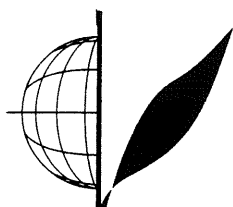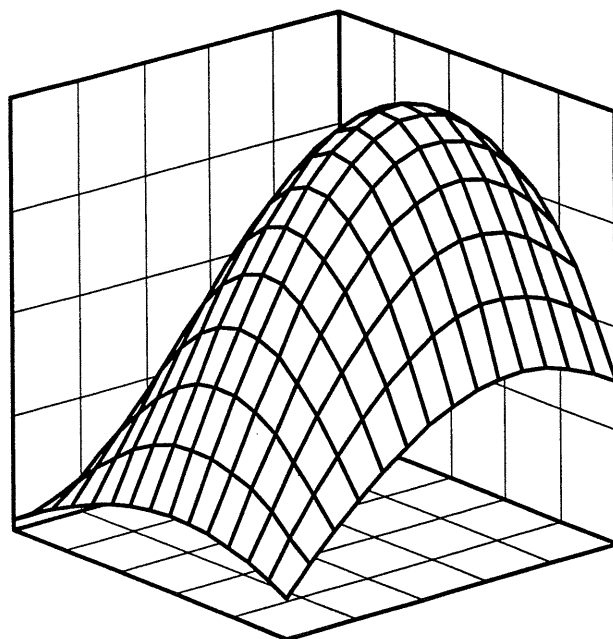# Remote sensing subroutines in crop growth simulation models

Quantitative Approaches in Systems Analysis

Quantitative Approaches in Systems Analysis supports publications in reviewed journals on dynamic simulation models, optimization programs, Geographic Information Systems (GIS), expert systems, data bases, and utilities for the quantitative analysis of agricultural and environmental systems. The series provides staff members, students and visitors to AB-DLO and PE with an opportunity to publish updates of previously published models, extensive data sets used for validation, background material to refereed journal articles, and other documentation that is valuable to others. The inclusion of listings of programs in an Appendix is encouraged.

All manuscript are reviewed by an editorial board comprising one AB-DLO and one PE staff member: B.A.M. Bouman (AB-DLO) and M.K. van Ittersum (TPE-WAU). The editorial board may consult external reviewers. The review process includes assessing the following: relevance of the topic to the series, overall scientific soundness, clear structure and presentation, and completeness of the presented material(s). The editorial board evaluates manuscripts on language and lay-out matters in a general sense. However, the sole responsibility for the contents of the reports, the use of correct language and lay-out rests with the authors. Manuscripts or suggestions should be submitted to the editorial board. Reports of the series are available on request.

Quantitative Approaches in Systems Analysis are issued by the DLO Research Institute for Agrobiology and Soil Fertility (AB-DLO) and The C.T. de Wit Graduate School for Production Ecology (PE). AB-DLO, with locations in Wageningen and Haren, carries out research into plant physiology, soil science and agro-ecology with the aim of improving the quality of soils and agricultural produce and of furthering sustainable plant production systems.
The 'Production Ecology' Graduate School explores options for crop production systems associated with sustainable land use and natural resource management; its activities comprise research on crop production and protection, soil management, and cropping and farming systems.

Remote sensing sub-routines in crop growth simulation models

B.A.M. Bouman

Keywords

Optical, radar, remote sensing, crop growth, simulation, model

Guidelines 'Quantitative Approaches in Systems Analysis'

Manuscripts or suggestions should be submitted to the editorial board (B.A.M. Bouman, AB-DLO, or M.K. van Ittersum, TPE-WAU). The final version of the manuscripts should be delivered to the editors camera-ready for reproduction. The submission letter should indicate the scope and aim of the manuscript (e.g. to support scientific publications in journals, program manual, educational purposes). The costs of printing and mailing are to be borne by the authors.

The English language is preferred. Authors are responsible for correct language and lay-out. Overall guidelines for the format of the texts, figures and graphs can be obtained from the publication editor at AB-DLO, or from the PE office:

J.M. Braber
AB-DLO

P.O. Box 14
NL-6700 AA Wageningen
Phone: 31(0).317.475723
Fax: 31(0).317.423110
E-mail: braber@ab.dlo.nl

Th.H. Jetten
Secretariat C.T. de Wit Graduate School
for Production Ecology
Lawickse Allee 13
NL-6701 AN Wageningen
Phone: 31(0).317.485116
Fax: 31(0).317.484855
E-mail:theo.jetten@beleid.spp.wau.nl

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.

Table of Contents

Samenvatting

Dit rapport beschrijft de implementatie van optische en radar remote-sensing modellen in de vorm van Fortran-routines, en de koppeling hiervan met simulatiemodellen van gewasgroei die geschreven zijn in Fortran Simulation Environment (FSE), versie 2.1. Gekoppelde remote-sensing - gewasgroeimodellen kunnen gebruikt worden voor het volgen van actuele gewas-groei en -ontwikkeling, oogstvoorspelling, optimalisatie van remote-sensing opname tijd-stippen 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 WDVI. 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 gewasgroeimodellen 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 geprogammeerd, 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 gewasgroeimodellen. 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, optimi-sation 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 WDVI. 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 implemen-ted 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 com-plete 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 'operationalized' 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 operationalized 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; Verhoef, 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, WDVI (Clevers, 1988; 1989), Table 1. From a comparative analysis, the WDVI 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 WDVI (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.

IR/R Ratio	NDVI	WDVI
$\dfrac{r_{ir}}{r_r}$ (Eq. 1)	$\dfrac{r_{ir} - r_r}{r_{ir} + r_r}$ (Eq. 2)	$c = \dfrac{r_{ir} - cr_r}{r_{r,s}}$ (Eq. 3)

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° (the Normalised Radar Cross Section NRCS, which is the radar cross-section per unit area illuminated by the antenna) is:

$$\gamma = \frac{\sigma^0}{\cos\theta}$$ (Eq. 4)

where q 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:

$$\gamma(dB) = {}^{10}Log(\gamma(m^2 m^{-2}))$$ (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 $\approx$ 24 cm), S-band (3.2 GHz $\approx$ 9.4 cm), C-band (5.3 GHz $\approx$ 5.7 cm), X-band (9.5 GHz $\approx$ 3.1 cm), Ku_1-band (13.7 GHz $\approx$ 2.2 cm) and Ku_2-band (17.3 GHz $\approx$ 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 geo-metry 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 collec-tion 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 WDVI (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 μm 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 (σ), leaf angle distribution function (F)), soil parameters (hemispherical soil reflection coefficient (ρ)), and illumination parameters (solar elevation angle (β), 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 WDVI to LAI of the canopy via an exponential extinction equation (Clevers, 1988, 1989):

$$WDVI = \frac{(1-e^{(-kL)})}{\beta} \ (\%) \tag{Eq. 6}$$

where b = the inverse of the asymptotic value of WDVI at infinite L (%$^{-1}$), k = extinction coefficient (-); L = Leaf Area Index (LAI) (-). 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):

$$WDVI = \beta(L + \alpha)\,(\%)$$

(Eq. 7)

where a = regression coefficient (-); b = 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 a and b.

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:

$$\gamma = C_\theta(1 - e^{(\frac{-DW}{\cos\theta})}) + G_\theta e^{(\frac{mK-DW}{\cos\theta})} \quad (m^2 m^{-2})$$

(Eq. 8)

where: 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_q = 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):

$$\gamma = C2_\theta(1 - e^{(\frac{-D2W2}{\cos\theta})}) +$$
$$C1_\theta(1 - e^{(\frac{-D1W1}{\cos\theta})})e^{(\frac{-D2W2}{\cos\theta})} +$$
$$G_\theta e^{mK} e^{(\frac{-D2W2+D1W1}{\cos\theta})}$$

(Eq. 9)

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 W1, W2 and m; model parameters (to be found by fitting the model to observations) are C1, $C2_q$, G_q, D1, D2 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-, 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, σ, and for the hemispherical reflectance of the bare soil, ρ. 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 2a.   Parameter values of the leaf scatter coefficient σ and of the soil hemispherical reflection coefficient ρ of the EXTRAD model.

Parameter	Units	Sugar beet	Potato	Wheat
σ green (548 nm)	-	0.294	0.331	0.341
σ red (650 nm)	-	0.079	0.120	0.123
σ infra-red (823 nm)	-	0.974	0.981	0.960
ρ green (548 nm)	-	0.146	0.143	0.134
ρ red (650 nm)	-	0.166	0.163	0.145
ρ infra-red (823 nm)	-	0.199	0.172	0.174

The leaf scatter coefficients σ of Table 2a are crop type specific, but derived from a data set that included various cultivars. Since values for σ 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.

	Uniform	Spherical	Erectophile	Planophile	Plagiophile	Extremophile
Distribution function	2π	$\sin\theta$	$\dfrac{2(1-\cos2\theta)}{\pi}$	$\dfrac{2(1+\cos2\theta)}{\pi}$	$\dfrac{2(1-\cos4\theta)}{\pi}$	$\dfrac{2(1+\cos4\theta)}{\pi}$
Classes:						
0.-10	0.111	0.015	0.002	0.220	0.009	0.213
10-20	0.111	0.045	0.023	0.207	0.057	0.166
20-30	0.111	0.074	0.033	0.182	0.130	0.092
30-40	0.111	0.100	0.073	0.149	0.195	0.028
40-50	0.111	0.123	0.111	0.111	0.220	0.022
50-60	0.111	0.143	0.149	0.073	0.195	0.028
60-70	0.111	0.158	0.182	0.033	0.130	0.092
70-80	0.111	0.168	0.207	0.023	0.057	0.166
80-90	0.111	0.174	0.220	0.002	0.009	0.213

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 WDVI 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).

Parameter	Units	Sugar beet	Potato	Wheat
b	$\%^{-1}$	0.02056	0.0194	0.02128
k	-	0.485	0.588	0.400

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 WDVI

Empirical relationships between WDVI 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 WDVI 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 WDVI and LAI was sufficiently accurately described by the CLAIR model. The empirical relationships for potato and wheat are based on WDVI 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 WDVI and LAI:
WDVI = b (LAI + a) % (Equation 7). Units of a: no units; units of b: %

Crop	LAI range	a (-)	b (%)
Potato	0 - 0.89	0	20.83
	> 0.89	0.87	10.99
Wheat	0 - 0.60	0	20.13
	0.60 - 4.06	1.00	7.54
	> 4.06	10.37	2.65

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/algorithm 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_θ and G_θ :m^2 m^{-2}; b: D: m^2 kg^{-1}; K: %$^{-1}$. (see Equations 8 and 9).

a

	10°	20°	30°	40°	50°	60°	70°	75°
Beet								
C_θ	1.060	1.190	1.200	1.150	1.170	1.150	0.980	0.930
G_θ	0.525	0.174	0.120	0.095	0.076	0.065	0.055	0.042
Potato								
C_θ	0.870	0.710	0.630	0.560	0.490	0.440	0.320	0.300
G_θ	0.214	0.195	0.170	0.151	0.135	0.117	0.093	0.071
Wheat								
$C2_\theta$	0.101	0.048	0.039	0.040	0.054	0.79	0.130	0.172
G_θ	0.344	0.326	0.088	0.057	0.019	0.010	0.012	0.009

b

	Beet	Potato	Wheat
D	0.46	1.02	-
$D1$	-	-	1.153
$D2$	-	-	2.057
$C1$	-	-	0.185
K	0.06	0.06	0.06

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).

Parameter	Units	Sugar beet	Potato	Wheat
C_θ	$m^2\ m^{-2}$	0.2717	0.3416	0.005
		(0.0365)	(0.0359)	(-)
D	$m^2\ kg^{-1}$	0.1678	0.398	0.200
		(0.0946)	(0.188)	(-)
G_θ	$m^2\ m^{-2}$	0.0122	0.0483	0.045
		(0.0152)	(0.0294)	(-)
K	$\%^{-1}$	0.1251	0.0834	0.078
		(0.0495)	(0.0308)	(-)

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.

Rijckenberg & van Leeuwen (1994) calculated Cloud parameters for sugar beet for the JERS configuration from airborne DUTSCAT data collected in the Agriscatt 1988 campaign, and from airborne NASA JPL SAR data collected in the MacEurope campaign 1991.

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).

Parameter	Units	Sugar beet	Potato	Wheat
C_θ	$m^2\,m^{-2}$	0.11424	0.1972	-
$C1$	$m^2\,m^{-2}$	--	-	0.0486
$C2_\theta$	$m^2\,m^{-2}$	-	-	0.0676
D	$m^2\,kg^{-1}$	1.1025	0.574	-
$D1$	$m^2\,kg^{-1}$	-	-	0.2678
$D2$	$m^2\,kg^{-1}$	-	-	2.0789
G_θ	$m^2\,m^{-2}$	0.00070	0.00185	0.0022
K	$\%^{-1}$	0.1	0.1	0.1

5   Model implementation

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

Table 8.   Name of scientific model, name in Fortran implementation and indication of subroutine or function.

Scientific model name	Fortran name	Subroutine or function
EXTRAD	EXTRAD	subroutine
CLAIR	CLAIR	function
Empirical WDVI relations	EMPWHE (wheat), EMPPOT (potato)	function
Cloud one-layer	CLOUD1	subroutine
Cloud two-layer	CLOUD2	subroutine

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 WDVI 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.

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

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.

Symbol	Model abbreviation	Explanation	Minimum	Maximum
L	LAI	Leaf Area Index	0	10
r	RHOS	hemispherical soil reflectance	0	1
s	SCAT	scatter coefficient leaf	0	1
b	BETA	solar height	0	90
f	FRDIF_T	instantaneous fraction diffuse radiation	0	1

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.)  CALL ERROR ('EXTRAD', 'BETA greater than 89')
        IF (FRDIF_T.LT.0.)  CALL ERROR ('EXTRAD','FRDIF_T less than 0')
        IF (FRDIF_T.GT.1.)  CALL ERROR ('EXTRAD','FRDIF_T greater than 1')

*       Special check on maximum LAI i.r.t. declared array lenghts:
        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 wavelenghts at LAI values below 5, and at visible wavelenghts 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.
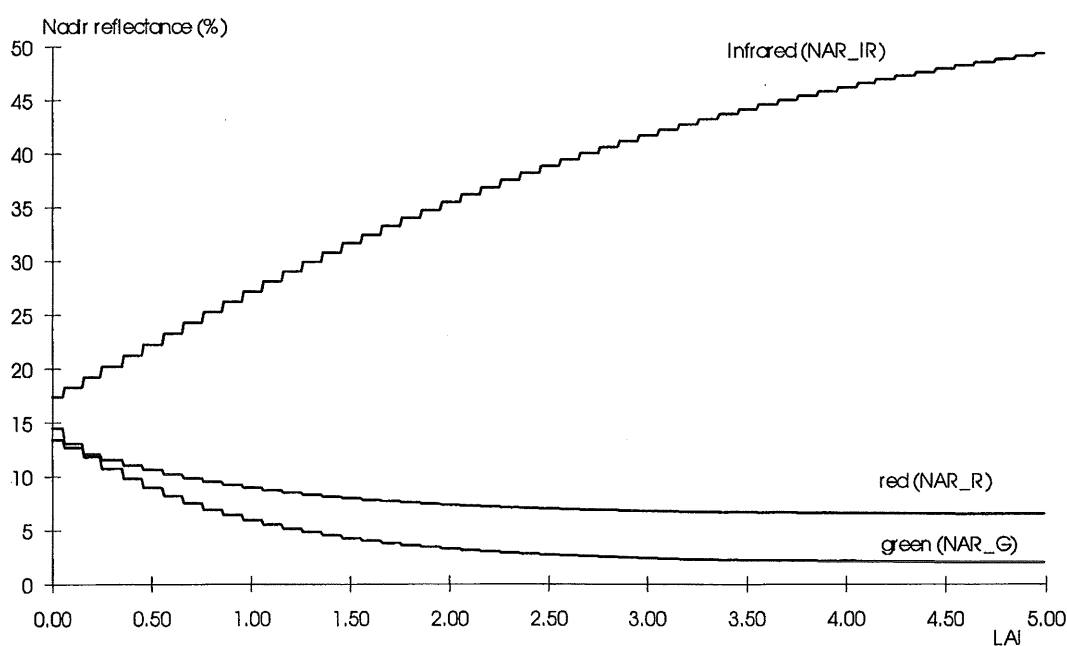
Figure 1.   Nadir reflectance (green, red and infrared) as function of Leaf Area Index, calculated with the Subroutine EXTRAD.

20
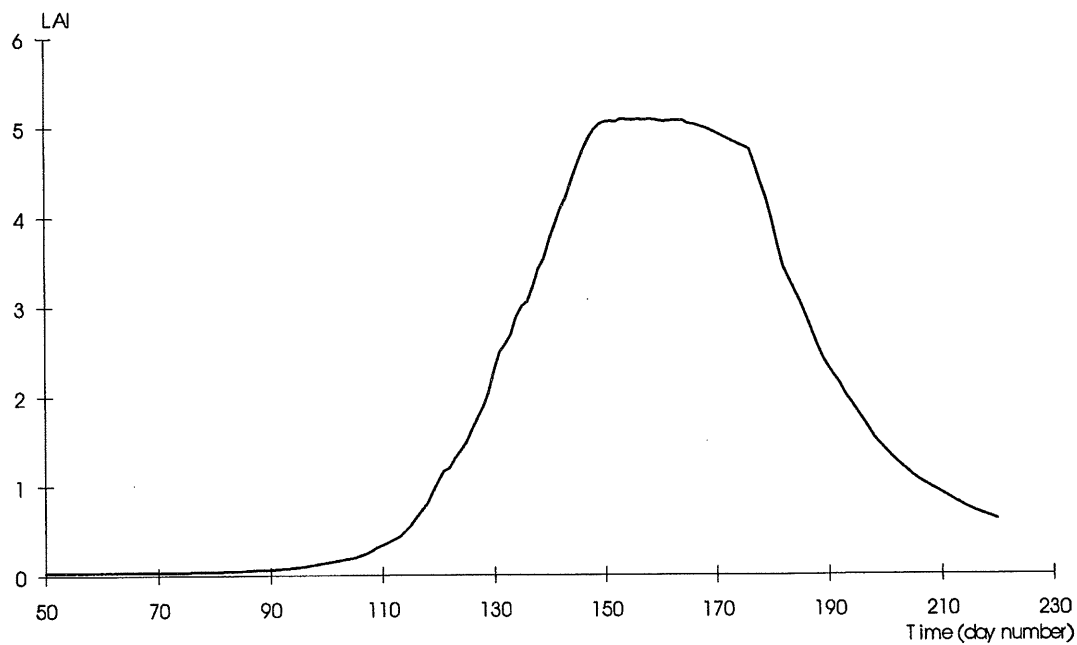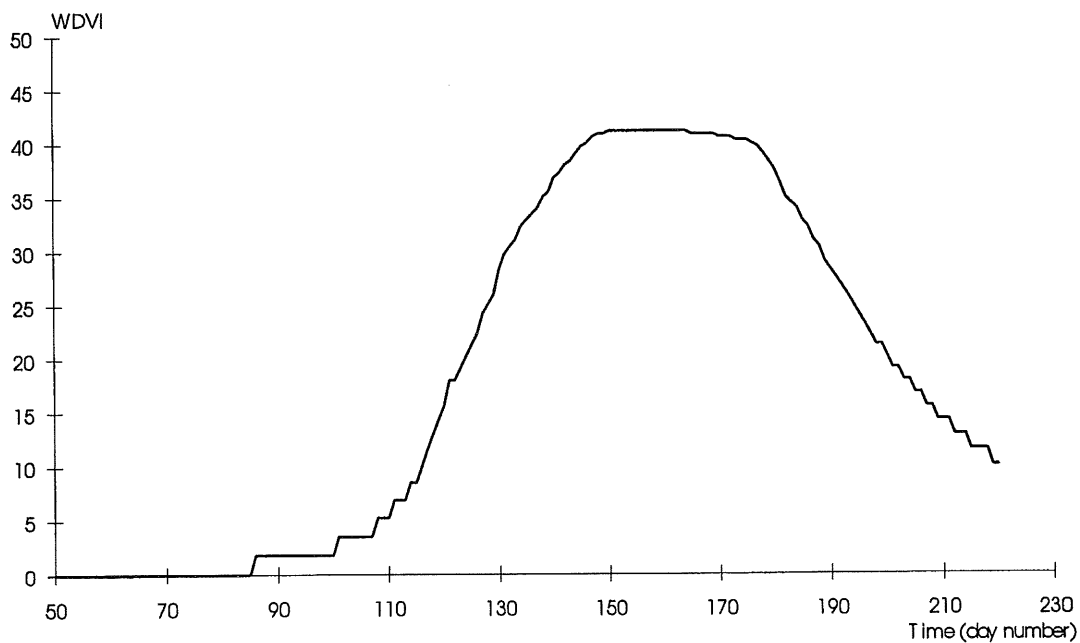
Figure 2. Simulated time curve of Leaf Area Index (2a) and Weighted Difference Vegetation Index (2b), using the EXTRAD subroutine in the SUCROS-Wheat crop growth simulation model.

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.

Symbol	Model abbreviation	Explanation	Units	Type
k	KCLAIR	extinction coefficient	-	IP
b	BCLAIR	inverse of asymptotic value WDVI at infinite L	$\%^{-1}$	IP
L	LAI	Leaf Area Index	-	IV
WDVI	CLAIR*	WDVI	%	OV*

*: 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.-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 WDVI: EMPWHE and EMPPOT

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

The empirical relations (Eq. 7) that relate WDVI to LAI are implemented in two crop-type specific functions: EMPWHE for wheat and EMPPOT for potato. The coefficients of the linear relations between WDVI 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 WDVI and LAI, and therefore there is no function of this type for sugar beet.

Table 12. Explanation of the argument list of EMPWHE and EMPPOT: main variable and parameter names, the corresponding symbols used in the regression equation, units, and indications of the data type: IV = Input variable (driving variable), OV = Output Variable.

Symbol	Model abbreviation	Explanation	Units	Type
L	LAI	Leaf Area Index	-	IV
WDVI	EMPWHE* EMPPOT*	WDVI	%	OV*

*: 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):

```
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):

```
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

```
SUBROUTINE CLOUD1(PLWCRO,MCSOIL,NOINCA,ANGLE,GS,KS,
$    DCROP, CCROP, 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.

Symbol	Model abbreviation	Explanation	Units	Type
W	PLWCRO	plant water amount in canopy	$kg\ m^{-2}$	IV
m	MCSOIL	volumetric moisture content top soil	%	IV
-	NOINCA	number of incidence angles (array)	-	IP
θ	ANGLE	incidence angle (array)	degree	IP
G_θ	GS	backscattering of dry soil (array)	$m^2\ m^{-2}$	IP
k	KS	moisture coefficient of top soil	$\%^{-1}$	IP
D	DCROP	coefficient of attenuation of canopy	$m^2\ kg^{-1}$	IP
C_θ	CCROP	backscattering coefficient of canopy (array)	$m^2\ m^{-2}$	IP
g_θ	RBGAM	radar backscatter (gamma), (array)	dB	OV
-	RBSOIL	radar backscatter contribution soil, (array)	dB	OV

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:

```
DO I=1,NOINCA
    ACROP(I)   = DCROP*PLWCRO/COS(DEGTRAD*ANGLE(I))
    RSOIL(I)   = GS(I)*EXP(KS*MCSOIL-ACROP(I))
    RCROP(I)   = CCROP(I)*(1.-EXP(-ACROP(I)))
    RBGAM(I)   = 10.*ALOG10(RSOIL(I)+RCROP(I))
    RBSOIL(I)  = 10.*ALOG10(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 RCROP 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.

Symbol	Model abbreviation	Explanation	Minimum	Maximum
W	PLWCRO	water in canopy per unit soil surface	0	-
m	MCSOIL	volumetric moisture content top soil	0	100
θ	ANGLE	incidence angle	0	90

In Fortran code:

```
IF (MCSOIL.LT.0. .OR. MCSOIL.GE.100.) THEN
    CALL ERROR ('CLOUD1', 'Soil moisture MCSOIL out of bounds')
END IF

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

DO I=1,NOINCA
    IF (ANGLE(I).LE.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, MCSOIL, NOINCA, ANGLE,
&                  GS, CEAR, KS, DVEG, DEAR, CVEG, RBGAM, 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.

Symbol	Model abbreviation	Explanation	Units	Type
$W1$	PLWVEG	plant water amount in vegetative layer	kg m^{-2}	IV
$W2$	PLWEAR	plant water amount in ear layer	kg m^{-2}	IV
m	MCSOIL	volumetric moisture content top soil	%	IV
-	NOINCA	number of incidence angles	-	IP
θ	ANGLE	incidence angle (array)	degree	IP
G_θ	GS	backscattering of dry soil (array)	m^2 m^{-2}	IP
$C2_\theta$	CEAR	backscattering coefficient of ear layer (array)	m^2 m^{-2}	IP
k	KS	moisture coefficient of top soil	%$^{-1}$	IP
$D1$	DVEG	coefficient of attenuation of vegetative layer	m^2 kg^{-1}	IP
$D2$	DEAR	coefficient of attenuation of ear layer	m^2 kg^{-1}	IP
$C1$	CVEG	backscattering coefficient of vegetative layer	m^2 m^{-2}	IP
g_θ	RBGAM	radar backscatter (gamma) (array)	dB	OV
-	RBSOIL	radar backscatter contribution soil, (array)	dB	OV

CLOUD2 is used in the same way as CLOUD1 (see above). The Fortran implementation of the model equation (9) is:

```
DO I=1,NOINCA
    AVEG(I)    = DVEG*PLWVEG/COS (DEGTRAD*ANGLE(I))
    AEAR(I)    = DEAR*PLWEAR/COS (DEGTRAD*ANGLE(I))
    ASOIL(I)   = (DEAR*PLWEAR+DVEG*PLWVEG)/COS (DEGTRAD*ANGLE(I))
    RSOIL(I)   = GS(I)*EXP (KS*MCSOIL)*EXP (-ASOIL(I))
    RVEG(I)    = CVEG*(1.-EXP (-AVEG(I)))*EXP (-AEAR(I))
    REARS(I)   = CEAR(I)*(1.-EXP (-AEAR(I)))
    RBGAM(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), AEAR 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 16.   Boundary conditions of input parameter and variable values tested in the CLOUD2 subroutine.

Symbol	Model abbreviation	Explanation	Minimum	Maximum
$W1$	PLWVEG	water in vegetative layer per unit soil surface	0	-
$W2$	PLWEAR	water in ear layer per unit soil surface	0	-
m	MCSOIL	volumetric moisture content top soil	0	100
θ	ANGLE	incidence angle	0	90

In Fortran code:

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

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

```
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:

```
PLWCRO = 0.0001*TADRW*MCCROP/(100.-MCCROP)
```

where PLWCRO 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 MCCROP is moisture content of the crop (%). The moisture content of the crop is defined as

$$\frac{(fresh.weight.crop - dry.weight.crop)}{fresh.weight.crop} * 100\%$$
(Eq. 10)

The value of MCCROP is read from the remote sensing input file. For sugar beet, MCCROP 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:

```
PLWVEG = 0.0001*(WLV+WST)*MCVEG/(100.-MCVEG)
PLWEAR = 0.0001*WSO*MCEAR/(100.-MCEAR)
```

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  =  LINT(MCVEGT,IMCVN,DVS)
MCEAR  =  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  =  OBSTRG(100.*WCLQT(1),  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:

```
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.

7 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.
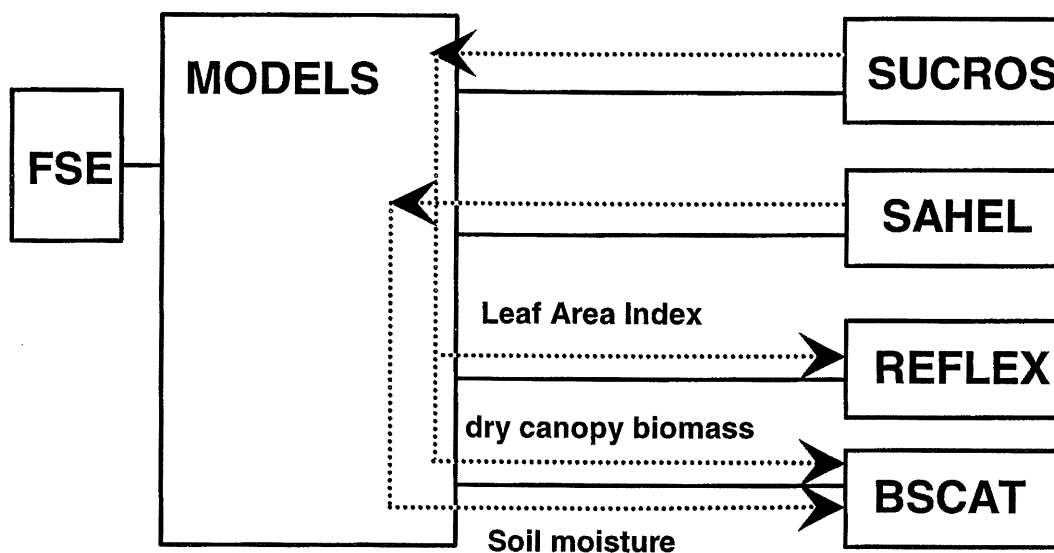
Figure 3.   Schematic illustration of the use of the REFLEX and BSCAT remote sensing interfaces in FSE crop growth simulation models. FSE is the main program; MODELS is a general interface; SUCROS simulates above-ground crop growth; SAHEL simulates the water balance of the soil; REFLEX simulates optical reflectance and WDVI; 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 a this common output file.

All parameter and variable values supplied in the remote sensing input data file can be over-written 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 skye 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 over-passes.

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)


INUM_X   ANGLE_X  GS_X    CCROP_X
1        10.      0.525   1.060
2        20.      0.174   1.190
3        30.      0.120   1.200
5        40.      0.095   1.150
6        50.      0.076   1.170
7        60.      0.065   1.150
8        70.      0.055   0.980
9        75.      0.042   0.930


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:

```
INUM_C   ANGLE_C  GS_C     CCROP_C
1        20.      0.01964  0.58845


KS_C     = 0.0580  ! Cloud K parameter for the soil (-)
DCROP_C  = 0.1009  ! Cloud D parameter for the crop (m-2 kg)
```

Example of L-band data:

```
INUM_L    ANGLE_L   GS_L      CCROP_L
1         40.       0.00070   0.11424


KS_L    = 0.1000   ! Cloud K parameter for the soil (-)
DCROP_L = 1.1025   ! Cloud D parameter for the crop (m-2 kg)
```

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:

```
MCSOIL_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
```

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 MSOIL_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_TRC =
1989.,  112.,  0.,
1989.,  122.,  0.,
1989.,  165.,  1.,
1989.,  186.,  1.,
1989.,  195.,  2.,
1989.,  207.,  2.,
1989.,  228.,  0.
```

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 =
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
```

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.

Variable	Explanation	Units
Optical:		
IROG**	Infra-red/green reflectance ratio	-
NAR_G**	Nadir crop reflectance green	%
NAR_R**	Nadir crop reflectance red	%
NAR_IR**	Nadir crop reflectance infra-red	%
NDVI**	Normalized Difference Vegetation Index	-
WDVI_CLA	Weighted Difference Vegetation Index, calculated using CLAIR model	%
WDVI_EMP***	Weighted Difference Vegetation Index, calculated using empirical relationships	%
WDVI_EXT**	Weighted Difference Vegetation Index, calculated sing EXTRAD model	%
WDVI_OBS *	Observed Weighted Difference Vegetation Index	%
Radar:		
ERS_OBS *	Observed radar backscatter ERS (gamma)	dB
RBGAM_X	Array with X-band radar backscatter (gamma), at various incidence angles	dB
RBGAM_C	Array with C-band radar backscatter (gamma), at various incidence angles (ERS)	dB
RBGAM_L	Array with L-band radar backscatter (gamma), at various incidence angles (JERS)	dB
RBSOIL_C	Array with C-band radar backscatter cantribtion from the soil, at various incidence angles	dB
RBSOIL_L	Array with L-band radar backscatter cantribtion from the soil, at various incidence angles	dB
RBSOIL_X	Array with X-band radar backscatter cantribtion from the soil, at various incidence angles	dB
JERS_OBS *	Observed radar backscatter JERS (gamma)	dB
MCSOIL	Volumetric moisture content top soil	%
MCSOIL_SIM	Simulated volumetric soil moisture content top soil (by SAHEL)	%
MCSOIL_OBS *	Observed volumetric soil moisture content top soil	%
PLWCROP	Plant water amount in canopy	kg m^{-2}
PLWVEG	Plant water amount in vegetative layer	kg m^{-2}
PLWEAR	Plant water amount in ear layer	kg m^{-2}

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

Attema, E.P.W. & F.T. Ulaby, 1978.
Vegetation modelled as a water cloud, Radio Science 13(2): 357-364

Bouman, B.A.M., 1987.
Radar backscattering from three agricultural crops: beet, potatoes and peas, CABO report 71, Wageningen, The Netherlands. 39 pp.

Bouman, B.A.M., 1992a.
Accuracy of estimating the leaf area index from vegetation indices derived from crop reflectance characteristics, a simulation study. International Journal of Remote Sensing 13: 3069-3084.

Bouman, 1992b.
SBFLEVO and WWFLEVO, Growth models to simulate crop growth, optical reflectance and radar backscatter of sugar beet and winter wheat, calibrated for Flevoland. CABO-DLO report 163, CABO-DLO Wageningen, The Netherlands. 116 pp.

Bouman, B.A.M. 1992c.
Linking physical remote sensing models with crop growth simulation models, applied for sugar beet, 1992. International Journal of Remote Sensing vol 13, no 14: 2565-2581.

Bouman, B.A.M. & D.H. Hoekman, 1993.
Multi-temporal, multi-frequency radar measurements of agricultural crops during the Agriscatt-88 campaign in The Netherlands. International Journal of Remote Sensing, vol. 14, no 8, 1595-1614.

Bouman, B.A.M., H.W.J. van Kasteren & D. Uenk, 1992.
Standard relations to estimate ground cover and LAI of agricultural crops from reflectance measurements. European Journal of Agronomy 1: 249-262.

Bouman, B.A.M., H. van Keulen, H.H. van Laar & R. Rabbinge, 1996. The 'School of de Wit' crop growth simulation models: pedigree and historical overview. Agricultural Systems, In press.

Bouman, B.A.M., D.W.G. van Kraalingen & W. Stol., In prep.
User manuals SUCROS-Wheat, SUCROS-Beet and SUCROS-Potato.

Bunnik, N.J.J., 1978.
The multispectral reflectance of shortwave radiation by agricultural crops in relation with their morphological and optical properties, Thesis, Agricultural University Wageningen, 78-1, The Netherlands. 176 pp.

Clevers, J.G.P.W., 1988.
The derivation of a simplified reflectance model for the estimation of leaf area index, Remote Sensing of Environment, 25:53-69.

Clevers, J.G.P.W., 1989.
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

Clevers, J.G.P.W., C. Büker, H.J.C. van Leeuwen & B.A.M. Bouman, 1994.
A framework for monitoring crop growth by combining directional and spectral remote sensing information. Remote Sensing of Environment, 50, 161-170.

Dulk, J.A. den, 1989.
    The interpretation of remote sensing, a feasibility study, Thesis, Agricultural University
    Wageningen, The Netherlands. 173 pp.

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

Goodman, J.M., 1980.
    Environmental constraints in earth-space propagations, in Agard Conference Proceedings,
    CP-284: 35.1-35.27

Goudriaan, J., 1977.
    Crop micrometeorology: a simulation study. Pudoc, Wageningen, The Netherlands. 249 pp.

Hoekman, D.H., 1981.
    Modelvorming radar backscatter voor gewassen, Delft University of Technology,
    Department of Electrical Engineering, The Netherlands, Master's Thesis,
    Report 05-1-533-AV-90'81 (in Dutch). 110 pp.

Hoekman, D.H., L. Krul & E.P.W. Attema, 1982.
    A multilayer model for radar backscattering from vegetation canopies, Digest of the 2nd
    IEEE International Geoscience and Remote Sensing Symposium, Münich, West Germany,
    1-4 June, pp. 4.1-4.7

Jordan, C.F., 1969.
    Derivation of leaf area index from quality of light on the forest floor, Ecology, 50: 663-666.

Karam, M.A. & A.K. Fung, 1988.
    Electromagnetic scattering from a layer of finite length, randomly oriented, dielectric,
    circular cylinders over a rough surface with application to vegetation, International Journal
    of Remote Sensing, 9(6): 1109-1134.

Keulen, H. van & J. Wolf (Eds.), 1986.
    Modelling of agricultural production: weather, soils and crops. Simulation monographs,
    PUDOC, Wageningen. 479 pp.

Kraalingen, D.W.G. van, 1995.
    The FSE system for crop simulation, version 2.1. Quantitative Approaches in Systems
    Analysis, 1. AB-DLO, Wageningen, The Netherlands. 58 pp.

Kuusk, A. and T. Nilson, 1989.
    The reflectance of shortwave radiation from multilayer plant canopies, Academy of sciences
    of the Estonian SSR section of physics and astronomy, Tallinn, Estonia, USSR.

Penning de Vries, F.W.T., D.M. Jansen, H.F.M. ten Berge & A. Bakema, 1989.
    Simulation of ecophysiological processes of growth in several annual crops. Simulation
    monographs, PUDOC, Wageningen, 271 pp.

Rijckenberg, G.J., 1994.
    Physical modelling in relation to the application of ERS-1 to agricultural studies. In:
    Nieuwenhuis, G.J.A. & W.W.L. van Rooij (Eds.), 1994. Application of ERS-1 SAR data in
    agriculture and forestry. SC-DLO report 101. SC-DLO, Wageningen, The Netherlands.
    pp 21-52.

Rijckenberg, G.J. & H.J.C. van Leeuwen, 1994.
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.

Rouse, J.W., R.H. Haas, J.A. Schell & D.W. Deering, 1973.
Monitoring vegetation systems in the great plains with ERTS. Third ERTS Symposium, NASA SP-351: 309-317.

Schanda, E., 1986.
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.

Ulaby, F.T, and R.P. Jedlicka, (1984).
Microwave dielectric properties of plant materials, IEEE Transactions on Geoscience and Remote Sensing, GE-22(4): 406-415.

Ulaby, F.T., R.K. Moore & A.K. Fung, 1981.
Microwave remote sensing, Vol. I, Addison-Wesley, Reading Massachusettes, USA. 456 pp.

Ulaby, F.T., R.K. Moore & A.K. Fung, 1982.
Microwave remote sensing, Vol. II, Addison-Wesley, Reading Massachusettes, USA. pp 457-1064.

Ulaby, F.T., R.K. Moore & A.K. Fung, 1986.
Microwave remote sensing, Vol. III, Artech House, Washington, USA. pp 1065-.

Ulaby, F.T.W., K. Sarabandi, K. McDonald, M.Whitt & M.C. Dobson, 1990.
'Michican Microave 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 model, Remote Sensing of Environment, 16:125-141.

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)

Name	Explanation	Units
ACROP	Attenuation of microwaves by the canopy	-
AEAR	Attenuation of microwaves by the ear layer	-
ANGLE	Incidence angle	degrees
ANGLE_C	Incidence angle (for C-band data)	degrees
ANGLE_L	Incidence angle (for L-band data)	degrees
ANGLE_X	Incidence angle (for X-band data)	degrees
ASOIL	Intermediate variable in Cloud model	-
AVEG	Attenuation of microwaves by the vegetative layer	-
BCLAIR	Inverse of asymptotic value of WDVI at infinite LAI	$\%^{-1}$
BETA	Solar height	degrees
CCROP	Radar backscatterring coefficient canopy (gamma)	$m^2.m^{-2}$
CCROP_C	Radar backscatterring coefficient canopy (gamma); C-band	$m^2.m^{-2}$
CCROP_L	Radar backscatterring coefficient canopy (gamma); L-band	$m^2.m^{-2}$
CCROP_X	Radar backscatterring coefficient canopy (gamma); X-band	$m^2.m^{-2}$
CEAR	Radar backscatterring coefficient ear layer (gamma)	$m^2.m^{-2}$
CEAR_C	Radar backscatterring coefficient ear layer; C-band (gamma)	$m^2.m^{-2}$
CEAR_L	Radar backscatterring coefficient ear layer; L-band (gamma)	$m^2.m^{-2}$
CEAR_X	Radar backscatterring coefficient ear layer; X-band (gamma)	$m^2.m^{-2}$
CLAIR	Weighted Difference Vegetation Index (calculated using CLAIR model)	-
CVEG	Radar backscatterring coefficient vegetative layer (gamma)	$m^2.m^{-2}$
CVEG_C	Radar backscatterring coefficient vegetative layer; C-band (gamma)	$m^2.m^{-2}$
CVEG_L	Radar backscatterring coefficient vegetative layer; L-band (gamma)	$m^2.m^{-2}$
CVEG_X	Radar backscatterring coefficient vegetative layer; X-band (gamma)	$m^2.m^{-2}$
DCROP	Coefficient of microwave attenuation canopy	$m^2.kg^{-1}$
DCROP_C	Coefficient of microwave attenuation canopy; C-band	$m^2.kg^{-1}$
DCROP_L	Coefficient of microwave attenuation canopy; L-band	$m^2.kg^{-1}$
DCROP_X	Coefficient of microwave attenuation canopy; X-band	$m^2.kg^{-1}$

Name	Explanation	Units
DEAR	Coefficient of microwave attenuation ear layer	$m^2.kg^{-1}$
DEAR_C	Coefficient of microwave attenuation ear layer; C-band	$m^2.kg^{-1}$
DEAR_L	Coefficient of microwave attenuation ear layer; L-band	$m^2.kg^{-1}$
DEAR_X	Coefficient of microwave attenuation ear layer; X-band	$m^2.kg^{-1}$
DEGTRAD	Conversion coefficient from degrees to radians	$radians.degrees^{-1}$
DOY	Day number since 1 January (day of year)	d
DVEG	Coefficient of microwave attenuation vegetative layer	$m^2.kg^{-1}$
DVEG_C	Coefficient of microwave attenuation vegetative layer; C-band	$m^2.kg^{-1}$
DVEG_L	Coefficient of microwave attenuation vegetative layer; L-band	$m^2.kg^{-1}$
DVEG_X	Coefficient of microwave attenuation vegetative layer; X-band	$m^2.kg^{-1}$
DVS	Development stage of the crop	-
EMPPOT	Function that calculates WDVI of potato using empirical (linear) relationships	WDVI; %
EMPWHE	Function that calculates WDVI of wheat using empirical (linear) relationships	WDVI; %
F	Leaf angle distribution factor	-
FILERS	Input file with remote sensing data	-
FRDIF_T	Instantaneous fraction diffuse radiation	-
FRDIR	Instantaneous fraction direct radiation	-
GS	Radar backscatterring dry soil (gamma)	$m^2.m^{-2}$
GS_C	Radar backscatterring dry soil (gamma) ; C-band	$m^2.m^{-2}$
GS_L	Radar backscatterring dry soil (gamma); L-band	$m^2.m^{-2}$
GS_X	Radar backscatterring dry soil (gamma); X-band	$m^2.m^{-2}$
I	DO-loop counter	
ICLOUD	Length of array Cloud model variables	-
IMCEN	Length of array MCVEART	-
IMCVEG	Length of array MCVEG	-
IMCVN	Number of elements in MCVEGT	-
IMMCEA	Number of elements in MCEART	-
IN1	Length of arrays in EXTRAD variables	-
IN2	Length of arrays in EXTRAD variables	-
INC_C	Length of input array Cloud parameters; C-band	-
INC_L	Length of input array Cloud parameters; C-band	-
INC_X	Length of input array Cloud parameters; C-band	-

Name	Explanation	Units
INF	Lenght of array F	-
INUM_C	Sequence number of input array Cloud parameters; C-band	-
INUM_L	Sequence number of input array Cloud parameters; L-band	-
INUM_X	Sequence number of input array Cloud parameters; X-band	-
IROG	Infrared/green reflectance ratio	-
ITASK	Task that subroutine should perform	-
IUNITD	Unit number that is used for input files	-
IUNITL	Unit number that is used for log file	-
IUNITO	Unit number that is used for output file	-
J	DO-loop counter	-
JCLOUD	Length of array Cloud model variables	-
K	DO-loop counter	-
KCLAIR	Extinction coefficient the CLAIR model	-
KS	Moisture coefficient of the top soil	$\%^{-1}$
KS_C	Moisture coefficient of the top soil; C-band	$\%^{-1}$
KS_L	Moisture coefficient of the top soil; L-band	$\%^{-1}$
KS_X	Moisture coefficient of the top soil; X-band	$\%^{-1}$
LAI	Green leaf area index	m^2 leaf.m^{-2} ground
LAIEXT	Green leaf area index	m^2 leaf.m^{-2} ground
LAIMAX	Maximum value of LAI during growing season	m^2 leaf.m^{-2} ground
MCCROP	Moisture content canopy	$100*g.g^{-1}$ (%)
MCEAR	Moisture content ear layer	$100*g.g^{-1}$ (%)
MCEART	Table of moisture content ear layer as function of DVS	$100*g.g^{-1}$ (%)
MCSOIL	Volumetric moisture content top soil	$100*cm^3.cm^{-3}$ (%)
MCSOIL_SIM	Volumetric moisture content top soil, simulated value	$100*cm^3.cm^{-3}$ (%)
MCVEG	Moisture content vegetative layer	$100*g.g^{-1}$ (%)
MCVEGT	Table of moisture content vegetative layer as function of DVS	$100*g.g^{-1}$ (%)
NAR	Nadir crop reflectance	%
NAR_G	Nadir crop reflectance green	%
NAR_IR	Nadir crop reflectance infrared	%
NAR_R	Nadir crop reflectance red	%

Name	Explanation	Units
NDVI	Normalized Difference Vegetation Index	-
NOINCA	Number of incidence angles	-
OUTPUT	Flag to indicate if output should be done	-
PI	Ratio of circumference to diameter	-
PLWEAR	Plant water amount in ear layer	kg H_2O / m^2
PLWCRO	Plant water amount in canopy	kg H_2O / m^2
PLWVEG	Plant water amount in vegetative layer	kg H_2O / m^2
RBGAM	Array with radar backscatter (gamma) at various incidence angles	dB
RBGAM_C	Array with C-band radar backscatter (gamma) at various incidence angles (ERS)	dB
RBGAM_L	Array with L-band radar backscatter (gamma) at various incidence angles (JERS)	dB
RBGAM_X	Array with X-band radar backscatter (gamma) at various incidence angles	dB
RBSOIL	Array with radar backscatter contribution of the soil at various incidence angles	dB
RBSOIL_C	Array with C-band radar backscatter contribution of the soil at various incidence angles	dB
RBSOIL_L	Array with L-band radar backscatter contribution of the soil at various incidence angles	dB
RBSOIL_X	Array with X-band radar backscatter contribution of the soil at various incidence angles	dB
RCROP	Radar backscatter contribution canopy, intermediate value	$m^2.m^{-2}$
REARS	Radar backscatter contribution ear layer, intermediate value	$m^2.m^{-2}$
RHOM	Nadir soil reflectance	%
RHOMG	Nadir soil reflectance green	%
RHOMIR	Nadir soil reflectance infra-red	%
RHOMR	Nadir soil reflectance red	%
RHOS	Hemispherical soil reflectance	-
RHOSG	Hemispherical soil reflectance green	-
RHOSIR	Hemispherical soil reflectance infra-red	-
RHOSR	Hemispherical soil reflectance red	-
RSOIL	Radar backscatter contribution soil, intermediate value	$m^2.m^{-2}$
RVEG	Radar backscatter contribution vegetative layer, intermediate value	$m^2.m^{-2}$

Name	Explanation	Units
SCAT	Scatter coefficient leaf	-
SCATG	Scatter coefficient leaf green	-
SCATIR	Scatter coefficient leaf infra-red	-
SCATR	Scatter coefficient leaf red	-
SINB	Sine of solar height	-
SWIREF	Switch to indicate the use of EXTRAD model	-
TADRW	Total above-ground dry weight	kg.ha^{-1}
TERMNL	Flag to indicate if simulation is to stop	-
WCLQT	Volumetric water content in soil compartments	cm^3 H$_2$O.cm^{-3} soil
WDVI	Weighted Difference Vegetation Index	-
WDVIC	Weighted Difference Vegetation Index (calculated using CLAIR model)	-
WDVIE	Weighted Difference Vegetation Index (calculated using empirical relation)	-
WDVI_CLA	Weighted Difference Vegetation Index (calculated using CLAIR model)	-
WDVI_EMP	Weighted Difference Vegetation Index (calculated using empirical relation)	-
WDVI_EXT	Weighted Difference Vegetation Index (calculated using EXTRAD model)	-
WDVIMAX	Maximum value of WDVI during growing season	%
WLV	Dry weight of the leaves (green + dead)	kg.ha^{-1}
WLVG	Dry weight of the green leaves	kg.ha^{-1}
WSO	Dry weight of storage organs	kg.ha^{-1}
WST	Dry weight of the stems	kg.ha^{-1}

Appendix II:

Optical reflectance routines

```
*-----------------------------------------------------------------*
* SUBROUTINE REFLEX                                               *
*                                                                 *
* Author(s): B.A.M. Bouman                                        *
* Date    : 24-Aug-199, Version: 1.0                              *
*          :(this version for wheat)                              *
* Purpose : Interface with SUCROS model to calculate optical      *
*           reflectance and some Vegetation Indices: WDVI, NDVI,   *
*           IR/GR ratio.                                           *
*                                                                 *
* Reference: see the various sub-routine headers                  *
*            For comparison of Vegetation Indices, e.g.: Bouman, B.A.M.*
*            1992. Accuracy of estimating the leaf area index from *
*            vegetation indices derived from reflectance           *
*            characteristics, a simulation study. International Journ. *
*            of Remote Sensing, 13:3069-3084.                      *
*                                                                 *
* FORMAL PARAMETERS:  (I=input,O=output,C=control,IN=init,T=time) *
* name   type meaning (unit)                          class *
* ----   ---- ---------------                         ----- *
* ITASK   I4  Task that subroutine should perform (-)      I *
* IUNITD  I4  Unit number that is used for input files (-) I *
* IUNITL  I4  Unit number that is used for log file (-)    I *
* FILERS  C*  Input file with remote sensing data (-)      I *
* OUTPUT  L4  Flag to indicate if output should be done (-) I *
* TERMNL  L4  Flag to indicate if simulation is to stop (-) I/O *
* LAI     R4  Green leaf area index (m2 leaf.m-2 ground)   I *
*-----------------------------------------------------------------*

      SUBROUTINE REFLEX (ITASK , IUNITD, IUNITL, FILERS,
     &                   OUTPUT, TERMNL, LAI)

      IMPLICIT NONE

*     Formal parameters
      INTEGER ITASK, IUNITD, IUNITL
      REAL LAI
      LOGICAL OUTPUT, TERMNL
      CHARACTER FILERS*(*)

*     Local variables
      REAL KCLAIR, BCLAIR, RHOSG, RHOSR, RHOSIR
      REAL SCATG, SCATR, SCATIR, BETA, FRDIF_T
      REAL NAR, RHOM, RHOMG, RHOMR, RHOMIR, LAIEXT
      REAL NAR_G, NAR_R, NAR_IR, NDVI, WDVI, IROG, WDVIE, WDVIC

      INTEGER INF
      PARAMETER (INF=9)
      REAL F(INF)

      REAL WDVIMAX,LAIMAX
      INTEGER SWIREF

*     Functions
      REAL GETOBS, CLAIR, EMPWHE
      LOGICAL INQOBS

      SAVE

      IF (ITASK.EQ.1) THEN

*        Initialization section
*        ----------------------

*        Read input data from the remote sensing data file
         CALL RDINIT (IUNITD, IUNITL, FILERS)

         CALL RDSREA ('KCLAIR', KCLAIR)
         CALL RDSREA ('BCLAIR', BCLAIR)
         CALL RDSINT ('SWIREF', SWIREF)

      IF (SWIREF.EQ.0) THEN
*        EXTRAD subroutine should not be run
         CONTINUE
      ELSE IF (SWIREF.EQ.1) THEN
*        EXTRAD subroutine should be run, read input
         CALL RDSREA ('RHOSG' , RHOSG)
         CALL RDSREA ('RHOSR' , RHOSR)
         CALL RDSREA ('RHOSIR', RHOSIR)
         CALL RDSREA ('SCATG' , SCATG)
         CALL RDSREA ('SCATR' , SCATR)
         CALL RDSREA ('SCATIR', SCATIR)
         CALL RDSREA ('BETA'  , BETA)
         CALL RDSREA ('FRDIF_T' , FRDIF_T)
         CALL RDFREA ('F', F,   INF, INF)
      ELSE
         CALL ERROR ('REFLEX','Incorrect value of SWIREF')
      END IF

      CLOSE (IUNITD)

      WDVIMAX = 0.
      LAIMAX  = 0.

      ELSE IF (ITASK.EQ.2) THEN

*        Rate calculation section
*        ------------------------

*        Optical reflectance calculations
         IF (SWIREF.EQ.0) THEN
            NDVI = -99.
            IROG = -99.
            WDVI = -99.

         ELSE IF (SWIREF.EQ.1) THEN

*           LAI can at the most be 10.0 in EXTRAD: to avoid stopping the
*           simulation runs, the LAI value passed-on to EXTRAD (LAIEXT)
*           is kept at a maximum of 10.
            IF (LAI.GT.10.) THEN
               LAIEXT = 10.
               CALL OUTCOM ('Warning: LAI > 10 => LAIEXT set to 10.')
            ELSE
               LAIEXT = LAI
            END IF

            CALL EXTRAD (RHOSG,SCATG,BETA,F,INF,LAIEXT,FRDIF_T,
     &                   NAR,RHOM)
            NAR_G = NAR
            RHOMG = RHOM

            CALL EXTRAD (RHOSR,SCATR,BETA,F,INF,LAIEXT,FRDIF_T,
     &                   NAR,RHOM)
            NAR_R = NAR
            RHOMR = RHOM

            CALL EXTRAD (RHOSIR,SCATIR,BETA,F,INF,LAIEXT,FRDIF_T,
     &                   NAR,RHOM)
            NAR_IR = NAR
            RHOMIR = RHOM

            NDVI = (NAR_IR-NAR_G)/(NAR_IR+NAR_G)
            IROG = NAR_IR/NAR_G
            WDVI = NAR_IR-(RHOSIR/RHOSG)*NAR_G

         END IF

*        Calculation of WDVI via CLAIR model
         WDVIC = CLAIR (KCLAIR,BCLAIR,LAI)
*        Calculation of WDVI via empirical relations
         WDVIE = EMPWHE(LAI)
```

```
*         Print data
          IF (OUTPUT) THEN
              IF (INQOBS (FILERS,'WDVI')) CALL OUTDAT
     &           (2,0,'WDVI_OBS ', GETOBS (FILERS, 'WDVI'))
              CALL OUTDAT (2, 0, 'WDVI_CLA', WDVIC)
              CALL OUTDAT (2, 0, 'WDVI_EMP', WDVIE)

              IF (SWIREF.EQ.1) THEN
                  CALL OUTDAT (2, 0, 'WDVI_EXT', WDVI)
                  CALL OUTDAT (2, 0, 'NDVI', NDVI)
                  CALL OUTDAT (2, 0, 'IROG', IROG)
                  CALL OUTDAT (2, 0, 'NAR_G', NAR_G)
                  CALL OUTDAT (2, 0, 'NAR_R', NAR_R)
                  CALL OUTDAT (2, 0, 'NAR_IR', NAR_IR)
              END IF
          END IF

      ELSE IF (ITASK.EQ.3) THEN

*         State calculation section
*         ------------------------

*         Maximum WDVI from the empirical equations
          WDVIMAX = MAX (WDVIMAX,WDVIE)

          LAIMAX  = MAX (LAIMAX, LAI)

      ELSE IF (ITASK.EQ.4) THEN

*         Terminal section
*         ----------------

C         CALL OPSTOR ('LAIMAX' , LAIMAX )
C         CALL OPSTOR ('WDVIMAX', WDVIMAX)
          CONTINUE
      END IF

      RETURN
      END
```

```
*----------------------------------------------------------------------*
* SUBROUTINE EXTRAD                                                    *
*                                                                      *
* Author(s): J. Goudriaan, adapted by B.A.M. Bouman                    *
* 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: -; 1992 (as in SBFLEVO and WWFLEVO)                         *
* Version: 2.0; April 1995; adapted by Bouman.                         *
*                                                                      *
* Reference: Goudriaan, J., 1977. Crop micrometeorology: a            *
*             simulation study. Wageningen, published by Pudoc         *
*             (simulation monograph)                                   *
*                                                                      *
* FORMAL PARAMETERS:  (I=input,O=output,C=control,IN=init,T=time)      *
* name   type meaning (unit)                               class *
* ----   ---- ---------------                               ----- *
* RHOS    R4   Hemispherical soil reflectance (-)              I *
* SCAT    R4   Scatter coefficient leaf (-)                    I *
* BETA    R4   Solar height (degrees)                          I *
* F       R4   Leaf angle distribution factor (-)              I *
* INF     I4   Lenght of array F (-)                           I *
* LAI     R4   Green leaf area index (m2 leaf.m-2 ground)      I *
* FRDIF_T R4   Instantaneous fraction diffuse radiation (-)    I *
* NAR     R4   Nadir crop reflectance (%)                      O *
* RHOM    R4   Nadir soil reflectance (%)                      O *
*                                                                      *
* Subroutines and functions called: none                              *
* Libraries used: TTUTIL                                               *
* Fatal error checks: on declared lengths of arrays; on boundaries    *
*                     of the input parameter values.                  *
```

```
*----------------------------------------------------------------------*

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

      IMPLICIT NONE

*     Formal parameters
      INTEGER INF
      REAL F(INF)
      REAL RHOS, SCAT ,BETA, LAI, FRDIF_T, NAR, RHOM

*     Local parameters
      INTEGER IN2
      PARAMETER (IN2=9)
      REAL BL(IN2), MI(IN2), MT(IN2), OAV(IN2), BU(IN2)

      INTEGER IN1
      PARAMETER (IN1=101)
      REAL TPHIU(IN1), TPHID(IN1)

      REAL PHID(IN2,IN1), PHIU(IN2,IN1)

      REAL FRDIR, LS, SBL, SINB, COSB, SINL, COSL, O

*     Miscellaneous
      INTEGER I, J, K, IS, ITER, ITERM, N, N1
      REAL INTER, PI, DEGTRAD
      PARAMETER (PI=3.1415926, DEGTRAD=0.017453292)

      SAVE

      DATA BU/0.03015,0.08682,0.13302,0.16318,0.17365,
     &        0.16318,0.13302,0.08682,0.03015/

*     Error checks
*     INF and IN1 (length of array) should be 9:
      IF (INF.NE.9) CALL ERROR ('EXTRAD','INF is not 9')
      IF (IN2.NE.9) CALL ERROR ('EXTRAD','IN2 is not 9')

*     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.) CALL ERROR ('EXTRAD', 'BETA greater than 90')
      IF (FRDIF_T.LT.0.)  CALL ERROR ('EXTRAD','FRDIF_T less than 0')
      IF (FRDIF_T.GT.1.)  CALL ERROR ('EXTRAD','FRDIF_T greater than 1')

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

*     Initialisation; calculations for leaf angle distribution
*     -----------------------------------------------------------
      FRDIR = 1.-FRDIF_T
      LS    = 0.1
      IF (BETA.LT.90.) THEN
          IS = 1+INT (BETA*0.1)
      ELSE
          IS = 9
      END IF

      SBL   = 0.

      DO K=1,IN2
          SINB  = SIN (DEGTRAD*(10.*(REAL (K)-0.5)))
          COSB  = COS (DEGTRAD*(10.*(REAL (K)-0.5)))
          OAV(K) = 0.
          DO I=1,IN2
              SINL = SIN (DEGTRAD*(10.*(REAL (I)-0.5)))
```

```
        COSL = COS (DEGTRAD*(10.*(REAL (I)-0.5)))
        IF (K.GE.I) THEN
           O = SINB*COSL
        ELSE
           O = 2.*(SINB*COSL*ASIN (SINB*COSL/(SINL*COSB))+
     &          SQRT (SINL**2-SINB**2))/PI
        END IF

*        OAV(K) is the leaf projection into direction K:
         OAV(K) = OAV(K)+O*F(I)
      END DO

*     Fraction intercepted MI and transmitted MT:
      MI(K) = OAV(K)*LS/SINB
      MT(K) = 1.-MI(K)

*     SBL is needed for normalization of the view factors BL(K):
      SBL = SBL+BU(K)*MI(K)
      END DO

*     Initialization according to leaf layers
      N  = INT (LAI/LS+0.5)
      N1 = N+1

*     Initialization of radiation profile:
      DO K=1,IN2
        DO J=1,N1
           PHIU(K,J) = 0.
           PHID(K,J) = 0.
        END DO

        BL(K) = BU(K)*MI(K)/SBL
*     Diffuse radiation is distributed according to BU(K):
        PHID(K,1) = 100.*BU(K)*FRDIF_T
      END DO

*     The direct incoming component is added:
      PHID(IS,1) = PHID(IS,1)+100.*FRDIR

*     Main routine for the profile calculation
*     ----------------------------------------

*     Number of iterations depends on scattering coefficient:
      ITERM=1
      IF (SCAT.GT.0.1)      ITERM = 2
      IF (SCAT.GT.0.5)      ITERM = 5
      IF (SCAT.GT.0.9)      ITERM = 10
      IF (SCAT.GT.0.99)     ITERM = 20
      IF (SCAT*RHOS.GT.0.99) ITERM = 50

      DO ITER=1,ITERM

*        First a calculation from top to bottom:
         DO J=2,N1
            INTER = 0.
            DO K=1,IN2
               INTER = INTER + MI(K)*(PHID(K,J-1)+PHIU(K,J))
            END DO

            DO K=1,IN2
               PHID(K,J) = PHID(K,J-1)*MT(K)+0.5*SCAT*INTER*BL(K)
            END DO
         END DO

*        Reflected radiation at the soil surface:
         INTER = 0.
         DO K=1,IN2
            INTER = INTER+PHID(K,N1)
         END DO
```

```
         DO K=1,IN2
            PHIU(K,N1) = RHOS*INTER*BU(K)
         END DO

*        Now the calculation from bottom to top:
         DO J=N,1,-1
            INTER = 0.
            DO K=1,IN2
               INTER = INTER+MI(K)*(PHID(K,J)+PHIU(K,J+1))
            END DO
            DO K=1,IN2
               PHIU(K,J)=PHIU(K,J+1)*MT(K)+0.5*SCAT*INTER*BL(K)
            END DO
         END DO

      END DO

*     End of routine for profile calculations
*     ----------------------------------------

*     Calculating the nadir reflection and reflectance

      DO J=1,1+INT(LAI/LS),5
         TPHIU(J) = 0.
         TPHID(J) = 0.
         DO K=1,IN2
            TPHIU(J) = TPHIU(J)+PHIU(K,J)
            TPHID(J) = TPHID(J)+PHID(K,J)
         END DO
      END DO

      RHOM = 100.*TPHIU(1)/TPHID(1)
      NAR  = PHIU(IN2,1)/BU(IN2)

      RETURN
      END
```

```
*---------------------------------------------------------------------*
* FUNCTION CLAIR                                                      *
*                                                                    *
* Author(s): B.A.M. Bouman                                           *
* Date     : 24-Aug-1995, Version: 1.0                               *
* Purpose  : Calculates WDVI of agricultural crops, using the        *
*            (inverted) CLAIR model                                  *
*                                                                    *
* Reference: Clevers, J.G.P., 1988, the derivation of a simplified   *
*            reflectance model for the estimation of Leaf Area Index *
*            Remote Sensing of Environment, 25:53-69.                *
*            Bouman, B.A.M., H.W.J. van Kasteren & D. Uenk, 1992.    *
*            Standard relations to estimate ground cover and LAI of  *
*            agricultural crops from reflectance measurements. Eur.  *
*            Journal of Agronomy, 1(4):249-262.                      *
*                                                                    *
* FORMAL PARAMETERS:  (I=input,O=output,C=control,IN=init,T=time)    *
* name   type meaning (unit)                               class *
* ----   ---- ---------------                               ----- *
* CLAIR  R4   Weighted difference vegetation index (calculated      *
*             using CLAIR model) (-)                          O  *
* KCLAIR R4   K-factor of the CLAIR model (-)                 I  *
* BCLAIR R4   Beta-factor of the CLAIR model (-)              I  *
* LAI    R4   Green leaf area index (m2 leaf.m-2 ground)      I  *
*                                                                    *
* Subroutines and functions called: none                            *
* Libraries used: none                                              *
* Fatal error checks: input data boundaries                         *
*---------------------------------------------------------------------*

      REAL FUNCTION CLAIR (KCLAIR,BCLAIR,LAI)
```

```
      IMPLICIT NONE


*     Formal parameters
      REAL KCLAIR, BCLAIR, LAI


      SAVE


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


      CLAIR = (1.-EXP (-KCLAIR*LAI))/BCLAIR


      RETURN
      END
```

```
*-----------------------------------------------------------------------*
* FUNCTION EMPWHE                                                        *
*                                                                       *
* Author(s): B.A.M. Bouman                                              *
* Date     : 24-Aug-1995, Version: 1.1                                  *
* Purpose  : Calculates WDVI of wheat using empirical (linear)          *
*            relationships.                                             *
* Version  : 1.1 improved parameters (DvK)                              *
*                                                                       *
* Reference: Bouman, B.A.M., H.W.J. van Kasteren & D. Uenk, 1992.       *
*            Standard relations to estimate ground cover and LAI of     *
*            agricultural crops from reflectance measurements. Eur.     *
*            Journal of Agronomy, 1(4):249-262.                         *
*                                                                       *
* FORMAL PARAMETERS:  (I=input,O=output,C=control,IN=init,T=time)       *
* name    type meaning (unit)                                  class *
* ----    ---- ---------------                                ----- *
* EMPWHE  R4   Function that calculates WDVI of wheat using            *
*              empirical (linear) relationships (?)            O  *
* LAI     R4   Green leaf area index (m2 leaf.m-2 ground)      I  *
*-----------------------------------------------------------------------*
      REAL FUNCTION EMPWHE(LAI)

      IMPLICIT NONE

*     Formal parameters
      REAL LAI


      SAVE


      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


      RETURN
      END
```

```
*-----------------------------------------------------------------------*
* FUNCTION EMPPOT                                                        *
*                                                                       *
* Author(s): B.A.M. Bouman                                              *
* Date     : 24-Aug-1995, Version: 1.1                                  *
* Purpose  : Calculates WDVI of potato using empirical (linear)         *
*            relationships.                                             *
*                                                                       *
* Reference:                                                            *
*            Bouman, B.A.M., H.W.J. van Kasteren & D. Uenk, 1992.       *
*            Standard relations to estimate ground cover and LAI of     *
*            agricultural crops from reflectance measurements. Eur.     *
*            Journal of Agronomy, 1(4):249-262.                         *
```

```
*                                                                       *
* FORMAL PARAMETERS:  (I=input,O=output,C=control,IN=init,T=time)       *
* name    type meaning                              units class *
* ----    ---- -------                              ----- ----- *
* EMPPOT  R4   Function that calculates WDVI of wheat using            *
*              empirical (linear) relationships           O  *
* LAI     R4   Green leaf area index (m2 leaf.m-2 ground)      I  *
*                                                                       *
* Subroutines and functions called: none                               *
* Libraries used: none                                                 *
* Fatal error checks: input data boundaries                            *
*-----------------------------------------------------------------------*
      REAL FUNCTION EMPPOT(LAI)

      IMPLICIT NONE

*     Formal parameters
      REAL LAI


      SAVE


      IF (LAI.LT.0.) THEN
         CALL ERROR ('EMPPOT','LAI smaller than 0')
      ELSE IF (LAI.GE.0..AND.LAI.LE.0.89) THEN
         EMPPOT=20.83*LAI
      ELSE IF (LAI.GT.0.89) THEN
         EMPPOT=10.989*(LAI+0.867)
      ENDIF


      RETURN
      END
```

Appendix III:

Radar backscatter routines

```
*--------------------------------------------------------------*
* SUBROUTINE BSCAT1                                            *
* 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: B.A.M. Bouman                                        *
* Version: 1.0; January, 1996                                  *
*                                                              *
* FORMAL PARAMETERS:                                           *
* name:  type:  meaning:                    units:    I/O  *
* ----   ----   ---------                    ------    ---  *
* ITASK  I4  Task that subroutine should perform    -       I  *
* IUNITD I4  Unit that can be used for input files   -       I  *
* IUNITL I4  Unit used for log file                  -       I  *
* FILERS C*  Name of input file no. 1                -       I  *
* OUTPUT L4  Flag to indicate if output should be done -     I  *
* TERMNL L4  Flag to indicate if simulation is to stop -    I/O  *
* WCLQT  R4  Vomuteric soil water content        cm3/cm3   I  *
* TADRW  R4  Total above-ground dry biomass       kg/ha    I  *
*                                                              *
* SUBROUTINES called: CLOUD1                                   *
* FUNCTIONS called: 'GETOBS' system, OBSTRG                    *
* LIBRARIES used: TTUTIL                                       *
*--------------------------------------------------------------*
      SUBROUTINE BSCAT1 (ITASK ,IUNITD, IUNITL,FILERS,
     $                   OUTPUT, TERMNL, WCLQT, TADRW)

      IMPLICIT NONE

*---- Formal parameters
      INTEGER ITASK,IUNITD,IUNITL
      REAL  WCLQT(1), TADRW
      LOGICAL OUTPUT, TERMNL
      CHARACTER FILERS*(*)

*---- Local variables
*     Crop and soil variables
      REAL MCCROP, PLWCRO, MCSOIL

*     Cloud model
      INTEGER ICLOUD
      PARAMETER (ICLOUD = 10)

      INTEGER INC_X, INUM_X(ICLOUD)
      REAL ANGLE_X(ICLOUD),GS_X(ICLOUD), RBGAM_X(ICLOUD)
      REAL CCROP_X(ICLOUD), RBSOIL_X(ICLOUD)
      REAL KS_X, DCROP_X

      INTEGER INC_C, INUM_C(ICLOUD)
      REAL ANGLE_C(ICLOUD),GS_C(ICLOUD), RBGAM_C(ICLOUD)
      REAL CCROP_C(ICLOUD), RBSOIL_C(ICLOUD)
      REAL KS_C, DCROP_C

      INTEGER INC_L, INUM_L(ICLOUD)
      REAL ANGLE_L(ICLOUD),GS_L(ICLOUD), RBGAM_L(ICLOUD)
      REAL CCROP_L(ICLOUD), RBSOIL_L(ICLOUD)
      REAL KS_L, DCROP_L

*---- Functions
      REAL GETOBS, OBSTRG
      LOGICAL INQOBS

      SAVE

*************************************************************
*     Initalization section
```

```
*************************************************************
      IF (ITASK.EQ.1) THEN

*------ Read input data from the remote sensing data file
        CALL RDINIT(IUNITD, IUNITL, FILERS)

*       Moisture content parameters
        CALL RDSREA ('MCCROP',MCCROP)

*       X-band Cloud
        CALL RDAINT ('INUM_X', INUM_X, ICLOUD, INC_X)
        CALL RDFREA ('ANGLE_X', ANGLE_X, ICLOUD, INC_X)
        CALL RDFREA ('GS_X', GS_X, ICLOUD, INC_X)
        CALL RDPREA ('CCROP_X', CCROP_X, ICLOUD, INC_X)
        CALL RDSREA ('KS_X', KS_X)
        CALL RDSREA ('DCROP_X', DCROP_X)

*       ERS C-band Cloud
        CALL RDAINT ('INUM_C', INUM_C, ICLOUD, INC_C)
        CALL RDFREA ('ANGLE_C', ANGLE_C, ICLOUD, INC_C)
        CALL RDFREA ('GS_C', GS_C, ICLOUD, INC_C)
        CALL RDFREA ('CCROP_C', CCROP_C, ICLOUD, INC_C)
        CALL RDSREA ('KS_C', KS_C)
        CALL RDSREA ('DCROP_C', DCROP_C)

*       JERS L-band Cloud
        CALL RDAINT ('INUM_L', INUM_L, ICLOUD, INC_L)
        CALL RDFREA ('ANGLE_L', ANGLE_L, ICLOUD, INC_L)
        CALL RDFREA ('GS_L', GS_L, ICLOUD, INC_L)
        CALL RDFREA ('CCROP_L', CCROP_L, ICLOUD, INC_L)
        CALL RDSREA ('KS_L', KS_L)
        CALL RDSREA ('DCROP_L', DCROP_L)

        CLOSE (IUNITD)

*************************************************************
*     Rate calculation section
*************************************************************
      ELSE IF (ITASK.EQ.2) THEN

*       Calculation of total above-ground plant water (kg/m2)
*       from total above-ground dry weight (kg/ha).
        PLWCRO = 0.0001*TADRW*MCCROP/(100.-MCCROP)

*       Daily values of soil moisture content. Options to use simulated
*       values, observed values, or a combination. Note that observed
*       values are generally 0-5 cm topsoil (%), whereas simulated values
*       are generally 0-20/30 cm topsoil (-)
        MCSOIL = OBSTRG(100.*WCLQT(1), FILERS, 'MCSOIL')

*       Calculation of radar backscatter X-band
        CALL CLOUD1(PLWCRO,MCSOIL,INC_X,ANGLE_X,GS_X,KS_X,
     $    DCROP_X, CCROP_X, RBGAM_X, RBSOIL_X)

*       Calculation of radar backscatter C-band
        CALL CLOUD1(PLWCRO,MCSOIL,INC_C,ANGLE_C,GS_C,KS_C,
     $    DCROP_C, CCROP_C, RBGAM_C, RBSOIL_C)

*       Calculation of radar backscatter L-band
        CALL CLOUD1(PLWCRO,MCSOIL,INC_L,ANGLE_L,GS_L,KS_L,
     $    DCROP_L, CCROP_L, RBGAM_L, RBSOIL_L)

*       Print data
        IF (OUTPUT) THEN
          IF (INQOBS (FILERS,'MCSOIL')) CALL OUTDAT
     $      (2, 0, 'MCSOIL_OBS',GETOBS(FILERS,'MCSOIL'))
          IF (INQOBS (FILERS,'X10')) CALL OUTDAT
     $      (2, 0, 'X10_OBS',GETOBS(FILERS,'X10'))
          IF (INQOBS (FILERS,'X20')) CALL OUTDAT
```

```
     $       (2, 0, 'X20_OBS',GETOBS(FILERS,'X20'))
             IF (INQOBS (FILERS,'X30')) CALL OUTDAT
     $       (2, 0, 'X30_OBS',GETOBS(FILERS,'X30'))
             IF (INQOBS (FILERS,'X40')) CALL OUTDAT
     $       (2, 0, 'X40_OBS',GETOBS(FILERS,'X40'))
             IF (INQOBS (FILERS,'X50')) CALL OUTDAT
     $       (2, 0, 'X50_OBS',GETOBS(FILERS,'X50'))
             IF (INQOBS (FILERS,'X60')) CALL OUTDAT
     $       (2, 0, 'X60_OBS',GETOBS(FILERS,'X60'))
             IF (INQOBS (FILERS,'X70')) CALL OUTDAT
     $       (2, 0, 'X70_OBS',GETOBS(FILERS,'X70'))
             IF (INQOBS (FILERS,'ERS')) CALL OUTDAT
     $       (2, 0, 'ERS_OBS',GETOBS(FILERS,'ERS'))
             IF (INQOBS (FILERS,'JERS')) CALL OUTDAT
     $       (2, 0, 'JERS_OBS',GETOBS(FILERS,'JERS'))
             CALL OUTDAT (2, 0, 'MCSOIL_SIM', WCLQT(1)*100.)
             CALL OUTDAT (2, 0, 'MCSOIL', MCSOIL )
             CALL OUTDAT (2, 0, 'PLWCRO',  PLWCRO)
             CALL OUTARR (2, 0, 'RBGAM_X',RBGAM_X,1,INC_X)
             CALL OUTARR (2, 0, 'RBSOIL_X',RBSOIL_X,1,INC_X)
             CALL OUTARR (2, 0, 'RBGAM_C',RBGAM_C,1,INC_C)
             CALL OUTARR (2, 0, 'RBSOIL_C',RBSOIL_C,1,INC_C)
             CALL OUTARR (2, 0, 'RBGAM_L',RBGAM_L,1,INC_L)
             CALL OUTARR (2, 0, 'RBSOIL_L',RBSOIL_L,1,INC_C)
          END IF

*********************************************************************
*        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

          RETURN
          END

*----------------------------------------------------------------------*
* SUBROUTINE BSCAT2                                                     *
*                                                                      *
* Author(s): B.A.M. Bouman                                             *
* Date     : 24-Aug-1995, Version: 1.0                                 *
* Purpose  : Interface with SUCROS 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,IN=init,T=time)      *
* name   type meaning (unit)                              class *
* ----   ---- --------------                              ----- *
* ITASK  I4   Task that subroutine should perform (-)        I *
* IUNITD I4   Unit number that is used for input files (-)   I *
* IUNITL I4   Unit number that is used for log file (-)      I *
* FILERS C*   Input file with remote sensing data (-)        I *
* OUTPUT L4   Flag to indicate if output should be done (-)  I *
* TERMNL L4   Flag to indicate if simulation is to stop (-)  I *
* WCLQT  R4   Volumetric water content in soil compartments    *
*             (cm3 H2O.cm-3 soil)                            I *
* WLV    R4   Dry weight of the leaves (green + dead) (kg.ha-1) I *
```

```
* WST    R4   Dry weight of the stems (kg.ha-1)              I *
* WSO    R4   Dry weight of storage organs (kg.ha-1)         I *
* DVS    R4   Development stage of the crop (-)              I *
*                                                              *
* SUBROUTINES called: CLOUD2                                   *
* FUNCTIONS called: 'GETOBS' system                           *
* LIBRARIES used: TTUTIL                                       *
*----------------------------------------------------------------------*

          SUBROUTINE BSCAT2 (ITASK , IUNITD, IUNITL, FILERS,
     &                       OUTPUT, TERMNL, WCLQT ,
     &                       WLV  , WST  , WSO  , DVS)

          IMPLICIT NONE

*    Formal parameters
          INTEGER ITASK,IUNITD,IUNITL
          REAL WCLQT(1), WLV, WST, WSO, DVS
          LOGICAL OUTPUT, TERMNL
          CHARACTER FILERS*(*)

*    Local variables
*    Crop and soil variables
          REAL MCVEG, MCEAR, MCSOIL, PLWVEG, PLWEAR

          INTEGER IMCVEG, IMCVN
          PARAMETER (IMCVEG=20)
          REAL MCVEGT(IMCVEG)

          INTEGER IMMCEA, IMCEN
          PARAMETER (IMMCEA=20)
          REAL MCEART(IMMCEA)

*    Cloud model
          INTEGER ICLOUD
          PARAMETER (ICLOUD=10)

          INTEGER INUM_X(ICLOUD),INC_X
          REAL ANGLE_X(ICLOUD),GS_X(ICLOUD),CEAR_X(ICLOUD),RBGAM_X(ICLOUD)
          REAL RBSOIL_X(ICLOUD)
          REAL KS_X        ,DVEG_X     ,DEAR_X       ,CVEG_X

          INTEGER INUM_C(ICLOUD), INC_C
          REAL RBSOIL_C(ICLOUD)
          REAL ANGLE_C(ICLOUD),GS_C(ICLOUD),CEAR_C(ICLOUD),RBGAM_C(ICLOUD)
          REAL KS_C        ,DVEG_C     ,DEAR_C       ,CVEG_C

          INTEGER INUM_L(ICLOUD), INC_L
          REAL RBSOIL_L(ICLOUD)
          REAL ANGLE_L(ICLOUD),GS_L(ICLOUD),CEAR_L(ICLOUD),RBGAM_L(ICLOUD)
          REAL KS_L        ,DVEG_L     ,DEAR_L       ,CVEG_L

*    Functions
          REAL LINT, GETOBS, OBSTRG
          LOGICAL INQOBS

          SAVE

          IF (ITASK.EQ.1) THEN

*         Initialization section
*         ----------------------

*         Read input data from the remote sensing data file
             CALL RDINIT (IUNITD, IUNITL, FILERS)

*         Moisture content parameters
             CALL RDAREA ('MCVEGT', MCVEGT, IMCVEG, IMCVN)
             CALL RDAREA ('MCEART', MCEART, IMMCEA, IMCEN)
```

```
*       X-band Cloud                                              IF (INQOBS (FILERS,'X20')) CALL OUTDAT
        CALL RDAINT ('INUM_X' , INUM_X , ICLOUD, INC_X)     &         (2, 0, 'X20_OBS',GETOBS(FILERS,'X20'))
        CALL RDFREA ('ANGLE_X', ANGLE_X, ICLOUD, INC_X)         IF (INQOBS (FILERS,'X30')) CALL OUTDAT
        CALL RDFREA ('GS_X'   , GS_X   , ICLOUD, INC_X)     &         (2, 0, 'X30_OBS',GETOBS(FILERS,'X30'))
        CALL RDFREA ('CEAR_X' , CEAR_X , ICLOUD, INC_X)         IF (INQOBS (FILERS,'X40')) CALL OUTDAT
        CALL RDSREA ('KS_X'   , KS_X)                       &         (2, 0, 'X40_OBS',GETOBS(FILERS,'X40'))
        CALL RDSREA ('DVEG_X' , DVEG_X)                         IF (INQOBS (FILERS,'X50')) CALL OUTDAT
        CALL RDSREA ('DEAR_X' , DEAR_X)                     &         (2, 0, 'X50_OBS',GETOBS(FILERS,'X50'))
        CALL RDSREA ('CVEG_X' , CVEG_X)                         IF (INQOBS (FILERS,'X60')) CALL OUTDAT
                                                            &         (2, 0, 'X60_OBS',GETOBS(FILERS,'X60'))
                                                                IF (INQOBS (FILERS,'X70')) CALL OUTDAT
*       ERS C-band Cloud                                    &         (2, 0, 'X70_OBS',GETOBS(FILERS,'X70'))
        CALL RDAINT ('INUM_C' , INUM_C , ICLOUD, INC_C)         IF (INQOBS (FILERS,'ERS')) CALL OUTDAT
        CALL RDFREA ('ANGLE_C', ANGLE_C, ICLOUD, INC_C)     &         (2, 0, 'ERS_OBS',GETOBS(FILERS,'ERS'))
        CALL RDFREA ('GS_C'   , GS_C   , ICLOUD, INC_C)         IF (INQOBS (FILERS,'JERS')) CALL OUTDAT
        CALL RDFREA ('CEAR_C' , CEAR_C , ICLOUD, INC_C)     &         (2, 0, 'JERS_OBS',GETOBS(FILERS,'JERS'))
        CALL RDSREA ('KS_C'   , KS_C)                           CALL OUTDAT (2, 0, 'MCSOIL_SIM', WCLQT(1)*100.)
        CALL RDSREA ('DVEG_C' , DVEG_C)                         CALL OUTDAT (2, 0, 'MCSOIL', MCSOIL )
        CALL RDSREA ('DEAR_C' , DEAR_C)                         CALL OUTDAT (2, 0, 'PLWVEG',  PLWVEG)
        CALL RDSREA ('CVEG_C' , CVEG_C)                         CALL OUTDAT (2, 0, 'PLWEAR',  PLWEAR)
                                                                CALL OUTARR ('RBGAM_X',RBGAM_X,1,INC_X)
                                                                CALL OUTARR ('RBSOIL_X',RBSOIL_X,1,INC_X)
*       JERS L-band Cloud                                       CALL OUTARR ('RBGAM_C',RBGAM_C,1,INC_C)
        CALL RDAINT ('INUM_L' , INUM_L , ICLOUD, INC_L)         CALL OUTARR ('RBSOIL_C',RBSOIL_C,1,INC_C)
        CALL RDFREA ('ANGLE_L', ANGLE_L, ICLOUD, INC_L)         CALL OUTARR ('RBGAM_L',RBGAM_L,1,INC_L)
        CALL RDFREA ('GS_L'   , GS_L   , ICLOUD, INC_L)         CALL OUTARR ('RBSOIL_L',RBSOIL_L,1,INC_L)
        CALL RDFREA ('CEAR_L' , CEAR_L , ICLOUD, INC_L)     END IF
        CALL RDSREA ('KS_L'   , KS_L)
        CALL RDSREA ('DVEG_L' , DVEG_L)
        CALL RDSREA ('DEAR_L' , DEAR_L)                 ELSE IF (ITASK.EQ.3) THEN
        CALL RDSREA ('CVEG_L' , CVEG_L)
                                                        *       Integration section
                                                        *       -------------------
        CLOSE (IUNITD)
                                                        *       No statements here
                                                                CONTINUE
        ELSE IF (ITASK.EQ.2) THEN
                                                                ELSE IF (ITASK.EQ.4) THEN
*       Rate calculation section
*       ------------------------                        *       Terminal section
                                                        *       ----------------
                                                        *       No statements here
*       Calculation of plant water (kg/m2) for ears and vegetative     CONTINUE
*       matter from their dry weights (kg/ha).
        MCVEG  = LINT (MCVEGT,IMCVN,DVS)                        END IF
        MCEAR  = LINT (MCEART,IMCEN,DVS)
        PLWVEG = 0.0001*(WLV+WST)*MCVEG/(100.-MCVEG)           RETURN
        PLWEAR = 0.0001*WSO*MCEAR/(100.-MCEAR)                 END


*       Daily values of soil moisture content. Options to use simulated
*       values, observed values, or a combination. Note that observed     **************************************************************
*       values are generally 0-5 cm topsoil (%), whereas simulated values * SUBROUTINE CLOUD1                                          *
*       are generally 0-20/30 cm topsoil (-)                            * Purpose: Calculates radar backscatter (gamma) of sugar beet or *
                                                                        * potato using the one-layer Cloud model.                   *
                                                                        *                                                           *
        MCSOIL = OBSTRG (100.*WCLQT(1), FILERS, 'MCSOIL')      * Programmed by: B.A.M. Bouman                              *
                                                                        * Version: 1.0                                              *
*       Calculation of radar backscatter X-band                         * Date: 21 june 1995                                        *
        CALL CLOUD2 (PLWVEG,PLWEAR,MCSOIL,INC_X,ANGLE_X,GS_X,CEAR_X,    *                                                           *
     &           KS_X, DVEG_X, DEAR_X, CVEG_X, RBGAM_X, RBSOIL_X)       * Reference: CLOUD model: Attema, E.P.W & F.T. Ulaby, 1978. *
                                                                        *            Vegetation modelled as a water cloud, Radio Science *
*       Calculation of radar backscatter C-band                         *            13(2): 357-364. Hoekman, D.H., L. Krul & E.P.W. Attema, *
        CALL CLOUD2 (PLWVEG,PLWEAR,MCSOIL,INC_C,ANGLE_C,GS_C,CEAR_C,    *            1982. A multilayer model for radar backscattering from *
     &           KS_C, DVEG_C, DEAR_C, CVEG_C, RBGAM_C, RBSOIL_C)       *            vegetation canopies, Digest of the 2nd IEEE     *
                                                                        *            International Geoscience and Remote Sensing Symposium, *
*       Calculation of radar backscatter L-band                         *            Munich, West Germany, pp. 4.1-4.7.             *
        CALL CLOUD2 (PLWVEG,PLWEAR,MCSOIL,INC_L,ANGLE_L,GS_L,CEAR_L,    *                                                           *
     &           KS_L, DVEG_L, DEAR_L, CVEG_L, RBGAM_L, RBSOIL_L)       * FORMAL PARAMETERS:                                        *
                                                                        * name: type:  meaning:                         units:  I/O *
*       Print data                                                      * ----  ----   --------                         ------  --- *
        IF (OUTPUT) THEN                                                * PLWCRO R4    total plant water above-ground     kg/m2   I   *
            IF (INQOBS (FILERS,'MCSOIL')) CALL OUTDAT
     &         (2, 0, 'MCSOIL_OBS',GETOBS(FILERS,'MCSOIL'))
            IF (INQOBS (FILERS,'X10')) CALL OUTDAT
     &         (2, 0, 'X10_OBS',GETOBS(FILERS,'X10'))
```

```
* MCSOIL R4   topsoil moisture content        %(vol.)   I   *
* NOINCA I4   Number of incidence angles         -       I   *
* ANGLE  R4   incidence angle                  degree    I   *
* GS     R4   Backscatter (gamma) dry soil       dB      I   *
* CCROP  R4   Maximum backscatter (gamma) crop   dB      I   *
* KS     R4   Soil moisture attenuation factor   -       I   *
* DCROP  R4   Attenuation factor crop            -       I   *
* RBGAM  R4   Radar backscatter (gamma)          dB      O   *
* RBSOIL R4   Radar backscatter contribution soil dB     O   *
*                                                            *
* SUBROUTINES called: none                                   *
* LIBRARIES used: none                                       *
* FATAL ERROR CHECKS: Data input bounds                      *
*************************************************************

      SUBROUTINE CLOUD1(PLWCRO,MCSOIL,NOINCA,ANGLE,GS,KS,
     $    DCROP, CCROP, RBGAM, RBSOIL)

      IMPLICIT NONE

*     Formal parameters
      INTEGER NOINCA
      REAL ANGLE(NOINCA),GS(NOINCA),CCROP(NOINCA),RBGAM(NOINCA)
      REAL RBSOIL(NOINCA)
      REAL KS,DCROP,PLWCRO,MCSOIL

*     Local variables
      INTEGER JCLOUD
      PARAMETER (JCLOUD=10)
      REAL ACROP(JCLOUD), RCROP(JCLOUD), RSOIL(JCLOUD)

*     Miscelaneous
      INTEGER I
      REAL DEGTRAD

      PARAMETER (DEGTRAD=0.017453292)

      SAVE

*     Check on lengths of arrys
      IF (NOINCA.GT.JCLOUD) THEN
         CALL ERROR ('CLOUD1', 'Declared arrays too short, JCLOUD')
      END IF

*     Check on data input values
      IF (MCSOIL.LT.0. .OR. MCSOIL.GE.100.) THEN
         CALL ERROR ('CLOUD1', 'Soil moisture MCSOIL out of bounds')
      END IF

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

      DO I=1,NOINCA
         IF (ANGLE(I).LE.0 .OR. ANGLE(I) .GE. 90.) THEN
            CALL ERROR ('CLOUD1','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,NOINCA
         ACROP(I) =DCROP*PLWCRO/COS(DEGTRAD*ANGLE(I))
         RSOIL(I) =GS(I)*EXP(KS*MCSOIL-ACROP(I))
         RCROP(I) =CCROP(I)*(1.-EXP(-ACROP(I)))
         RBGAM(I) =10.*ALOG10(RSOIL(I)+RCROP(I))
         RBSOIL(I) = 10.*ALOG10(RSOIL(I))
      END DO

      RETURN
      END
```

```
*-------------------------------------------------------------------*
* SUBROUTINE CLOUD2                                                  *
*                                                                    *
* Author(s): B.A.M. Bouman                                           *
* Date     : 24-Aug-1995, Version: 1.0                               *
* Purpose  : Calculates radar backscatter (gamma) of cereal crops    *
*            using the two-layer Cloud model.                        *
*                                                                    *
* Reference: CLOUD model: Attema, E.P.W. & F.T. Ulaby, 1978.         *
*            Vegetation modelled as a water cloud, Radio Science     *
*            13(2): 357-364. Hoekman, D.H., L. Krul & E.P.W. Attema, *
*            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.                       *
*                                                                    *
* FORMAL PARAMETERS:  (I=input,O=output,C=control,IN=init,T=time)    *
* name    type meaning (unit)                               class *
* ----    ---- --------------                               ----- *
* PLWVEG  R4   Plant water amount in vegetative layer (kg H2O/m2)  I *
* PLWEAR  R4   Plant water amount in ear layer (kg H2O/m2)         I *
* MCSOIL  R4   Topsoil moisture content (100*cm3.cm-3 (%))         I *
* NOINCA  I4   Number of incidence angles (-)                      I *
* ANGLE   R4   Incidence angle (degrees)                           I *
* GS      R4   Radar backscatter (gamma) dry soil (dB)             I *
* CEAR    R4   Maximum radar backscatter (gamma) ear layer (dB)    I *
* KS      R4   Soil moisture attenuation factor (-)                I *
* DVEG    R4   Attenuation factor vegetative layer (-)             I *
* DEAR    R4   Attenuation factor ear layer (-)                    I *
* CVEG    R4   Maximum radar backscatter (gamma) vegetative layer    *
*              (dB)                                                 I *
* RBGAM   R4   Radar backscatter (gamma) (dB)                      O *
* RBSOIL  R4   Radar backscatter contribution soil (dB)            O *
*                                                                    *
* SUBROUTINES called: none                                           *
* LIBRARIES used: none                                               *
* FATAL ERROR CHECKS: Data input bounds                              *
*-------------------------------------------------------------------*

      SUBROUTINE CLOUD2 (PLWVEG, PLWEAR, MCSOIL, NOINCA, ANGLE,
     &           GS, CEAR, KS, DVEG, DEAR, CVEG, RBGAM, RBSOIL)

      IMPLICIT NONE

*     Formal parameters
      INTEGER NOINCA
      REAL ANGLE(NOINCA), GS(NOINCA), CEAR(NOINCA), RBGAM(NOINCA)
      REAL RBSOIL(NOINCA)
      REAL KS, DVEG, DEAR, CVEG, PLWVEG, PLWEAR, MCSOIL

*     Local variables
      INTEGER JCLOUD
      PARAMETER (JCLOUD=10)
      REAL AVEG(JCLOUD), AEAR(JCLOUD), ASOIL(JCLOUD), RSOIL(JCLOUD)
      REAL RVEG(JCLOUD) , REARS(JCLOUD)

*     Miscellaneous
      INTEGER I
      REAL DEGTRAD

      PARAMETER (DEGTRAD=0.017453292)

      SAVE

*     Check on lengths of arrays
      IF (NOINCA.GT.JCLOUD) CALL ERROR
     &    ('CLOUD2', 'Incoming arrays too short, increase JCLOUD')

*     Check on data input values
      IF (MCSOIL.LT.0. .OR. MCSOIL.GE.100.) THEN
```

```
         CALL ERROR ('CLOUD2', 'Soil moisture MCSOIL out of bounds')
      END IF


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


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


      DO I=1,NOINCA
         AVEG(I)  = DVEG*PLWVEG/COS (DEGTRAD*ANGLE(I))
         AEAR(I)  = DEAR*PLWEAR/COS (DEGTRAD*ANGLE(I))
         ASOIL(I) = (DEAR*PLWEAR+DVEG*PLWVEG)/COS (DEGTRAD*ANGLE(I))
         RSOIL(I)  = GS(I)*EXP (KS*MCSOIL)*EXP (-ASOIL(I))
         RVEG(I)  = CVEG*(1.-EXP (-AVEG(I)))*EXP (-AEAR(I))
         REARS(I)  = CEAR(I)*(1.-EXP (-AEAR(I)))
         RBGAM(I)  = 10.*ALOG10 (RSOIL(I)+RVEG(I)+REARS(I))
         RBSOIL(I)= 10.*ALOG10(RSOIL(I))
      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)
MCVEGT = 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).         *
* Reference:  Hoekman, D.H., L. Krul & E.P.W. Attema,             *
*             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)
```

```
INUM_X    ANGLE_X   GS_X    CEAR_X
1         10.       0.344   0.101
2         20.       0.326   0.048
3         30.       0.088   0.039
4         40.       0.057   0.040
5         50.       0.019   0.054
6         60.       0.010   0.079
7         70.       0.012   0.130
8         75.       0.009   0.172
```

```
KS_X    = 0.06      ! Cloud K parameter for the soil (-)
DVEG_X  = 1.1530    ! Cloud D parameter for vegetative matter (m2/kg)
DEAR_X  = 2.0565    ! Cloud D parameter for ear layer (m2/kg)
CVEG_X  = 0.1850    ! Cloud C parameter for ear layer (m2/m2)
```

```
*----------------------------------------------------------------*
* 1.3 Cloud model parameters C- and L-band. Data taken from      *
* AGRISCATT 1988 campaign in Flevoland.                          *
* Reference: Bouman, B.A.M., 1992. SBFLEVO and WWFLEVO, CABO-DLO *
* report 163.                                                    *
*----------------------------------------------------------------*
INUM_C    ANGLE_C   GS_C    CEAR_C
1         20.       0.0200  0.2249
```

```
* Maybe better to use 40 degree incidence angle data?
*INUM_C   ANGLE_C   GS_C    CEAR_C
*1        40.       0.0090  0.1302
```

```
KS_C    = 0.0580   ! Cloud K parameter for the soil (-)
DVEG_C  = 0.0033   ! Cloud D parameter for vegetative matter (m2/kg)
DEAR_C  = 0.0717   ! Cloud D parameter for ear layer (m2/kg)
CVEG_C  = 0.1727   ! Cloud C parameter for ear layer (m2/m2)
```

```
INUM_L    ANGLE_L   GS_L    CEAR_L
1         40.       0.0022  0.0676
```

```
KS_L    = 0.1000   ! Cloud K parameter for the soil (-)
DVEG_L  = 0.2678   ! Cloud D parameter for vegetative matter (m2/kg)
DEAR_L  = 2.0789   ! Cloud D parameter for ear layer (m2/kg)
CVEG_L  = 0.04867  ! Cloud C parameter for ear layer (m2/m2)
```

```
********************************************************************
* 2. Optical model input                                         *
********************************************************************
```

```
*----------------------------------------------------------------*
* 2.1 CLAIR model parameters (taken from large data set)         *
*          Bouman, B.A.M., H.W.J. van Kasteren & D. Uenk, 1992.  *
*          Standard relations to estimate ground cover and LAI of *
*          agricultural crops from reflectance measurements. Eur. *
*          Journal of Agronomy, 1(4):249-262.                    *
*----------------------------------------------------------------*
```

```
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. SBFLEVO and WWFLEVO, CABO-DLO  *
* report 163.                                                 *
*------------------------------------------------------------*
RHOSG   = 0.134 ! green reflection coefficient soil (-)
RHOSR   = 0.145 ! red reflection coefficient soil (-)
RHOSIR  = 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_FRC = 2


*------------------------------------------------------------*
* 3.2 Radar backscatter and WDVI                             *
*------------------------------------------------------------*
* First number: year number, second number: day number, third number:
* measurement (X-band, ERS and JERS: in dB; WDVI 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)
MCVEGT = 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).          *
* Reference:  Hoekman, D.H., L. Krul & E.P.W. Attema,              *
*             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)
```