization, frequency and angles of incidence. The number of incidence angles is specified by the parameter NOINCA, and can vary between 1 and 10 (see Paragraph 7.2.2). By calling CLOUD1 with different sets of model parameters, radar backscatter at different states of polarization, frequencies and incidence angles can be simulated.

The implementation of the one-layer Cloud model (Equation 8) in Fortran is:

```fortran
DO I=1,NOINCA
   ACROP(I) = DCROP*PLWCRO/COS(DEGTRAD*ANGLE(I))
   RSOIL(I) = GS(I)*EXP(KS*MCSOIL-ACROP(I))
   RCRP(I) = CCROP(I)*(-ACROP(I))
   RBGAM(I) = 10.*LOG10(RSOIL(I)+RCROP(I))
   RBSOIL(I) = 10.*LOG10(RSOIL(I))
END DO
```

Where ACROP is an intermediate variable that quantifies the attenuation of microwaves by the crop, RSOIL is the backscatter contribution from the soil background (intermediate variable), and RCRP is the backscatter contribution by the crop (intermediate variable). The counter I numbers the angles of incidence. Since the cosine function in Fortran assumes the argument to be in radians, the angle of incidence that is supplied in degree, is converted using the parameter DEGTRAD (calculated as \(\pi/180\)).

```
PARAMETER (DEGTRAD=0.017453292)
```

The boundary conditions of the following input parameters and variables are checked (Table 14):
Table 14. Boundary conditions of input parameter and variable values tested in the CLOUD1 subroutine.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Model abbreviation</th>
<th>Explanation</th>
<th>Minimum</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>W</td>
<td>PLWCRO</td>
<td>water in canopy per unit soil surface</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td>m</td>
<td>MCOSOIL</td>
<td>volumetric moisture content top soil</td>
<td>0</td>
<td>100</td>
</tr>
<tr>
<td>θ</td>
<td>ANGLE</td>
<td>incidence angle</td>
<td>0</td>
<td>90</td>
</tr>
</tbody>
</table>

In Fortran code:

```
IF (MCOSOIL.LT.0.0. OR. MCOSOIL.GE.100.) THEN
  CALL ERROR ('CLOUD1', 'Soil moisture MCOSOIL out of bounds')
END IF

IF (PLWCRO.LT.0.) CALL ERROR('CLOUD1','PLWCRO negative value')

DO I=1,NOINC
  IF (ANGLE(I).LE.0.0. OR. ANGLE(I) .GE. 90.) THEN
    CALL ERROR ('CLOUD1', 'incidence angle out of bounds')
  END IF
END DO
```

5.2.2 Cloud two-layer

SUBROUTINE CLOUD2 (PLWVEG, PLWEAR, MCOSOIL, NOINC, ANGLE, 
&                 GS, CEAR, KS, DVEG, DEAR, CVEG, RGBAM, RBSOIL)

Table 15 explains the argument list of the subroutine, and gives the relationship between the names of the model variables and parameters as used in the scientific model description, and the names as used in the Fortran subroutine.

Table 15. Explanation of the argument list of CLOUD2: main variable and parameter names, the corresponding symbols used in the scientific model description, units, and indications of the data type: IV = Input variable (driving variable), IP = Parameter (input model parameter), OV = Output Variable.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Model abbreviation</th>
<th>Explanation</th>
<th>Units</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>W1</td>
<td>PLWVEG</td>
<td>plant water amount in vegetative layer</td>
<td>kg m⁻²</td>
<td>IV</td>
</tr>
<tr>
<td>W2</td>
<td>PLWEAR</td>
<td>plant water amount in ear layer</td>
<td>kg m⁻²</td>
<td>IV</td>
</tr>
<tr>
<td>m</td>
<td>MCOSOIL</td>
<td>volumetric moisture content top soil</td>
<td>%</td>
<td>IV</td>
</tr>
<tr>
<td>-</td>
<td>NOINC</td>
<td>number of incidence angles</td>
<td>-</td>
<td>IP</td>
</tr>
<tr>
<td>θ</td>
<td>ANGLE</td>
<td>incidence angle (array)</td>
<td>degree</td>
<td>IP</td>
</tr>
<tr>
<td>G₀</td>
<td>GS</td>
<td>backscattering of dry soil (array)</td>
<td>m² m⁻²</td>
<td>IP</td>
</tr>
<tr>
<td>C₂₀</td>
<td>CEAR</td>
<td>backscattering coefficient of ear layer (array)</td>
<td>m² m⁻²</td>
<td>IP</td>
</tr>
<tr>
<td>k</td>
<td>KS</td>
<td>moisture coefficient of top soil</td>
<td>%⁻¹</td>
<td>IP</td>
</tr>
<tr>
<td>D₁</td>
<td>DVEG</td>
<td>coefficient of attenuation of vegetative layer</td>
<td>m² kg⁻¹</td>
<td>IP</td>
</tr>
<tr>
<td>D₂</td>
<td>DEAR</td>
<td>coefficient of attenuation of ear layer</td>
<td>m² kg⁻¹</td>
<td>IP</td>
</tr>
<tr>
<td>C₁</td>
<td>CVEG</td>
<td>backscattering coefficient of vegetative layer</td>
<td>m² m⁻²</td>
<td>IP</td>
</tr>
<tr>
<td>g₀</td>
<td>RGBAM</td>
<td>radar backscatter (gamma) (array)</td>
<td>dB</td>
<td>OV</td>
</tr>
<tr>
<td>-</td>
<td>RBSOIL</td>
<td>radar backscatter contribution soil (array)</td>
<td>dB</td>
<td>OV</td>
</tr>
</tbody>
</table>
CLOUD2 is used in the same way as CLOUD1 (see above). The Fortran implementation of the model equation (9) is:

```fortran
DO I=1,NOINCA
    AVEG(I)  = DVEG*PLWVEG/COS (DEGRAD*ANGLE(I))
    ASOIL(I) = (DEGRAD*PLWEAR+DVEG*PLWVEG)/COS (DEGRAD*ANGLE(I))
    RSOIL(I) = GS(I)*EXP (KS*MCSOIL)*EXP (-ASOIL(I))
    RVEG(I)  = CVEG*(1.-EXP (-AVEG(I)))*EXP (-ASOIL(I))
    REARS(I) = CEAR(I)*EXP (-ASOIL(I))
    RGBAM(I) = 10.*ALOG10 (RSOIL(I)+RVEG(I)+REARS(I))
    RBSOIL(I) = 10.*ALOG10(RSOIL(I))
END DO
```

Where AVEG is an intermediate variable that quantifies the attenuation of microwaves by the layer of vegetative material (leaves, stems), ASOIL quantifies the attenuation of microwaves by the ear layer, RSOIL is the backscatter contribution from the soil background (intermediate variable), RVEG is the backscatter contribution by the layer of vegetative material (intermediate variable), and REARS is the backscatter contribution by the ear-layer (intermediate variable).

The boundary conditions of the following input parameters and variables are checked (Table 16):

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Model abbreviation</th>
<th>Explanation</th>
<th>Minimum</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>W1</td>
<td>PLWVEG</td>
<td>water in vegetative layer per unit soil surface</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td>W2</td>
<td>PLWEAR</td>
<td>water in ear layer per unit soil surface</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td>m</td>
<td>MCSOIL</td>
<td>volumetric moisture content top soil</td>
<td>0</td>
<td>100</td>
</tr>
<tr>
<td>θ</td>
<td>ANGLE</td>
<td>incidence angle</td>
<td>0</td>
<td>90</td>
</tr>
</tbody>
</table>

In Fortran code:

```fortran
* Check on data input values
  IF (MCWOIL.LT.0. .OR. MCWOIL.GE.100.) THEN
    CALL ERROR ('CLOUD2', 'Soil moisture MCSOIL out of bounds')
  END IF

  IF (NLWVEG.LT.0.) CALL ERROR ('CLOUD2', 'PLWVEG negative value')
  IF (NLWEAR.LT.0.) CALL ERROR ('CLOUD2', 'PLWEAR negative value')

  DO I=1,NOINCA
    IF (ANGLE(I).LE.0. .OR. ANGLE(I) .GE. 90.) THEN
      CALL ERROR ('CLOUD2', 'incidence angle out of bounds')
    END IF
  END DO
```
6 Interface with crop growth models

Interfaces were developed to facilitate the link between crop growth simulation models written in FSE, and the remote sensing subroutines and functions presented in Chapter 5: REFLEX for optical reflectance, and BSCAT for radar backscatter. These interface subroutines can be called from the MODEL section of any FSE crop growth model, provided that the required input driving variables are available (i.e. calculated by the crop growth model). REFLEX and BSCAT are written in FSE Fortran. So far, REFLEX and BSCAT have been implemented in FSE-SUCROS models for sugar beet, potato and wheat (Bouman et al., in prep). The interfaces, however, can easily be adapted for other crops. Appendices II and III list the source codes of the interfaces together with those of the remote sensing subroutines.

6.1 Optical: REFLEX

REFLEX takes care of the following:
- calling the optical remote sensing subroutines and functions EXTRAD, CLAIR and optionally EMPWHE or EMPPOT,
- reading the required input data for the remote sensing subroutines/functions,
- calculation of VI's from simulated reflectance values in single wavelength bands (from EXTRAD), writing output.

A number of variables needs to be passed to REFLEX to take care of the interface with FSE: ITASK, IUNITD, IUNITO, IUNITL and FILERS. The ITASK statements in the subroutine are governed by FSE, and indicate initialization (ITASK = 1), calculation of rates (ITASK = 2), calculation of states (ITASK = 3), and terminal calculations (ITASK = 4). IUNITD, IUNITO and IUNITL are numbers of units for input files, output files and timer file of FSE. FILERS is the name of the remote sensing input data file as specified in CONTROL.DAT, the input file that specifies the names of all input and output files of FSE models. For more information on FSE, the reader is referred to the FSE 2.1 manual by van Kraalingen (1995).

The only model input that is needed in REFLEX and that should be calculated by the crop growth model is LAI. All other model input parameters and variables are read in the subroutine itself.

REFLEX allows the comparison between simulated optical reflectance and VI values and observed ones in the generated output file. It makes use of the INQOBS and GETOBS subroutines of the FSE-TTUTIL library to find and retrieve observed data from the input files. Both functions are called by REFLEX at the section for output writing (ITASK = 3) for any observed variable that is wanted for, e.g for WDVI:

```fortran
IF (INQOBS (FILERS, 'WDVI')) CALL OUTDAT
$ 2, 0, 'WDVI_OBS', GETOBS(FILERS, 'WDVI'))
```

INQOBS 'looks' in the remote sensing input file, as specified at the variable name FILERS, for a variable with the name WDVI and extension _OBS (from 'observed'). If such a variable WDVI_OBS with a set of values has been found, GETOBS retrieves these data. The call to OUTDAT writes these variable values to the output file.
6.2 Radar: BSCAT

There are two versions of BSCAT: BSCAT1 for one-layer crops such as sugar beet and potato, and BSCAT2 for two-layer crops such as wheat. BSCAT takes care of the following:
- calling the CLOUD1 (BSCAT1) or CLOUD2 (BSCAT2) subroutine,
- reading the required input data for the Cloud subroutines,
- writing output.

A number of variables is passed to BSCAT to take care of the interface with FSE: ITASK, IUNITD, IUNITO, IUNITL and FILERS. The ITASK statements in the subroutine are governed by FSE, and indicate initialization (ITASK = 1), calculation of rates (ITASK = 2), calculation of states (ITASK = 3), and terminal calculations (ITASK = 4). IUNITD, IUNITO and IUNITL are numbers of units for input files, output files and timer file of FSE. FILERS is the name of the remote sensing input data file as specified in CONTROL.DAT, the input file that specifies the names of all input and output files of FSE models. The model input driving variables that are needed in BSCAT to run the Cloud subroutines are the amount of plant water in the crop and the volumetric moisture content of the top soil. All model input parameters are read from file in BSCAT.

6.2.1 Amount of crop water

The amount of crop water is calculated from the amount of dry canopy biomass as simulated by the crop growth model. The calculations of the amount of crop water from (simulated) dry canopy biomass for one-layer crops in BSCAT1 is as follows:

\[
\text{PLWCR0} = 0.0001 \times \text{TADRW} \times \text{MCROP} / (100 - \text{MCROP})
\]

where PLWCR0 is the amount of water in the canopy per unit soil surface (kg m\(^{-2}\)), TADRW is (simulated) total above ground dry weight (kg ha\(^{-1}\)), and MCROP is moisture content of the crop (%). The moisture content of the crop is defined as

\[
\left( \frac{\text{fresh}\_\text{weight}\_\text{crop} - \text{dry}\_\text{weight}\_\text{crop}}{\text{fresh}\_\text{weight}\_\text{crop}} \right) \times 100\%
\]

(Eq. 10)

The value of MCROP is read from the remote sensing input file. For sugar beet, MCROP was found to be stable throughout the growing season at 90.8% (Bouman, 1992b), and for potato, MCSOIL was found to be 90.6% from Agriscatt 1987-1988 data.

The calculations of the amount of crop water from (simulated) dry canopy biomass for two-layer crops in BSCAT2 is as follows:

\[
\text{PLWVEG} = 0.0001 \times (\text{WLV} + \text{WST}) \times \text{MCVEG} / (100 - \text{MCVEG})
\]
\[
\text{PLWEAR} = 0.0001 \times \text{WSO} \times \text{MCLEAR} / (100 - \text{MCLEAR})
\]

where PLWVEG is the amount of water in the vegetative layer per unit soil surface (kg m\(^{-2}\)), PLWEAR is the amount of water in the ear-layer per unit soil surface (kg m\(^{-2}\)), WLV is (simulated) dry weight of the leaves (kg ha\(^{-1}\)), WST is (simulated) dry weight of stems (kg ha\(^{-1}\)), WSO is (simulated) dry weight of the ears (storage organs) (kg ha\(^{-1}\)), MCVEG is moisture
content of the vegetative layer (%), and MCEAR is moisture content of the ear layer (%). The moisture contents of the vegetative layer and of the ear layer are read from input file. From Agriscatt 1987-1988 data, relationships between MCVEG and MCEAR and the development stage of the crop were derived (Bouman, 1992b). For wheat, MCVEG and MCEAR are read as a table-function of simulated development stage (DVS) from the remote sensing input file. During dynamic simulation, actual values of MCVEG and MCEAR are determined by linear interpolation using the LINT function of the FSE-TTUTIL library:

\[
MCVEG = \text{LINT}(MCVEGT, IMCVN, DVS) \\
MCEAR = \text{LINT}(MCEART, IMCEN, DVS)
\]

### 6.2.2 Soil moisture content

Two options have been implemented to select a value for the moisture content of the top soil: either the simulated soil moisture content of soil layer 1 of the water balance model, or an observed value as given in the remote sensing input file. The following statement is implemented in BSCAT for the choice between simulated or observed data for MCSoIL:

\[
MCSoIL = \text{OBSTRG}(100.*WCLQT(1), \text{FILERS}, 'MCSoIL')
\]

where WCLQT(1) is simulated moisture content of the first soil layer (%), generally 20-30 cm thick; FILERS is the variable in which the name of the remote sensing input file with the observed values of MCSoIL is stored (defined in CONTROL.DAT), and MCSoIL is the name of the observed variable, with extension _OBS, to be searched for in the remote sensing input file. WCLQT(1) is a variable that should be available to BSCAT from simulations with a soil water balance such as implemented in the FSE-SUCROS crop growth models for sugar beet, potato and wheat (using the SAHEL water balance). The switch that controls the choice between the use of simulated values or observed values is set in the remote sensing input file, and is called MCSoIL_FRC. More information on handling the input data and the values of the switch MCSoIL_FRC is given in Chapter 7.

### 6.2.3 Observed data

BSCAT allows the comparison between simulated radar backscatter values and observed ones in the generated output files. It makes use of the INQOBS and GETOBS subroutines of the FSE-TTUTIL library to find and retrieve observed data from the input files. Both functions are called by BSCAT at the section for output writing for any observed variable that is wanted for, e.g for ERS data:

```plaintext
IF (INQOBS (FILERS,'ERS')) CALL OUTDAT
$ (2, 0, 'ERS_OBS', GETOBS(FILERS,'ERS'))
```

INQOBS 'looks' in the remote sensing input file, as specified in the variable name FILERS, for variables with the name ERS (in this example, ERS are observed ERS-1 radar backscatter data) and extension _OBS (from 'observed'). If such a variable with a set of values has been found, GETOBS retrieves these data. The call to OUTDAT writes these variable values to the output file.
Implementation in crop growth models

7.1 Model structure

The structure of implementation of the remote sensing subroutines using the interfaces REFLEX and BSCAT in crop growth simulation models in FSE is shown in Figure 3. The subroutine MODELS calls respectively the subroutines SUCROS (for above-ground crop growth), SAHEL (for the soil water balance), and REFLEX and BSCAT. For optical reflectance calculations, the simulated variable LAI is passed from the SUCROS model to REFLEX. For radar backscatter calculations, the simulated variable TADRW (Total Above Ground Dry Weight) is passed from SUCROS to BSCAT for one-layer crops, and the simulated variables WST (Weight Stem), WLV (Weight LeaVes) and WSO (Weight Storage Organ) for two-layer crops. The simulated variable WCLQT(1) (Soil moisture content in layer 1 of the soil) is passed to BSCAT from the water balance model SAHEL. At each time step in the crop growth model (usually one day), optical reflectance and radar backscatter are calculated from the growing crop.

Figure 3. Schematic illustration of the use of the REFLEX and BSCAT remote sensing interfaces in FSE crop growth simulation models. FSE is the main program; MODELS is a general interface; SUCROS simulates above-ground crop growth; SAHEL simulates the water balance of the soil; REFLEX simulates optical reflectance and WDV; BSCAT simulates radar backscatter. Boxes indicate subroutines; dotted lines indicate the exchange of variable names; solid lines indicate the calls to subroutines.

Model input parameters for REFLEX and BSCAT, and any observed remote sensing variables are read from a common input data file. The name of this input file is specified in the file CONTROL.DAT at the variable FILEI4 (fourth input data file). The name specified here is passed in the model under the variable FILERS (input file remote sensing), see Chapter 6. The output generated by REFLEX and BSCAT is written to the common output file of the whole FSE-
SUCROS model, as specified in the file CONTROL.DAT at the variable FILEON (normal output file; generally RES.OUT). Therefore, simulated crop growth variables, water balance variables and remote sensing variables are all found in this common output file. All parameter and variable values supplied in the remote sensing input data file can be overwritten by new values for model reruns using the rerun option of FSE (van Kraalingen, 1996).

7.2 Remote sensing input file

The input data for the remote sensing input file as read by REFLEX and BSCAT is explained in this paragraph. The input file taken for explanation is one for sugar beet, where the one-layer Cloud model is used for the calculation of radar backscatter. A complete listing of a remote sensing input file for sugar beet is given in Appendix IV.

7.2.1 Optical reflectance data

The value of a switch, SWIREF, is needed that indicates whether the subroutine EXTRAD should be executed:

SWIREF = 0 ! no execution
SWIREF = 1 ! execution

The model parameters of the EXTRAD model need to be supplied, e.g.:

RHOSG = 0.146 ! green reflection coefficient soil (-)
RHOSR = 0.166 ! red reflection coefficient soil (-)
RHOSIR = 0.199 ! infra-red reflection coefficient soil (-)
SCATG = 0.294 ! green scatter coefficient leaves (-)
SCATR = 0.079 ! red scatter coefficient leaves (-)
SCATIR = 0.974 ! infra-red scatter coefficient leaves (-)
BETA = 60. ! solar height (degree)
FRDF_T = 0.5 ! fraction diffuse sky radiation (-)
F = 0.015, 0.045, 0.074, 0.1, 0.123, 0.143, 0.158, 0.168, 0.174 ! leaf angle distribution factor

As a standard, the leaf angle distribution function is that for a uniform distribution. These values however, can easily be adapted to characterize other distributions (Paragraph 4.1.1). The solar height BETA is set to 60°, representing the general height at many satellite overpasses.

The model parameters of the CLAIR model need to supplied, e.g.:

KCLAIR = 0.485 ! K parameter CLAIR model (-)
BCLAIR = 0.02056 ! β parameter CLAIR model (-)
7.2.2 Radar data

First the moisture content of the crop needs to be supplied, e.g:

MCCROP = 91.0 ! percentage

Next, the Cloud model parameters need to be supplied for all frequency bands ‘asked for’ in BSCAT. In this example, model parameters are given for X-, C- and L-band. The data structure is as follows: The model parameters that are incidence-angle dependent, namely G and C, are given in an array per ‘available’ angle of incidence. The number of incidence angles, and therefore the length of the array, is not fixed; parameter values for one to a maximum of ten angles of incidence can be supplied. In the example below, data for nine angles of incidence are supplied for the X-band, whereas data for only one angle of incidence is supplied for the C- and the L-band. The data supplied for the C- and L-band represent the incidence angles of the ERS and JERS satellites respectively. However, the length of this data array can be increased just as in the example for the X-band. For the Cloud model parameters that are independent of angle of incidence, namely K and D, of course only one value is given. Note that for each frequency band, the suffixes _X, _C and _L are used as extension of the variable names explained in Table 14.

Example of X-band data:

*INUM = Sequence number of array of incidence angles and Cloud parameters
*ANGLE = Angle of incidence (degree)
*GS = G-parameter of the Cloud model (m-2 m-2)
*CCROP = C-parameter of the crop of the Cloud model (m-2 m-2)

<table>
<thead>
<tr>
<th>INUM</th>
<th>ANGLE_X</th>
<th>GS_X</th>
<th>CCROP_X</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10.</td>
<td>0.525</td>
<td>1.060</td>
</tr>
<tr>
<td>2</td>
<td>20.</td>
<td>0.174</td>
<td>1.190</td>
</tr>
<tr>
<td>3</td>
<td>30.</td>
<td>0.120</td>
<td>1.200</td>
</tr>
<tr>
<td>5</td>
<td>40.</td>
<td>0.095</td>
<td>1.150</td>
</tr>
<tr>
<td>6</td>
<td>50.</td>
<td>0.076</td>
<td>1.170</td>
</tr>
<tr>
<td>7</td>
<td>60.</td>
<td>0.065</td>
<td>1.150</td>
</tr>
<tr>
<td>8</td>
<td>70.</td>
<td>0.055</td>
<td>0.980</td>
</tr>
<tr>
<td>9</td>
<td>75.</td>
<td>0.042</td>
<td>0.930</td>
</tr>
</tbody>
</table>

KS_X  = 0.06 ! Cloud K parameter for the soil (-)
DCROP_X = 0.46 ! Cloud D parameter for the crop (m² kg)

Example of C-band data:

<table>
<thead>
<tr>
<th>INUM_C</th>
<th>ANGLE_C</th>
<th>GS_C</th>
<th>CCROP_C</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>20.</td>
<td>0.01964</td>
<td>0.58845</td>
</tr>
</tbody>
</table>

KS_C  = 0.0580 ! Cloud K parameter for the soil (-)
DCROP_C = 0.1009 ! Cloud D parameter for the crop (m² kg)
Example of L-band data:

\[
\begin{array}{llll}
\text{INUM}_L & \text{ANGLE}_L & \text{GS}_L & \text{CCROP}_L \\
1 & 40. & 0.00070 & 0.11424 \\
\end{array}
\]

\begin{align*}
\text{KS}_L &= 0.1000 \quad \text{! Cloud K parameter for the soil (-)} \\
\text{DCROP}_L &= 1.1025 \quad \text{! Cloud D parameter for the crop (m-2 kg)}
\end{align*}

### 7.2.3 Observed data

All observed variables are supplied under the names of the variables as simulated by the model, but with extension _OBS (from observed).

Measured soil content (MCSoIL) data need to be supplied as arrays in the following manner: <year of observation>, <day number of observation>, <MCSoIL values> (all values as REAL). For example:

\[
\begin{aligned}
\text{MCSoIL}_\text{OBS} &= \\
1988.0, & 112.0, & 31.00, \\
1988.0, & 122.0, & 30.40, \\
1988.0, & 165.0, & 28.30, \\
1988.0, & 186.0, & 44.70, \\
1988.0, & 195.0, & 39.40, \\
1988.0, & 207.0, & 38.10, \\
1988.0, & 228.0, & 24.50
\end{aligned}
\]

In BSCat, there is the option to use either the observed values of soil moisture content in the Cloud calculations, or the simulated values from the water balance model. The switch to control this option is set in the remote sensing input file, and is called MCSoIL\_FRC. This switch is 'supplemented' by the variable MCSoIL\_TRC, which contains a so-called 'triggering table'. The explanation of the (combined) use of MCSoIL\_FRC and MCSoIL\_TRC is as follows:

- MCSoIL\_FRC = 0: use simulated values only,
- MCSoIL\_FRC = 1: reset simulated values to observed values on dates of observation,
- MCSoIL\_FRC = 2: use interpolated values from observed data between dates that observations are present. Before the first observation date and after the last observation date, simulated values are used.

When the option MCSoIL\_FRC is 1 is chosen, the 'triggering table' MCSoIL\_TRC indicates on which dates (corresponding to observation dates) the simulated MCSoIL values should be reset. The sequence of data entry for the triggering table is <year of observation for triggering>, <day number of observation for triggering>, <triggering value>. MCSoIL\_TRC can have the following values:

- MCSoIL\_TRG = 0 do not force; simulated values are used during whole simulation,
- MCSoIL\_TRG = 1 do point reset on dates of observation; use simulated values in-between,
- MCSoIL\_TRG = 2 do point reset on dates of observation; use interpolated values with MCSoIL from next point of observation in-between.
For example, the switch MCSoIL_FRC = 1, in combination with the triggering table

\[
MCSoIL_\_FRC =
\begin{array}{ccc}
1989., & 112., & 0., \\
1989., & 122., & 0., \\
1989., & 165., & 1., \\
1989., & 186., & 1., \\
1989., & 195., & 2., \\
1989., & 207., & 2., \\
1989., & 228., & 0.
\end{array}
\]

means the following: Until day 165, simulated values of MCSoIL are used. On day 165, MCSoIL is reset to the observed value on this day, and simulation of MCSoIL is continued from this value onwards. On day 186, MCSoIL is again reset to the observed value on this day, and simulation of MCSoIL is continued from this value onwards. On day 195, MCSoIL is reset to the observed value on this day, and MCSoIL values from this day onwards are interpolated between this day’s value and the next observed value on day 207. On day 207, the MCSoIL equals the observed value, and MCSoIL values from this day onwards are interpolated between this day’s value and the next observed value (on day 228). From day 228 onwards, simulated values are again used.

When no soil moisture data have been measured, the following values should be entered:

\[
MCSoIL_\_OBS = -99.
\]

\[
MCSoIL_\_TRG = -99.
\]

\[
MCSoIL_\_FRC = 0
\]

Next to the observations on soil moisture content, observed remote sensing variables can be supplied with the extension _OBS. In principle, these variables are optional, i.e. need not be supplied at all. The read routines of FSE-TTUTIL used by BSCAT and REFLEX to retrieve these data checks whether these variables have been supplied or not. When they are supplied, they are written to the output file for comparison with simulated values; when they are not supplied, the writing statement is simply ‘ignored’. However, it is advised here to give the value of -99 when no data are available; this way the -99 values can be ‘over-written’ by rerun files using the rerun facility of FSE. The following measured remote sensing variables can be supplied:

- **WDVI_OBS** (observed WDVI)
- **X10, X20, , X70** (observed X-band radar backscatter at 10°, 20°,, 70° incidence angle)
- **ERS_OBS** (observed radar backscatter of ERS satellite, or comparable configuration)
- **JERS_OBS** (observed radar backscatter of JERS satellite, or comparable configuration)

The data need to be supplied as arrays in the following manner: <year of observation>, <day number of observation>, <measured value>; for example:

\[
ERS_\_OBS =
\begin{array}{ccc}
1988.0, & 112.0, & -12.6, \\
1988.0, & 122.0, & -9.9, \\
1988.0, & 165.0, & -2.7, \\
1988.0, & 186.0, & -4.3, \\
1988.0, & 195.0, & -1.6, \\
1988.0, & 207.0, & -1.0, \\
1988.0, & 228.0, & -4.1
\end{array}
\]
7.3 Output file

The (normal) output file as specified in CONTROL.DAT (generally RES.OUT) contains, next to simulated crop growth and water balance variables, the following simulated remote sensing variables (Table 17)

Table 17. Names, explanation and units of simulated variables written to the normal output file (RES.OUT) by REFLEX and BSCAT.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Explanation</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>IROG**</td>
<td>Infra-red/green reflectance ratio</td>
<td>-</td>
</tr>
<tr>
<td>NAR_G**</td>
<td>Nadir crop reflectance green</td>
<td>%</td>
</tr>
<tr>
<td>NAR_R**</td>
<td>Nadir crop reflectance red</td>
<td>%</td>
</tr>
<tr>
<td>NAR_IR**</td>
<td>Nadir crop reflectance infra-red</td>
<td>%</td>
</tr>
<tr>
<td>NDVI**</td>
<td>Normalized Difference Vegetation Index</td>
<td>-</td>
</tr>
<tr>
<td>WDVI_CLA</td>
<td>Weighted Difference Vegetation Index, calculated using CLAIR model</td>
<td>%</td>
</tr>
<tr>
<td>WDVI_EMP***</td>
<td>Weighted Difference Vegetation Index, calculated using empirical relationships</td>
<td>%</td>
</tr>
<tr>
<td>WDVI_EXT**</td>
<td>Weighted Difference Vegetation Index, calculated sing EXTRAD model</td>
<td>%</td>
</tr>
<tr>
<td>WDVI_OBS *</td>
<td>Observed Weighted Difference Vegetation Index</td>
<td>%</td>
</tr>
<tr>
<td>ERS_OBS</td>
<td>Observed radar backscatter ERS (gamma)</td>
<td>dB</td>
</tr>
<tr>
<td>RBGAM_X</td>
<td>Array with X-band radar backscatter (gamma), at various incidence angles</td>
<td>dB</td>
</tr>
<tr>
<td>RBGAM_C</td>
<td>Array with C-band radar backscatter (gamma), at various incidence angles (ERS)</td>
<td>dB</td>
</tr>
<tr>
<td>RBGAM_L</td>
<td>Array with L-band radar backscatter (gamma), at various incidence angles (JERS)</td>
<td>dB</td>
</tr>
<tr>
<td>RBSOIL_C</td>
<td>Array with C-band radar backscatter contribution from the soil, at various incidence angles</td>
<td>dB</td>
</tr>
<tr>
<td>RBSOIL_L</td>
<td>Array with L-band radar backscatter contribution from the soil, at various incidence angles</td>
<td>dB</td>
</tr>
<tr>
<td>RBSOIL_X</td>
<td>Array with X-band radar backscatter contribution from the soil, at various incidence angles</td>
<td>dB</td>
</tr>
<tr>
<td>JERS_OBS</td>
<td>Observed radar backscatter JERS (gamma)</td>
<td>dB</td>
</tr>
<tr>
<td>MCOIL</td>
<td>Volumetric moisture content top soil</td>
<td>%</td>
</tr>
<tr>
<td>MCOIL_SIM</td>
<td>Simulated volumetric soil moisture content top soil (by SAHEL)</td>
<td>%</td>
</tr>
<tr>
<td>MCOIL_OBS</td>
<td>Observed volumetric soil moisture content top soil</td>
<td>%</td>
</tr>
<tr>
<td>PLW_CROP</td>
<td>Plant water amount in canopy</td>
<td>kg m$^{-2}$</td>
</tr>
<tr>
<td>PLW_VEG</td>
<td>Plant water amount in vegetative layer</td>
<td>kg m$^{-2}$</td>
</tr>
<tr>
<td>PLW_EAR</td>
<td>Plant water amount in ear layer</td>
<td>kg m$^{-2}$</td>
</tr>
</tbody>
</table>

Note: *: only when observed values have been supplied in the remote sensing input file

**: only when EXTRAD was executed during simulation

***: only for wheat and potato

The simulated radar backscatter variables RBGAM_X, RBGAM_C and RBGAM_L are written as arrays, where 'i' indexes the sequence number of the angles of incidence as specified in the remote sensing input file by INUM (Paragraph 7.2.2): RBGAM_X(i), RBGAM_C(i), RBGAM_L(i).
References

Vegetation modelled as a water cloud, Radio Science 13(2): 357-364


Standard relations to estimate ground cover and LAI of agricultural crops from reflectance measurements. European Journal of Agronomy 1: 249-262.


User manuals SUCROS-Wheat, SUCROS-Beet and SUCROS-Potato.


The application of a weighted infrared-red vegetation index for estimating leaf area index by correcting for soil moisture, Remote Sensing of Environment, 29:25-37

Dulk, J.A. den, 1989.

Eom, H.J. & A.K. Fung, 1986,
Scattering from a random layer embedded with dielectric needles, Remote Sensing of Environment 19:139-149.

Environmental constraints in earth-space propagations, in Agard Conference Proceedings, CP-284: 35.1-35.27


A multilayer model for radar backscattering from vegetation canopies, Digest of the 2nd IEEE International Geoscience and Remote Sensing Symposium, München, West Germany, 1-4 June, pp. 4.1-4.7

Derivation of leaf area index from quality of light on the forest floor, Ecology, 50: 663-666.


Keulen, H. van & J. Wolf (Eds.), 1986.


The reflectance of shortwave radiation from multilayer plant canopies, Academy of sciences of the Estonian SSR section of physics and astronomy, Tallinn, Estonia, USSR.


Modelling and synergetic use of optical and microwave remote sensing. Report 6: Radar
backscatter modelling for synergetic use with optical and microwave remote sensing to
agricultural crops. BCRS Report., BCRS, Delft, the Netherlands.

Monitoring vegetation systems in the great plains with ERTS. Third ERTS Symposium,

Physical fundamentals of remote sensing, Springer-Verlag Berlin Heidelberg, Germany.
187 pp.

Suits, G.H., 1972.
The calculation of the directional reflectance of a vegetation canopy, Remote Sensing of
Environment, 2: 117-125.

Microwave dielectric properties of plant materials, IEEE Transactions on Geoscience and


Microwave remote sensing, Vol. II, Addison-Wesley, Reading Massachusetts, USA.
pp 457-1064.

Microwave remote sensing, Vol. III, Artech House, Washington, USA. pp 1065-.

'Michigan Microwave canopy scattering model'. International Journal of Remote Sensing,
11(7): 1223-1253.

Verhoef, W., 1984.
Light scattering by leaf layers with application to canopy reflectance modelling: The SAIL
## Appendix I: Variable name listing

Variable name listing of remote sensing subroutines and functions (REFLEX, EXTRAD, CLAIR, EMPWHE, EMPPOT, BSCAT1, BSCAT2, CLOUD1 and CLOUD2)

Note that variable name with extension _OBS are observed variables (not indicated per variable in this list)

<table>
<thead>
<tr>
<th>Name</th>
<th>Explanation</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACROP</td>
<td>Attenuation of microwaves by the canopy</td>
<td>-</td>
</tr>
<tr>
<td>AEAR</td>
<td>Attenuation of microwaves by the ear layer</td>
<td>-</td>
</tr>
<tr>
<td>ANGLE</td>
<td>Incidence angle</td>
<td>degrees</td>
</tr>
<tr>
<td>ANGLE_C</td>
<td>Incidence angle (for C-band data)</td>
<td>degrees</td>
</tr>
<tr>
<td>ANGLE_L</td>
<td>Incidence angle (for L-band data)</td>
<td>degrees</td>
</tr>
<tr>
<td>ANGLE_X</td>
<td>Incidence angle (for X-band data)</td>
<td>degrees</td>
</tr>
<tr>
<td>ASOIL</td>
<td>Intermediate variable in Cloud model</td>
<td>-</td>
</tr>
<tr>
<td>AVEG</td>
<td>Attenuation of microwaves by the vegetative layer</td>
<td>-</td>
</tr>
<tr>
<td>BCLAIR</td>
<td>Inverse of asymptotic value of WDV1 at infinite LAI</td>
<td>%⁻¹</td>
</tr>
<tr>
<td>BETA</td>
<td>Solar height</td>
<td>degrees</td>
</tr>
<tr>
<td>CCROP</td>
<td>Radar backscattering coefficient canopy (gamma)</td>
<td>m².m⁻²</td>
</tr>
<tr>
<td>CCROP_C</td>
<td>Radar backscattering coefficient canopy (gamma); C-band</td>
<td>m².m⁻²</td>
</tr>
<tr>
<td>CCROP_L</td>
<td>Radar backscattering coefficient canopy (gamma); L-band</td>
<td>m².m⁻²</td>
</tr>
<tr>
<td>CCROP_X</td>
<td>Radar backscattering coefficient canopy (gamma); X-band</td>
<td>m².m⁻²</td>
</tr>
<tr>
<td>CEAR</td>
<td>Radar backscattering coefficient ear layer (gamma)</td>
<td>m².m⁻²</td>
</tr>
<tr>
<td>CEAR_C</td>
<td>Radar backscattering coefficient ear layer; C-band (gamma)</td>
<td>m².m⁻²</td>
</tr>
<tr>
<td>CEAR_L</td>
<td>Radar backscattering coefficient ear layer; L-band (gamma)</td>
<td>m².m⁻²</td>
</tr>
<tr>
<td>CEAR_X</td>
<td>Radar backscattering coefficient ear layer; X-band (gamma)</td>
<td>m².m⁻²</td>
</tr>
<tr>
<td>CLAIR</td>
<td>Weighted Difference Vegetation Index (calculated using CLAIR model)</td>
<td>-</td>
</tr>
<tr>
<td>CVEG</td>
<td>Radar backscattering coefficient vegetative layer (gamma)</td>
<td>m².m⁻²</td>
</tr>
<tr>
<td>CVEG_C</td>
<td>Radar backscattering coefficient vegetative layer; C-band (gamma)</td>
<td>m².m⁻²</td>
</tr>
<tr>
<td>CVEG_L</td>
<td>Radar backscattering coefficient vegetative layer; L-band (gamma)</td>
<td>m².m⁻²</td>
</tr>
<tr>
<td>CVEG_X</td>
<td>Radar backscattering coefficient vegetative layer; X-band (gamma)</td>
<td>m².m⁻²</td>
</tr>
<tr>
<td>DCROP</td>
<td>Coefficient of microwave attenuation canopy</td>
<td>m².kg⁻¹</td>
</tr>
<tr>
<td>DCROP_C</td>
<td>Coefficient of microwave attenuation canopy; C-band</td>
<td>m².kg⁻¹</td>
</tr>
<tr>
<td>DCROP_L</td>
<td>Coefficient of microwave attenuation canopy; L-band</td>
<td>m².kg⁻¹</td>
</tr>
<tr>
<td>DCROP_X</td>
<td>Coefficient of microwave attenuation canopy; X-band</td>
<td>m².kg⁻¹</td>
</tr>
<tr>
<td>Name</td>
<td>Explanation</td>
<td>Units</td>
</tr>
<tr>
<td>------------</td>
<td>------------------------------------------------------------------------------</td>
<td>----------------</td>
</tr>
<tr>
<td>DEAR</td>
<td>Coefficient of microwave attenuation ear layer</td>
<td>m².kg⁻¹</td>
</tr>
<tr>
<td>DEAR_C</td>
<td>Coefficient of microwave attenuation ear layer; C-band</td>
<td>m².kg⁻¹</td>
</tr>
<tr>
<td>DEAR_L</td>
<td>Coefficient of microwave attenuation ear layer; L-band</td>
<td>m².kg⁻¹</td>
</tr>
<tr>
<td>DEAR_X</td>
<td>Coefficient of microwave attenuation ear layer; X-band</td>
<td>m².kg⁻¹</td>
</tr>
<tr>
<td>DEGTRAD</td>
<td>Conversion coefficient from degrees to radians</td>
<td>radians.degrees⁻¹</td>
</tr>
<tr>
<td>DOY</td>
<td>Day number since 1 January (day of year)</td>
<td>d</td>
</tr>
<tr>
<td>DVEG</td>
<td>Coefficient of microwave attenuation vegetative layer</td>
<td>m².kg⁻¹</td>
</tr>
<tr>
<td>DVEG_C</td>
<td>Coefficient of microwave attenuation vegetative layer; C-band</td>
<td>m².kg⁻¹</td>
</tr>
<tr>
<td>DVEG_L</td>
<td>Coefficient of microwave attenuation vegetative layer; L-band</td>
<td>m².kg⁻¹</td>
</tr>
<tr>
<td>DVEG_X</td>
<td>Coefficient of microwave attenuation vegetative layer; X-band</td>
<td>m².kg⁻¹</td>
</tr>
<tr>
<td>DVS</td>
<td>Development stage of the crop</td>
<td></td>
</tr>
<tr>
<td>EMPPOT</td>
<td>Function that calculates WDMI of potato using empirical (linear) relationships</td>
<td>WDMI; %</td>
</tr>
<tr>
<td>EMPWHE</td>
<td>Function that calculates WDMI of wheat using empirical (linear) relationships</td>
<td>WDMI; %</td>
</tr>
<tr>
<td>F</td>
<td>Leaf angle distribution factor</td>
<td></td>
</tr>
<tr>
<td>FILERS</td>
<td>Input file with remote sensing data</td>
<td></td>
</tr>
<tr>
<td>FRDF_T</td>
<td>Instantaneous fraction diffuse radiation</td>
<td></td>
</tr>
<tr>
<td>FRDIR</td>
<td>Instantaneous fraction direct radiation</td>
<td></td>
</tr>
<tr>
<td>GS</td>
<td>Radar backscattering dry soil (gamma)</td>
<td>m².m⁻²</td>
</tr>
<tr>
<td>GS_C</td>
<td>Radar backscattering dry soil (gamma); C-band</td>
<td>m².m⁻²</td>
</tr>
<tr>
<td>GS_L</td>
<td>Radar backscattering dry soil (gamma); L-band</td>
<td>m².m⁻²</td>
</tr>
<tr>
<td>GS_X</td>
<td>Radar backscattering dry soil (gamma); X-band</td>
<td>m².m⁻²</td>
</tr>
<tr>
<td>I</td>
<td>DO-loop counter</td>
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<td>Length of array Cloud model variables</td>
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</tr>
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<td>IMCEN</td>
<td>Length of array MCVEART</td>
<td></td>
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<tr>
<td>IMCVEG</td>
<td>Length of array MCVEG</td>
<td></td>
</tr>
<tr>
<td>IMCVN</td>
<td>Number of elements in MCVEGT</td>
<td></td>
</tr>
<tr>
<td>IMMCEA</td>
<td>Number of elements in MCEART</td>
<td></td>
</tr>
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</tr>
<tr>
<td>IN2</td>
<td>Length of arrays in EXTRAD variables</td>
<td></td>
</tr>
<tr>
<td>INC_C</td>
<td>Length of input array Cloud parameters; C-band</td>
<td></td>
</tr>
<tr>
<td>INC_L</td>
<td>Length of input array Cloud parameters; C-band</td>
<td></td>
</tr>
<tr>
<td>INC_X</td>
<td>Length of input array Cloud parameters; C-band</td>
<td></td>
</tr>
<tr>
<td>Name</td>
<td>Explanation</td>
<td>Units</td>
</tr>
<tr>
<td>---------------</td>
<td>-----------------------------------------------------------------------------</td>
<td>---------------</td>
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<td>INF</td>
<td>Length of array F</td>
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<tr>
<td>INUM_C</td>
<td>Sequence number of input array Cloud parameters; C-band</td>
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</tr>
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<td>INUM_L</td>
<td>Sequence number of input array Cloud parameters; L-band</td>
<td></td>
</tr>
<tr>
<td>INUM_X</td>
<td>Sequence number of input array Cloud parameters; X-band</td>
<td></td>
</tr>
<tr>
<td>IROG</td>
<td>Infrared/green reflectance ratio</td>
<td></td>
</tr>
<tr>
<td>ITASK</td>
<td>Task that subroutine should perform</td>
<td></td>
</tr>
<tr>
<td>IUNITD</td>
<td>Unit number that is used for input files</td>
<td></td>
</tr>
<tr>
<td>IUNITL</td>
<td>Unit number that is used for log file</td>
<td></td>
</tr>
<tr>
<td>IUNITO</td>
<td>Unit number that is used for output file</td>
<td></td>
</tr>
<tr>
<td>J</td>
<td>DO-loop counter</td>
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<td>JCLOUD</td>
<td>Length of array Cloud model variables</td>
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</tr>
<tr>
<td>K</td>
<td>DO-loop counter</td>
<td></td>
</tr>
<tr>
<td>KCLAIR</td>
<td>Extinction coefficient the CLAIR model</td>
<td></td>
</tr>
<tr>
<td>KS</td>
<td>Moisture coefficient of the top soil</td>
<td>%^{-1}</td>
</tr>
<tr>
<td>KS_C</td>
<td>Moisture coefficient of the top soil; C-band</td>
<td>%^{-1}</td>
</tr>
<tr>
<td>KS_L</td>
<td>Moisture coefficient of the top soil; L-band</td>
<td>%^{-1}</td>
</tr>
<tr>
<td>KS_X</td>
<td>Moisture coefficient of the top soil; X-band</td>
<td>%^{-1}</td>
</tr>
<tr>
<td>LAI</td>
<td>Green leaf area index</td>
<td>m^2leaf.m^{-2} ground</td>
</tr>
<tr>
<td>LAIEXT</td>
<td>Green leaf area index</td>
<td>m^2 leaf.m^{-2} ground</td>
</tr>
<tr>
<td>LAIMAX</td>
<td>Maximum value of LAI during growing season</td>
<td>m^2 leaf.m^{-2} ground</td>
</tr>
<tr>
<td>MCCROP</td>
<td>Moisture content canopy</td>
<td>100*g.g^{-1} (%)</td>
</tr>
<tr>
<td>MCEAR</td>
<td>Moisture content ear layer</td>
<td>100*g.g^{-1} (%)</td>
</tr>
<tr>
<td>MCEART</td>
<td>Table of moisture content ear layer as function of DVS</td>
<td>100*g.g^{-1} (%)</td>
</tr>
<tr>
<td>MCSOIL</td>
<td>Volumetric moisture content top soil</td>
<td>100*cm^3.cm^{-3} (%)</td>
</tr>
<tr>
<td>MCSOIL_SIM</td>
<td>Volumetric moisture content top soil, simulated value</td>
<td>100*cm^3.cm^{-3} (%)</td>
</tr>
<tr>
<td>MCVEG</td>
<td>Moisture content vegetative layer</td>
<td>100*g.g^{-1} (%)</td>
</tr>
<tr>
<td>MCVEGT</td>
<td>Table of moisture content vegetative layer as function of DVS</td>
<td>100*g.g^{-1} (%)</td>
</tr>
<tr>
<td>NAR</td>
<td>Nadir crop reflectance</td>
<td>%</td>
</tr>
<tr>
<td>NAR_G</td>
<td>Nadir crop reflectance green</td>
<td>%</td>
</tr>
<tr>
<td>NAR_IR</td>
<td>Nadir crop reflectance infrared</td>
<td>%</td>
</tr>
<tr>
<td>NAR_R</td>
<td>Nadir crop reflectance red</td>
<td>%</td>
</tr>
<tr>
<td>Name</td>
<td>Explanation</td>
<td>Units</td>
</tr>
<tr>
<td>------------</td>
<td>-----------------------------------------------------------------------------</td>
<td>-------------------</td>
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<td>NDVI</td>
<td>Normalized Difference Vegetation Index</td>
<td>-</td>
</tr>
<tr>
<td>NOINCA</td>
<td>Number of incidence angles</td>
<td>-</td>
</tr>
<tr>
<td>OUTPUT</td>
<td>Flag to indicate if output should be done</td>
<td>-</td>
</tr>
<tr>
<td>PI</td>
<td>Ratio of circumference to diameter</td>
<td>-</td>
</tr>
<tr>
<td>PLWEAR</td>
<td>Plant water amount in ear layer</td>
<td>kg H₂O / m²</td>
</tr>
<tr>
<td>PLWCRO</td>
<td>Plant water amount in canopy</td>
<td>kg H₂O / m²</td>
</tr>
<tr>
<td>PLWVEG</td>
<td>Plant water amount in vegetative layer</td>
<td>kg H₂O / m²</td>
</tr>
<tr>
<td>RBGAM</td>
<td>Array with radar backscatter (gamma) at various incidence angles</td>
<td>dB</td>
</tr>
<tr>
<td>RBGAM_C</td>
<td>Array with C-band radar backscatter (gamma) at various incidence angles (ERS)</td>
<td>dB</td>
</tr>
<tr>
<td>RBGAM_L</td>
<td>Array with L-band radar backscatter (gamma) at various incidence angles (ERS)</td>
<td>dB</td>
</tr>
<tr>
<td>RBGAM_X</td>
<td>Array with X-band radar backscatter (gamma) at various incidence angles</td>
<td>dB</td>
</tr>
<tr>
<td>RBSOIL</td>
<td>Array with radar backscatter contribution of the soil at various incidence angles</td>
<td>dB</td>
</tr>
<tr>
<td>RBSOIL_C</td>
<td>Array with C-band radar backscatter contribution of the soil at various incidence angles</td>
<td>dB</td>
</tr>
<tr>
<td>RBSOIL_L</td>
<td>Array with L-band radar backscatter contribution of the soil at various incidence angles</td>
<td>dB</td>
</tr>
<tr>
<td>RBSOIL_X</td>
<td>Array with X-band radar backscatter contribution of the soil at various incidence angles</td>
<td>dB</td>
</tr>
<tr>
<td>RCRP</td>
<td>Radar backscatter contribution canopy, intermediate value</td>
<td>m².m²</td>
</tr>
<tr>
<td>REARS</td>
<td>Radar backscatter contribution ear layer, intermediate value</td>
<td>m².m²</td>
</tr>
<tr>
<td>RHOM</td>
<td>Nadir soil reflectance</td>
<td>%</td>
</tr>
<tr>
<td>RHOMG</td>
<td>Nadir soil reflectance green</td>
<td>%</td>
</tr>
<tr>
<td>RHOMIR</td>
<td>Nadir soil reflectance infra-red</td>
<td>%</td>
</tr>
<tr>
<td>RHOMR</td>
<td>Nadir soil reflectance red</td>
<td>%</td>
</tr>
<tr>
<td>RHOS</td>
<td>Hemispherical soil reflectance</td>
<td>-</td>
</tr>
<tr>
<td>RHOSG</td>
<td>Hemispherical soil reflectance green</td>
<td>-</td>
</tr>
<tr>
<td>RHOSIR</td>
<td>Hemispherical soil reflectance infra-red</td>
<td>-</td>
</tr>
<tr>
<td>RHOSR</td>
<td>Hemispherical soil reflectance red</td>
<td>-</td>
</tr>
<tr>
<td>RSOIL</td>
<td>Radar backscatter contribution soil, intermediate value</td>
<td>m².m²</td>
</tr>
<tr>
<td>RVEG</td>
<td>Radar backscatter contribution vegetative layer, intermediate value</td>
<td>m².m²</td>
</tr>
<tr>
<td>Name</td>
<td>Explanation</td>
<td>Units</td>
</tr>
<tr>
<td>------------</td>
<td>------------------------------------------------------------------</td>
<td>---------------</td>
</tr>
<tr>
<td>SCAT</td>
<td>Scatter coefficient leaf</td>
<td></td>
</tr>
<tr>
<td>SCATG</td>
<td>Scatter coefficient leaf green</td>
<td></td>
</tr>
<tr>
<td>SCATIR</td>
<td>Scatter coefficient leaf infra-red</td>
<td></td>
</tr>
<tr>
<td>SCATR</td>
<td>Scatter coefficient leaf red</td>
<td></td>
</tr>
<tr>
<td>SINB</td>
<td>Sine of solar height</td>
<td></td>
</tr>
<tr>
<td>SWIREF</td>
<td>Switch to indicate the use of EXTRAD model</td>
<td></td>
</tr>
<tr>
<td>TADRW</td>
<td>Total above-ground dry weight</td>
<td>kg.ha(^{-1})</td>
</tr>
<tr>
<td>TERMNL</td>
<td>Flag to indicate if simulation is to stop</td>
<td></td>
</tr>
<tr>
<td>WCLQT</td>
<td>Volumetric water content in soil compartments</td>
<td>cm(^3) H(_2)O.cm(^{-3}) soil</td>
</tr>
<tr>
<td>WDVIE</td>
<td>Weighted Difference Vegetation Index</td>
<td></td>
</tr>
<tr>
<td>WDVIC</td>
<td>Weighted Difference Vegetation Index (calculated using CLAIR model)</td>
<td></td>
</tr>
<tr>
<td>WDVIE</td>
<td>Weighted Difference Vegetation Index (calculated using empirical relation)</td>
<td></td>
</tr>
<tr>
<td>WDVIE_CLA</td>
<td>Weighted Difference Vegetation Index (calculated using CLAIR model)</td>
<td></td>
</tr>
<tr>
<td>WDVIE_EMP</td>
<td>Weighted Difference Vegetation Index (calculated using empirical relation)</td>
<td></td>
</tr>
<tr>
<td>WDVIE_EXT</td>
<td>Weighted Difference Vegetation Index (calculated using EXTRAD model)</td>
<td></td>
</tr>
<tr>
<td>WDVIMAX</td>
<td>Maximum value of WDVIE during growing season</td>
<td>%</td>
</tr>
<tr>
<td>WLV</td>
<td>Dry weight of the leaves (green + dead)</td>
<td>kg.ha(^{-1})</td>
</tr>
<tr>
<td>WLVG</td>
<td>Dry weight of the green leaves</td>
<td>kg.ha(^{-1})</td>
</tr>
<tr>
<td>WSO</td>
<td>Dry weight of storage organs</td>
<td>kg.ha(^{-1})</td>
</tr>
<tr>
<td>WST</td>
<td>Dry weight of the stems</td>
<td>kg.ha(^{-1})</td>
</tr>
</tbody>
</table>
Appendix II:

Optical reflectance routines
SUBROUTINE REFLEX

INTEGER ITARK, INIUNIT, INIFILE
REAL LAI
LOGICAL OUTPUT, TENDEL, LAI
CHARACTER*20 FILERS(*)

LOCAL VARIABLES
REAL SCIAIR, SCLEAR, BKG0, BKG1, BKG2, BKG3
REAL SCGRAD, SCNIT, SCNT, BETA, PROF_T
REAL VAR, BGM, RG, REXE, ELMN, ELMN, LAIEXT
REAL VAR_G, VAR_R, VAR_L, ING, GENT, IRON, MOVIC

EXTERNAL INF
PARAMETER (INF=3)
REAL PINF
REAL MOVMAX, LADMAX

FUNCTION
REAL SCNIT, CLAIR, EMAP, SOURCE
LOGICAL INDIR

SAVE

IF (ITARK.EQ.1) THEN
  ! Initialization section
  ! Read input data from the remote sensing data file
  CALL RECDAT (INIUNIT, INIFILE)

  CALL BSEPAR ("ECLEAR", RCLEAR)
  CALL BSEPAR ("ECGRT", ECGRT)
  CALL BSEPAR ("ESCRIP", ESCRIP)

  IF (INSTR.EQ.0) THEN
    ! Extraroutine should not be run
    CONTINUE
  ELSEIF (INSTR.EQ.1) THEN
    ! Extraroutine should be run, read input
    CALL BSEPAR ("BKG0", BKG0)
    CALL BSEPAR ("BKG1", BKG1)
    CALL BSEPAR ("BKG2", BKG2)
    CALL BSEPAR ("SCGRAD", SCGRAD)
    CALL BSEPAR ("SCNIT", SCNIT)
    CALL BSEPAR ("BETA", BETA)
    CALL BSEPAR ("PROF", PROF)
    CALL BSEPAR ("F", F, INF, INF)
  ELSE
    CALL ERROR ("REFLEX", "Incorrect value of INSTR")
  END IF

  CLOSE (INUNIT)
  MOVMAX = 0.
  LADMAX = 0.

  ELSEIF (ITARK.EQ.2) THEN
    ! Rate calculation section
    ! Optical reflectance calulations
    IF (SCGRT.EQ.0) THEN
      MOVIC = -999.
      ELMN = -999.
      LAI = -999.
    ELSEIF (SCGRT.EQ.1) THEN
      LAI can at the most be 10.0 in extraroutine to avoid stopping the simulation runs. the LAI value passed-on to extraroutine is kept at a maximum of 10.
      IF (LAI.GT.10.) THEN
        LAIEXT = 10.
        CALL OUTPUT ("Warning: LAI > 10 => LAI set to 10")
      ELSE
        LAIEXT = LAI
      END IF
    END IF

    CALL EXTRAD (BKG0, SCGRAD, BETA, P, INF, LAIEXT, PROF, T, VAR, BGM)

    VAR_G = VAR
    CALL EXTRAD (BKG1, SCNIT, BETA, P, INF, LAIEXT, PROF, T, VAR, BGM)

    VAR_R = VAR
    CALL EXTRAD (BKG2, ELMN, P, INF, LAIEXT, PROF, T, VAR, BGM)

    VAR_L = VAR
    CALL EXTRAD (BKG0, SCGRT, BETA, P, INF, LAIEXT, PROF, T, VAR, BGM)

    MOVIC = MOVIC
    CALL EXTRAD (BKG1, SCNIT, BETA, P, INF, LAIEXT, PROF, T, VAR, BGM)

    END IF
* Print data
  IF (OUTPUT) THEN
    IF (.INQ(FILMS, 'MDVI')) CALL OUTDAT
    & (2,0,'MDVI.0SM', GETORS (FILMS, 'MDVI'))
    CALL OUTDAT (2,0,'MDVI.0CA', WVDU)
    CALL OUTDAT (2,0,'MDVI.0RP', WVDU)
  IF (.INQ(ERD,1)) THEN
    CALL OUTDAT (2,0,'MDVI.0SE', MDVI)
    CALL OUTDAT (2,0,'MDVI.0NE', MDVI)
    CALL OUTDAT (2,0,'MDVI.0W', MDVI)
    CALL OUTDAT (2,0,'MDVI.0S', MDVI)
    CALL OUTDAT (2,0,'MDVI.0I', MDVI)
    CALL OUTDAT (2,0,'MDVI.0N', MDVI)
  END IF
  END IF
ELSE IF (ITERATION.GT.1) THEN
  * State calculation section
  *
  * Maximum MDVI from the empirical equations
  
  \[ \text{MDVMAX} = \max (\text{MDVMAX}, \text{MDVI}) \]

  LAITHMAX = MAX (LAITHMAX, LAI)
ELSE IF (ITERATION.EQ.4) THEN
  * Terminal section
  *
  C CALL GOUTOR ('LAITHMAX', LAITHMAX)
  C CALL GOUTOR ('MDVMAX', MDVMAX)
  CONTINUE
END IF
RETURN
END

*SUBROUTINE EXTRAD
*
* Author(s): J. Soussain, adapted by B.A.M. Brouwer
* Date : 24-Aug-1995, Version: 1.0
* Purpose: Calculation of optical reflectance of agricultural crops.
*          The calculated reflectances are nadir reflectance in a
*          +10 degree upward 'cone' around nadir.
*          
* Version: 2.0: April 1995; adapted by Brouwer.
*          
*          simulation study. Wageningen, published by Pudoc
*          (simulation monograph).
*          
* FORMAL PARAMETERS: (L input, I output, O control, N initialize, T time)
*          
*          NAME TYPE MEANING UNITS CLASS
*          --------------- --------------- ----
*          RHOI R4 Semireflectance of soil [-] I
*          SCAT R4 Scattering coefficient leaf [-] I
*          RSA R4 Solar height (degrees) I
*          F R4 Leaf angle distribution factor [-] I
*          IMF R4 Lenght of array F [-] I
*          LAI R4 Green leaf area index (m^2 leaf/m^2 ground) I
*          FMDIV,T R4 Instantaneous fraction diffuse radiation [-] I
*          NMDIV R4 Radiation crop reflectance [-] O
*          RMDIV R4 Nadir soil reflectance [-] O
*          SUBROUTINES and functions called: none
*          Libraries used: TUVFL
*          Fatal error checks: on declared lengths of arrays; on boundaries
*          of the input parameter values.
*
* SUBROUTINE EXTRAD (RHOI,SCAT,RSA,IMF,LA,PRDIV,T,NMDIV,RMDIV)
*
* FORMAL PARAMETERS
* INTEGER IMF
* REAL RHOI,SCAT,RSA,LA,PRDIV,T,NMDIV
*
* LOCAL PARAMETERS
* INTEGER INJ
* PARAMETER (INJ=1)
* REAL RHOI,SCAT,RA,PRDIV,T,NMDIV
*
* Miscellaneous
* INTEGER J,K,L,IR,IVIVR,ITERM,SI,SI1
* REAL INV,RIV,PI,HEXXAD
* PARAMETER (PI=3.1415926, HEXXAD=0.87455292)
*
* DATA RH0/0.030353,0.0483,0.13302,0.16316,0.17345,
*       1.0
*       0.16316,0.13302,0.0483,0.030353/0.030353
*
* Error checks
* IMF and INJ (length of array) should be 19;
* IF (INJ.NE.I) CALL ERROR ('EXTRAD', 'INJ is not 19')
* IF (INJ.NE.1) CALL ERROR ('EXTRAD', 'INJ is not 9')

  * Check on impossible values input data:
  IF (LA.GT.100) CALL ERROR ('EXTRAD', 'LAI smaller than 100')
  IF (RHOI.GT.6) CALL ERROR ('EXTRAD', 'RHOI less/equal 6')
  IF (RMDIV.GT.1) CALL ERROR ('EXTRAD', 'RMDIV greater than 1')
  IF (SCAT.GT.6) CALL ERROR ('EXTRAD', 'SCAT less than 6')
  IF (SCAT.LT.1) CALL ERROR ('EXTRAD', 'SCAT greater than 1')
  IF (IMF.GT.5) CALL ERROR ('EXTRAD', 'IMF less than 5')
  IF (IMF.LT.3) CALL ERROR ('EXTRAD', 'IMF greater than 3')
  IF (PRDIV.LT.3) CALL ERROR ('EXTRAD', 'PRDIV less than 3')
  IF (PRDIV.GT.8) CALL ERROR ('EXTRAD', 'PRDIV greater than 8')
  IF (FMDIV.GT.1) CALL ERROR ('EXTRAD', 'FMDIV greater than 1')
  IF (FMDIV.LT.1) CALL ERROR ('EXTRAD', 'FMDIV less than 1')

  * Special check on maximum LAI i.e.: declared array lengths:
  IF (LA.GT.10) CALL ERROR ('EXTRAD', 'LAI larger than 10')

  * Initialization: calculations for leaf angle distribution
  *
  PIVR = 1.-PRDIV
  LS = 0.1
  IF (RA.LT.50.0) THEN
    LS = 1.+INF (RA<0.1)
  ELSE
    LS = 0.1
  END IF

  RIV = 0.
  DO K=1,INJ
    SIND = SIN (HEXXAD*(10.*(RA-0.5)))
    COSS = COS (HEXXAD*(10.*(RA-0.5)))
    RIV(K) = 0.
    DO L=1,INJ
      SIND = SIN (HEXXAD*(10.*(RA-0.5)))
COSL = COS(DEG2RAD*(18.*REAI(1)-0.5))
IF (REAI(1).LT.0.5) THEN
  O = SINL*COSL
ELSE
  O = 2.*SINL*COSL*SIN((SINL*COSL/SINL*COSL)+(SINL*COSL/SINL*COSL))**.5
END IF

DAY(K) is the leaf projection into direction K:
DAY(K) = GAY(K)-GAF(F)
END DO

Fraction intercepted NI and transmitted NT:
NI(K) = GAY(K)*COS(2)*PI
NT(K) = 1.-NI(K)

SRL is needed for normalisation of the view factors SL(K):
SRL = SRL*NI(K)/NI(K)
END DO

Inventory according to leaf layers
N = UAD(1)+U(4)+0.5
H1 = R

Initialisation of radiation profile:
DO K=1,N1
  PHI(K,1) = 0.
  PHI(K,2) = 0.
END DO

SL(K) = NI(K)*N1/SLN

Diffuse radiation is distributed according to NI(K):
PHI(K,1) = 100.*NI(K)**PHI(1)
END DO

The direct incoming component is added:
PHI(DNS,1) = PHI(DNS,1)+100.*PHI(DN)

Main routine for the profile calculation

Number of iterations depends on scattering coefficient:
ITEM=1
IF (SCATT.GT.0.5) ITEM = 2
IF (SCATT.GT.8.5) ITEM = 5
IF (SCATT.GT.16.5) ITEM = 10
IF (SCATT.GT.32.5) ITEM = 20
IF (SCATT.GT.64.5) ITEM = 50
END IF

DO ITEM=1,ITEM
  First a calculation from top to bottom:
  DO J=1,N1
    DI = 0.
    DO K=1,N1
      DI = DI + PHI(K,J)*NI(K)+PHI(K,J)
    END DO
    PHI(K,J) = PHI(K,J)+0.5*DI*ITEM**.6*H1
  END DO
  END DO

  Reflective radiation at the soil surface:
  DI = 0.
  DO K=1,N1
    DI = DI + PHI(K,NI)*NI(K)
  END DO
END IF
IMPLICIT NONE

* Formal parameters
REAL RCALAB, BCLAIR, LAI
SAVE

IF (LAI.LE.0.0) CALL ERROR ('CLAIR', 'LAI smaller than 0')

CLAIR = (1.-EXP(-RCALAB*LAI))/RCALAB
RETURN
END

* FUNCTION EMPIRE

* Author(s): B.A.H. Bowen
* Date: 26-Aug-1995, Version: 1.1
* Purpose: Calculates WVI of wheat using empirical (linear) relationships.
* Version: 1.1 Improved parameters (DKE)
* FORMAL PARAMETERS: (L-input, O-output, C-control, IN-inittime)
* name type meaning unit class
* ------- ---- ------- ------ ----
* EMPIRE B4 Function that calculates WVI of wheat using empirical (linear) relationships (?)
* LAI B4 Green leaf area index (m2 leaf.m-2 ground) 1

REAL FUNCTION EMPIRE(LAI)

IMPLICIT NONE

* Formal parameters
REAL LAI
SAVE

IF (LAI.LE.0.0) THEN
   CALL ERROR ('EMPIRE', 'LAI smaller than 0')
ELSE IF (LAI.GE.0.0.AND.LAI.LE.0.6) THEN
   EMPIRE = -20.1366*LA
ELSE IF (LAI.GT.0.6.AND.LAI.LE.4.06) THEN
   EMPIRE = -7.5461*LA+7.55619
ELSE IF (LAI.GT.4.06) THEN
   EMPIRE = 2.8425*LA+37.431
END IF
RETURN
END

* FUNCTION EMPPOT

* Author(s): B.A.H. Bowen
* Date: 26-Aug-1995, Version: 1.1
* Purpose: Calculates WVI of potato using empirical (linear) relationships.
Appendix III:

Radar backscatter routines
SUBROUTINE BCARI

Purpose:
Interface with SUCROS model to calculate radar backscatter; this version for "one-layer" crops: sugar beet or potato. Radar backscatter is calculated using the Cloud model.

This version for sugar beet.

Author: D.A.M. Boundary
Version: 1.0, January, 1994

FORMAL PARAMETERS:

NAME: Type: Meaning: UNITS: I/O

TRANK  I  Task that subroutine should perform - 1
INITI0  I  Unit that can be used for input files - 1
INITI1  I  Unit used for log file - I
FILERS  C  Name of input file no. 1 - 1
OUTPUT  I  Flag to indicate if output should be done - I
TRENCH  I  Flag to indicate if simulation is to stop - 1/0
WLCUT  S  Volumetric soil water content cm/cm 1
THROW  S  Total above-ground dry biomass Mg/ha 1

SUBROUTINES called: CLOUDS

 FUNCTIONS called: GETSOR system, OUTPUT

LIBRARIES used: NDSUFL

SUBROUTINE BCARI (TRANK, INITI0, INITI1, FILERS, 
OUTPUT, TRENCH, WLCUT, THROW)

IMPLICIT NONE

---- Formal parameters

INTEGER TRANK, INITI0, INITI1, 
REAL WLCUT(2), THROW
LOGICAL OUTPUT, TRENCH
CHARACTER FILERS(*)

---- Local variables

Crop and soil variables
REAL NCHOP, NCROG, MCGOIL

Cloud model

INTEGER ICGID
PARAMETER (ICGID = 10)

INTEGER INCIP, INMC, INCN, INC0, INC1, INC2, INC3, INC4
REAL ANGLE, X(ICGID), ORG, XX(INC1), XX(INC2)
REAL ERRICH(ICGID), ERRHIC, XXX1, XXX2

--+ Functions

REAL GETSOR, OBTRIG
LOGICAL INGORS
SAVE

-- Initialization section

IF (TRANK.EQ.1) THEN

---- Read input data from the remote sensing data file
CALL READ1(INITI1, INITI0, FILERS)

Moisture content parameters
CALL RBDRAA (NCHOP, NCROG)

X-band Cloud
CALL RBDRAA ('INMC', INCN, ICNO, INCX)
CALL RBDRAA ('ANGL', ANG, ICN, INCX, INCX)
CALL RBDRAA ('ORGL', ORG, ICN, ICNO, INCX)
CALL RBDRAA ('CROG', CROG, ICN, ICNO, INCX)
CALL RBDRAA ('XX01', XX01)
CALL RBDRAA ('XX02', XX02)

--- ERS C-band Cloud
CALL RBDRAA ('INMC', INCN, ICNO, INCX)
CALL RBDRAA ('ANGL', ANG, ICN, ICNO, INCX)
CALL RBDRAA ('ORGL', ORG, ICN, ICNO, INCX)
CALL RBDRAA ('CROG', CROG, ICN, ICNO, INCX)
CALL RBDRAA ('XX01', XX01)
CALL RBDRAA ('XX02', XX02)

--- JERS L-band Cloud
CALL RBDRAA ('INMC', INCN, ICNO, ICNO)
CALL RBDRAA ('ANGL', ANG, ICN, ICNO, ICNO)
CALL RBDRAA ('ORGL', ORG, ICN, ICNO, ICNO)
CALL RBDRAA ('CROG', CROG, ICN, ICNO, ICNO)
CALL RBDRAA ('XX01', XX01)
CALL RBDRAA ('XX02', XX02)

CLOSE (INITI0)

END IF (TRANK.EQ.1)

ELSE IF (TRANK.EQ.2) THEN

Calculation of total above-ground plant water (kg/m2)
from total above-ground dry weight (kg/ha).
PLACE = 0.001*(IRAND1*MCROG1)/(100.-MCROG1)

Daily values of soil moisture content. Options to use simulated values, observed values, or a combination. Note that observed values are generally 5-10 cm tape soil (9), whereas simulated values are generally 0-20 cm tape soil (-1)
MCROG = OBSRND(100.,MCROG1), FILERS, MCGOIL

Calculation of radar backscatter X-band
CALL CLOUDS(PLACE, MCGOIL, INCM, ANG, ORG, XX01)
$ DCHROG, NCROG, ERRHIC, XXX2

Calculation of radar backscatter C-band
CALL CLOUDS(PLACE, MCGOIL, INCM, ANG, ORG, XX01)
$ DCHROG, NCROG, ERRHIC, XXX2

Calculation of radar backscatter L-band
CALL CLOUDS(PLACE, MCGOIL, INCM, ANG, ORG, XX01)
$ DCHROG, NCROG, ERRHIC, XXX2

Print data
IF (OUTPUT) THEN
IF (INGORS (FILERS, MCGOIL)) CALL OUTPUT
$ (2, 6, 'MCROG_OBS', GETSOR (FILERS, MCGOIL))
IF (INGORS (FILERS, 'XID')) CALL OUTPUT
$ (2, 6, 'XID_OBS', GETSOR (FILERS, 'XID'))
IF (INGORS (FILERS, 'XID')) CALL OUTPUT

ENDIF

ENDIF

ENDIF
$ (2, 0, 'X0', OBSORS(FILERS, 'X20'))
IF (INQORS(FILERS, 'X30')) CALL OUT04
$ (2, 0, 'X0', OBSORS(FILERS, 'X30'))
IF (INQORS(FILERS, 'X40') CALL OUT04
$ (2, 0, 'X0', OBSORS(FILERS, 'X40'))
IF (INQORS(FILERS, 'X50') CALL OUT04
$ (2, 0, 'X5', OBSORS(FILERS, 'X50'))
IF (INQORS(FILERS, 'X60') CALL OUT04
$ (2, 0, 'X5', OBSORS(FILERS, 'X60'))
IF (INQORS(FILERS, 'X70') CALL OUT04
$ (2, 0, 'X70', OBSORS(FILERS, 'X70')
IF (INQORS(FILERS, 'X80') CALL OUT04
$ (2, 0, 'X80', OBSORS(FILERS, 'X80'))
IF (INQORS(FILERS, 'X90') CALL OUT04
$ (2, 0, 'X90', OBSORS(FILERS, 'X90'))
END IF
CALL OUT04 0, 0, 'MOSOH', MJO"OCL(1)*100.
CALL OUT04 0, 0, 'MOSOH', MJO"OCL
CALL OUT04 0, 0, 'T’HNO', T’HNO
CALL OUT04 0, 0, 'BRO"O', BRO$O, 1, 1, INC, L
CALL OUT04 0, 0, 'BRO"O', BRO$O, 1, 1, INC, L
CALL OUT04 0, 0, 'BRO"O', BRO$O, 1, 1, INC, L
CALL OUT04 0, 0, 'BRO"O', BRO$O, 1, 1, INC, L
CALL OUT04 0, 0, 'BRO"O', BRO$O, 1, 1, INC, L
CALL OUT04 0, 0, 'BRO"O', BRO$O, 1, 1, INC, L
CALL OUT04 0, 0, 'BRO"O', BRO$O, 1, 1, INC, L
END IF
END

* State calculation section

ELSE IF (ITASK EQ 3) THEN

* No statements here
CONTINUE

* Terminal section

ELSE IF (ITASK EQ 4) THEN

* No statements here
CONTINUE

END IF
END

* SUBROUTINE BIC2

* Author(s): R.A.M. Boman

* Date: 26-Sep-1995, Version: 1.0

* Purpose: Interface with BICMOD model to calculate radar
* backscatter; this version for 'two-layer' crops: wheat
* or barley. Radar backscatter is calculated using the
* Cloud model.

* FORMAL PARAMETERS: [I-Input, O-Output, C-Control, M-Init, T-Time]
* NAME TYPE MEANING (UNIT) CLASS
* ---- ---- -------- --------
* INBI 14 Task that subroutine should perform [-]
* UNTI 14 Unit number that is used for input files [-]
* FILER 14 Unit number that is used for log file [-]
* OPUT 14 Flag to indicate if output should be done [-]
* TERNL 14 Flag to indicate if simulation is to stop [-]
* WETL 14 Volumeetric water content in soil compartments [-]
* (00 N2O-CN-2 soil) [-]
* WET 14 Dry weight of the leaves (green + dead) (kg ha-1) [-]
* DSO 14 Dry weight of storage organs (kg ha-1) [-]
* DUS 14 Development stage of the crop [-]
* WEI 54 Weight of the root system [-]
* MUS 54 Weight of the shoot system [-]
* SUBROUTINE BIC2 (ITASK, INITI, INITN, FILER, 
* OUTPUT, TERN, WCLGT, 
* MUS, WET, WSO, DUS, 
* INITM, INITI)
* IMPLICIT NONE

* Formal parameters

INTEGER ITASK, INITI, INITN
REAL WCLGT, MUS, WET, WSO, DUS
LOGICAL OUTPUT, TERN
CHARACTER FILER(*)

* Local variables

INTEGER IMUS, IMUS
PARAMETER (IMUS=20)
REAL MUS(MUS)
PARAMETER (IMUSC=20)
REAL MUSC(MUSC)

* Cloud model

INTEGER ICLOUD
PARAMETER (ICLOUD=10)
INTEGER IMUSL(ICLoud), IMUS
REAL ANGLR(ICLoud), ORL(ICLoud), ORG(RGICLoud), BRO$ICLoud
REAL BRO$ICLoud
REAL KX, KW$ICLoud, KRE$ICLoud

INTEGER IMUSC(ICLoud), IMUSC
REAL RS$ICLoud
REAL ANGLR(ICLoud), ORL(ICLoud), ORG(RGICLoud), BRO$ICLoud
REAL KX, KW$ICLoud, KRE$ICLoud

* Functions

REAL LIMK, OBN, OBNLOG
LOGICAL IINQ

SAVE

IF (ITASK EQ 1) THEN

* Initialization section

* Read input data from the remote sensing data file
CALL READI (INITI, INITN, FILER)

* Moisture content parameters

CALL READA ('MOURO', 'MOURO1', 'INVO', 'INVO')
CALL READA ('WCLGT', 'MUS', 'INUS', 'INUS')

*
IF (INQDR(FILERS,'X0')) CALL OUTOUT

ENDIF

ELSE IF (ITEMS.EQ.2) THEN

! Rate calculation section

* Calculation of plant water (kg/m2) for crops and vegetative cover from their dry weights (kg/m2)

NCAPD = LIMIT (SPDNT, INCN, D2V)
PLANTW = 0.00044*(INCN*8850)*MCAPD/(100.-NCAPD)
PLANTR = 0.000152*MCAPD/(100.-NCAPD)

* Daily values of soil moisture content. Options to use simulated evapotranspiration values, observed values, or a combination. Note that observed values are generally 0-3 cm topsoil (4), whereas simulated values are generally 0-20 cm topsoil (3)

NCAPM = OBSMD (100.-MCAPD(1), FILERS, 'NCAPM')

* Calculation of radar backscatter X-band

CALL CLOSER (PLARN, PLKNR, MCDS, INCN, ANGLL, ANGLR, 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0.
* MCSTIL  R4  topsoil moisture content  W(vol.) I *
* NOINC  R4  Number of incidence angles  - I *
* ANGLE  R4  incidence angle  degree I *
* GS  R4  Backscatter (gs) dry soil  dB I *
* CCORP  R4  Maximum backscatter (gs) crop  dB I *
* KS  R4  Soil moisture attenuation factor  - I *
* CCORP  R4  Attenuation factor crop  - I *
* BGSOIL  R4  Radar backscatter (gs) crop  dB O *
* ESBSOIL  R4  Radar backscatter contribution soil  dB O *
* SUBROUTINE called: none *
* LIBRARIES used: none *
* FATAL ERRORS check: Data input bounds *

SUBROUTINE CLOUDS(LMCPRO,MCSTIL,MNOICA,ANGLE,Gs,Ks,CCORP,BGSOIL,ESBSOIL)

Implicit NONE

* Formal parameters

INTER MNOICA
REAL ANGLE(MDNOICA),Gs(MDNOICA),CCORP(MDNOICA),BGSOIL(MDNOICA)
REAL ESBSOIL(MDNOICA)
REAL Gs,CCORP,LMCPRO,MCSTIL

* Local variables

INTER JCLOUD
PARAMETER (JCLMUD=0.017453293)

Save

* Check on length of array
* IF (MCSTIL.GT.JCLMUD) THEN
* CALL ERROR (‘CLOUDS’, ’Declared arrays too short, JCLMUD’) END IF

* Check on data input values
* IF (MCSTIL.LT.0. OR. MCSTIL.GT.100.) THEN
* CALL ERROR (‘CLOUDS’, ’Input moisture is out of bounds’) END IF

* IF (MCSTIL.LT.0.) CALL ERROR (‘CLOUDS’, ’MCSTIL negative value’)
DO I=1,MNOICA
IF (ANGLE(I).LE.0. OR. ANGLE(I) .GT. 90.) THEN
CALL ERROR (‘CLOUDS’, ’incidence angle out of bounds’) END IF
END DO

* Calculation section: radar backscatter using the two-layer
* Cloud equations: loop over the number of incidence angles
* DO I=1,MNOICA
* ACPRO(I) =CCORP*MCSTIL/(INTER*ANGLE(I))
* BKSOIL(I) = GS*(1.0*EXP(-MCSTIL*ACPRO(I))
* BKSOIL(I) = CCORP(I)*(1.0+EXP(-ACPRO(I))
* BKSOIL(I) = 10.*BKSOIL(BKSOIL(I))
END DO
* RETURN
END

SUBROUTINE CLOUDS(LMCPRO,MCSTIL,MNOICA,ANGLE,Gs,Ks,CCORP,BGSOIL,ESBSOIL)

Implicit NONE

* Formal parameters

INTER MNOICA
REAL ANGLE(MDNOICA),Gs(MDNOICA),CCORP(MDNOICA),BGSOIL(MDNOICA)
REAL ESBSOIL(MDNOICA)
REAL Gs,CCORP,LMCPRO,MCSTIL

* Local variables

INTER JCLOUD
PARAMETER (JCLMUD=0.017453293)

Save

* Check on length of array
* IF (MCSTIL.GT.JCLMUD) THEN
* CALL ERROR (‘CLOUDS’, ’Declared arrays too short, JCLMUD’) END IF

* Check on data input values
* IF (MCSTIL.LT.0. OR. MCSTIL.GT.100.) THEN
* CALL ERROR (‘CLOUDS’, ’Input moisture is out of bounds’) END IF

* IF (MCSTIL.LT.0.) CALL ERROR (‘CLOUDS’, ’MCSTIL negative value’)
DO I=1,MNOICA
IF (ANGLE(I).LE.0. OR. ANGLE(I) .GT. 90.) THEN
CALL ERROR (‘CLOUDS’, ’incidence angle out of bounds’) END IF
END DO

* Calculation section: radar backscatter using the two-layer
* Cloud equations: loop over the number of incidence angles
* DO I=1,MNOICA
* ACPRO(I) =CCORP*MCSTIL/(INTER*ANGLE(I))
* BKSOIL(I) = GS*(1.0*EXP(-MCSTIL*ACPRO(I))
* BKSOIL(I) = CCORP(I)*(1.0+EXP(-ACPRO(I))
* BKSOIL(I) = 10.*BKSOIL(BKSOIL(I))
END DO
* RETURN
END
CALL ERROR ('CLOUD2', 'Soil moisture NG0IL out of bounda')
END IF

IF (MAXULATE.EQ.0.) CALL ERROR ('CLOUD2', 'MAXULATE negative value')
IF (MINULATE.EQ.0.) CALL ERROR ('CLOUD2', 'MINULATE negative value')

DO 1=1,LSENCA
IF (ANGLE(1),LE.6. OR. ANGLE(1),GE. 90.) THEN
   CALL ERROR ('CLOUD2', 'incidence angle out of bounds')
END IF
END DO

* Calculation section: radar backscatter using the two-layer
* cloud equations; loop over the number of incidence angles

DO 1=1,LSENCA
  ANUG(1) = DVUG*PLANG0/COS (DEGTRAD*ANGLE(1))
  ANUG(1) = DEGTRAD*ANG001/COS [DEGTRAD*ANGLE(1)]
  ANUG(1) = (DEGTRAD*ANG01+DVUG*PLANG0)/COS [DEGTRAD*ANGLE(1)]
  ANUG(1) = ANUG(1)*EXP [K1*HUG01]*EXP (-ANUG(1))
  ANUG(1) = ANUG(1)*EXP (-ANUG(1))
  ANUG(1) = ANUG(1)*EXP (-ANUG(1))
  ANUG(1) = 10.*ANUG(1) + ANUG(1) + ANUG(1)
  ANUG(1) = 10.*ANUG(1) + ANUG(1)
END DO

RETURN
END
Appendix IV:

Example remote sensing input file

*---------------------------------------------------------------*
* RSWHE.DAT  *
* Input data for remote sensing modules CLOUD, EXTRAD and CLAIR for *
* radar backscatter and optical reflectance. This file for wheat.   *
*---------------------------------------------------------------*

* 1. Radar input

*---------------------------------------------------------------*
* 1.1 Moisture content crop
  * Reference: Bouman, B.A.M., 1992. SBFLEVO and WWFLEVO, CABO-DLO   *
  * report 163.

* First number: development stage; second number: moisture content of *
  * vegetative matter of the crop (in %; kg water/kg fresh biomass)

MCEBGT = 0.00, 83.0,
        0.80, 83.0,
        1.15, 74.0,
        1.70, 74.0,
        1.95, 61.0,
        2.00, 49.0,
        2.50, 49.0

* First number: development stage; second number: moisture content of *
* the ears (in %; kg water/kg fresh biomass)

MCEART = 0.00, 69.0,
        1.25, 69.0,
        1.70, 58.0,
        1.95, 40.0,
        2.00, 15.0,
        2.50, 15.0

*---------------------------------------------------------------*
* 1.2 Cloud model parameters X-band. Data taken from ground-based   *
* ROVE measurements at Droevendaal, 1979 (variety Okapi).          *
* 1982. A multilayer model for radar backscattering from          *
* vegetation canopies, Digest of the 2nd IEEE                   *
* International Geoscience and Remote Sensing Symposium,         *
* Munich, West Germany, pp. 4.1-4.7.                             *
*---------------------------------------------------------------*

*INUM  = Sequence number
*ANGLE  = Angle of incidence (degree)
*GS  = G-parameter of the Cloud model (m2/m2)
*CEAR  = C-parameter of the ears of the Cloud model (m2/m2)
<table>
<thead>
<tr>
<th>INUM_X</th>
<th>ANGLE_X</th>
<th>GS_X</th>
<th>CEAR_X</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10.</td>
<td>0.344</td>
<td>0.101</td>
</tr>
<tr>
<td>2</td>
<td>20.</td>
<td>0.326</td>
<td>0.048</td>
</tr>
<tr>
<td>3</td>
<td>30.</td>
<td>0.088</td>
<td>0.039</td>
</tr>
<tr>
<td>4</td>
<td>40.</td>
<td>0.057</td>
<td>0.040</td>
</tr>
<tr>
<td>5</td>
<td>50.</td>
<td>0.019</td>
<td>0.054</td>
</tr>
<tr>
<td>6</td>
<td>60.</td>
<td>0.010</td>
<td>0.079</td>
</tr>
<tr>
<td>7</td>
<td>70.</td>
<td>0.012</td>
<td>0.130</td>
</tr>
<tr>
<td>8</td>
<td>75.</td>
<td>0.009</td>
<td>0.172</td>
</tr>
</tbody>
</table>

$KS_X = 0.06$ ! Cloud $K$ parameter for the soil (-)

$DVEG_X = 1.1530$ ! Cloud $D$ parameter for vegetative matter (m$^2$/kg)

$DEAR_X = 2.0565$ ! Cloud $D$ parameter for ear layer (m$^2$/kg)

$CVEG_X = 0.1850$ ! Cloud $C$ parameter for ear layer (m$^2$/m$^2$)

* 1.3 Cloud model parameters C- and L-band. Data taken from
  * AGRISCATT 1988 campaign in Flevoland.
  * report 163.

<table>
<thead>
<tr>
<th>INUM_C</th>
<th>ANGLE_C</th>
<th>GS_C</th>
<th>CEAR_C</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>20.</td>
<td>0.0200</td>
<td>0.2249</td>
</tr>
</tbody>
</table>

* Maybe better to use 40 degree incidence angle data?

<table>
<thead>
<tr>
<th>INUM_C</th>
<th>ANGLE_C</th>
<th>GS_C</th>
<th>CEAR_C</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>40.</td>
<td>0.0090</td>
<td>0.1302</td>
</tr>
</tbody>
</table>

$KS_C = 0.0580$ ! Cloud $K$ parameter for the soil (-)

$DVEG_C = 0.0033$ ! Cloud $D$ parameter for vegetative matter (m$^2$/kg)

$DEAR_C = 0.0717$ ! Cloud $D$ parameter for ear layer (m$^2$/kg)

$CVEG_C = 0.1727$ ! Cloud $C$ parameter for ear layer (m$^2$/m$^2$)

<table>
<thead>
<tr>
<th>INUM_L</th>
<th>ANGLE_L</th>
<th>GS_L</th>
<th>CEAR_L</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>40.</td>
<td>0.0022</td>
<td>0.0676</td>
</tr>
</tbody>
</table>

$KS_L = 0.1000$ ! Cloud $K$ parameter for the soil (-)

$DVEG_L = 0.2678$ ! Cloud $D$ parameter for vegetative matter (m$^2$/kg)

$DEAR_L = 2.0789$ ! Cloud $D$ parameter for ear layer (m$^2$/kg)

$CVEG_L = 0.04867$ ! Cloud $C$ parameter for ear layer (m$^2$/m$^2$)

* 2. Optical model input

* 2.1 CLAIR model parameters (taken from large data set)
  * Standard relations to estimate ground cover and LAI of
    * agricultural crops from reflectance measurements. Eur.
KCLAIR = 0.40  ! K parameter CLAIR model (-)
BCLAIR = 0.02128 ! beta parameter CLAIR model (%-1)

*---------------------------------------------------------------*
* 2.2 EXTRAD model parameters (taken from large data set) *
* Reference: Bouman, B.A.M., 1992. SBFLKEVO and WWFLKEVO, CAPO-DLO *
* report 163. *
*---------------------------------------------------------------*

RHOSS = 0.134  ! green reflection coefficient soil (-)
RHOSSR = 0.145  ! red reflection coefficient soil (-)
RHOSSIR = 0.174  ! infrared reflection coefficient soil (-)
SCATG = 0.341  ! green scatter coefficient leaves (-)
SCATR = 0.123  ! red scatter coefficient leaves (-)
SCATIR = 0.960  ! infrared scatter coefficient leaves (-)
BETA  = 60.  ! solar height (degree)
FRDIF_T = 0.5  ! instantaneous fraction diffuse radiation (-)
F = 0.015, 0.045, 0.074, 0.1, 0.123, 0.143, 0.158, 0.168, 0.174
    ! leaf angle distribution factor

***************************************************************
* 3. Measured data input
***************************************************************

***************************************************************
* 3.1 Soil moisture content
***************************************************************

* Measured soil moisture data. If no measurements: fill-in dummy data)
* First number: year number, second number: day number, third number:
* moisture content (0-5 cm top soil; 100% cm3/cm3).
MCSoIL_OBS = -99.

* Triggering table to indicate if simulated soil moisture contents
* should be reset to observed values on that specific day.
MCSoIL_TRG = -99.

* Switch to indicate the combined use of simulated soil moisture
* contents with observed values:
* 0 = use simulated values only,
* 1 = reset simulated values to measured values on dates
* of observations (as indicated in MCSoIL_TRG table),
* 2 = use interpolated values from observed data between dates that
* observations are present (else use simulated values)
MCSoIL_PRC = 2

***************************************************************
* 3.2 Radar backscatter and WDI
***************************************************************

* First number: year number, second number: day number, third number:
* measurement (X-band, ERS and JERS: in dB; WDI in %).
* Observations at X-band; dB. Possibilities: X10, X20... X70. Example
X40_OBS = -99.
Appendix IV:
Example remote sensing input file

*-----------------------------------------------*
* RSWHE.DAT *
* Input data for remote sensing modules CLOUD, EXTRAD and CLAIR for *
* radar backscatter and optical reflectance. This file for wheat. *
*-----------------------------------------------*

* 1. Radar input *

*-----------------------------------------------*
* 1.1 Moisture content crop *
* Reference: Bouman, B.A.M., 1992. SBFLEVO and WWFLEVO, CABO-DLO *
* report 163. *

* First number: development stage; second number: moisture content of *
* vegetative matter of the crop (in %; kg water/kg fresh biomass) *
MCVBGT = 0.00, 83.0, 
  0.80, 83.0, 
  1.15, 74.0, 
  1.70, 74.0, 
  1.95, 61.0, 
  2.00, 49.0, 
  2.50, 49.0

* First number: development stage; second number: moisture content of *
* the ears (in %; kg water/kg fresh biomass) *
MCEART = 0.00, 69.0, 
  1.25, 69.0, 
  1.70, 58.0, 
  1.95, 40.0, 
  2.00, 15.0, 
  2.50, 15.0

*-----------------------------------------------*
* 1.2 Cloud model parameters X-band. Data taken from ground-based *
* ROVE measurements at Droevendaal, 1979 (variety Okapi). *
* 1982. A multilayer model for radar backscattering from *
* vegetation canopies, Digest of the 2nd IEEE *
* International Geoscience and Remote Sensing Symposium, *
* Munich, West Germany, pp. 4.1-4.7. *

*-----------------------------------------------*
*INUM = Sequence number *
*ANGLE = Angle of incidence (degree) *
*GS = G-parameter of the Cloud model (m2/m2) *
*CEAR = C-parameter of the ears of the Cloud model (m2/m2) *