The SPART model

A soil-plant-atmosphere radiative transfer model for satellite measurements in the solar spectrum

Version 1.10 User Manual

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# Brief history of the model

In 2018, the Netherlands Organization for Space Research decided to grant a proposal with the title ‘Exploring vegetation strategies to utilize light and water for primary productivity through remote sensing of reflectance and fluorescence’ lead by Dr. Christiaan van der Tol from the ITC institute in The Netherlands and carried out by Dr. Peiqi Yang as a post-doc researcher. The project is a User Support Programme Space Research Proposal that aims to provide support to researchers working in the Netherlands during the (preparation for) use of infrastructure in space for the purpose of high quality research.

The main idea of this proposal was to come up with a better understanding of terrestrial vegetation by means of multi-angular and multi-sensor remote sensing observations of vegetation. We proposed to use data of OLCI and SLSTR on Sentinel-3 satellites together with GOME-2 sun-induced chlorophyll fluorescence (SIF) data, to analyse strategies of plants to utilize light and water and avoid stress. For the purpose of better interpreting satellite measurements, a model had to be constructed that **links surface and atmospheric properties with top-of-atmosphere observations**. The original idea is to couple a vegetation radiative transfer model (RTM), namely PROSAIL, with the MODTRAN atmosphere RTM following the work by Wout Verhoef et al, (2003, 2007 and 2018). This type of coupled model is suitable for forward simulations despite it may take several minutes to run MODTRAN due to its complexity. However, for the purpose of retrieving vegetation properties, one would need to know the atmospheric properties first, which are used to simulate the optical coefficients (atmospheric transmittance factors), which were then used to translate TOC reflectance to TOA reflectance. This procedure is, strictly, not a combined surface-atmosphere retrieval.

The objective of the SPART is to link land surface and atmospheric properties with TOA observations, in particular for inversion purpose. We use three sub-models, namely the BSM soil reflectance model, the PROSAIL canopy RTM and the SMAC atmosphere RTM. This coupled model stands alone and simulates TOA reflectance for given sensors.

The root of this coupled model is the four-stream theory and the adding method. In 1981, Wout Verhoef developed the Scattering of Arbitrarily Inclined Leaves (SAIL) model for calculation of the bidirectional reflectance of vegetation canopies. The first article about this model in the journal Remote Sensing of Environment appeared in 1984 and this was followed by a long series of other articles that discussed various applications and SAIL extensions of the model. This model is often coupled with the PROSPECT leaf RTM resulting so-called PROSAIL.

Soil reflectance is given as input in PROSAIL. However, it is not always available especially in large-scale applications. To simulate the reflectance of soil, Wout Verhoef extended a global spectral vector model for soil reflectance, separated soil brightness effects, and included soil moisture effects on soil reflectance. The resulted model is the brightness-shape-moisture (BSM) model. Peiqi Yang modified the BSM model to account for the absorption by the water films more accurately.

The SMAC model was chosen because its simplicity yet satisfactory accuracy for atmosphere radiative transfer modelling. The model was developed for atmospheric correction. We modified the model according to the four-stream theory and made it applicable for the adding method. These allow the integration with the canopy vegetation RTM.

Questions about the model can be addressed to Peiqi Yang ([p.yang@utwente.nl](mailto:p.yang@utwente.nl) or [peiqiyangweb@gmail.com](mailto:peiqiyangweb@gmail.com)).

**References**

Verhoef, W., & Bach, H. (2003). Simulation of hyperspectral and directional radiance images using coupled biophysical and atmospheric radiative transfer models. Remote sensing of environment, 87(1), 23-41.

Verhoef, W., & Bach, H. (2007). Coupled soil–leaf-canopy and atmosphere radiative transfer modeling to simulate hyperspectral multi-angular surface reflectance and TOA radiance data. Remote Sensing of Environment, 109(2), 166-182.

Verhoef, W., Van Der Tol, C., & Middleton, E. M. (2018). Hyperspectral radiative transfer modeling to explore the combined retrieval of biophysical parameters and canopy fluorescence from FLEX–Sentinel-3 tandem mission multi-sensor data. Remote sensing of environment, 204, 942-963.

Rahman, H., & Dedieu, G. (1994). SMAC: a simplified method for the atmospheric correction of satellite measurements in the solar spectrum. Remote Sensing, 15(1), 123-143.

# Software requirements

The model SPART\_v1.10 is written in Matlab R2017b. The model also works with Matlab R2015a or higher version. No statistical toolbox is required.

The input of version 1.10 has to be specified in an Excel spreadsheet. If you cannot modify .xls(x) files, then please define the input in the Matlab script files instead of an Excel spreadsheet.

# Model architecture

A flow chart of the model is presented in Figure 1. After reading in the main input file (a spreadsheet called ‘input\_data.xlsx’), the supporting data are loaded. These consist of soil, leaf, canopy and atmospheric properties, sun-observer geometry and sensor characteristics.

Each simulation starts with the soil reflectance model BSM, the leaf optical model PROSPECT and the radiative transfer model SAIL for scaling from leaf to canopy, and then the modified SMAC model for translating TOC reflectance to TOA reflectance.

|  |
| --- |
| Figure 1. Flow chart of the SPART model |

Table 2 lists the directory structure of the model. There are three main directories: one containing data in files (input data), and one containing the model code and one containing model. The input data folder contains several subfolders with data specific for SPART, such as soil reflectance, leaf optical properties, and PROSPECT, and SMAC parameters.

Table 2: Directory structure of the SPART model. The data are saved at the same level as the model.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Level 1** | **Level 2** | **Level 3** | **Level 4** | **Description** |
| Model | inputdata | Sensors | Named by sensors | ASCII files with sensor configuration  SMAC fitting coefficients |
| SLC\_inputs | .mat files | BSM soil vectors and leaf absorption coefficients |
| BRDF\_files |  | ASCII files for sampling of angles for BRDF simulations |
| output | User\_defined projects | TOC/TOA reflectance | ASCII files for model simulation results |
| src\_SPART | BSM |  | Soil reflectance model |
| PROSPECT\_5D |  | Leaf reflectance and transmittance model |
| SAILH |  | Canopy RTM, SAIL with hotspot effects |
| SMAC |  | Modified SMAC model |
| define\_bands |  | Spectral region |
| read\_coeffs |  | Read SMAC coefficients |
| read\_or\_create\_srf |  | Read or create spectral response functions |
| spectral\_convolution |  | Spectral convolution |
| readme |  |  |  | Terms of use |
| Documents | User manual |  |  | User manual of the model |

The folder ‘SPART\_v1.20’ has the code, and documentations. The spreadsheet with the basic model input (parameters and links to input data file) is located in ‘model’. When the model is executed, then the output will automatically appear in a new directory under output, with the name of the simulation run. The spreadsheet with parameters is saved along with the model output.

# Getting started

SPART consists of several scripts and functions (hereafter called modules), which can be used separately or as parts of the integrated SPART model. When the modules are used separately, then it is important to provide input in the structures specified below. When the integrated model is called, then the input is automatically loaded from the spreadsheet and from the files specified therein. Basic knowledge of the use of Matlab is required to operate the model.

The application of the model involves the following steps:

1. **To unpack the zip file**

Unpack the model, and leave the directory structure intact.

1. **Run the model once**

Running the model once, before modifying the parameters and input, will check whether the software works under your system. The model is executed by opening Matlab, navigating to the directory where the matlab code is (**‘cd … SPART\_v1.20/model/runSPART’**), and running **‘**SPART’. There will be graphs appearing showing the freshly produced output together with the expected output. If all is ok then no graphs or warnings are produced.

1. **Evaluate and complete the spreadsheet ‘SPART\_input\_user\_defined.xlsx’.**

The required input is specified in the spreadsheet file ‘**SPART\_input\_user\_defined**.**xlsx’**. Open this file. It has one sheet:

* Inputparameters: specify all the parameters and input variables.

1. **Simulation option ‘Individual runs’**

The last simulation option is important: to run the model for a few cases only, choose the option: simulation = 0. In that case the model runs for the input specified in the InputData sheet. It is possible to specify more than one value for one input variable, by filling in values in the next column. The model will run as many simulations as there are columns in the input data spreadsheet, say *n* runs. For run *i* it will select the data from column *i* for all variables that have *n* values. For all other variables, it will select the first value only. For example:

Cab 10 20 30

Cdm 0.012

N 1.5 2

It will do three runs, the first time with Cab = 10, Cdm = 0.012, and N = 1.5; the second time with Cab = 20, Cdm = 0.012, and N = 1.5; and a third time with Cab = 30, Cdm = 0.012 and N = 1.5. The value of N = 2 is ignored and the run cycle ends.

The output is the same as for the time series (see below), except that two additional files are produced: ‘pars\_and\_input.dat’ and ‘pars\_and\_input\_short.dat’. Both files always have a header. The first file lists the values of all parameters and input variables (that are part of the structure ‘v’) that were used in the simulations, one row for each simulation. The second file lists only the parameters that were varied. Suppose that, for example, if 3 parameters were given 10 different values, while the other parameters were given only 1 single value for each simulation. In that case the pars\_and\_input\_short.dat output file contains three columns with the parameter values corresponding to teach simulations.

1. **Simulation option Time series**

For the time series run, set simulation = 1. SCOPE now uses the meteorological input as saved in the ascii files specified in the sheet: ‘filenames’. SCOPE runs as many times as there are values in the ascii files. For all input that is not in files, it uses the first value specified in the ‘InputData’ sheet. An value for an input variable in the spreadsheet is **overwritten** by the value in the time series file of that variable, if this file is provided.

1. **Simulation option Lookup Table**

For the LUT option, specify ‘simulation = 2’. This option is similar to the ‘individual runs’, except that the model runs over all possible combinations of parameters. For example:

Cab 10 20 30

Cdm 0.012

N 1.5 2

It will do six runs, the first time with Cab = 10, Cdm = 0.012, and N = 1.5; the second time with Cab = 20, Cdm = 0.012, and N = 1.5; a third time with Cab = 30, Cdm = 0.012, and N = 1.5; then fourth with Cab = 10, Cdm = 0.012 and N = 2.0, etc, cycling through values for Cab again.

1. **To execute the model**

The model can be executed by calling ‘SCOPE’ in the command window of Matlab. Alternatively, separate modules can be called, provided that the required input is given. The modules have a help text describing how to do this, which can be called by typing ‘help modulename’, for example: ‘help ebal’. It is however more difficult, because the structures need to be provided.

The output of each simulation is automatically saved in an output directory, together with files documenting the parameters used for this simulation, and the spreadsheet in directory ‘Parameters’

1. **To plot the output**

An example of a module which creates graphs is provided with the model (plots.m). This function browses through the latest output directory, and plots all data present there in graphs. The titles of the graphs are the headings found in the output files.

# Model input

## User defined input parameters



## SLC input

In this directory, absorption spectra of different leaf components are provided, according to PROSPECT 3.1, as well as Fluspect input: standard spectra for PSI and PSII.

## Sensor

RTMo calculates spectra based on MODTRAN5 outputs. One .atm (atmospheric) file is provided in the data, 12 more are provided separately in a different .zip folder (in order to minimize the size of the SCOPE package, these are not provided standard). Note that in the input data (files as well as the spreadsheet), the broadband input radiation may be provided. SCOPE linearly scales the input spectra of the optical and the thermal domain in such a way, that the spectrally integrated input shortwave and long wave radiation matches with the measured values. A limitation of this approach is that the same *shape* of the input spectrum is used independent on the atmospheric conditions. If this scaling is not wanted, then leave ‘Rin’ and ‘Rli’ empty in the spreadsheet.

*NOTE: In earlier versions of the model (1.34 and older), two input spectra of solar and sky radiation were provided (rad.txt and rad2.txt) in this directory. The data were calculated with MODTRAN4. The ASCII file in this directory consisted of three columns containing the following. The first column contained the wavelength in nm, the second column the solar radiation in W m-2 μm-1, and the third column the sky radiation in W m-2 μm-1. These data are now obsolete (since version 1.40).*

In this directory, the soil spectrum is provided. The ASCII file in this directory consists of two columns containing the following: The first column contains the wavelength in μm, the following columns reflectance spectra.

# Output data

The module output\_file.m saves the output of SPART in an output directory. In SPART, output\_data is called after each calculation.

# Description of individual modules

**|-- documents**

**| `-- SPART\_v10 User manual.docx**

**|-- model**

**| |-- SPART\_input\_user\_defined.xlsx**

**| |-- inputdata**

**| | |-- BRDF\_files**

**| | | |-- brdf\_angles.dat**

**| | | `-- brdf\_angles2.dat**

**| | |-- SLC\_inputs**

**| | | |-- Extraterrestrial\_irradiance.mat**

**| | | |-- Optipar2017\_ProspectD\_BSM2019.mat**

**| | `-- Sensors**

**| | |-- spart\_sensor\_info\_LANDSAT4-TM.mat**

**| | |-- spart\_sensor\_info\_LANDSAT5-TM.mat**

**| | |-- spart\_sensor\_info\_LANDSAT7-ETM.mat**

**| | |-- spart\_sensor\_info\_LANDSAT8-OLI.mat**

**| | |-- spart\_sensor\_info\_Sentinel3A-OLCI.mat**

**| | |-- spart\_sensor\_info\_Sentinel3B-OLCI.mat**

**| | `-- spart\_sensor\_info\_TerraAqua-MODIS.mat**

**| |-- output**

**| | `-- TerraAqua-MODIS-testing**

**| | |-- TOA\_radiance.dat**

**| | |-- TOA\_reflectance.dat**

**| | |-- TOC\_reflectance.dat**

**| | |-- pars\_and\_input.dat**

**| | |-- wl\_sensor.dat**

**| | `-- wl\_spart.dat**

**| |-- run\_SPART.m**

**| |-- some\_examples**

**| | |-- Ex1\_LSA\_Cab\_SPART\_S3.m**

**| | |-- Ex2\_LSA\_LAI\_SPART\_S3.m**

**| | |-- Ex3\_LSA\_AOT\_SPART\_S3.m**

**| | `-- Ex4\_BRDF\_SPART\_S3.m**

**| `-- src\_SPART**

**| |-- BSM.m**

**| |-- Extraterrestrial\_radiance.m**

**| |-- PROSPECT\_5D.m**

**| |-- SAILH.m**

**| |-- SMAC.m**

**| |-- SPART\_main.m**

**| |-- Select\_parameter.m**

**| |-- Spectral\_convolution.m**

**| |-- define\_bands.m**

**| |-- output\_files.m**

**| |-- prepare\_LUT\_simulations.m**

**| |-- read\_coeffs.m**

**| |-- readme.txt**

**| |-- set\_input\_from\_excel.m**

**| `-- set\_input\_manually.m**

**|-- readme.txt**

**SPART\_main** calls all the scripts in the order presented in Figure 1.

**BSM** (function) simulates isotropic soil reflectance. It contains two submodules. The global soil vector (GSV) approach is used to simulate reflectance or dry soil, and the other submodule is an implementation of water film coating approach to account for the soil moisture effects. The output of BSM is soil reflectance. **soil.refl**

**PROSPECT\_5D (**function**)** simulates isotropic leaf reflectance and transmittance. It is based on the ‘plate model’. The output of PROSPECT-5D is leafopt.refl and leafopt.tran.

**SAILH (**function**)** simulates anisotropic canopy reflectance. It is based on the classic SAIL and includes the hot spot effects. It takes leaf optical properties and soil reflectance as inputs and simulates the canopy optical properties, which include canopy layer transmittance and reflectance and surface reflectance. The surface reflectance (rso, rdo, rdd, rsd) are used to couple with the atmosphere radiative transfer model.

**Extraterrestrial\_radiance.m**

**SAILH.m**

**SMAC.m**

**SPART\_main.m**

**Select\_parameter.m**

**Spectral\_convolution.m**

**define\_bands.m**

**output\_files.m**

**prepare\_LUT\_simulations.m**

**read\_coeffs.m**

**set\_input\_from\_excel.m**

**set\_input\_manually.m**

**Leafangles** (function) calculates the leaf inclination distribution from the parameters LIDFa and LIDFb.