ARTMO: a Toolbox for Automated Retrieval of Biophysical parameters through Inversion of Plant Radiative Transfer Models

J. Verrelst[1]*, J.P. Rivera[1], G. Leonenko[2], L. Alonso[1] & J. Moreno[1]

[1] Image Processing Laboratory (IPL), University of Valencia, Spain

[2] Department of Geography, College of Science, Swansea University, UK

*Jochem Verrelst
Image Processing Laboratory
University of Valencia, Spain
Jochem.verrelst@uv.es

1. Introduction

ARTMO, an Automated Radiative Transfer Models Operator toolbox

Radiative transfer (RT) models play a key role in earth observation (EO). They are needed to design and develop EO instruments, and to test and apply inversion algorithms. In the scientific community a number of often highly specialized leaf and canopy RT models has been developed, each of which emanates from a different set of original requirements. ARTMO (Automated Radiative Transfer Models Operator) is the first toolbox that brings a variety of leaf and canopy RT models together in one GUI. Moreover, ARTMO encompasses essential tools for EO applications such as defining your own sensor, plotting and exporting outputs and automated LUT-based model inversion. With ARTMO, maps of biophysical parameters can be rapidly derived from EO data. As the toolbox is constantly under development new features are presented here.

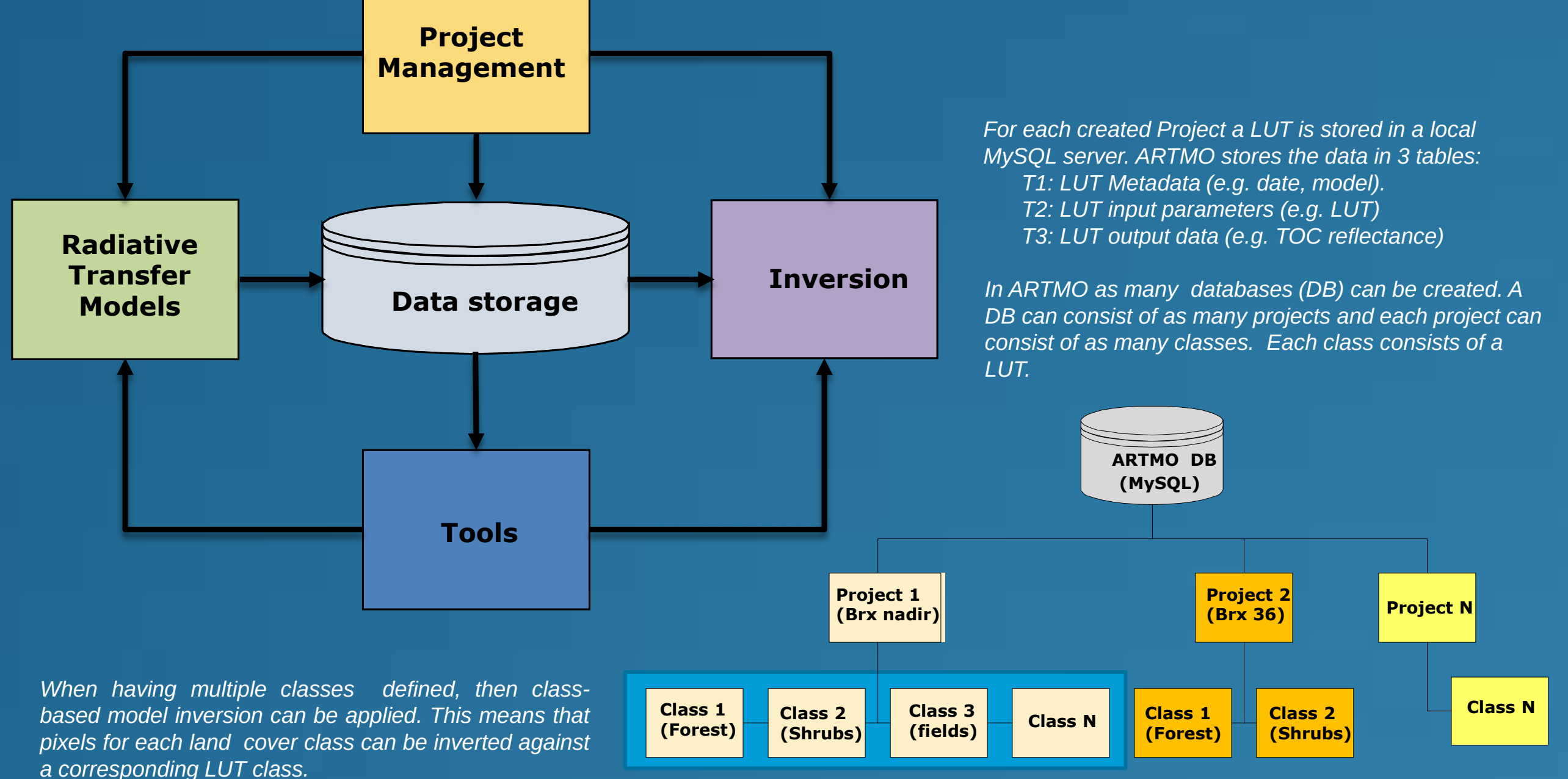
Objectives

The aim of this study was to expand ARTMO by offering advanced functions for improved retrieval performances through model inversion. Specifically, the objective was to implement a new inversion module that provides and evaluates a wide range of cost functions.

A secondary objective was to test these cost functions against a validation dataset (SPARC; Barrax, Spain).

2. Conceptual design

ARTMO is a toolbox written in Matlab that consists of a package of GUIs. ARTMO incorporates a variety of leaf and canopy radiative transfer models, which can be operated through the creation of' 'Projects'. Within a Project, Look Up Tables (LUT) can be created, which are then stored in a MySQL database (DB). These LUTs can then be evoked by various modules such as the Graphics module or the Inversion module for further processing. LUT-based inversion against an EO image finally leads to the retrieval of biophysical parameters.



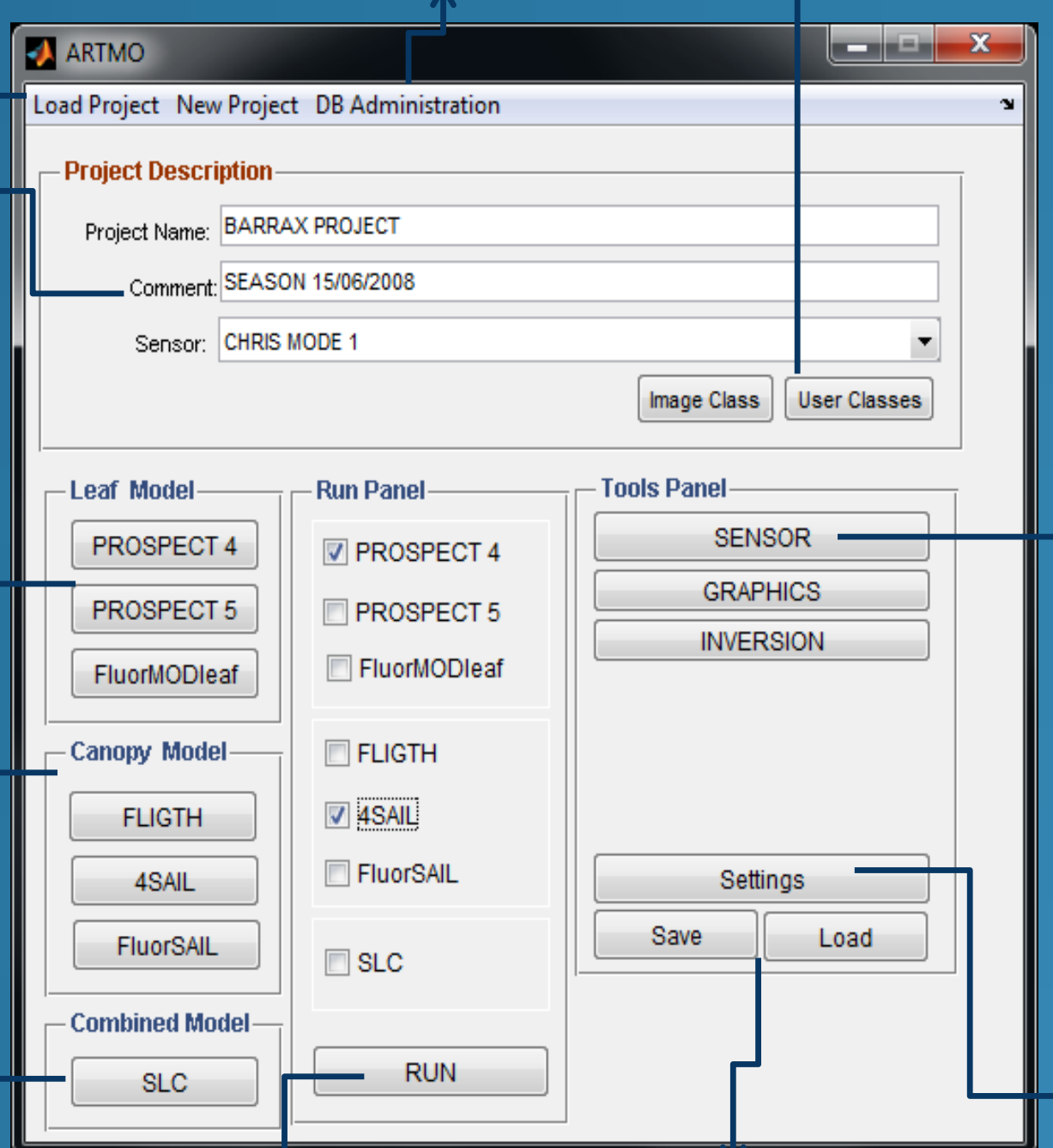
For each created Project a LUT is stored in a local MySQL server. ARTMO stores the data in 3 tables:
T1: LUT Metadata (e.g. date, model).
T2: LUT input parameters (e.g. LUT)
T3: LUT output data (e.g. TOC reflectance)

In ARTMO as many databases (DB) can be created. A DB can consist of as many projects and each project can consist of as many classes. Each class consists of a LUT.

When having multiple classes defined, then class-based model inversion can be applied. This means that pixels for each land cover class can be inverted against a corresponding LUT class.

3. ARTMO's main module

- *Choose stored project form MySQL*
- *Possibility to change DB*
- *Import, export project*
- *Delete class, project or DB*
- *Selection of classes from a classified map, or:*
- *Defining own user classes*



Project Name: BARRAX PROJECT
Comment: SEASON 15/06/2008
Sensor: CHRIS MODE 1
Run Panel: ☑ PROSPECT 4 ☐ PROSPECT 5 ☐ FluorMODleaf ☐ FLIGTH ☑ 4SAIL ☐ FluorSAIL ☐ SLC

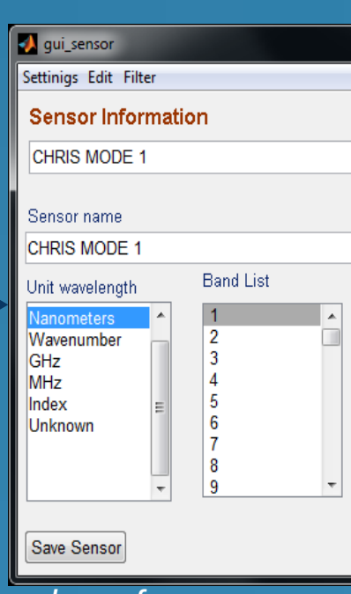
Provide a name of your project, and option to add a comment

Included leaf-level models

Included canopy-level models

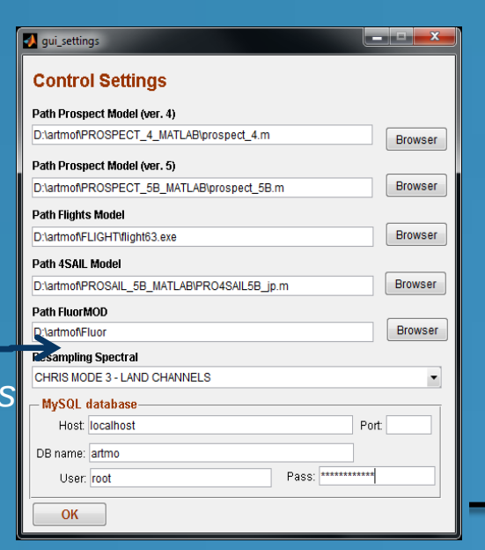
Combined soil, leaf and canopy (SLC) model

Run the configured models



CHRIS MODE 1
Sensor name: CHRIS MODE 1
Min: 406
Max: 415
Center: 411
Bwidth: 10

A number of sensors are already included:
- *CHRIS mode 1, 2, 3, 4, 5*
- *Sentinel-2*
- *MODIS*



Path Prospect Model (ver. 4): D:\artmo\PROSPECT_4_MATLAB\prospect_4.m
Path Prospect Model (ver. 5): D:\artmo\PROSPECT_5B_MATLAB\prospect_5B.m
Path Flights Model: D:\artmo\FLIGHT\flight63.exe
Path 4SAIL Model: D:\artmo\PROSAIL_5B_MATLAB\PRO4SAIL5B_jp.m
Path FluorMOD: D:\artmo\Fluor
Resampling Spectral: CHRIS MODE 3 - LAND CHANNELS
Host: localhost
DB name: artmo
User: root

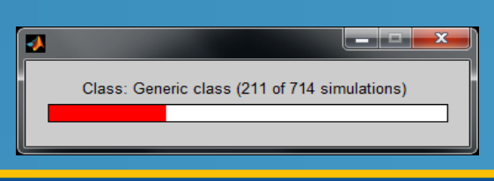
- *Paths to the models*
- *MySQL settings*
- *Save all inputs*
- *Load earlier saved inputs*

When selecting a sensor, all input data will be automatically resampled to the spectral settings of the selected sensor. This means that any type of spectra (e.g. from field spectrometer or from satellite observations) can be fed into the models (e.g. soil spectra). A warning message appears when ARTMO detects that spectral resampling is required. Any spectral settings can be defined by the user. This is helpful for simulations studies of new or upcoming sensors such as FLEX. Output data is then provided according to chosen sensor.

When a model has been configured it turns active in the 'Run Panel'. Any configured leaf model can be coupled with any configured canopy model. However note that FluorMODleaf needs to be coupled with FluorSAIL to simulate fluorescence emission at canopy level. When clicking on 'Run' then all combinations of the leaf and canopy LUTs will be simulated.

Input, output and meta data are directly stored in a MySQL data server.

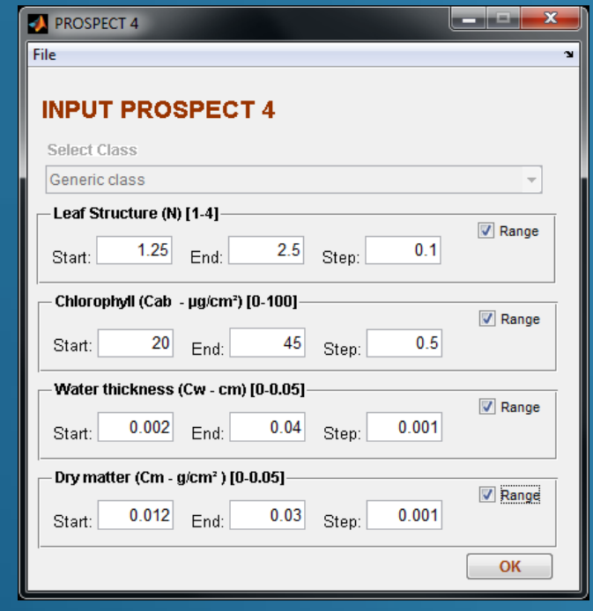
On time-consuming tasks, such as forward simulations and inversion calculations, ARTMO provides progress bars of processing time and executed simulations or inverted pixels, respectively.



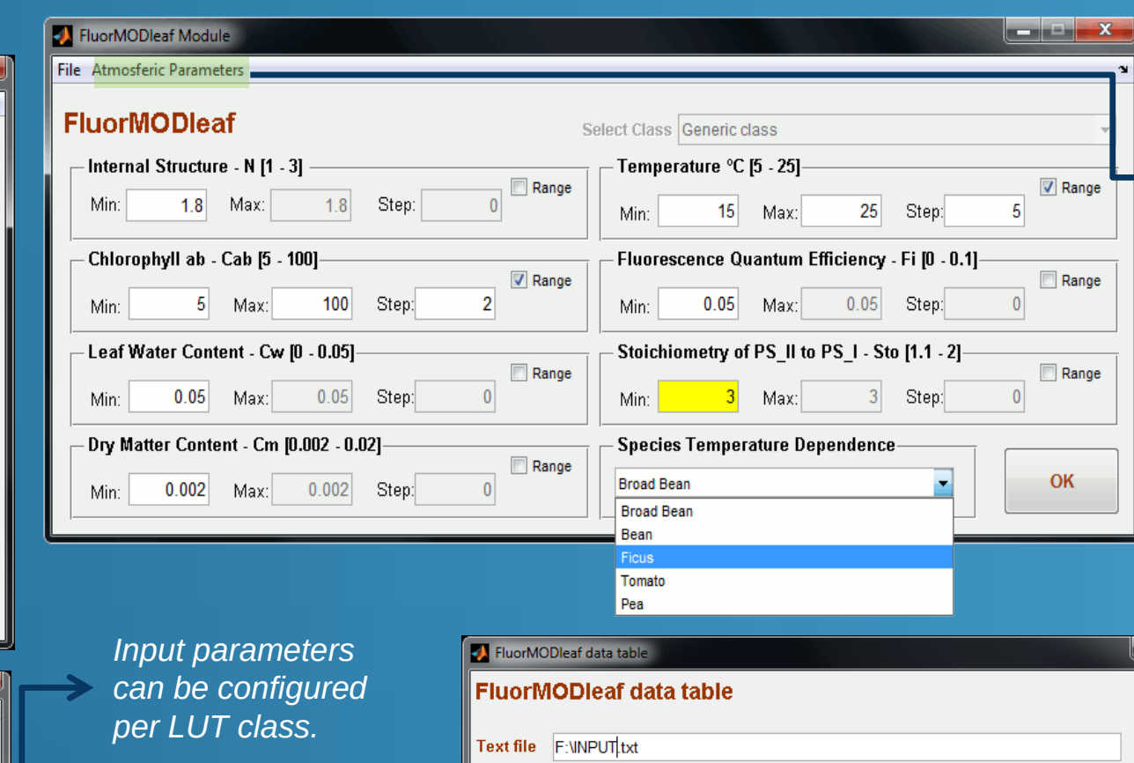
Class: Generic class (211 of 714 simulations)

4. Leaf-level models

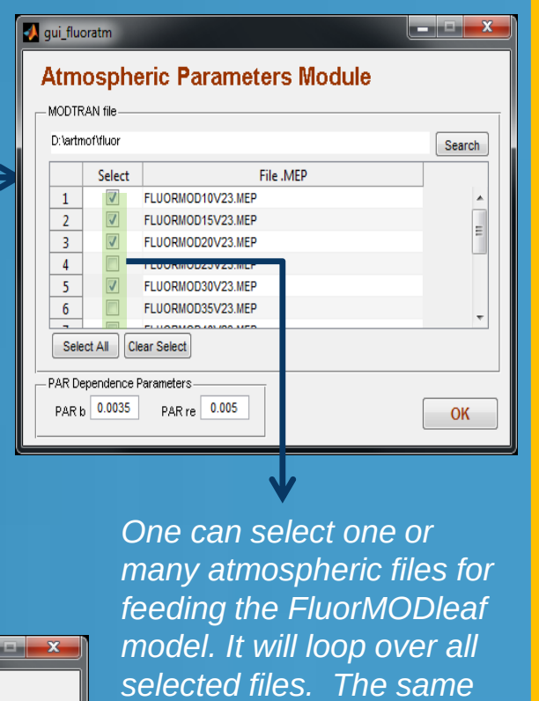
ARTMO incorporates the following leaf RT models: PROSPECT4, PROSPECT5 and FluorMODleaf. For each model parameter, a single value, a range of values or an array of user-defined input values can be inserted. All combinations will be simulated.



Leaf Structure (N) [1-4]: Start: 1.25 End: 2.5 Step: 0.1 ☑ Range
Chlorophyll (Cab - µg/cm²) [0-100]: Start: 20 End: 45 Step: 0.5 ☑ Range
Water thickness (Cw - cm) [0-0.05]: Start: 0.002 End: 0.04 Step: 0.001 ☑ Range
Dry matter (Cm - g/cm²) [0-0.05]: Start: 0.012 End: 0.03 Step: 0.001 ☑ Range

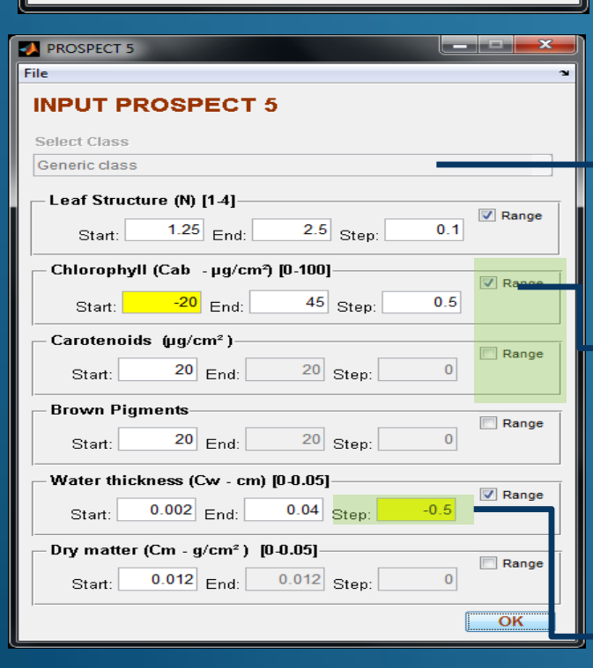


Internal Structure - N [1 - 3]: Min: 1.8 Max: 1.8 Step: 0 ☐ Range
Temperature °C [5 - 25]: Min: 15 Max: 25 Step: 5 ☑ Range
Chlorophyll ab - Cab [5 - 100]: Min: 5 Max: 100 Step: 2 ☑ Range
Fluorescence Quantum Efficiency - Fi [0 - 0.1]: Min: 0.05 Max: 0.05 Step: 0 ☐ Range
Leaf Water Content - Cw [0 - 0.05]: Min: 0.05 Max: 0.05 Step: 0 ☐ Range
Stoichiometry of PS_II to PS_I - Sto [1.1 - 2]: Min: 3 Max: 3 Step: 0 ☐ Range
Dry Matter Content - Cm [0.002 - 0.02]: Min: 0.002 Max: 0.002 Step: 0 ☐ Range
Species Temperature Dependence: Broad Bean (Broad Bean, Bean, Ficus, Tomato, Pea)



D:\artmo\fluor
FLUORMOD10V23.MEP
FLUORMOD15V23.MEP
FLUORMOD20V23.MEP
FLUORMOD25V23.MEP
FLUORMOD30V23.MEP
FLUORMOD35V23.MEP
PAR b: 0.0035 PAR re: 0.005

One can select one or many atmospheric files for feeding the FluorMODleaf model. It will loop over all selected files. The same atmospheric files will then be applied at canopy level for FluorSAIL.

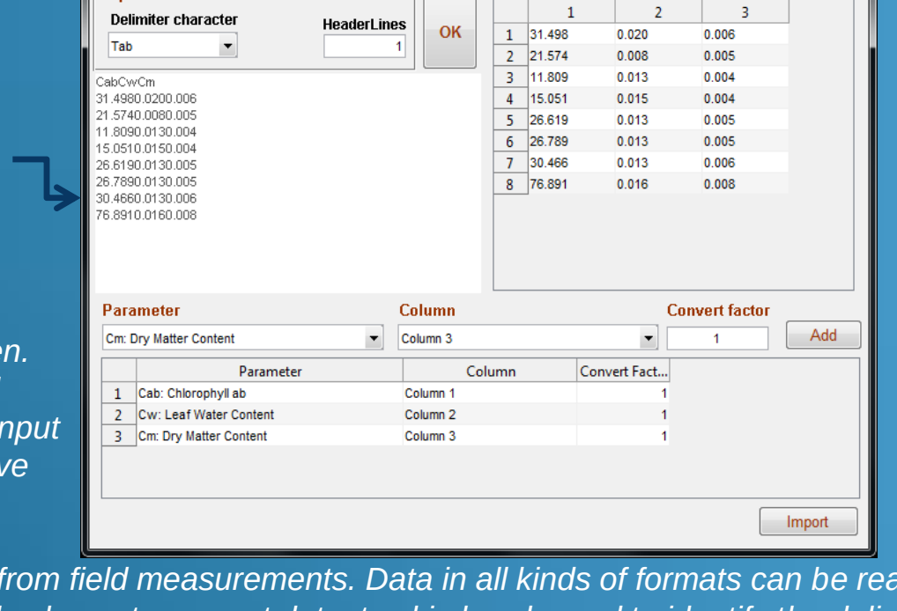


Leaf Structure (N) [1-4]: Start: 1.25 End: 2.5 Step: 0.1 ☑ Range
Chlorophyll (Cab - µg/cm²) [0-100]: Start: -20 End: 45 Step: 0.5 ☑ Range
Carotenoids (µg/cm²): Start: 20 End: 20 Step: 0 ☐ Range
Brown Pigments: Start: 20 End: 20 Step: 0 ☐ Range
Water thickness (Cw - cm) [0-0.05]: Start: 0.002 End: 0.04 Step: -0.5 ☑ Range
Dry matter (Cm - g/cm²) [0-0.05]: Start: 0.012 End: 0.012 Step: 0 ☐ Range

Input parameters can be configured per LUT class.

Model input values can either be a single value, a range of values with fixed steps, or a list of user-defined (measured) values from a text file.

Default values are given. ARTMO identifies and highlights impossible input values, such as negative values.



Text file: F:\INPUT.txt
Delimiter character: Tab
HeaderLines: 1

	1	2	3
1	31.498	0.020	0.006
2	21.574	0.008	0.005
3	11.809	0.013	0.004
4	15.051	0.015	0.004
5	26.619	0.013	0.005
6	26.789	0.013	0.005
7	30.466	0.013	0.006
8	76.891	0.016	0.008

	Parameter	Column	Convert Fact...
1	Cab: Chlorophyll ab	Column 1	1
2	Cw: Leaf Water Content	Column 2	1
3	Cm: Dry Matter Content	Column 3	1

ARTMO can read in text files with model input values, e.g. coming from field measurements. Data in all kinds of formats can be read. Data columns can be linked to a corresponding parameter. Options to select the required column, to convert data, to skip header and to identify the delimiter character are provided. When a model parameter is being fed by data then this parameter is disabled in the main input window. This parameter can then be combined with inputs of the remaining parameters (single value, range or user-defined values).

Conclusions

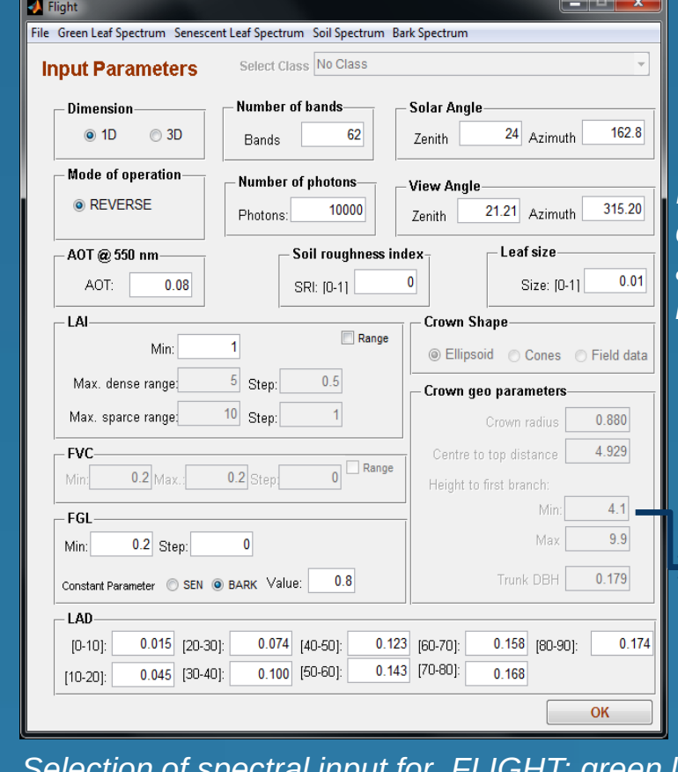
ARTMO aims to implement essential models and modules required for terrestrial EO applications in a graphical user interface (GUI) toolbox. ARTMO allows the user:

i) To choose between various leaf and canopy RT models.
ii) To choose between spectral band settings of various sensors, or to define own band settings.
iii) To simulate a massive amount of spectra based on look up tables (LUT) and storing it in a relational database
iv) To plot simulated spectra of multiple models and compare it with measured spectra.
v) To evaluate over 50 different cost functions against a validation dataset.
vi) To run model inversion against airborne or spaceborne images given class-based LUTs, a best-evaluated cost function and accuracy estimates.

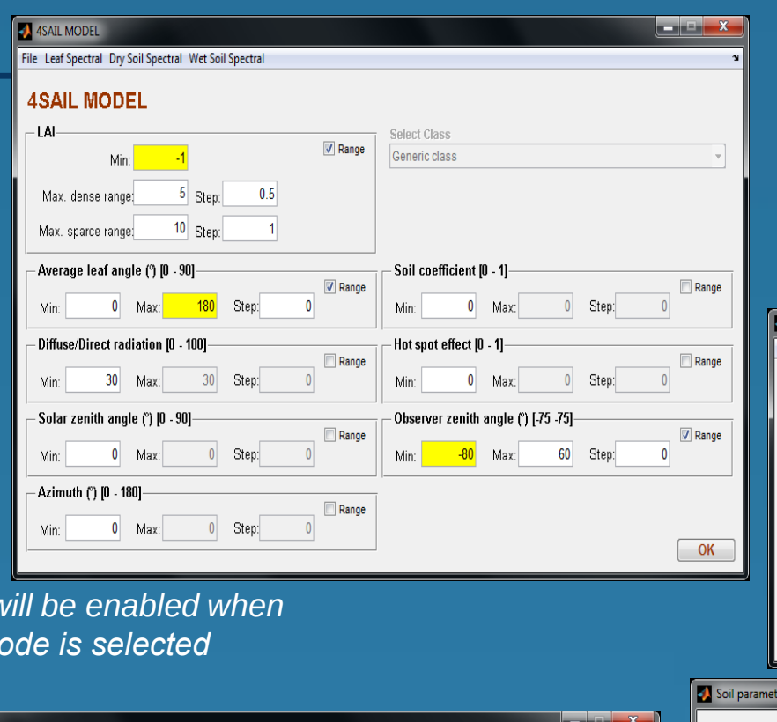
Here, the widely used RMSE was not evaluated as best performing cost function when using the SPARC dataset (Barrax, Spain). Also opting for a single best solution appeared to be suboptimal. Taking the average of multiple best solutions and adding noise led to best retrieval results.

5. Canopy-level models

ARTMO incorporates the following canopy models: 4SAIL, FluorSAIL, FLIGHT and then the combined soil-leaf-canopy (SLC) model. Similar to the leaf models, for each parameter a single value, a range or a text file with user-defined values can be inserted. Further, in contrary to leaf models, canopy models need spectral inputs for their elements such as leafs, soil, bark and senescent leaves. Therefore, for each model spectral data can be inserted by clicking on the associated name in the top bar. An input window will appear. When also a leaf model has been configured then those simulated spectra will be used as leaf spectral input into the canopy model. Multiple spectra of other elements can be inserted which then form part in building up the LUT.

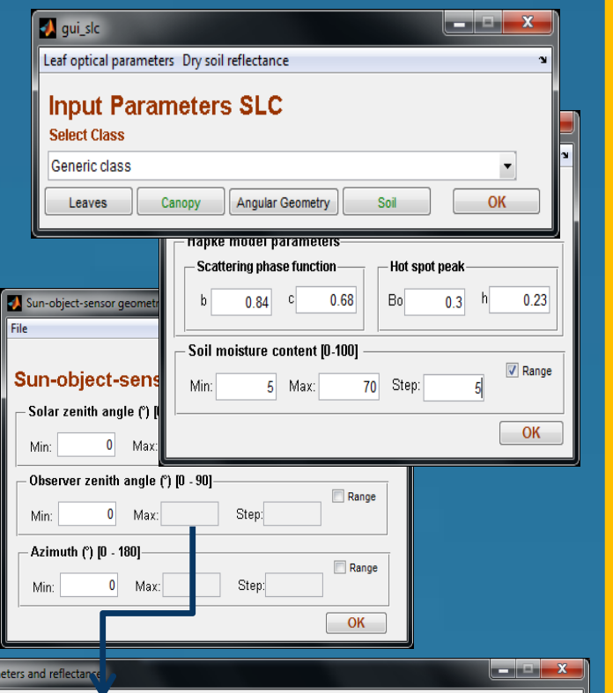


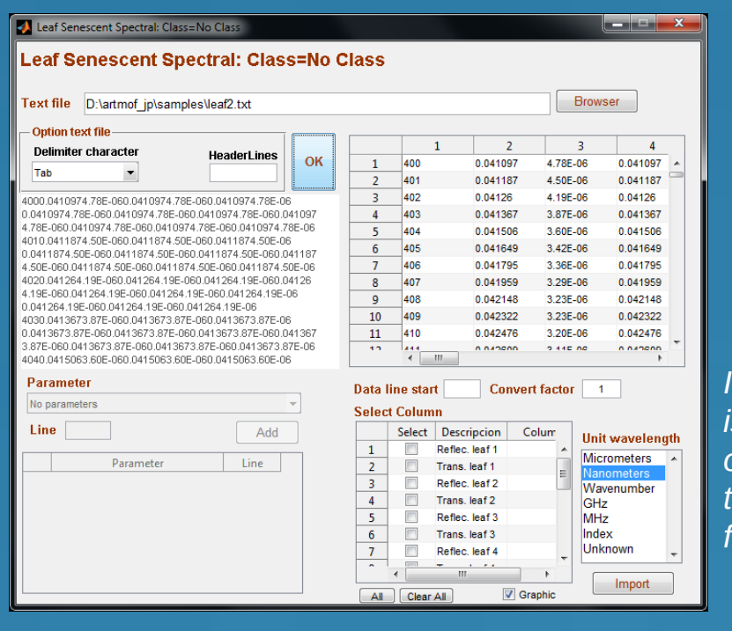
Selection of spectral input for FLIGHT: green leaf, senescent leaf, soil and woody elements . Once selected, the name turns red. Green leaf spectra either comes from spectral measurements or from a leaf model

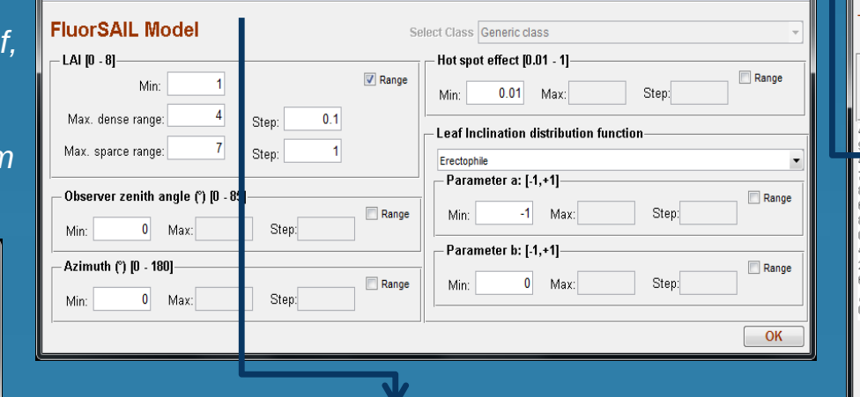


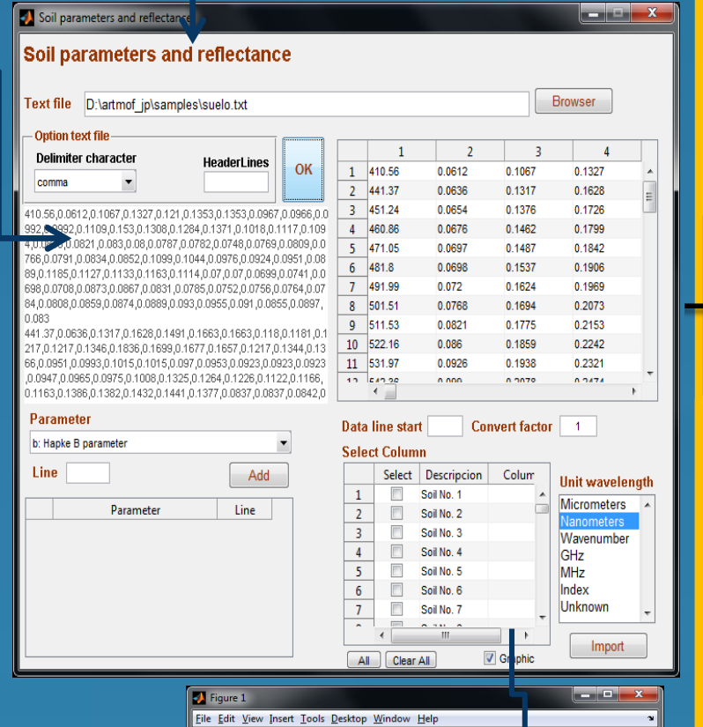
Input settings can be saved and reloaded.

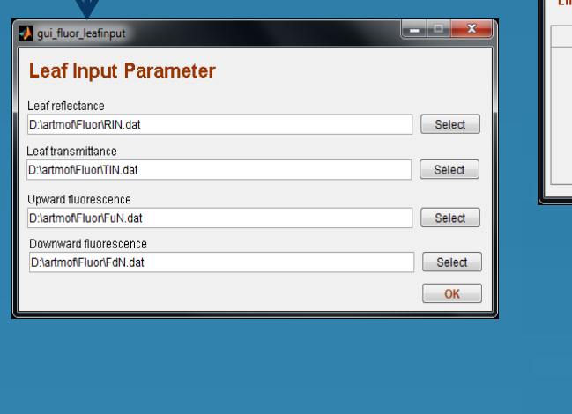
This part will be enabled when the '3D' mode is selected

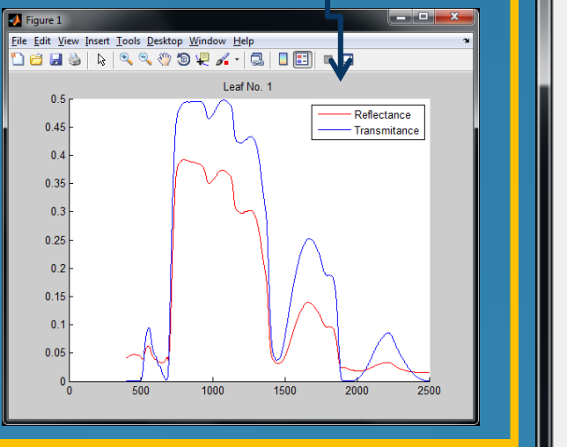










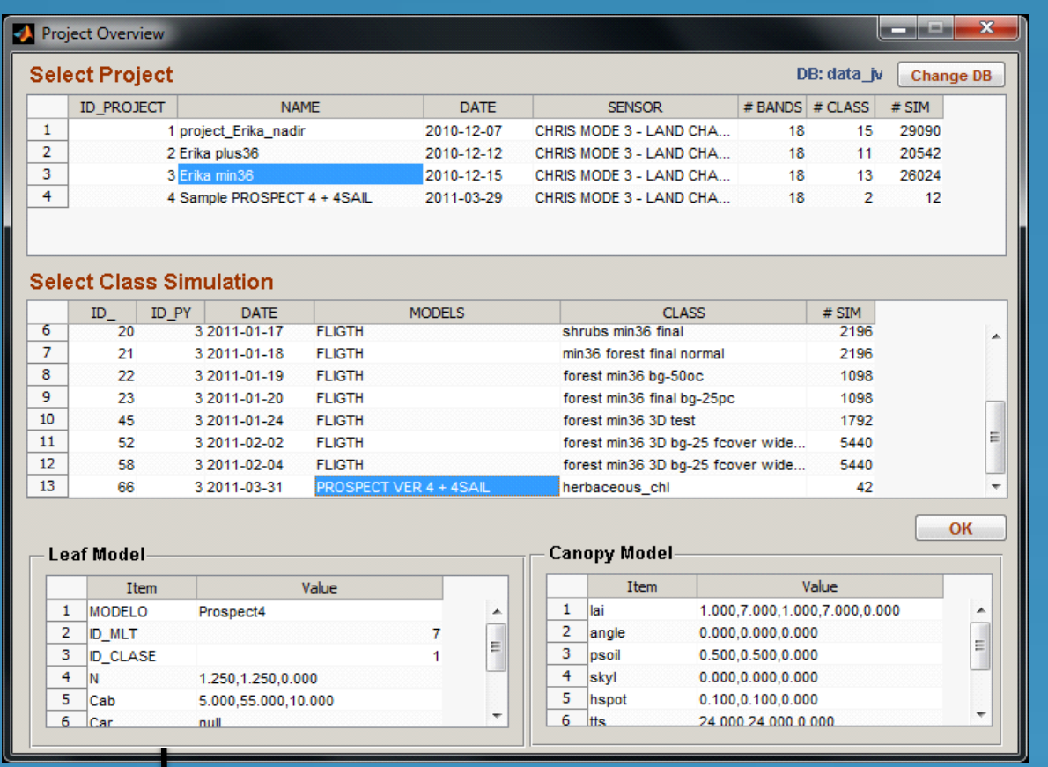


If FluorMODleaf is not configured, one can select their own input files.

One or various spectra can be selected as input in the canopy models. Any text file with columnar spectra can be read. Header lines can be removed and spectra can be converted to other units. Also different wavelength units can be chosen. The selected spectra can also be visualized by enabling the 'Graphics' button. As such it can be quickly viewed whether the right spectra is imported.

6. LUT access and metadata

In ARTMO s 'Project Overview' window an overview of all created projects and classes within the current DB are displayed. This 'Project Overview' can be accessed from ARTMO s main module (click on 'Load Project') or via the 'Graphics' or 'Inversion' modules. The top panel shows all Projects from the current DB along with its metadata such as date of creation, sensor, number of bands, classes and simulations. By clicking on one of the projects then in the middle panel its included classes are shown along with its metadata such as date of creation, used models, class name and number of simulations. Each class consists of a LUT. By clicking on a class then in the down panels then both at leaf level as at canopy level the complete LUT configurations and fixed parameters appear.



Select Project — DB: data_jv

	ID_PROJECT	NAME	DATE	SENSOR	# BANDS	# CLASS	# SIM
1	1	project_Erika_nadir	2010-12-07	CHRIS MODE 3 - LAND CHA...	18	15	29090
2	2	Erika plus36	2010-12-12	CHRIS MODE 3 - LAND CHA...	18	11	20542
3	3	Erika min36	2010-12-15	CHRIS MODE 3 - LAND CHA...	18	13	26024
4	4	Sample PROSPECT 4 + 4SAIL	2011-03-29	CHRIS MODE 3 - LAND CHA...	18	2	12

Select Class Simulation

	ID_	ID_PY	DATE	MODELS	CLASS	# SIM
6	20	3	2011-01-17	FLIGTH	shrubs min36 final	2196
7	21	3	2011-01-18	FLIGTH	min36 forest final normal	2196
8	22	3	2011-01-19	FLIGTH	forest min36 bg-50oc	1098
9	23	3	2011-01-20	FLIGTH	forest min36 final bg-25pc	1098
10	45	3	2011-01-24	FLIGTH	forest min36 3D test	1792
11	52	3	2011-02-02	FLIGTH	forest min36 3D bg-25 fcover wide...	5440
12	58	3	2011-02-04	FLIGTH	forest min36 3D bg-25 fcover wide...	5440
13	66	3	2011-03-31	PROSPECT VER 4 + 4SAIL	herbaceous_chl	42

Leaf Model

	Item	Value
1	MODELO	Prospect4
2	ID_MLT	7
3	ID_CLASE	1
4	N	1.250,1.250,0.000
5	Cab	5.000,55.000,10.000
6	Car	null

Canopy Model

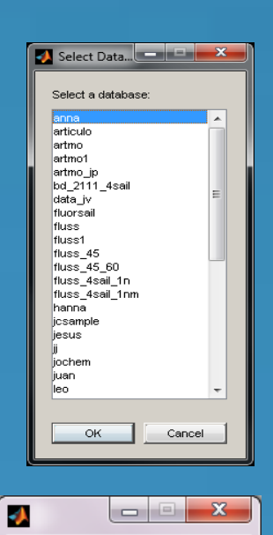
	Item	Value
1	lai	1.000,7.000,1.000,7.000,0.000
2	angle	0.000,0.000,0.000
3	psoil	0.500,0.500,0.000
4	skyl	0.000,0.000,0.000
5	hspot	0.100,0.100,0.000
6	tts	24.000,24.000,0.000

Overview of projects

Overview of classes from selected project

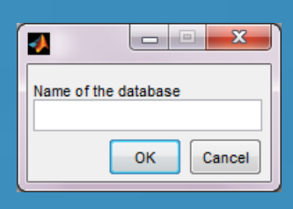
LUT configuration and fixed parameters of models that generated the class LUT.

By clicking on 'Change DB' then this window appears where the an overview of all created DBs are shown. By selecting one of them then all the projects will be loaded into the 'Project Overview' window.



anna
articulo
artmo
artmo1
artmo_jp
bd_2111_4sail
data_jv
fluorsail
fluss
fluss1
fluss_45
fluss_45_60
fluss_4sail_1n
fluss_4sail_1nm
hanna
jcsample
jesus
jj
jochem
juan
leo

In ARTMO's main module, in 'DB Administration' a new DB can be created or deleted. Here the GUI appears for naming a new DB.



7. Graphics module

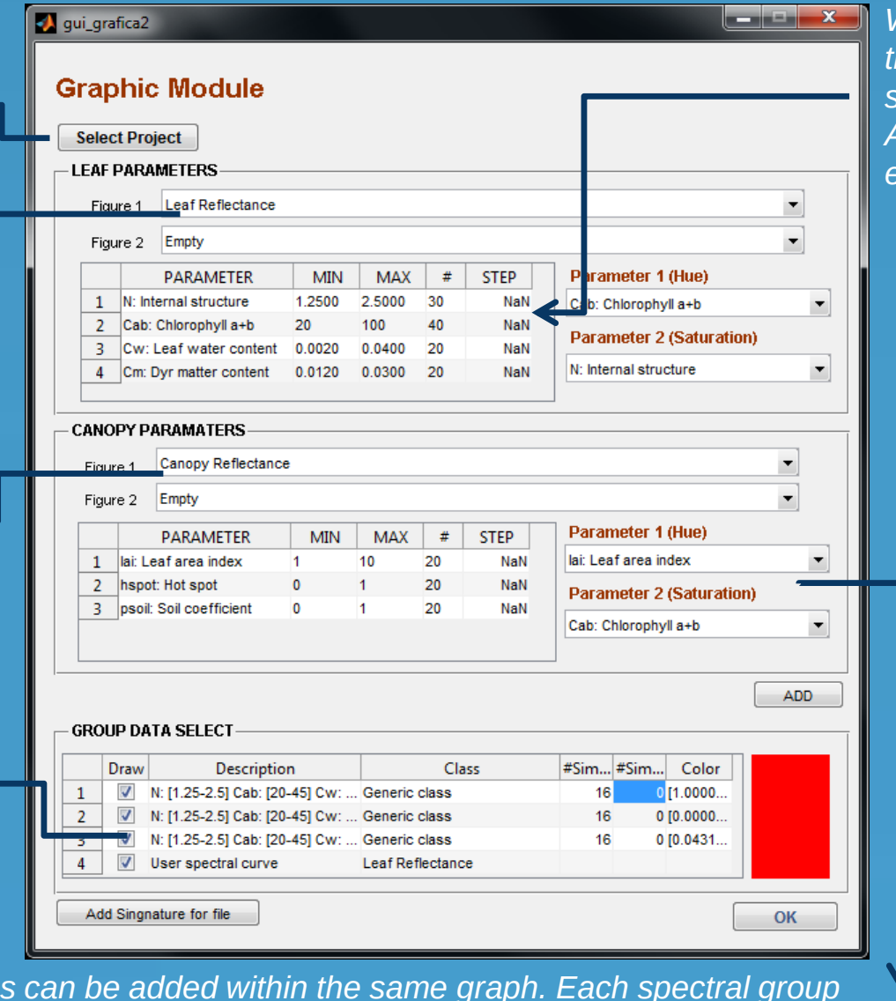
In ARTMO s 'Graphics' module simulated LUTs can be plotted and exported to a text file for further use. Multiple groups of output spectra, e.g. originating from different LUTs, can be plotted within the same plotting window. As such the output spectra from different models can be directly compared.

By clicking on this button one can change DB, select a project and a class. See also panel 6'.

Selection of plottings at leaf leaf-level (e.g. reflectance, transmittance, fluorescence).

Selection of plottings at canopy-level (e.g. TOC reflectance).

Information on the selected spectral groups. By right-clicking the selected can be exported to a text file.



Leaf: Figure 1: Leaf Reflectance; Figure 2: Empty

	PARAMETER	MIN	MAX	#	STEP
1	N: Internal structure	1.2500	2.5000	30	NaN
2	Cab: Chlorophyll a+b	20	100	40	NaN
3	Cw: Leaf water content	0.0020	0.0400	20	NaN
4	Cm: Dyr matter content	0.0120	0.0300	20	NaN

Parameter 1 (Hue): Cab: Chlorophyll a+b; Parameter 2 (Saturation): N: Internal structure

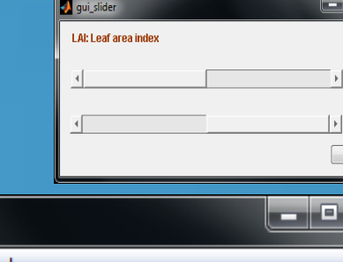
Canopy: Figure 1: Canopy Reflectance; Figure 2: Empty

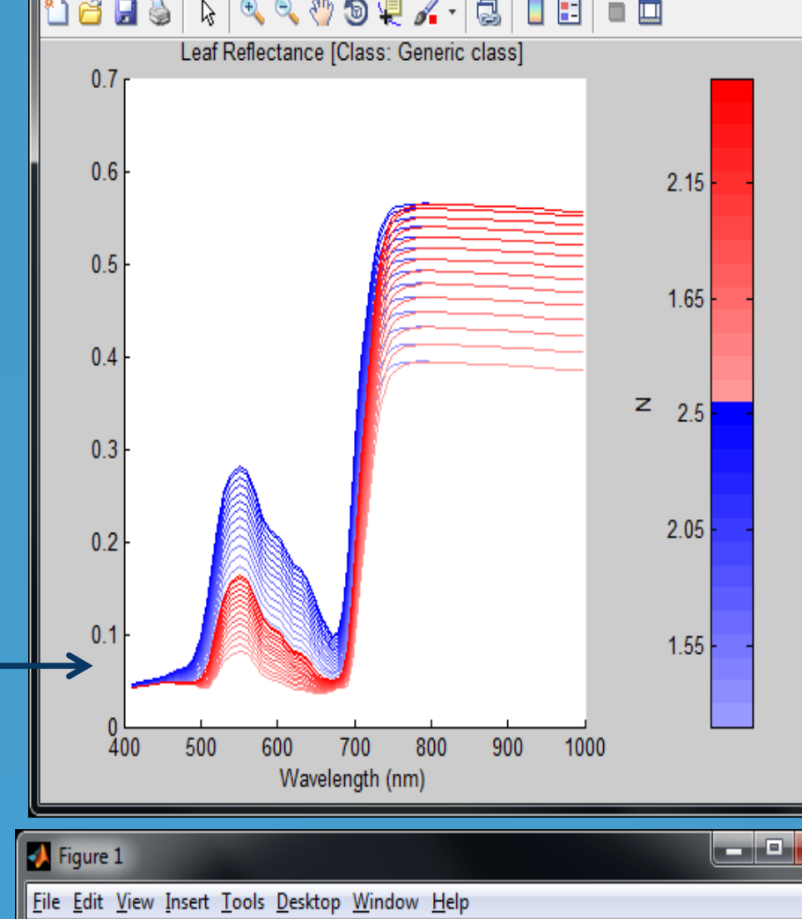
	PARAMETER	MIN	MAX	#	STEP
1	lai: Leaf area index	1	10	20	NaN
2	hspot: Hot spot	0	1	20	NaN
3	psoil: Soil coefficient	0	1	20	NaN

Parameter 1 (Hue): lai: Leaf area index; Parameter 2 (Saturation): Cab: Chlorophyll a+b

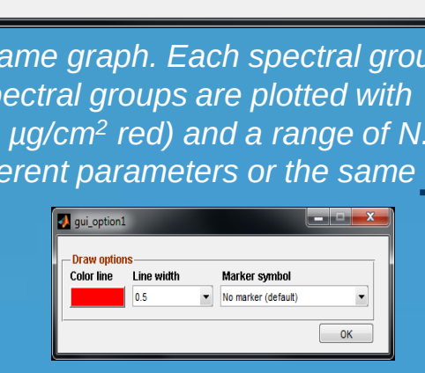
	Draw	Description	Class	#Sim...	#Sim...	Color
1	☑	N: [1.25-2.5] Cab: [20-45] Cw: ...	Generic class	16	0	[1.0000...
2	☑	N: [1.25-2.5] Cab: [20-45] Cw: ...	Generic class	16	0	[0.0000...
3	☑	N: [1.25-2.5] Cab: [20-45] Cw: ...	Generic class	16	0	[0.0431...
4	☑	User spectral curve	Leaf Reflectance			

When a parameter consists of more than one value it appears in the overview table. By clicking on the properties of a parameter a subselection of spectra can be made by means of sliders. Another way of subselection is setting a step (e.g. 3) so that only each another spectra is plotted.

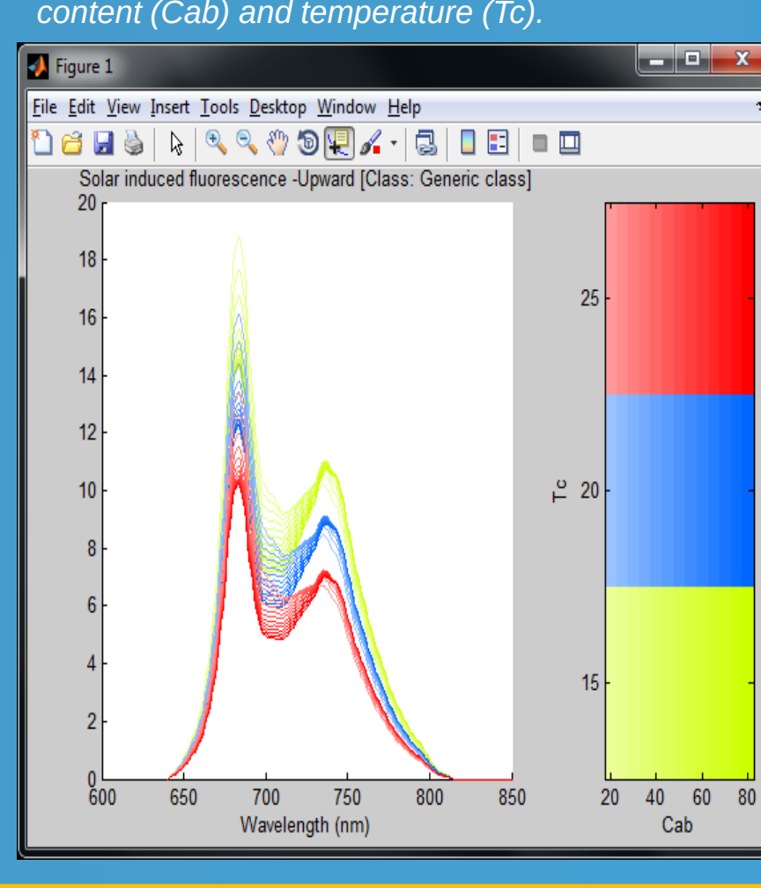




Multiple spectral groups can be added within the same graph. Each spectral group can be assigned to a user-defined color. Here 2 spectral groups are plotted with different chlorophyll contents (20 µg/cm²: blue, 45: µg/cm² red) and a range of N. Likewise, spectral groups could also consist of different parameters or the same parameter from different models.

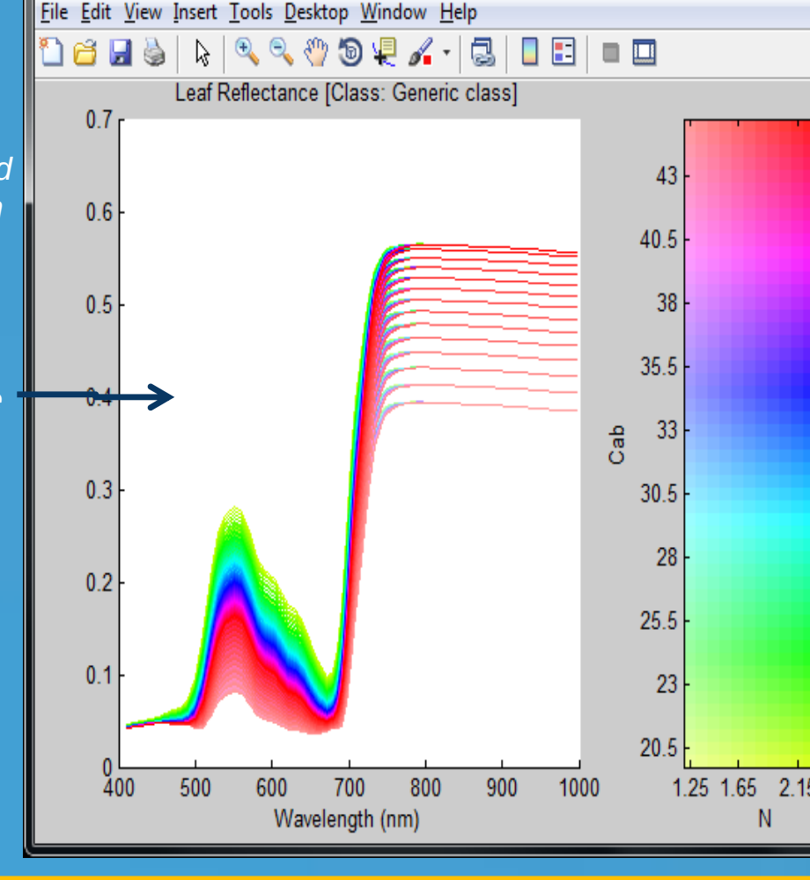


Example:
With FluorMODleaf simulations of upwards leaf fluorescence are plotted as a function of chlorophyll content (Cab) and temperature (Tc).



Simulated spectra can also be plotted with varying color tones as a function of 2 parameters. One parameter can be assigned to Hue (color), and another parameter can be assigned to Saturation (intensity). If both Hue and Saturation are assigned then the effects of these two parameters on reflectance can be visualized.

Additional spectra can be added to a plotting window, e.g. from a field instrument or from an image. Color, line width and marker can be modified.



8. Inversion module

ARTMO's most advanced module is the 'Inversion' module. This module enables automated mapping of biophysical parameters from mulitspectral or hyperspectral imagery based on pre-computed LUTs. Several cost functions and optimization options are provided. Most importantly, inversion can be done class-based. This means that different land cover classes can be linked to different LUTs. For instance, homogenous land covers such as agricultural fields can be interpreted by a turbid model (e.g. SAIL) while heterogeneous land covers such as forests can be interpreted by a 3D model (e.g. FLIGHT).

Here an image and optionally a land cover map can be loaded for model inversion against spectral observations. Note that the image should have the same band settings as the LUT simulations.

By clicking on 'Select Project' button one can select a project and LUT classes. See also panel 6.

More than 50 cost functions are provided. Several options have been included for optimizing inversion:
- *Inversion based on derivatives of spectra*
- *Adding white noise*
- *Results as a mean of % best matches.*
- *The option to map standard deviation and residuals.*

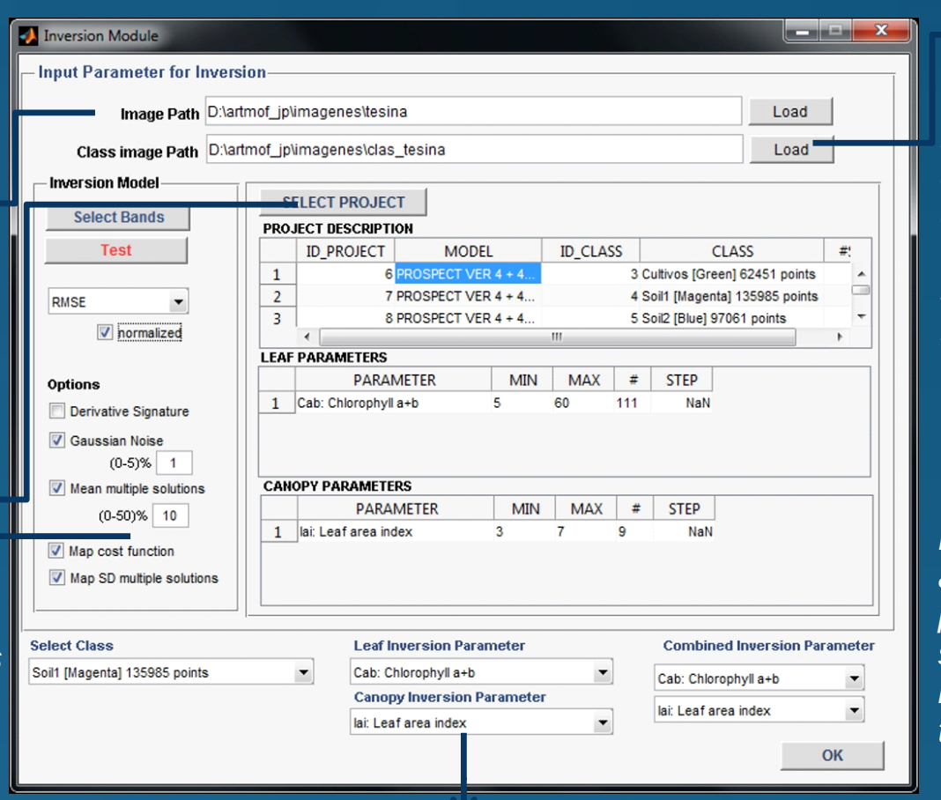


Image Path: D:\artmof_jp\imagenes\tesina
Class image Path: D:\artmof_jp\imagenes\clas_tesina
RMSE ☑ normalized
☐ Derivative Signature
☑ Gaussian Noise (0-5)%: 1
☑ Mean multiple solutions (0-50)%: 10
☑ Map cost function
☑ Map SD multiple solutions

	ID_PROJECT	MODEL	ID_CLASS	CLASS
1	6	PROSPECT VER 4 + 4...	3	Cultivos [Green] 62451 points
2	7	PROSPECT VER 4 + 4...	4	Soil1 [Magenta] 135985 points
3	8	PROSPECT VER 4 + 4...	5	Soil2 [Blue] 97061 points

Leaf parameters:

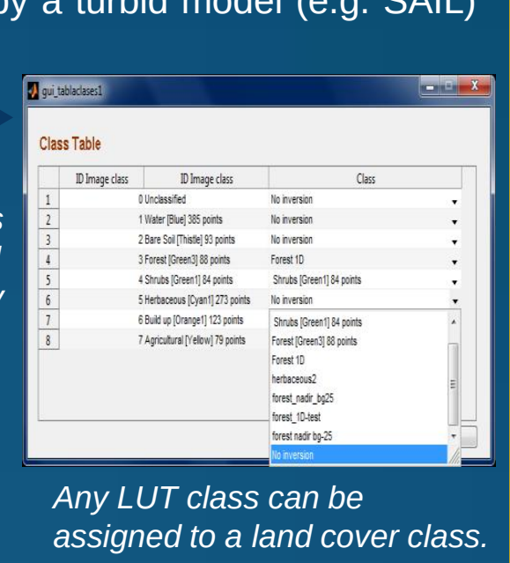
	PARAMETER	MIN	MAX	#	STEP
1	Cab: Chlorophyll a+b	5	60	111	NaN

Canopy parameters:

	PARAMETER	MIN	MAX	#	STEP
1	lai: Leaf area index	3	7	9	NaN

Select Class: Soil1 [Magenta] 135985 points
Leaf Inversion Parameter: Cab: Chlorophyll a+b
Canopy Inversion Parameter: lai: Leaf area index
Combined Inversion Parameter: Cab: Chlorophyll a+b; lai: Leaf area index

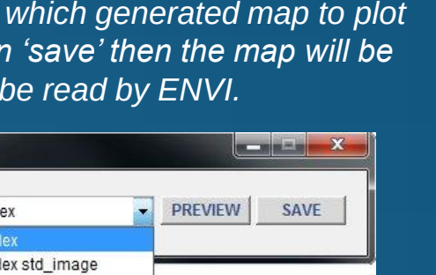
If a classified map is loaded, land cover classes are automatically detected and can be linked with any of the LUT classes. As such, model inversion can be done class-based.



0 Unclassified — No inversion
1 Water [Blue] 385 points — No inversion
2 Bare Soil [Thistle] 93 points — No inversion
3 Forest [Green3] 88 points — Forest 1D
4 Shrubs [Green1] 84 points — Shrubs [Green1] 84 points
5 Herbaceous [Cyan1] 273 points — No inversion
6 Build up [Orange1] 123 points — Shrubs [Green1] 84 points
7 Agricultural [Yellow] 79 points — Forest [Green3] 88 points

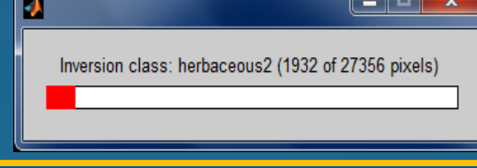
Any LUT class can be assigned to a land cover class.

By selecting a LUT class , also here the option is possible to include only a subselection of the parameter range by means of narrowing the sliders.



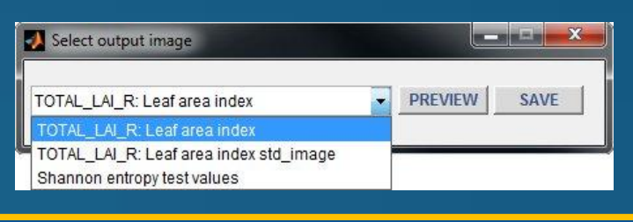
Model Inversion results can be shown per land cover class. The user can then choose to retrieve a leaf and/or a canopy parameter, or the product of both (e.g., Chl x LAI).

This GUI will appear when the inversion is finalized. Here, the user can choose which generated map to plot (preview). When clicking on 'save' then the map will be saved in a format that can be read by ENVI.



Inversion class: herbaceous2 (1932 of 27356 pixels)

Progress bars indicate progress time and number of processed pixels per land cover class.



TOTAL_LAI_R: Leaf area index
TOTAL_LAI_R: Leaf area index std_image
Shannon entropy test values

9. Provided cost functions

1. Information Measures

In order to apply some classes of distances between discrete distributions we assume that the reflectance data are normilised in the following way, where $R^*(\lambda_j)$ – satellite reflectance and $R_i(\lambda_j)$ – LUT reflectance. $R^*(\lambda_j), \lambda_j \in \Lambda$ and for $1 \le i \le N$ we introduce

$$Q = (q_1^*,\dots,q^*_n) = \frac{R^*(\lambda_1)}{\sum R^*(\lambda_j)},\dots,\frac{R^*(\lambda_N)}{\sum R^*(\lambda_j)},$$

$$P = (p_1^i,\dots,p^i_n) = \frac{R_i(\lambda_1)}{\sum R_i(\lambda_j)},\dots,\frac{R_i(\lambda_N)}{\sum R_i(\lambda_j)}$$

and $\sum q_l = 1, \sum p^i{}_l = 1.$

The class of distances can be written as follows: for a given strictly convex twice differential function f we define:

$$\Gamma_f[P,Q] = \sum_{l=1}^n q_l f\left(\frac{p_l^i}{q_l}\right),\ 1 \le i \le N.$$

$$\Gamma_f[P,Q] \to \min \text{ i f f } \ P = Q.$$

Examples

1. Bregman non-symmetric distance

$$\Gamma_f[P,Q] = \sum_{l=1}^n \left(q_l^a + \frac{1}{a-1}p_l^a - \frac{1}{a-1}p_l\, q_l^{a-1}\right), a \ne 1.$$

2. Arimoto (1971) $a > 0, a \ne 1$

$$\Gamma_f[P,Q] = \left(\frac{1}{a-1}\right)\left[\left(\sum_{l=1}^n\left(\frac{p_l+q_l}{2}\right)^{1/a}\right)^a - \frac{1}{2}\left(\sum_{l=1}^n p_l^{1/a}\right)^a + \frac{1}{2}\left(\sum_{l=1}^n q_l^{1/a}\right)^a\right]$$

3. Sharma and Mittal (1975), $a > 0, a \ne 1$

$$\Gamma_f[P,Q] = \left(\frac{1}{1-a}\right)\left[\exp\left((a-1)\sum_{l=1}^n\left(\frac{p_l+q_l}{2}\right)\log\left\{\frac{p_l+q_l}{2}\right\}\right) - \frac{1}{2}\exp\left((a-1)\sum_{l=1}^n p_l \log p_l\right) + \frac{1}{2}\exp\left((a-1)\sum_{l=1}^n q_l \log q_l\right)\right]$$

4. Sharma and Mittal (1975), $a > 0, b > 0, a, b \ne 1$

$$\Gamma_f[P,Q] = \left(\frac{1}{1-a}\right)\left[\left(\sum_{l=1}^n\left\{\frac{p_l+q_l}{2}\right\}^b\right)^{\frac{a-1}{b-1}} - \frac{1}{2}\left(\sum_{l=1}^n p_l^b\right)^{\frac{a-1}{b-1}} + \frac{1}{2}\left(\sum_{l=1}^n q_l^b\right)^{\frac{a-1}{b-1}}\right]$$

In "**Information measures**" we assume that our reflectance is some probability distribution and we compare "metrics" between two distribution functions.

In total we included about 50 different Information Measures in ARTMO. Although many perform similarly, quite some of them seem to perform better than the widely used RMSE.

2. Minimum Contrast Estimates

Let $\{Z_t\}$ be a stationary or harmonizable stochastic process with mean m and true spectral density $g(\lambda)$ (in our case satellite reflectance). Indeed the observations can be represented in the spectral domain in the form of periodogram $I_n(\lambda_k)$:

$$I_n(\lambda_k) = \frac{1}{2\pi n}\left|\sum_{j=1}^N (Z_j - m)e^{ij\lambda_k}\right|^2,\quad \lambda_k \in \Lambda.$$

We approximate $g(\lambda)$ by parametric family $f_\theta(\lambda)$, (LUT reflectance) and a minimum contrast estimator minimizes

$$D(f_\theta, g) = \int_{\lambda\in\Lambda} K\{f_\theta(\lambda)/g(\lambda)\}d\lambda.$$

Function $K(x)$ should be a three times continuously differentiable on $(0,\infty)$ and it has a unique minimum at $x = 1$.

$$D(f_\theta, g) = 0 \Leftrightarrow f_\theta = g.$$

Examples

1. Let $K(x) = \log x + 1/x$, then

$$D(f_\theta, g) = \sum_{\lambda_j} \log(f_\theta(\lambda_j)/g(\lambda_j) + g(\lambda_j)/f_\theta(\lambda_j))$$

2. $K(x) = (\log x)^2$, then

$$D(f_\theta, g) = \sum_{\lambda_j} \left|\log(f_\theta(\lambda_j)) - \log g(\lambda_j)\right|^2$$

3. $K(x) = x\log x - x$, then

$$D(f_\theta, g) = \sum_{\lambda_j} f_\theta(\lambda_j)g(\lambda_j)^{-1}\{\log(f_\theta(\lambda_j)g(\lambda_j)^{-1}) - 1\}$$

4. $K(x) = |x^\alpha - 1)|^2$, then

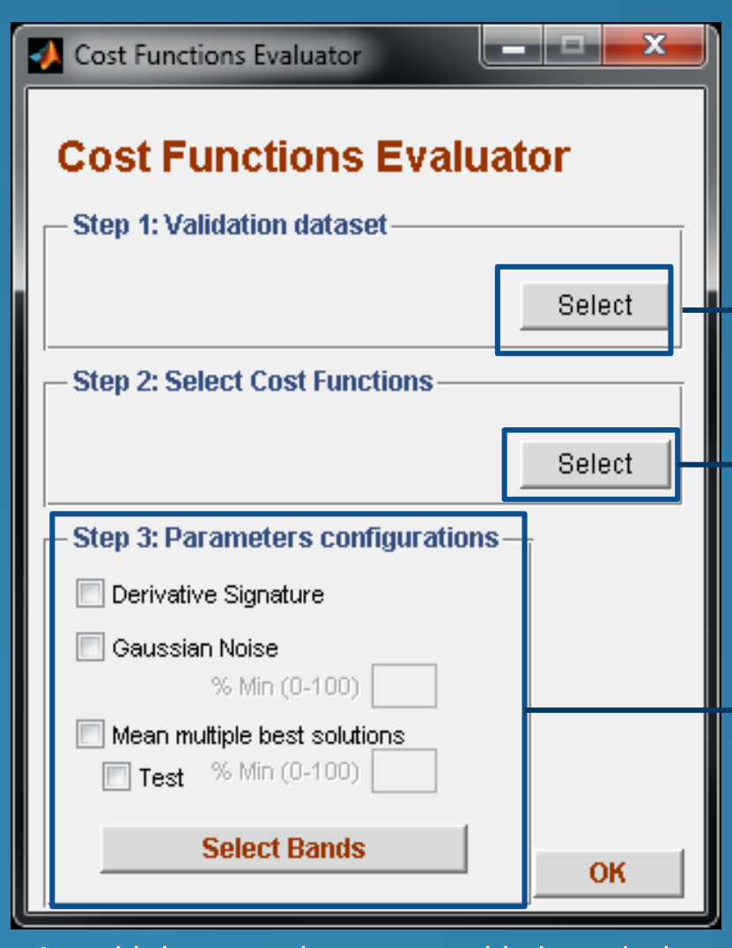
$$D(f_\theta, g) = \sum_{\lambda_j}\left|f_\theta(\lambda_j)/g(\lambda_j)^\alpha - 1\right|^2$$

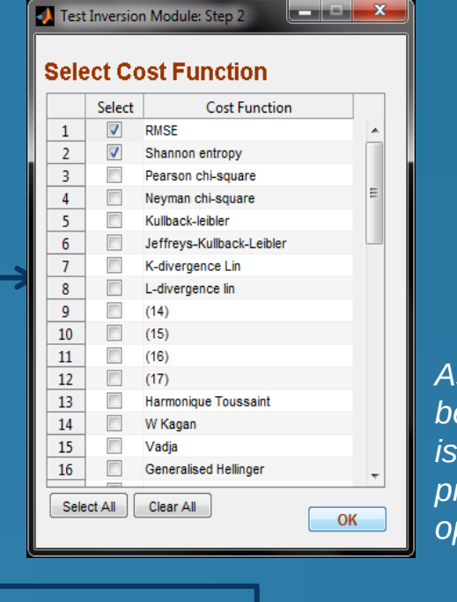
In "**Minimum Contrast estimate**" we assume that reflectance function is a spectral probability density function.

We are currently working on adding yet another family of distance functions "**M-estimates**". These are measures of location that are not as sensitive as the mean to outlier values.

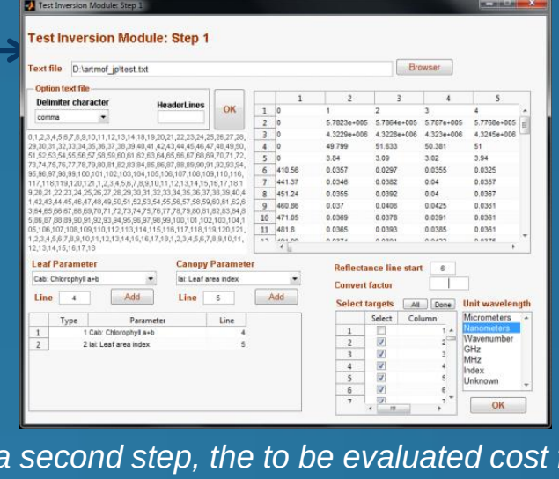
10. ARTMO's Cost functions evaluator

ARTMO offers the possibility to evaluate the range of included cost functions against validation data.

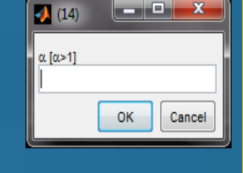




	Select	Cost Function
1	☑	RMSE
2	☑	Shannon entropy
3	☐	Pearson chi-square
4	☐	Neyman chi-square
5	☐	Kullback-leibler
6	☐	Jeffreys-Kullback-Leibler
7	☐	K-divergence Lin
8	☐	L-divergence lin
9	☐	(14)
10	☐	(15)
11	☐	(16)
12	☐	(17)
13	☐	Harmonique Toussaint
14	☐	W Kagan
15	☐	Vadja
16	☐	Generalised Hellinger



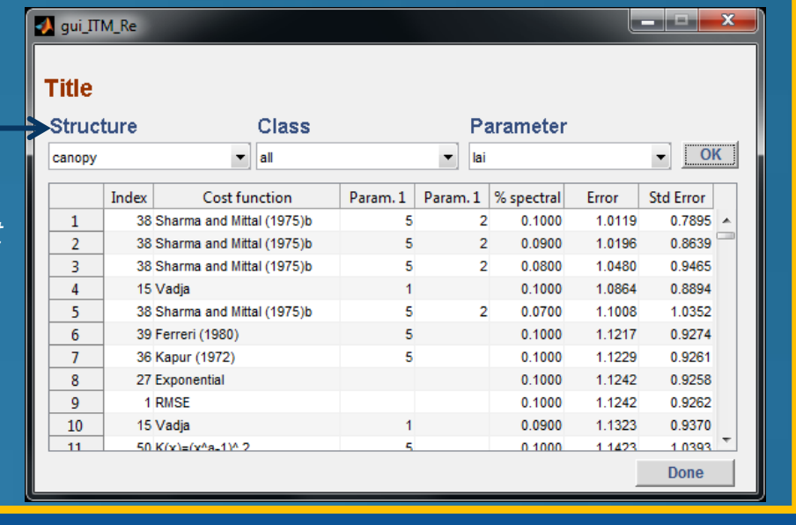
As a first step, a text file with ground truth data (parameters and associated spectral) can be imported. Options to convert or to exclude validation points are provided.



As a second step, the to be evaluated cost functions can be selected. For some cost functions a parameter value is needed. A GUI will appear where a value can be provided. We are currently working on automated optimizing this.

As a third step, options are provided to calculate the inversion on the derivatives, to add white noise or to evaluate the functions not only for the single best solution but for an average of multiple best solutions. Also bands can be removed from the inversion.

As a result, an overview table is created that that lists the performances of the cost functions. Listing can ranked per chosen parameter. When the option calculating the average of multiple solutions is selected then a range of best solutions will be added in the evaluation. Results can be exported to a text file.



Structure: canopy; Class: all; Parameter: lai

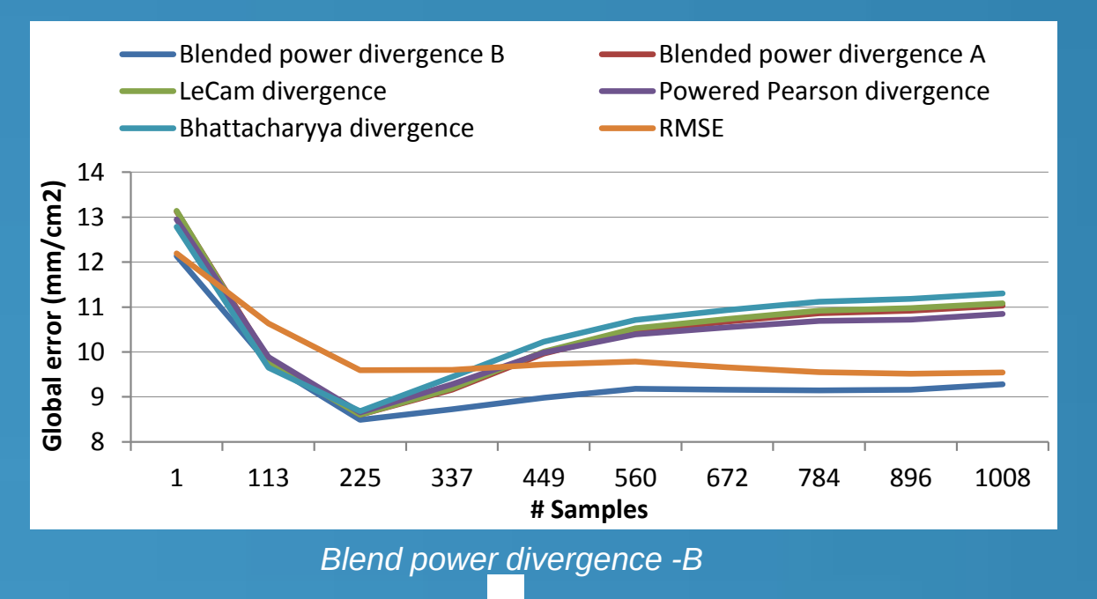
	Index	Cost Function	Param. 1	Param. 1	% spectral	Error	Std Error
1	38	Sharma and Mittal (1975)b	5	2	0.1000	1.0119	0.7895
2	38	Sharma and Mittal (1975)b	5	2	0.0900	1.0196	0.8639
3	38	Sharma and Mittal (1975)b	5	2	0.0800	1.0480	0.9465
4	15	Vadja	1		0.1000	1.0864	0.8894
5	38	Sharma and Mittal (1975)b	5	2	0.0700	1.1008	1.0352
6	39	Ferreri (1980)	5		0.1000	1.1217	0.9274
7	36	Kapur (1972)	5		0.1000	1.1229	0.9261
8	27	Exponential			0.1000	1.1242	0.9258
9	1	RMSE			0.1000	1.1242	0.9262
10	15	Vadja	1		0.0900	1.1323	0.9370
11	50	K(x)=(x^a-1)^2	5		0.1000	1.1423	1.0393

11. Results

By inputting a validation dataset (SPARC, Barrax, 2003) into ARTMO's cost function evaluator, all selected cost functions were evaluated. In the figures below the best 5 performing functions and additionally the commonly used RMSE are plotted. At X-axis, starting from the single best solution, the average of multiple best solutions is shown. It can be noted that not the single best solution led to best performances, but rather the average of a few hundred best solutions.

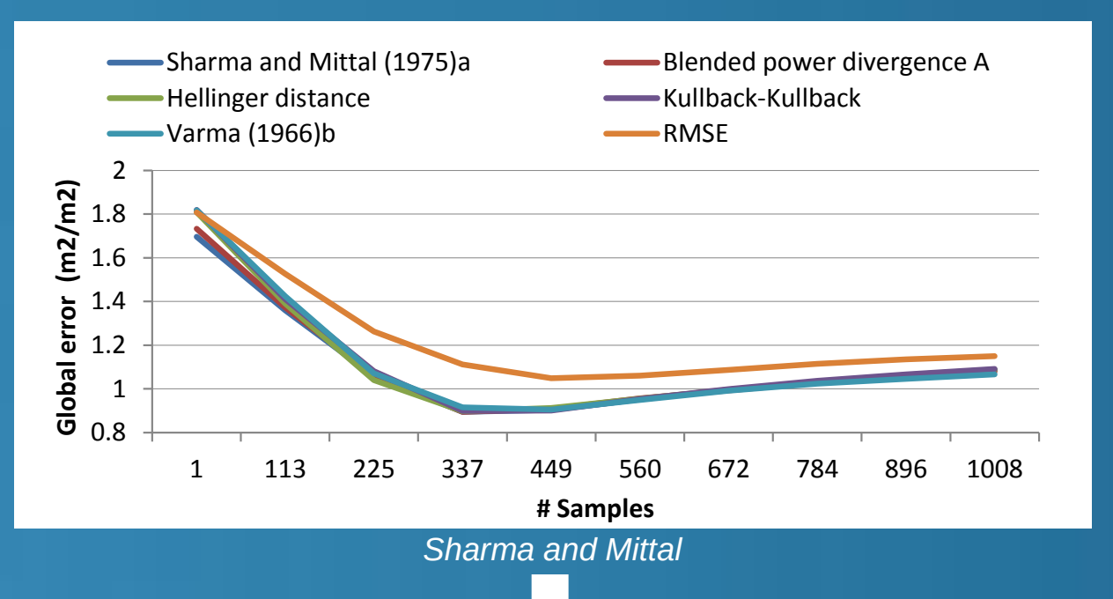
It can also be observed that RMSE was neither for chlorophyll content (Chl) nor for LAI evaluated as best performing cost function. Nevertheless, the best performing function also depends on the used parameter. For Chl the '*Blend power divergence-B'* led to best inversion performance, while for LAI the *'Sharma and Mittal*' led to best inversion performance. It was also found that adding Gaussian noise improved accuracies.

chlorophyll content (mm/cm²)
5% Gaussian noise added



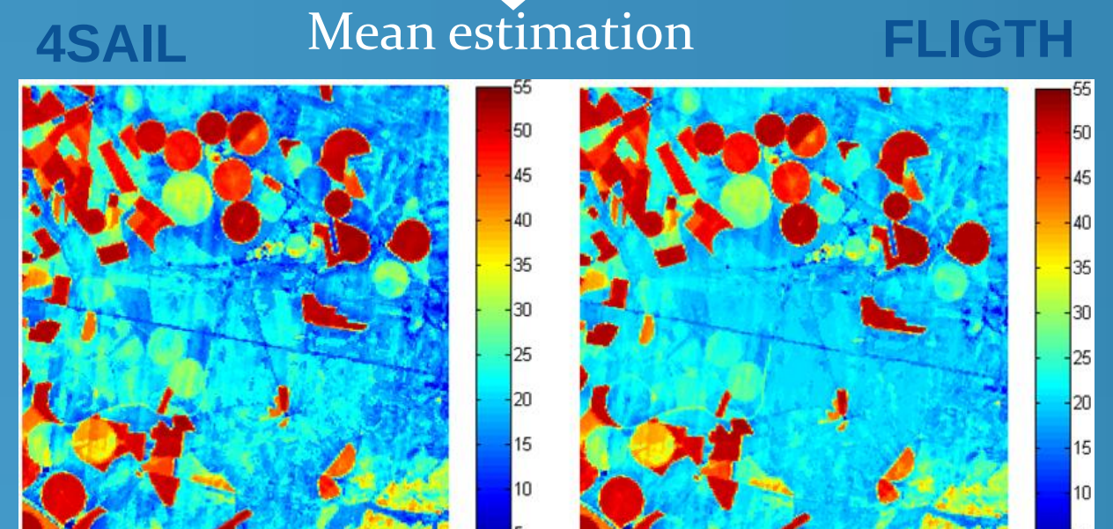
Blend power divergence -B

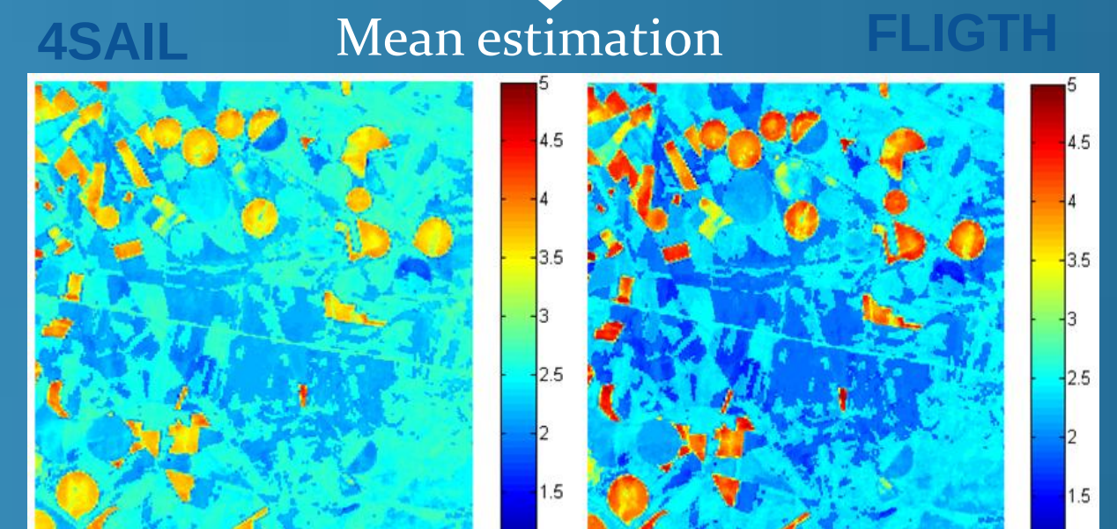
LAI (m²/m²)
10% Gaussian noise added



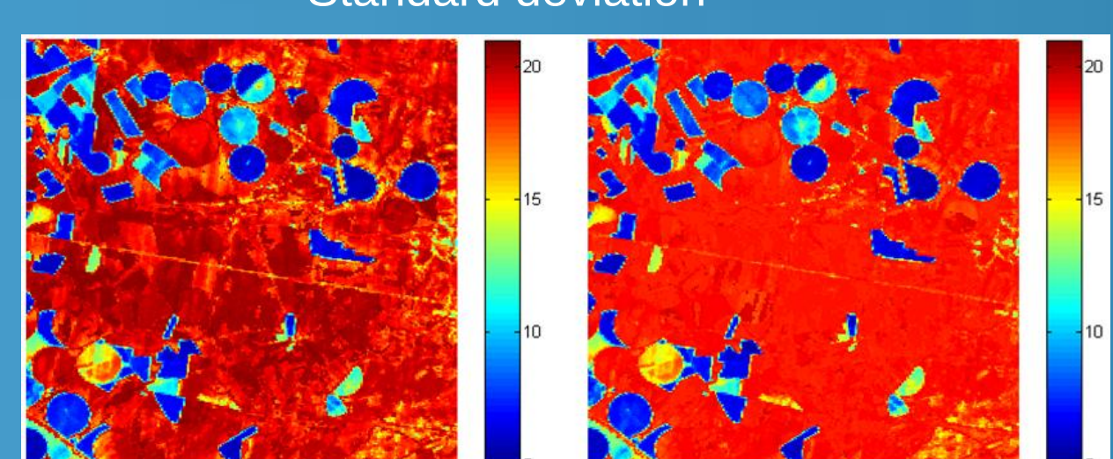
Sharma and Mittal

Mean estimation

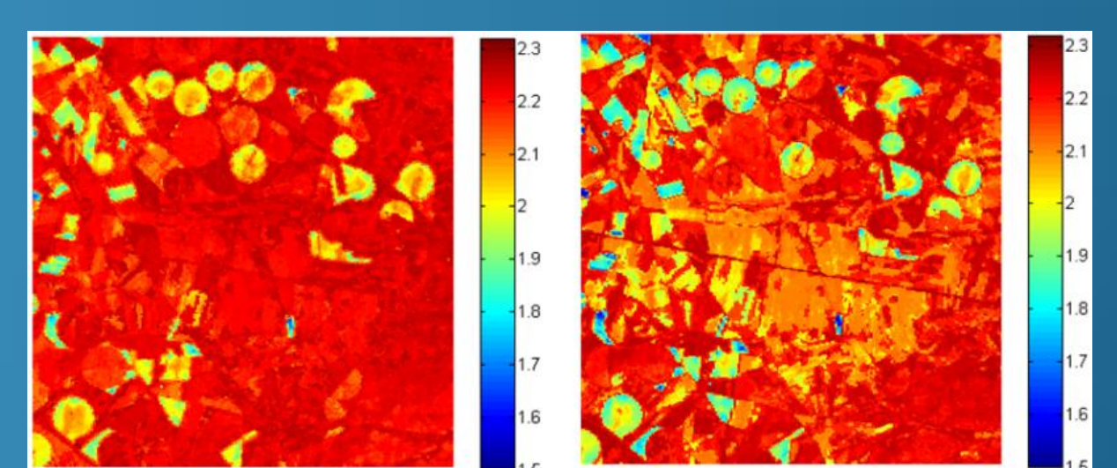




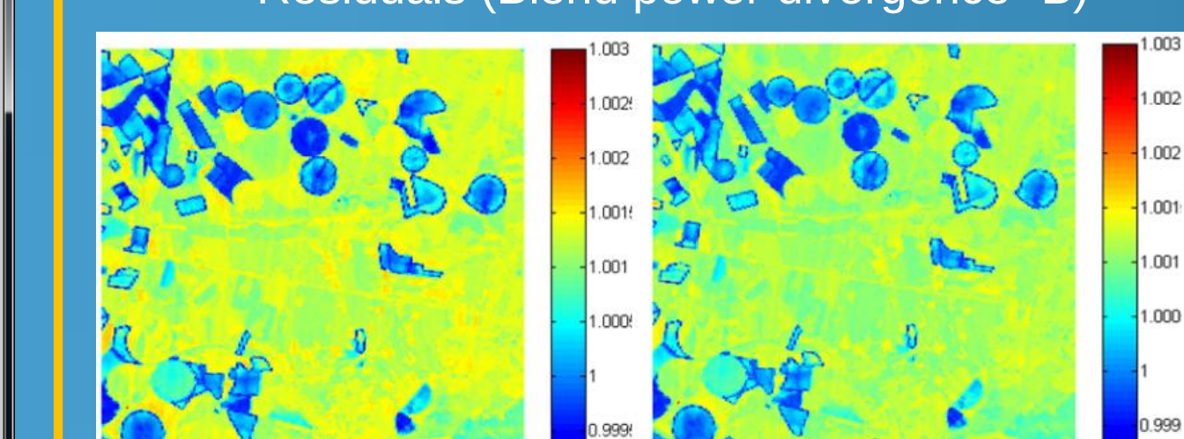
Standard deviation



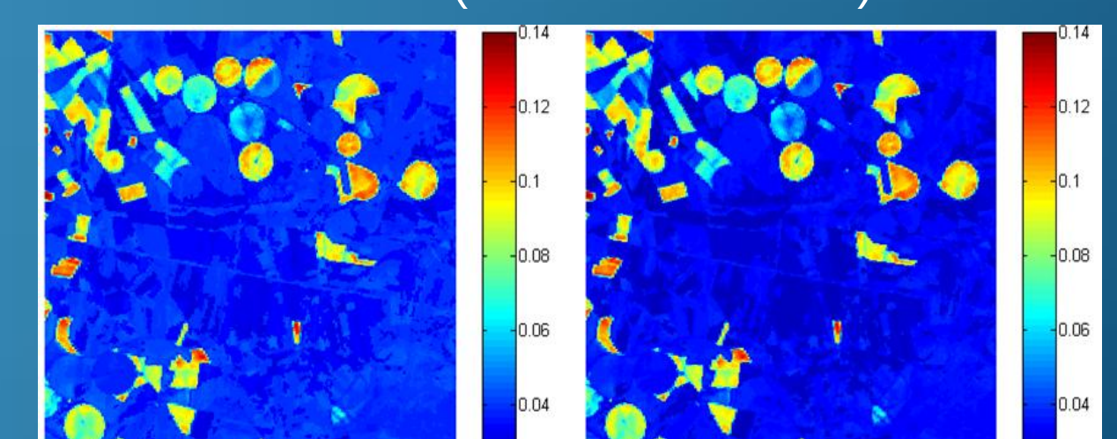
Standard deviation



Residuals (Blend power divergence -B)



Residuals (Sharma and Mittal)



With ARTMO the performance of 4SAIL and FLIGHT was compared when inverting these models against a CHRIS image for the retrieval of chlorophyll content and LAI. Both models performed alike in the retrieval of chlorophyll content, probably because they used the same PROSPECT model. However, more variation in LAI was observed when inverting FLIGHT. This can probably be explained by the different nature of FLIGHT (3D ray tracing model) as compared to SAIL (turbid medium model).