User Manual: **Interactive Visualization of Vegetation Reflectance Models (IVVRM)**

Martin Danner[1] & Matthias Wocher[1]

[1]Ludwig-Maximilians-Universität München, Department für Geographie, Luisenstr. 37, 80333 München
Contact: martin.danner@iggf.geo.uni-muenchen.de,
m.wocher@iggf.geo.uni-muenchen.de

1. About the application

The Interactive Visualization of Vegetation Reflectance Models (IVVRM) tool is an interactive reflectance modelling environment mainly focusing on the Prospect + Sail (PROSAIL; Jacquemoud et al. 2009) radiative transfer model (RTM) family. All code, including the spectral models themselves, is written in Python allowing a time-efficient computation and a progressive visualization of the results whenever parameter settings, sensor options or model members are changed by the user.

Main fields of application of the IVVRM tool are seen in education and training, particularly for students and PhD candidates who focus their research on vegetation remote sensing data analysis. The plasticity of the tool contributes to a better and faster understanding of the benefits and limitations of RTMs. Effects of changes in the concentration of diverse plant constituents become apparent especially in the accumulative plotting mode, where several parameters can be set independently and are visualized with relatable colors in a common plotting canvas for a local sensitivity analysis.

Moreover, the IVVRM tool can be used as a starting point for hyperspectral data analysis. A manual adjustment of biophysical leaf and canopy parameters with the aim to minimize deviations between modelled and measured spectra serves as a simple but didactically clear inversion approach. Such an analysis extends the capability of the model by the knowledge of the user and allows for a more specific interpretation of the underlying processes in the transfer of incident radiation and the biophysics of vegetation. Improved understanding of the model dynamics for different vegetation types may facilitate the choice of more sophisticated methods, like iterative optimization algorithms, LUT-inversions or machine learning applications for biophysical variable retrievals (Verrelst et al. 2015).

2. Getting started

In order to use IVVRM, the EnMAP-Box 3.0 or higher needs to be downloaded and properly installed as QGIS-plugin. Please visit https://bitbucket.org/hu-geomatics/enmap-box/wiki/Home for further instructions on how to link EnMAP-Box 3.0 with QGIS.

IVVRM is found in the Application menu item -> Agricultural Applications -> *Interactive Visualization of Vegetation Reflectance Models (IVVRM)*. The tool will open in a new window with default settings (Figure 1).

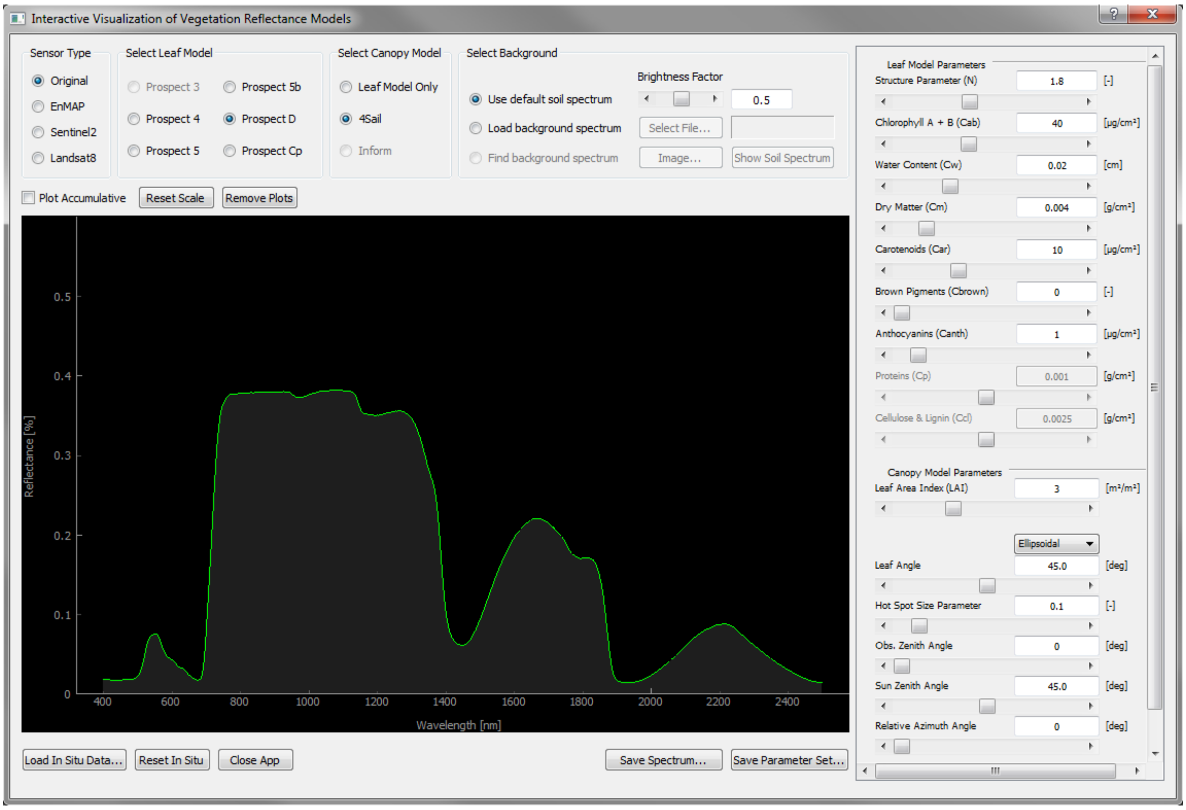

Figure 1: Screenshot of the Interactive Visualization of Vegetation Reflectance Models (IVVRM) main window with default settings.

Changing the input or post-processing settings of the model automatically invokes a new model run. The result is plotted in the black graph widget.

3. User input

3.1 Sensor type

By default, PROSAIL calculates reflectances with a spectral sampling width of 1 nm (original). If a different sensor type is selected, PROSAIL results are spectrally resampled to match this sensor (currently: EnMAP hyperspectral imager, Sentinel-2 multispectral imager, Landsat-8 operational land imager) in terms of number and wavelengths of band. The spectral response function of those earth observation systems are supplied with the tool and might change after the actual launch of EnMAP. Reflectances for the central wavelengths of all sensor bands are calculated as weighted averages of neighboring PROSAIL output bands.

Tip: *The resampling is a mathematical intensive process and takes longer than the actual model run. The more bands a target sensor has, the more inertly the tool will behave. Move the parameter sliders slowly when displaying model results as pseudo-EnMAP spectra (242 bands!).*

3.2 Leaf model

For a simulation of leaf optical properties, the user can choose from a variety of Prospect models, starting with Prospect 4, 5, 5B up to Prospect D (Féret et al. 2017). Prospect Cp is a modified version by Wang et al. (2015) in which dry matter content is split into proteins (C_P), cellulose & lignin (C_{cl}) as well as dry residuals (C_m). Depending on the selected model, in the biophysical input frame parameters will automatically be enabled or disabled accordingly. An overview of the Prospect parameters is contained in Table 1.

3.3 Canopy model

Prospect can optionally be coupled with a canopy architecture model to form top of canopy spectra. Up to now, only one version of SAIL (Scattering of Arbitrarily Inclined Leaves) – 4SAIL (Verhoef et al. 2007) – can be selected which enables the canopy model parameters listed in Table 1. For forestry applications, the Invertable Forest Reflectance Model (INFORM) is considered for implementation to pose an alternative for coupling the leaf model results.

Table 1: Overview of the PROSAIL parameters as used in the IVVRM tool. Some parameters, like e.g. the leaf chlorophyll content, are used in all Prospect versions, whereas other parameters were included in newer releases.

Parameter	Description	Model versions
N	Leaf structure parameter	Prospect (all)
C_{cab}	Leaf Chlorophyll$_{a+b}$ content	Prospect (all)
C_w	Leaf Equivalent Water content	Prospect (all)
C_m	Leaf Mass per Area	Prospect (all)
C_{car}	Leaf Carotenoids content	Prospect 5
C_{br}	Fraction of brown leaves	Prospect 5B
C_{anth}	Leaf Anthocyanins content	Prospect D
LAI	Leaf Area Index	SAIL
LIDF	Leaf Inclination Distribution Function	SAIL
ALIA	Average Leaf Inclination Angle	SAIL
Hspot	Hot Spot size parameter	SAIL
ρ_{soil}	Soil Reflectance (optional)	SAIL
P_{soil}	Soil Brightness Parameter	SAIL
SZA	Sun Zenith Angle	SAIL
OZA	Observer Zenith Angle	SAIL
rAA	relative Azimuth Angle	SAIL

3.4 Spectral background

When observing canopies instead of single leaves, information about the spectral background is required. By default, 4SAIL provides one typical bright and one typical dark soil spectrum, characterizing low and high moisture levels of the soil surface. The final background signal is computed using a soil brightness factor (P_{soil}), which can be defined by the user. A high value for P_{soil} gears towards the bright, a low value towards the dark soil spectrum.

If available, an individual background spectrum can be supplied via *Load background spectrum* (see chapter 4.2). In this case, the default 4SAIL background spectra are overwritten and P_{soil} becomes obsolete. This is especially useful if in situ observations of open soil are available for the desired study area.

For a future release, it is planned to select background spectra from images opened in the EnMAP-Box, allowing a reproduction of observations directly from remote sensing data.

3.5 Input parameters

On the right-hand side of the window, biophysical input parameters are grouped into leaf model parameters (Prospect) and canopy model parameters (SAIL). Each group can be collapsed to save space on the screen. If the list is still longer than the vertical extent of the window, a scroll bar will automatically appear.

A parameter is changed either by moving its horizontal slider, or by entering the value directly in the associated text box and hitting return. Both approaches are limited by min and max values to prevent math errors or implausible model results (see Table 2). Every time a model parameter is changed, the reflectance model is re-calculated and the spectrum is updated and shown in the graph widget.

One special case of parameter is the Leaf Angle. Here, the user can choose between two different leaf angle distribution functions: ellipsoidal or beta-distribution. The ellipsoidal distribution function asks for an average leaf inclination angle which has to be supplied by the user in the respective text box. If a beta distribution is chosen, the field becomes disabled and a distribution function type is selected from the dropdown menu instead. Learn more about leaf inclination distribution function types in Goel & Strebel (1984).

Table 2: Overview of the PROSAIL parameters and their according dimensions, as used in the IVVRM tool. Some parameters, like e.g. the leaf chlorophyll content, are used in all Prospect versions, whereas other parameters were included in newer releases.

Parameter	**Unit**	**Min**	**Max**
N	-	1.0	3.0
C_{cab}	µg cm^{-2}	0.0	100.0
C_w	cm	0.002	0.7
C_m	g cm^{-2}	0.00019	0.0165
C_{car}	µg cm^{-2}	0.0	30.0
C_{br}	-	0.0	1.0
C_{anth}	µg cm^{-2}	0.0	10.0
LAI	m^2 m^{-2}	0.01	10.0
ALIA	deg	0.0	90.0
Hspot	-	0.0	1.0
P_{soil}	-	0.0	1.0
SZA	deg	0.0	89.0
OZA	deg	0.0	89.0
rAA	deg	0.0	180.0

4. Working with the tool

4.1 Navigating in the graph widget

The graph widget is a canvas with black background in which the model results are plotted. To be precise, it is a QGraphWidget provided through the QGIS framework and PyQt. This widget can be used interactively, allowing the user to change appearance and display settings on the fly. The following interactions are possible:

- ✓ Zooming in & out via *mouse wheel*
- ✓ Moving the graph by *holding down left mouse button or mouse wheel* and *"dragging" the plot into the desired direction*
- ✓ Specifying ranges for the axes via *right click -> X-Axis (/ Y-Axis) -> Manual min & max*
- ✓ Optimizing both axes ranges *via right click -> View All*
- ✓ Toggle grid lines on / off via *right click -> Plot Options -> Grid*

In addition, ranges for X-axis and Y-axis are set back to default by hitting *Reset Scale* – a push button, located above the graph widget – and plots can be removed by clicking on *Remove Plots*, next to *Reset Scale*.

4.2 Importing in situ and background spectra

Whenever the push button *Load In Situ Data…* or *Select File…* in the background section is clicked, a child window appears (Figure 2)

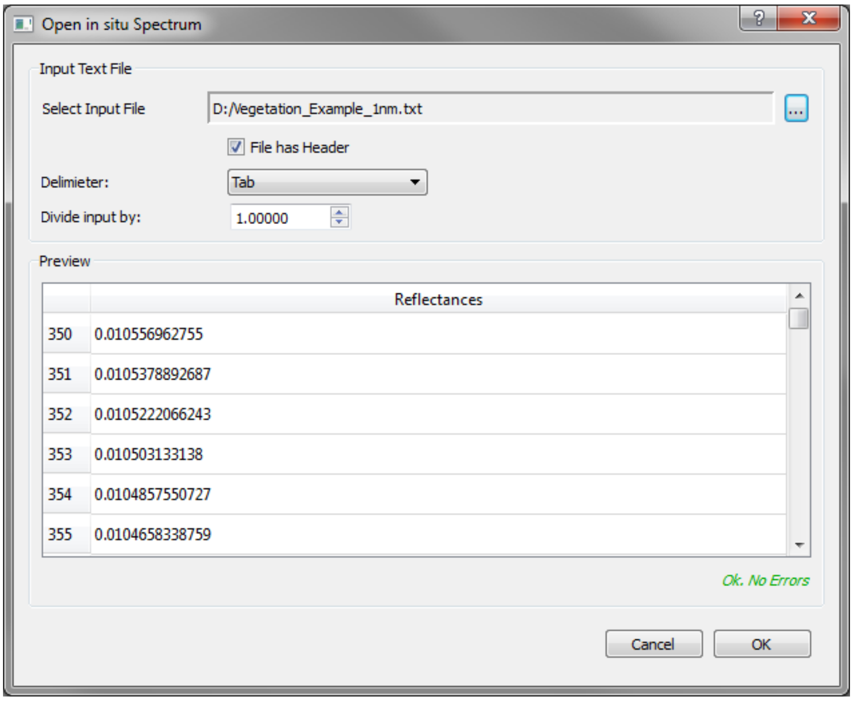

Figure 2: Example of the OPEN Dialog in IVVRM. The same dialog is used for both in situ spectra and background model spectra. A file has to be selected and the reader will automatically find out whether the file has a header and which delimiter is used to separate data columns. A division factor can be set to put model output and file input on the same scale. If no errors occur, the user can proceed with the import.

In this dialog, at first an input file (in situ or background) has to be selected (only *.csv or *.txt allowed). The path will be shown in the sunken label section. IVVRM will inspect the file and automatically check if the first row is a header or not and will guess the delimiter according to the most frequent appearance in the file. If this information is sufficient to read the file correctly, its content will be displayed in the Preview-section. The user can manually override header information and delimiter and check if the file is still readable. A status message in the lower right corner indicates possible issues. Only if there are no errors, the OK button is enabled and the user can proceed to the next step.

Tip: If a text file cannot be read, although delimiter and header type seem correct, you can check the valid construction of the file by comparing with one of the example files in the application folder. Check for unnecessary blanks in the header, the text format ('UTF-8' preferred) and the end-of-line character ('\n' preferred).

Sometimes reflectances are given as multiples of a fraction of one, so that they can be stored using integer data type. A value of 5,000 would e.g. mean 50% or 0.5 reflectance. To compare these data on different scales, a division factor can be set by the user. For the example mentioned, a division factor of 10,000 would put both data on the same scale.

Tip: For a multiplication of the in situ data, just apply a division factor between 0 and 1.

After confirming the import with *OK*, the user is directed to another dialog in which bands can be (de-)selected from/for processing (Figure 3). Multiple bands can be selected and moved to the list of excluded/included bands at once. When opening an in situ Spectrum, the excluded bands will be set to Python *NaN* value. In the graph widget, data gaps will be visualized by a straight line between valid neighbor data points, but they are ignored in the statistics. For background spectra, data gaps are visualized just the same, but the data points are in fact interpolated values that serve as valid input for the SAIL model.

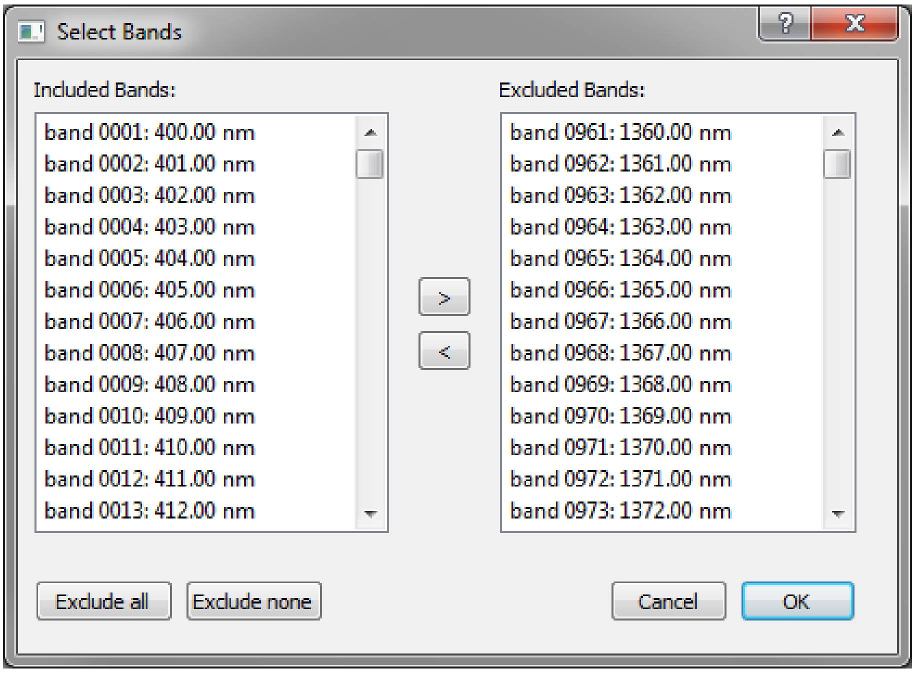

Figure 3: Single bands or ranges of bands can be excluded from the statistics of in situ and modelled spectra. For background spectra, the according wavelengths are interpolated linearly.

A default selection of bands / wavelengths is excluded or interpolated (Table 3). The according bands are filled automatically into the exclusion and inclusion list. Hit *Exclude None* to clear the selection.

Table 3: Default ranges for exclusion from statistics (in situ spectrum) or for interpolation (background signal) for narrow-band field spec data.

Band range	**Wavelength range [nm]**	**Error source**
961 – 1021	1360 – 1420	Atmospheric water absorption
1391 – 1551	1790 – 1950	Atmospheric water absorption
2001 – 2101	2400 – 2500	Sensor noise

If a spectrum text file consists of more than two columns, the first one is considered to provide wavelengths in nanometers and the others contain reflectance data. A mean value is calculated for each band in this case to form an average spectrum from all columns.

Tip: *ASCII files with multiple columns representing multiple spectra can be created with* ASD ViewSpec Pro*, the data processing tool for ASD field spectrometers. In the* ASCII Export *section check* Output to a Single File*. The resulting text file is readable in IVVRM.*

In situ spectral data is removed from the graph widget and from statistics when *Reset In Situ* is clicked. For a reset of background spectra, the radio button in the *Select Background* frame needs to be moved to *Use default soil spectrum*. IVVRM will forget about the imported spectra after each reset.

4.3 Statistical indices

When an in situ Spectrum is successfully loaded into the graph widget, IVVRM will try to compare reflectances of the modelled vs. measured spectrum band-wise. If both spectra have the same number of bands, statistics are computed and the result is showed in the upper right corner of the graph widget. If the number of bands differs, a sensor mismatch is assumed, but the spectrum will still be displayed. The following statistical indices are calculated: Root Mean Squared Error (RMSE, Eq. (1)), Mean Absolute Error (MAE, Eq. (2)), Nash-Sutcliffe Efficiency (NSE, Eq. (3)), modified Nash-Sutcliffe-Efficiency (mNSE, Eq. (4)) and the Coefficient of Determination (R^2, Eq. (5)).

$$\mathrm{RMSE} = \sqrt{\frac{1}{n}\cdot\sum_{i=1}^{n}\left(R_{\mathrm{measured}}(\lambda_i) - R_{\mathrm{simulated}}(\lambda_i)\right)^2} \tag{1}$$

$$\mathrm{MAE} = \sum_{i=1}^{n}\left|R_{\mathrm{measured}}(\lambda_i) - R_{\mathrm{simulated}}(\lambda_i)\right| \tag{2}$$

$$\mathrm{NSE} = 1 - \frac{\sum_{i=1}^{n}\left(R_{\mathrm{measured}}(\lambda_i) - R_{\mathrm{simulated}}(\lambda_i)\right)^2}{\sum_{i=1}^{n}\left(R_{\mathrm{measured}}(\lambda_i) - \overline{R}_{\mathrm{measured}}\right)^2} \tag{3}$$

$$\mathrm{mNSE} = 1 - \frac{\sum_{i=1}^{n}\left|R_{\mathrm{measured}}(\lambda_i) - R_{\mathrm{simulated}}(\lambda_i)\right|}{\sum_{i=1}^{n}\left|R_{\mathrm{measured}}(\lambda_i) - \overline{R}_{\mathrm{measured}}\right|} \tag{4}$$

$$R^2 = \left[\frac{\sum_{i=1}^{n}\left((R_{measured}(\lambda_i) - \bar{R}_{measured}) \cdot (R_{simulated}(\lambda_i) - \bar{R}_{simulated}\right)}{\sqrt{\sum_{i=1}^{n}(R_{measured}(\lambda_i) - \bar{R}_{measured})^2} \cdot \sqrt{\sum_{i=1}^{n}(R_{simulated}(\lambda_i) - \bar{R}_{simulated})^2}} \right]^2 \quad (5)$$

$R_{measured}(\lambda_i)$ is the measured and $R_{simulated}(\lambda_i)$ the modelled reflectance at wavelength λ for the i^{th} spectral sensor band. n is the total number of bands analyzed.

The statistics module is only active when accumulative plotting is switched off. Invalid reflectances are marked as *NaN*s.

4.4 Exporting spectra and parameter sets

The export buttons, both located on the right below the graph widget, allow capturing current model inputs and outputs. *Save Spectrum* exports the currently modelled reflectances as text files with two data columns: wavelength and reflectance. They are built such that they can be re-loaded into IVVRM via *Load In Situ Data*. A constellation of biophysical input parameters can be stored by clicking on *Save Parameter Set*. Only those parameters will be saved, however, that are used by the currently selected model.

Tip: Statistical indices can be used to approximate modelled and measured spectra until a suitable match is found. Now the parameter constellation can be saved to finish a simple variable retrieval via manual optimization.

4.5 Accumulative plotting

The *Accumulative Plotting* option is a check box above the upper left corner of the graph widget. It is disabled by default, so each call of PROSAIL overwrites the result of the previous model run and draws a graph in green.

If accumulative plotting is selected, results are in turn stored and new plots are added to the existing one(s) with a parameter-specific style. The color of each plot is associated with a single parameter and indicates which of them had been changed to invoke the latest model run.

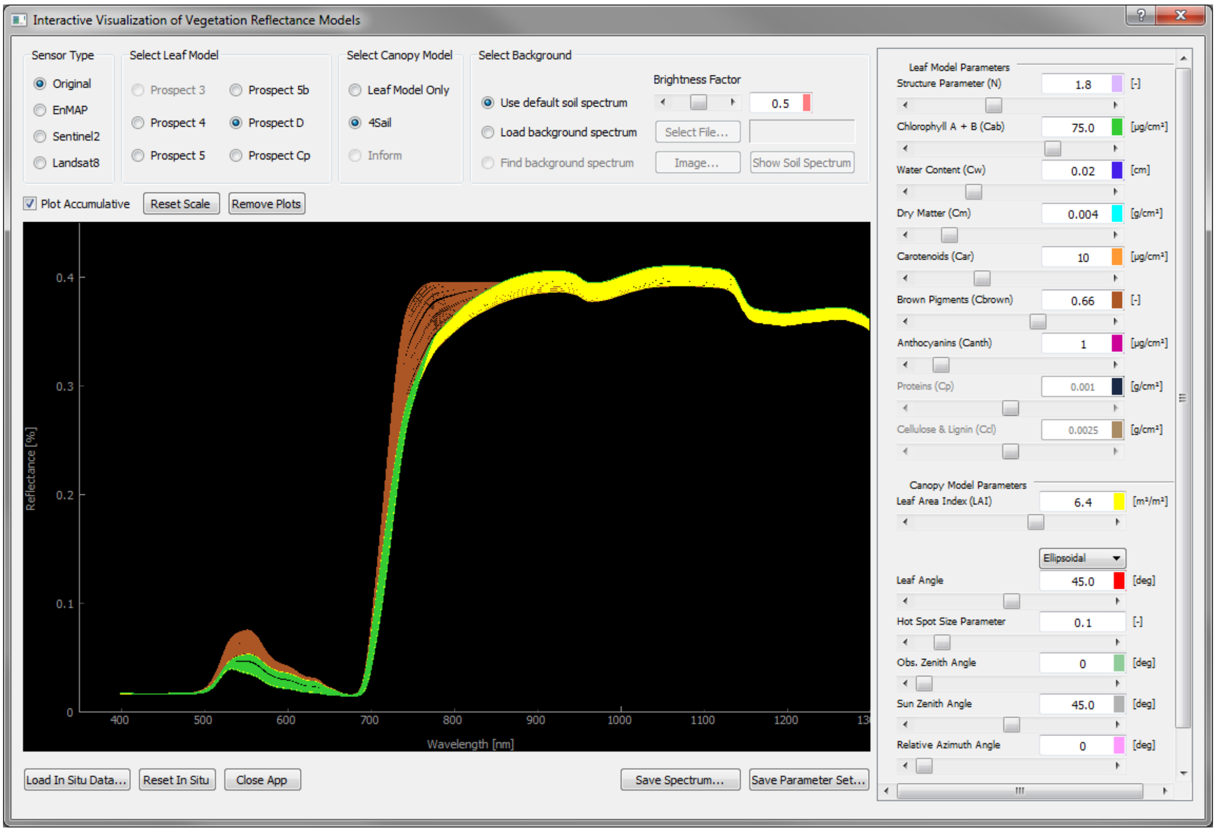

Figure 4: Accumulative plotting is enabled, so each biophysical model parameter is additionally labelled with a certain color. This color is in turn used for the graph whenever the parameter was changed to invoke a new model run. In this case, C_{br} was increased stepwise from 0.0 to 0.66, then LAI was increased from 4.0 to 6.4 $m^2 m^{-2}$ and finally C_{cab} was increased from 40 to 75 µg cm^{-2}.

Not only is this option suitable to track changes of the biophysical input parameters (e.g. for a local sensitivity analysis), but also changes between different sensor types. They are depicted by different line styles (see Figure 5 and Table 4)

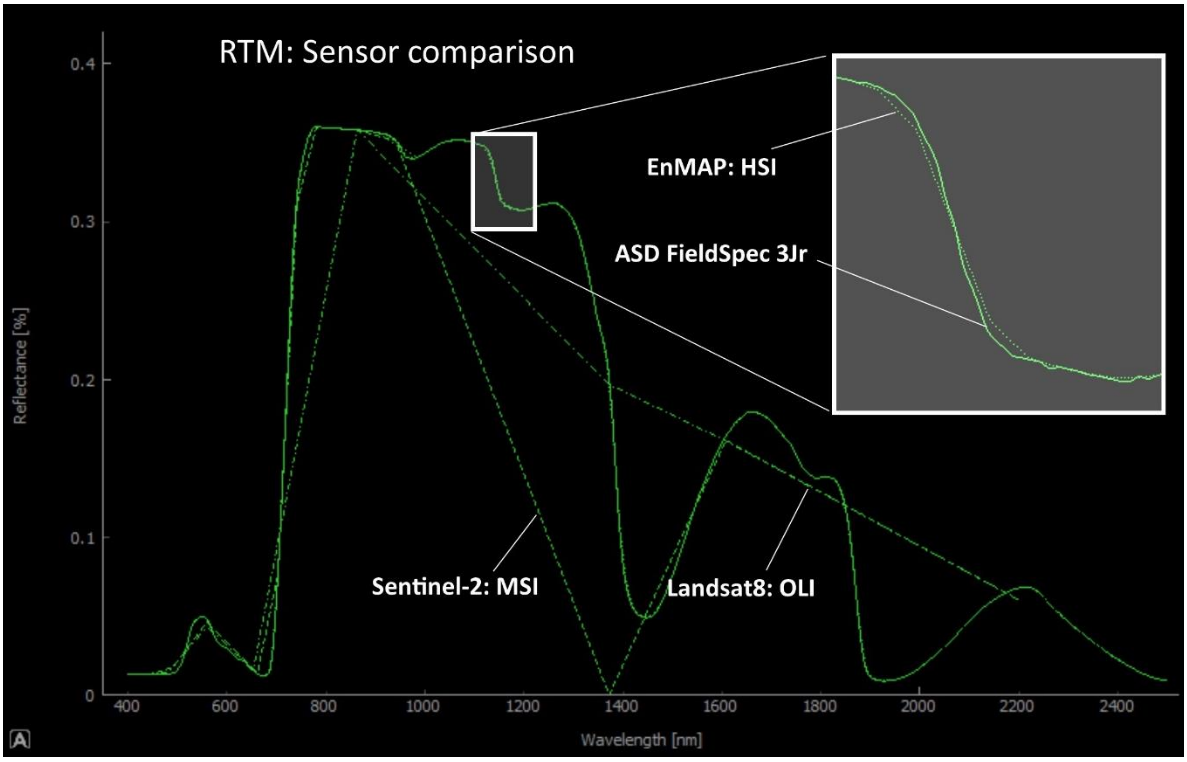

Figure 5: Another application of the accumulative plotting mode of IVVRM is the comparison of different spectral resolutions associated with different earth observation systems. Model output is displayed in different line styles for different sensors. Currently, four sensors are taken into account: solid (original model resolution, corresponds to most field spec sensors), dotted (EnMAP hyperspectral), dashed (Sentinel-2 multispectral) and dash-dot (Landsat8 multispectral). Hyperspectral resampling best reproduces the original shape of the PROSAIL output.

Table 4: Overview of spectral resampling to different sensor types and the line styles they are shown in for accumulative plotting.

Sensor Type	Line Style
Original (PROSAIL)	--------------
EnMAP hyperspectral	·················
Sentinel-2 multispectral	- - - - - - - - -
Landsat-8 multispectral	- - · - - · - - ·

Even though it looks as if more plots were just being added to the canvas, they are all in fact redrawn each time a new spectrum member comes in. For this reason, the tool becomes slower when too many spectra are contained in the graph widget, so it seems useful to remove the plots from time to time via *Remove Plots*.

5. Bug-fixes and version control

This is a first release of the IVVRM (v. 1.0). Please report bugs and major problems to martin.danner@iggf.geo.uni-muenchen.de or m.wocher@iggf.geo.uni-muenchen.de with a description of the problem including error message or screenshots. We are always willing to improve the tool if you feel like important features are missing.

Acknowledgement

Prospect: all credits to Stéphane JACQUEMOUD, Frédéric BARET and Jean-Baptiste FÉRET.

SAIL: all credits to Wouter VERHOEF and his team at the ITC.

Special thanks go to Humboldt-Universität zu Berlin (Sebastian van der LINDEN, Benjamin JAKIMOW, Andreas RABE) for their assistance with developing the IVVRM tool, working with PyQt, PyCharm and embedding the code into the EnMAP-Box.

References

Féret, J.B.; Gitelson, A.A.; Noble, S.D.; Jacquemoud, S. Prospect-d: Towards modeling leaf optical properties through a complete lifecycle. *Remote Sensing of Environment* **2017**, *193*, 204-215.

Goel, N. S. and D. E. Strebel. Simple beta distribution representation of leaf orientation in vegetation canopies. *Agronomy Journal* **1984**, 76(5), 800-802.

Jacquemoud, S.; Verhoef, W.; Baret, F.; Bacour, C.; Zarco-Tejada, P.J.; Asner, G.P.; François, C.; Ustin, S.L. Prospect + sail models: A review of use for vegetation characterization. *Remote Sensing of Environment* **2009**, *113, Supplement 1*, S56-S66.

Verhoef, W.; Jia, L.; Xiao, Q.; Su, Z. Unified optical-thermal four-stream radiative transfer theory for homogeneous vegetation canopies. *IEEE Transactions on Geoscience and Remote Sensing* **2007**, *45*, 1808-1822.

Verrelst, J.; Camps-Valls, G.; Muñoz-Marí, J.; Rivera, J.P.; Veroustraete, F.; Clevers, J.G.P.W.; Moreno, J. Optical remote sensing and the retrieval of terrestrial vegetation bio-geophysical properties – a review. *Isprs J Photogramm* **2015**, *108*, 273-290.

Wang, Z.; Skidmore, A.K.; Wang, T.; Darvishzadeh, R.; Hearne, J. Applicability of the prospect model for estimating protein and cellulose+lignin in fresh leaves. *Remote Sensing of Environment* **2015**, *168*, 205-218.

Citable Publication of IVVRM

Danner, M.; Wocher, M.; Berger, K.; Mauser, W. & Hank, T. Interactive Visualization of Vegetation Reflectance Models (IVVRM): a Guided User Interface for plotting and analyzing the output of PROSAIL. Submitted to *Environmental Modelling and Software* **2017**.