Optimizing LUT-based RTM inversion for retrieval of biophysical parameters

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Outline

I: **Principles of RTM inversion**

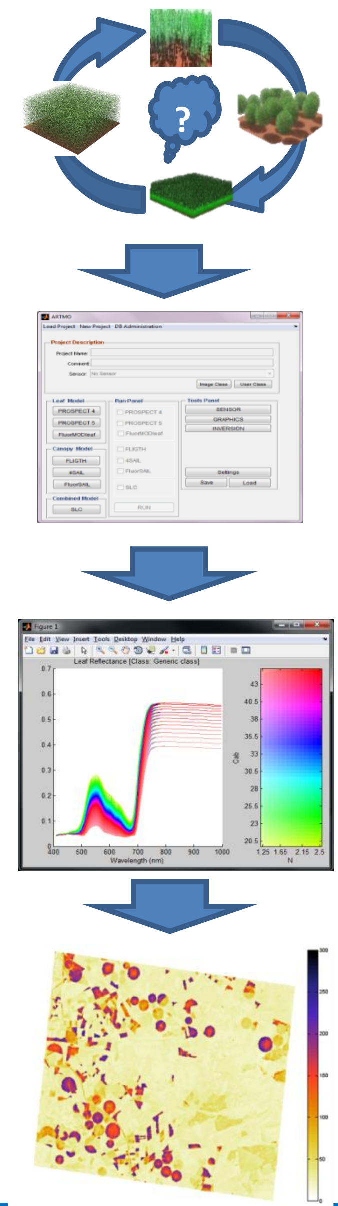
II: **ARTMO toolbox**

- **Design**
- **Modules**
- **Inversion strategy**

III: **LUT-based inversion using CHRIS data**

- **Optimizing inversion through regularization strategies**
- **Class-based inversion**

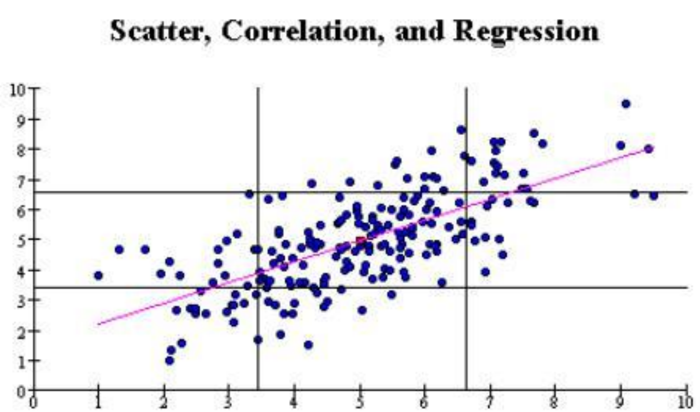
VI: **Outlook**



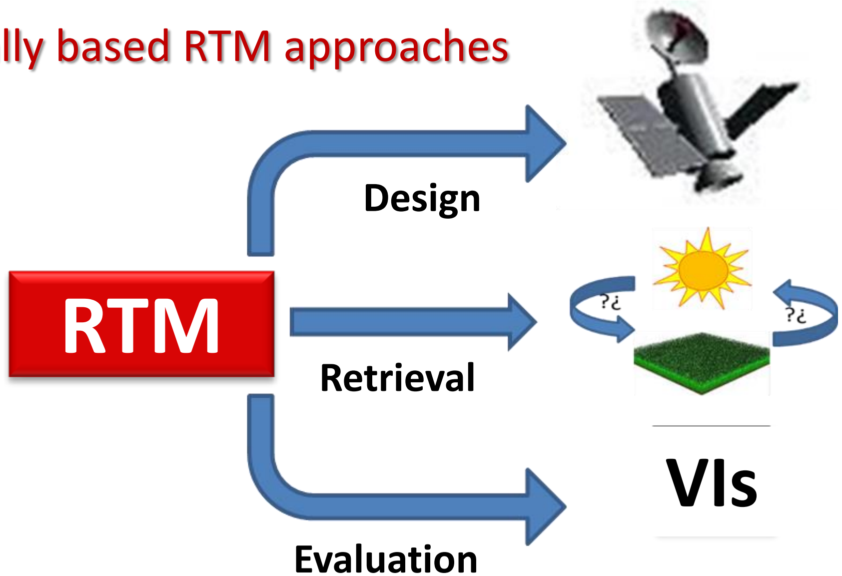
Basics biophysical parameter retrieval

Retrieval of biophysical parameters from optical EO data **always occurs through a model**; e.g. through **statistical models** or through **inversion** of physically-based **radiative transfer models** (RTM).

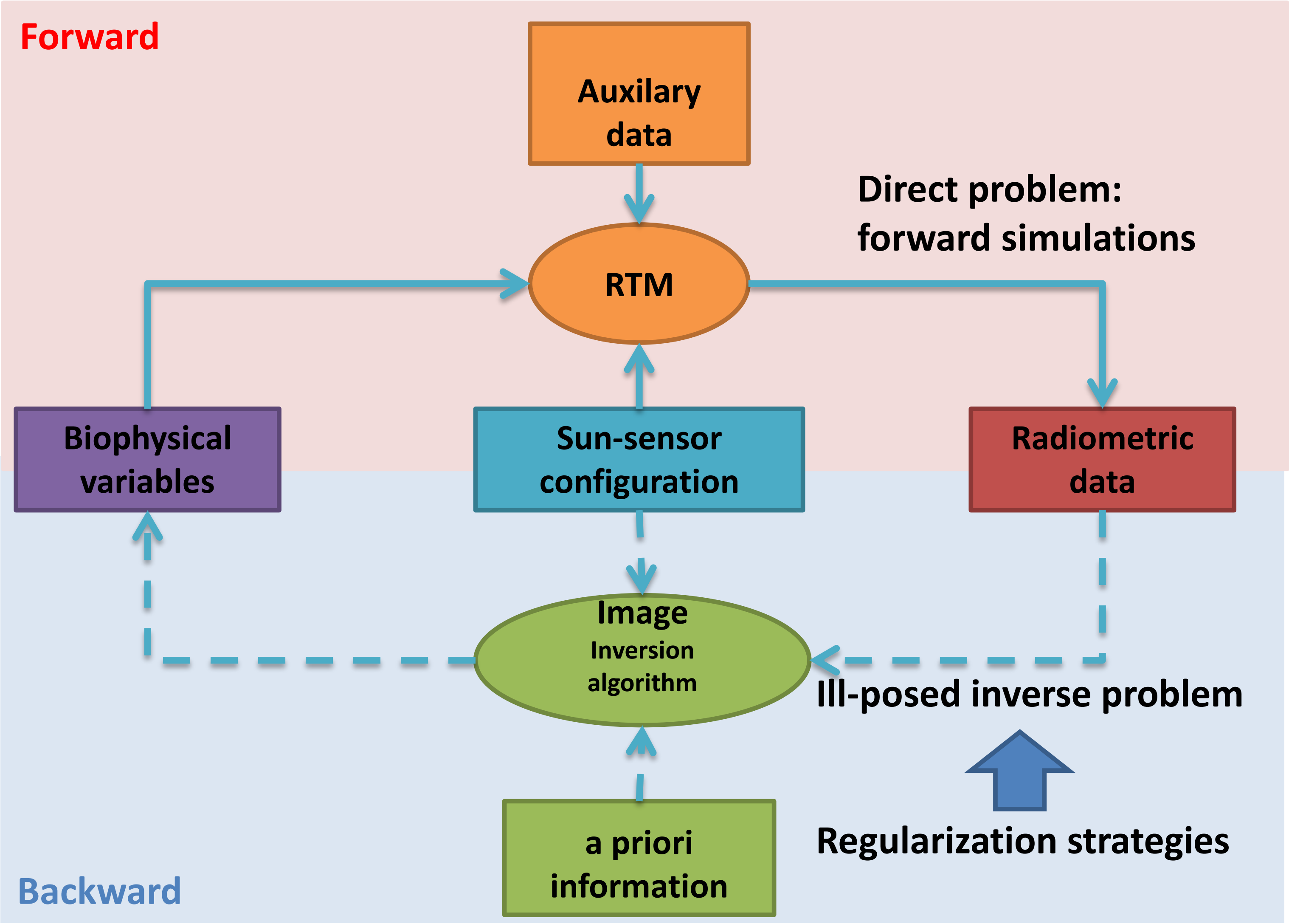
Statistical approaches



Physically based RTM approaches



Retrieval of biophysical parameters through RTM inversion:

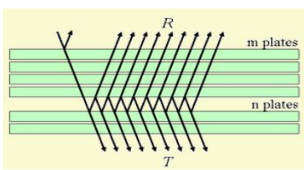


RTMs

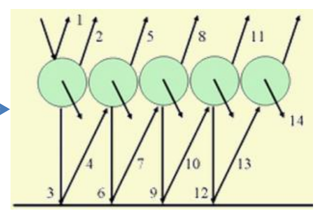
Leaf RTMs

Canopy RTMs

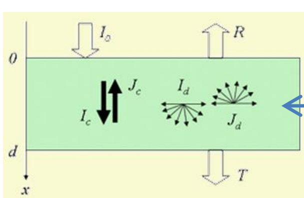
layers



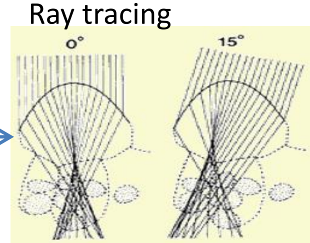
Compact spheres



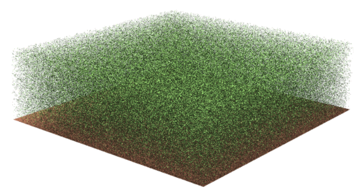
N-fluxes



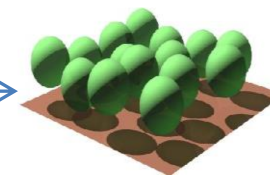
Ray tracing



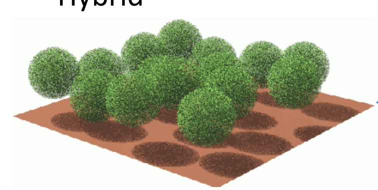
Turbid medium



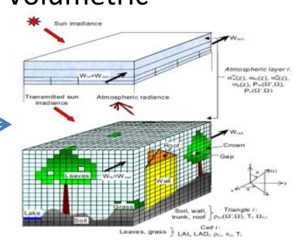
Geometric



Hybrid

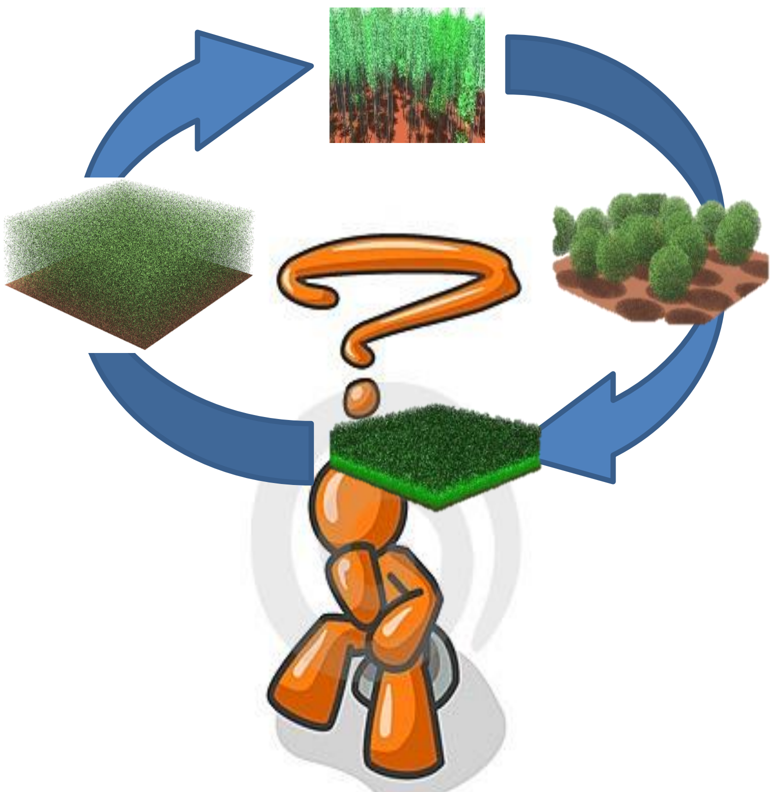


Volumetric

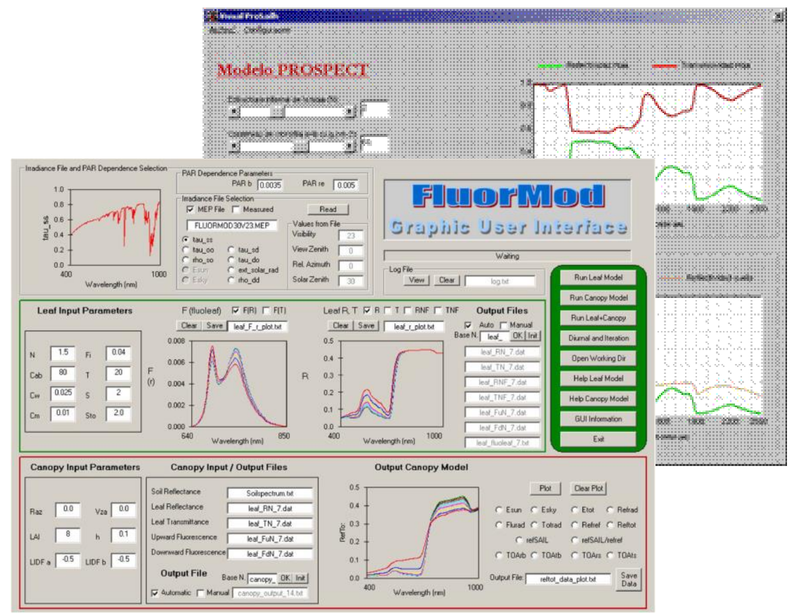


RTMs are important tools in EO research but for the broader community these models are perceived as complicated.

Which RTM is suitable?
Which RTM is available?



Only very few of them offer a GUI



(Zarco-Tejada et al., 2006)

- Until now there **exists no GUI that brings multiple RTMs together**.
- **None of existing GUIs provide inversion strategies** for biophysical parameters retrieval .

Gap to be filled:

- To develop a GUI toolbox that:
  - ✓ Enables operating various RTMs, both at leaf and at canopy level.
  - ✓ Provides tools for EO applications.
  - ✓ Enables semiautomatic retrieval of biophysical parameters through model inversion.
  - ✓ Accounts for variation in land cover during the inversion.

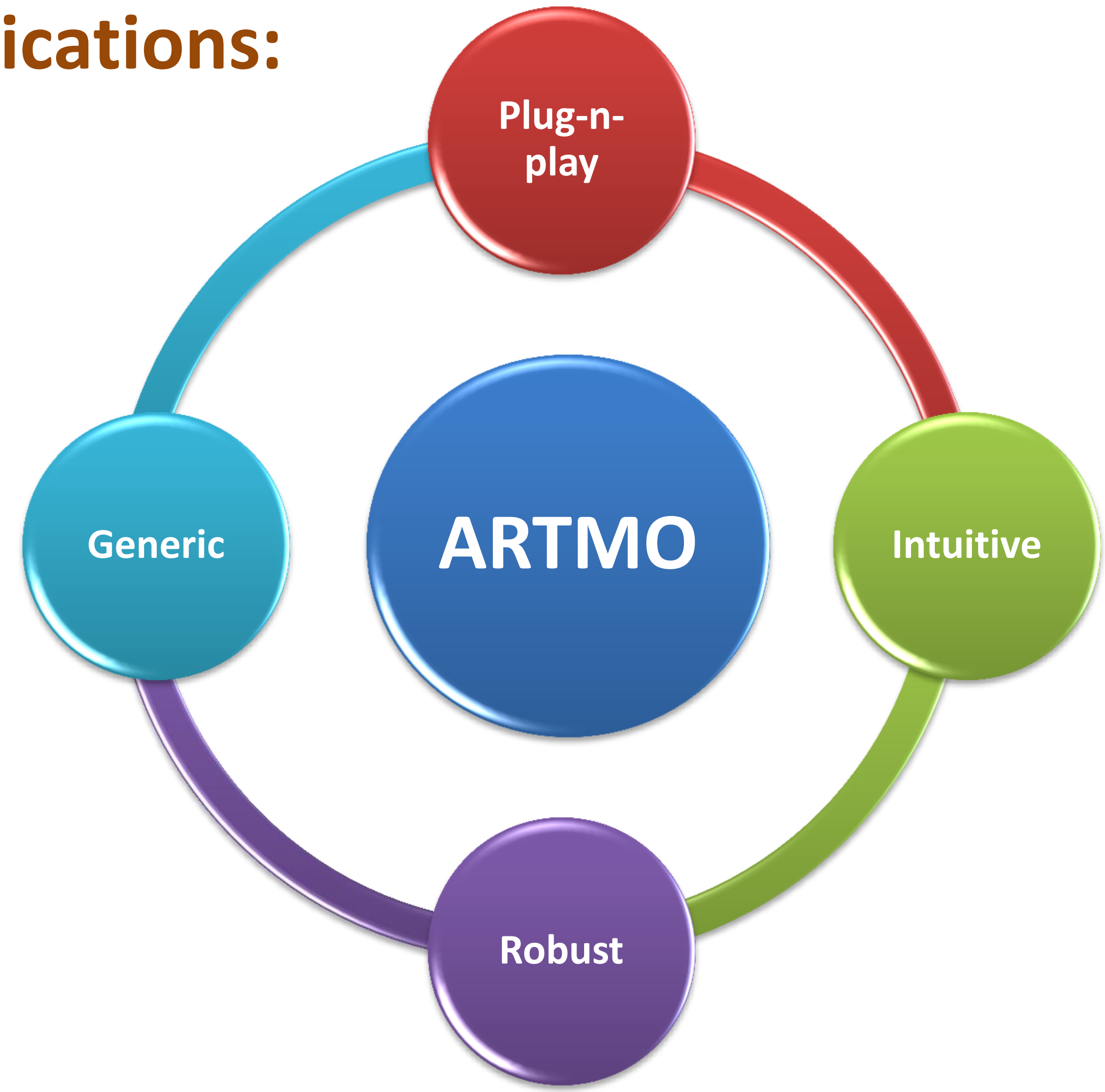
Objective:

- To optimize LUT-based inversion against hyperspectral CHRIS data by using the toolbox.

Toolbox for EO applications:

ARTMO:

Automated
Radiative
Transfer
Models
Operator



Selection RTMs:

- Reliable
- language
- Accessible
- Invertible

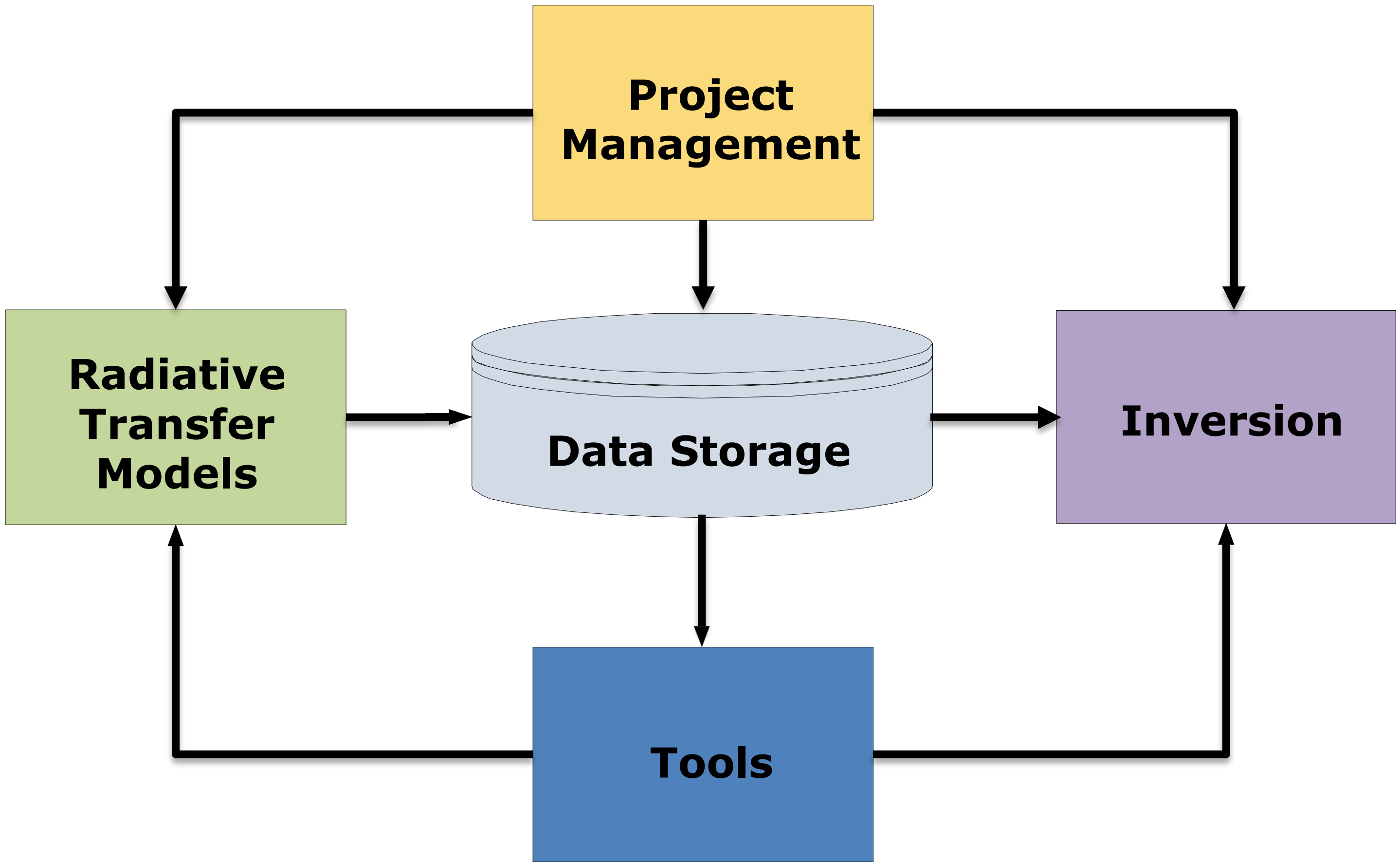
Model	Reference	Source code
Prospect-4	Feret et al., 2008	Matlab
Prospect-5	Feret et al., 2008	Matlab
FluorMODleaf	Pedrós et al., 2010	Executable file
4SAIL	Jacquemoud et al., 2009	Matlab
FluorSAIL	Zarco-Tejada et al., 2006	Executable file
FLIGHT	North, 1996	Executable file
SLC – Prospect + 4SAIL2	Verhoef & Bach, 2007	Mex file (Matlab)

Leaf RTM
Canopy RTM
Combined RTM

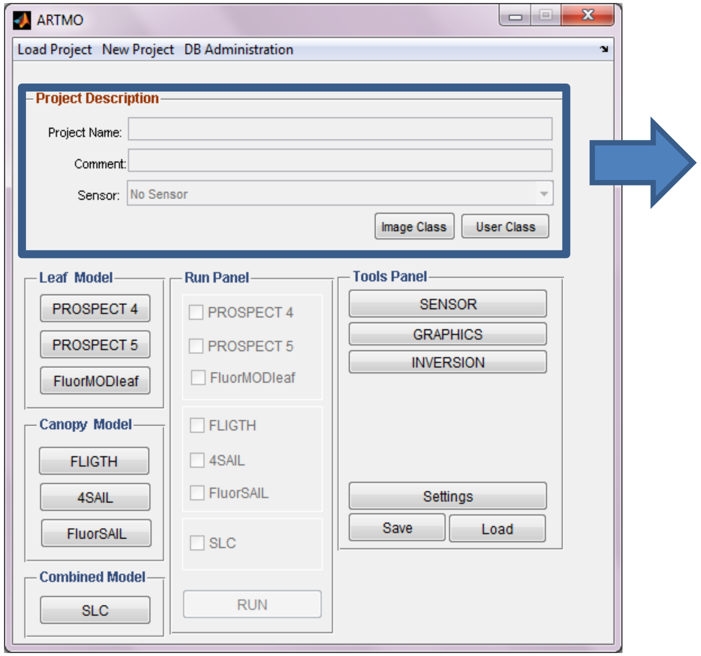
Software packages:

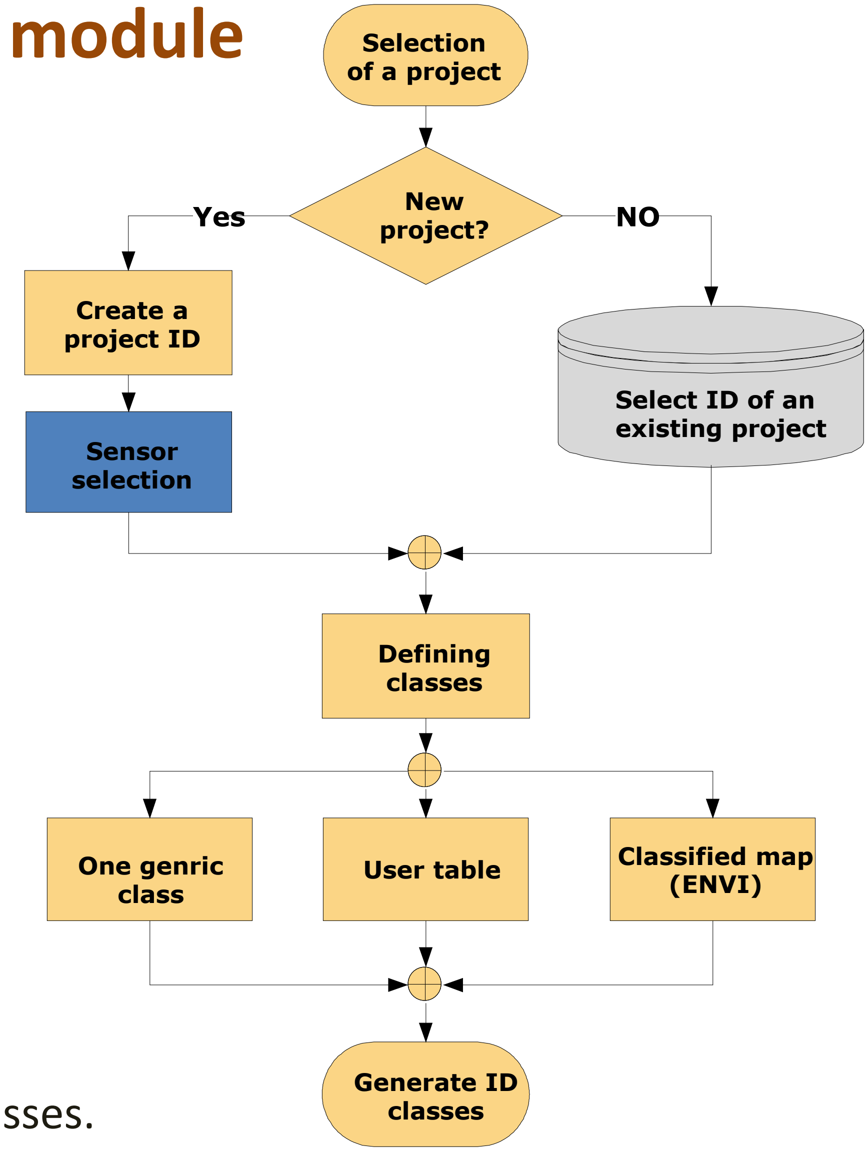
Programming language:	Matlab® (R2009b)
Database:	MySQL® (5.5.8)
Image processing software:	ENVI® 4.5

Conceptual Architecture ARTMO



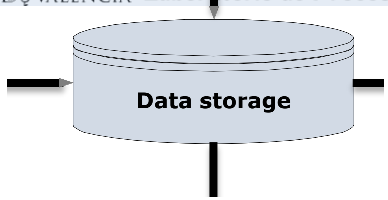
Project management module



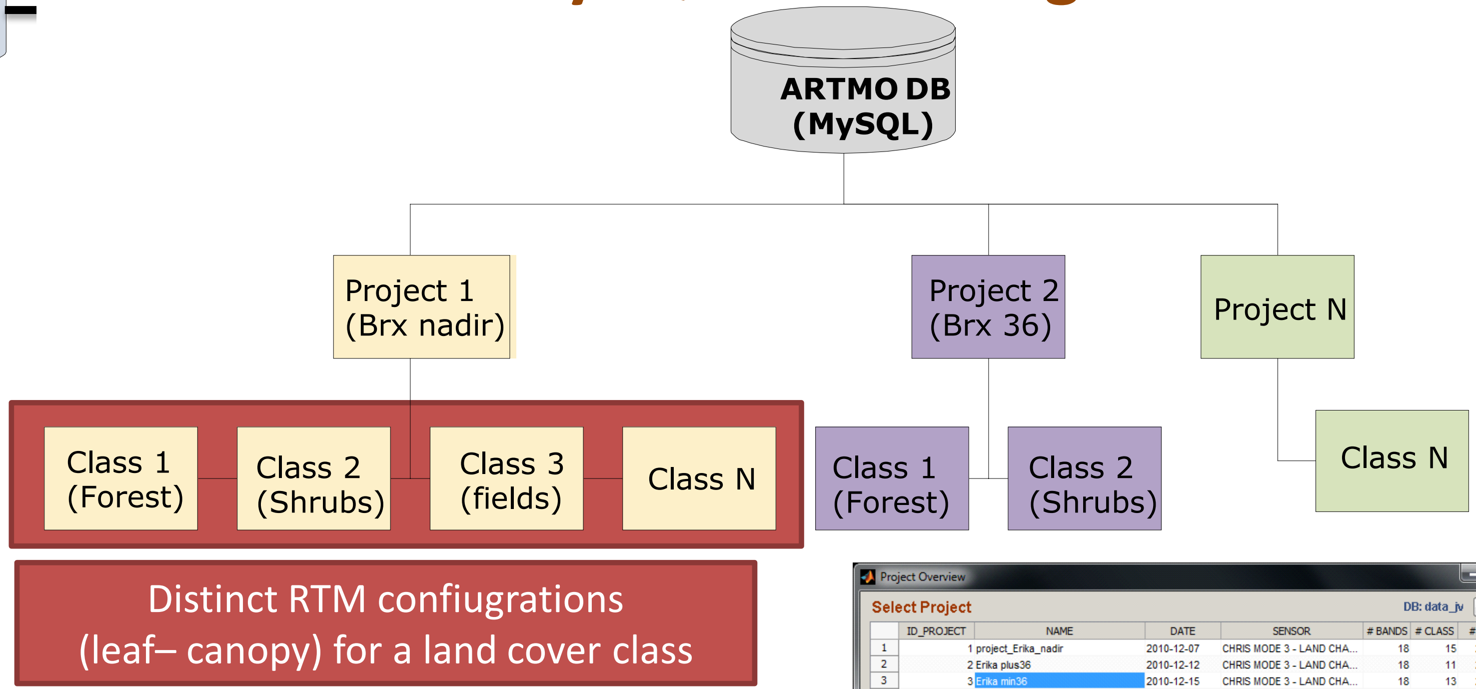


Important features:

- ✓ Load an existing project or create a new one.
- ✓ Select a Sensor
- ✓ Import/Export DBs, delete class/project/DB
- ✓ Choose whether a project should exist of LUT classes.

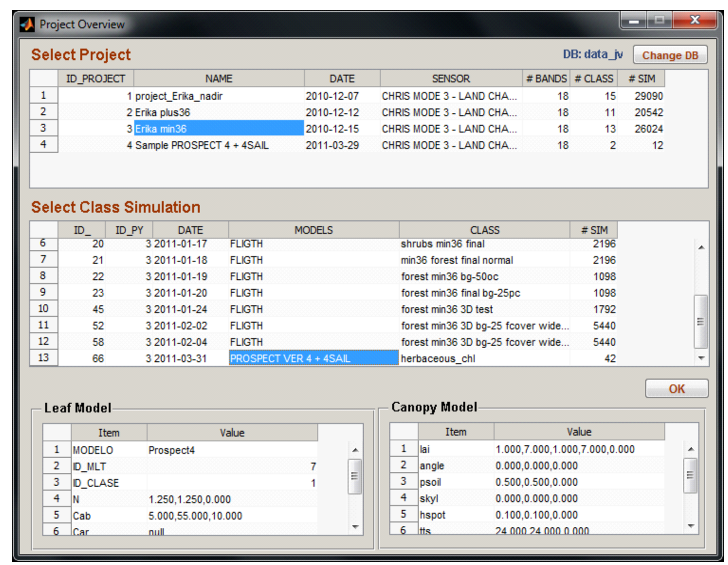


Underneath: MySQL data storage structure



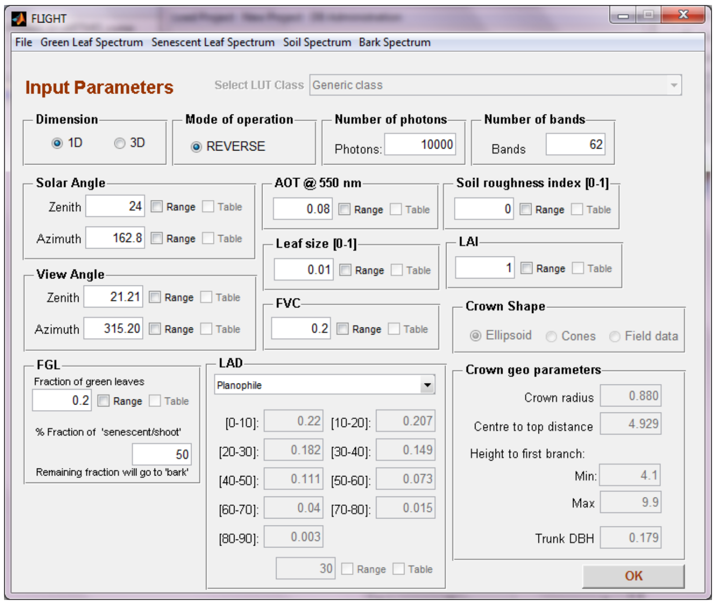
Important features:

- ✓ All input, output and metadata are stored in MySQL DB
- ✓ In 'Project Overview' metadata of all projects can be consulted.
- ✓ Classes can be accessed.
- ✓ All fixed input data and ranges of state parameters can be consulted.

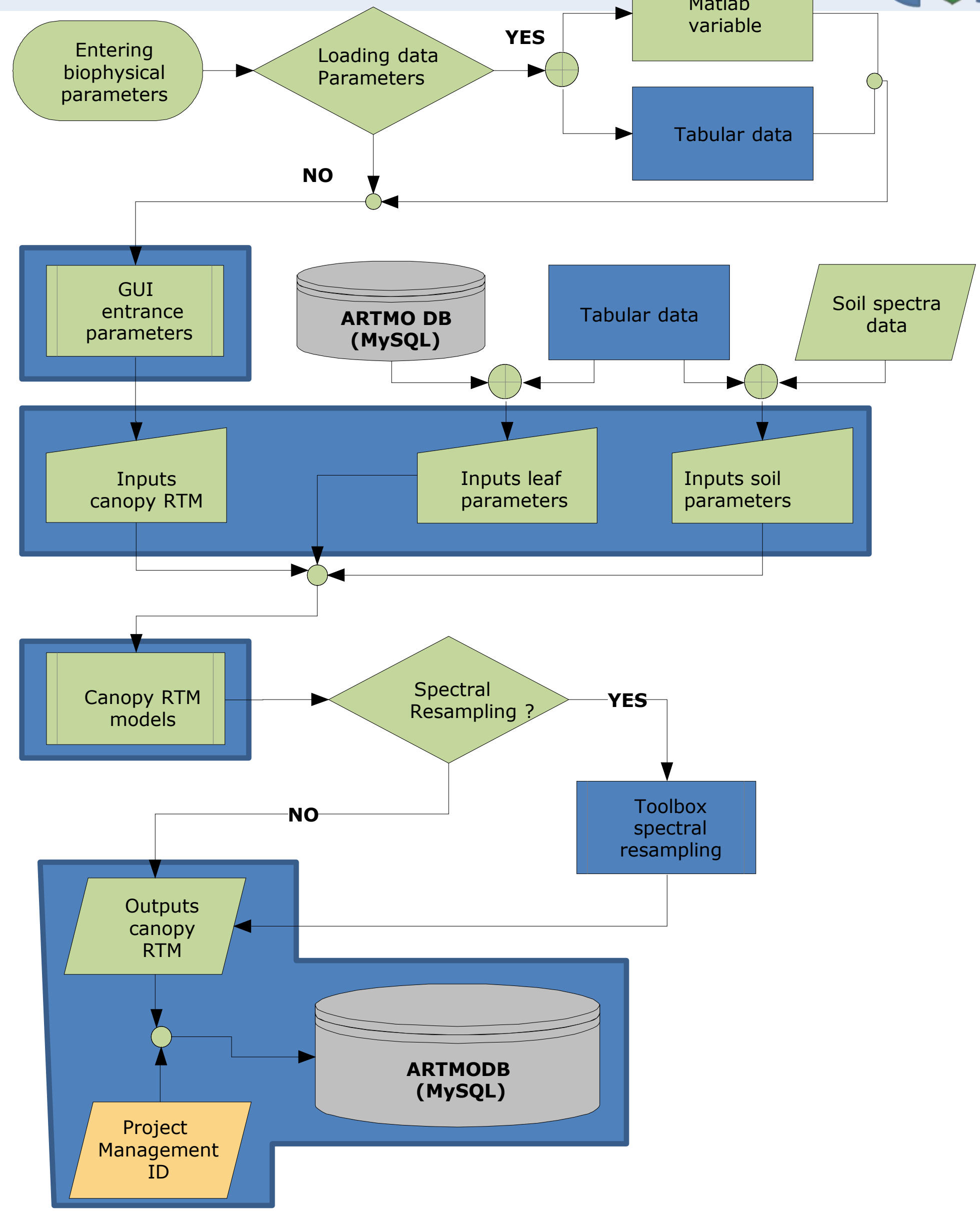


Radiative Transfer Models

RTM module



GUI of the FLIGTH model

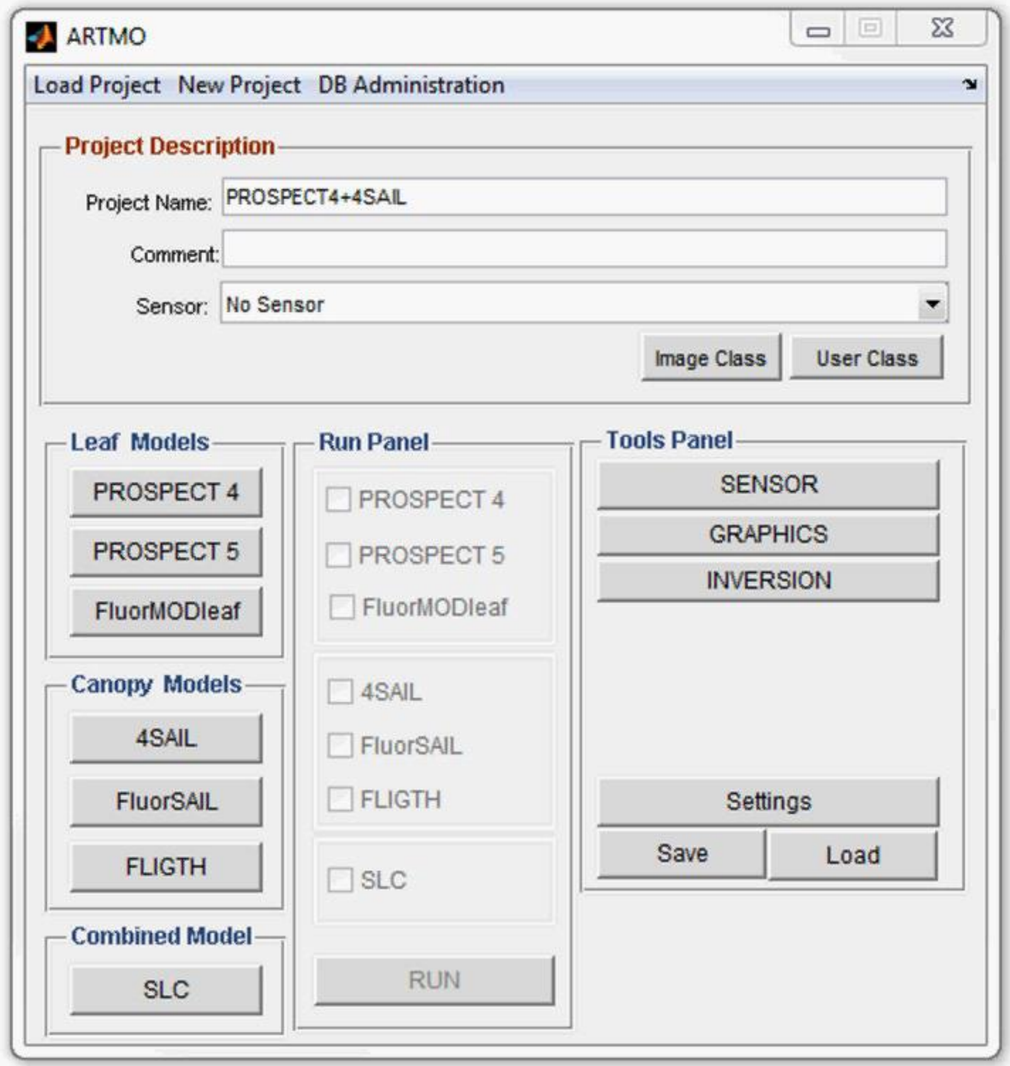


Important features:

- ✓ Insert a single value
- ✓ Insert user-defined input data
- ✓ Insert a range (stepwise or a distribution)
- ✓ Inset one or multiple spectra

Radiative Transfer Models

RTM input module

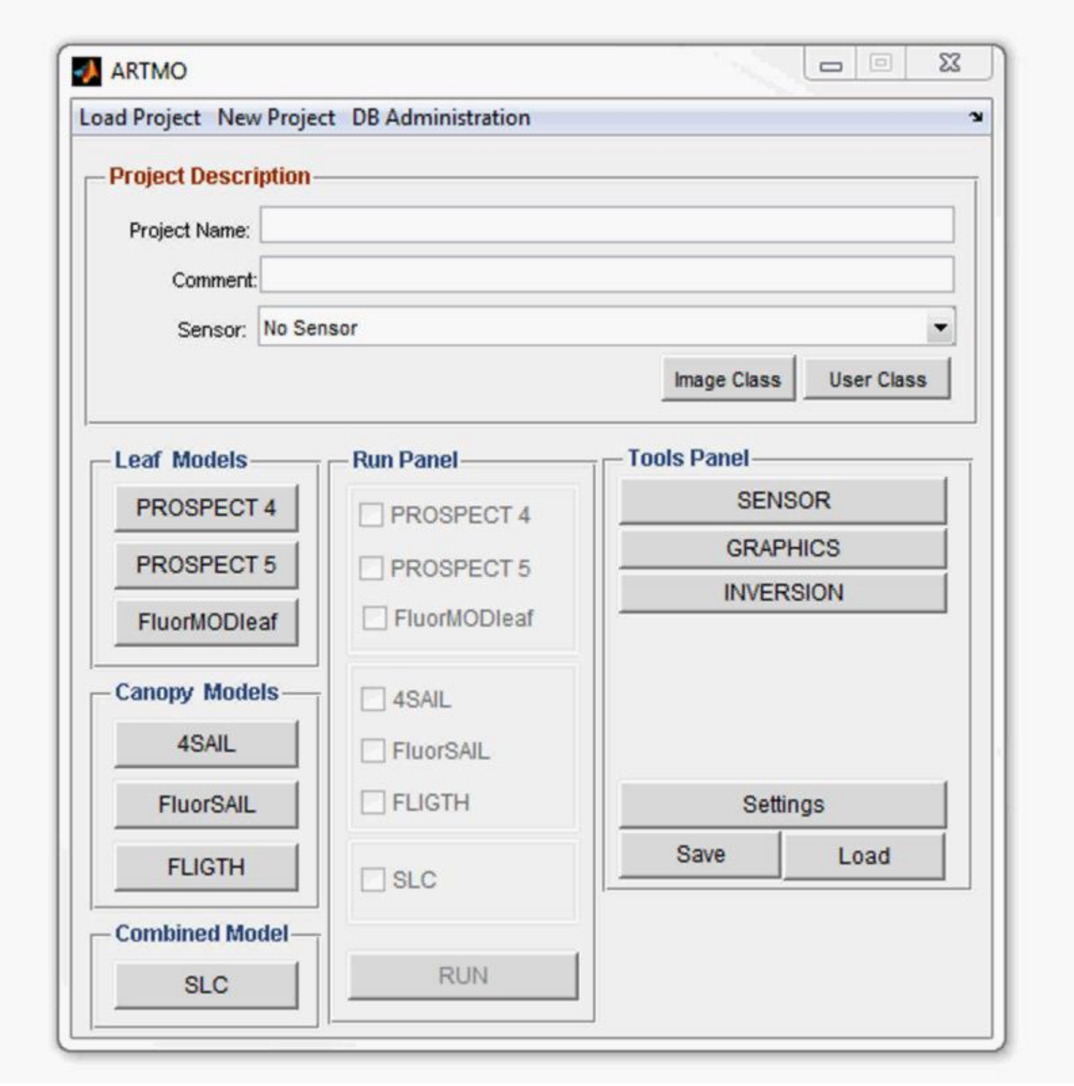


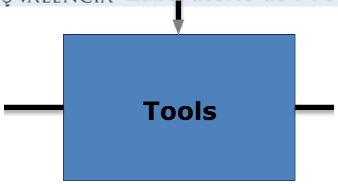
Tools

Tools

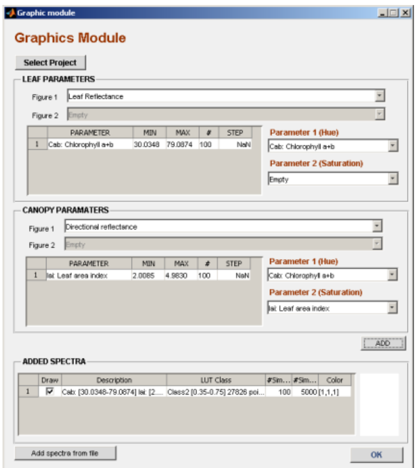
TOOLS

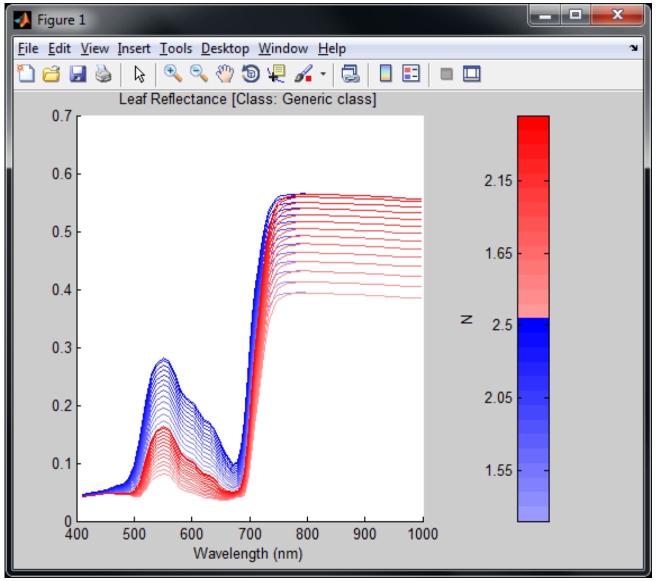
- Database management
- Settings models
- Graphics module
- Sensor module
- Error control
- Spectral resampling
- Gaussian noise
- Cost function evaluator

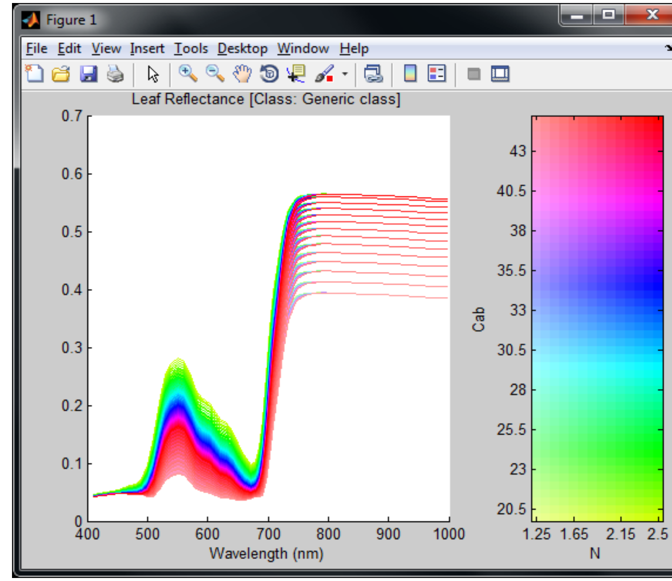


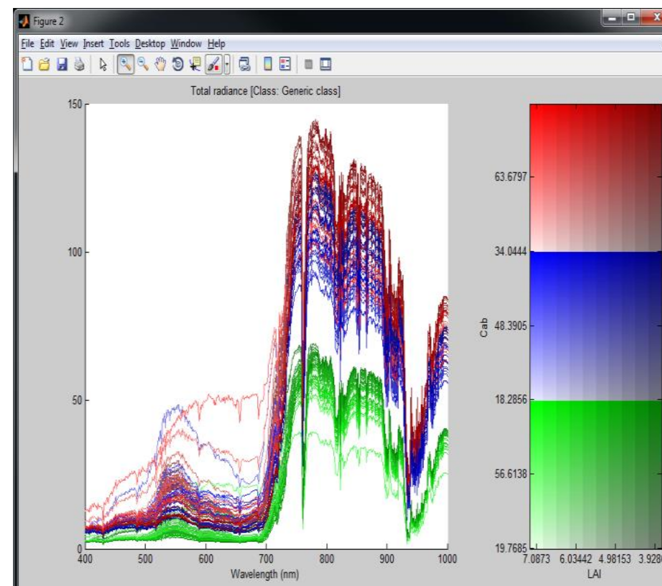


Plotting examples



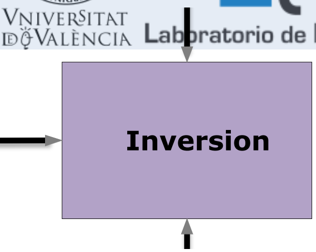






Important features:

- ✓ A group of spectra can be plotted according to a color range related to 1 parameter.
- ✓ Multiple groups can be added to the same plotting panel.
- ✓ A group of spectra can also be plotted according to 2 parameters, 1 as color hue and 1 as color saturation.
- ✓ External spectra can be added.
- ✓ The ‘Graphics’ module allows exporting spectra to a *.txt* file.



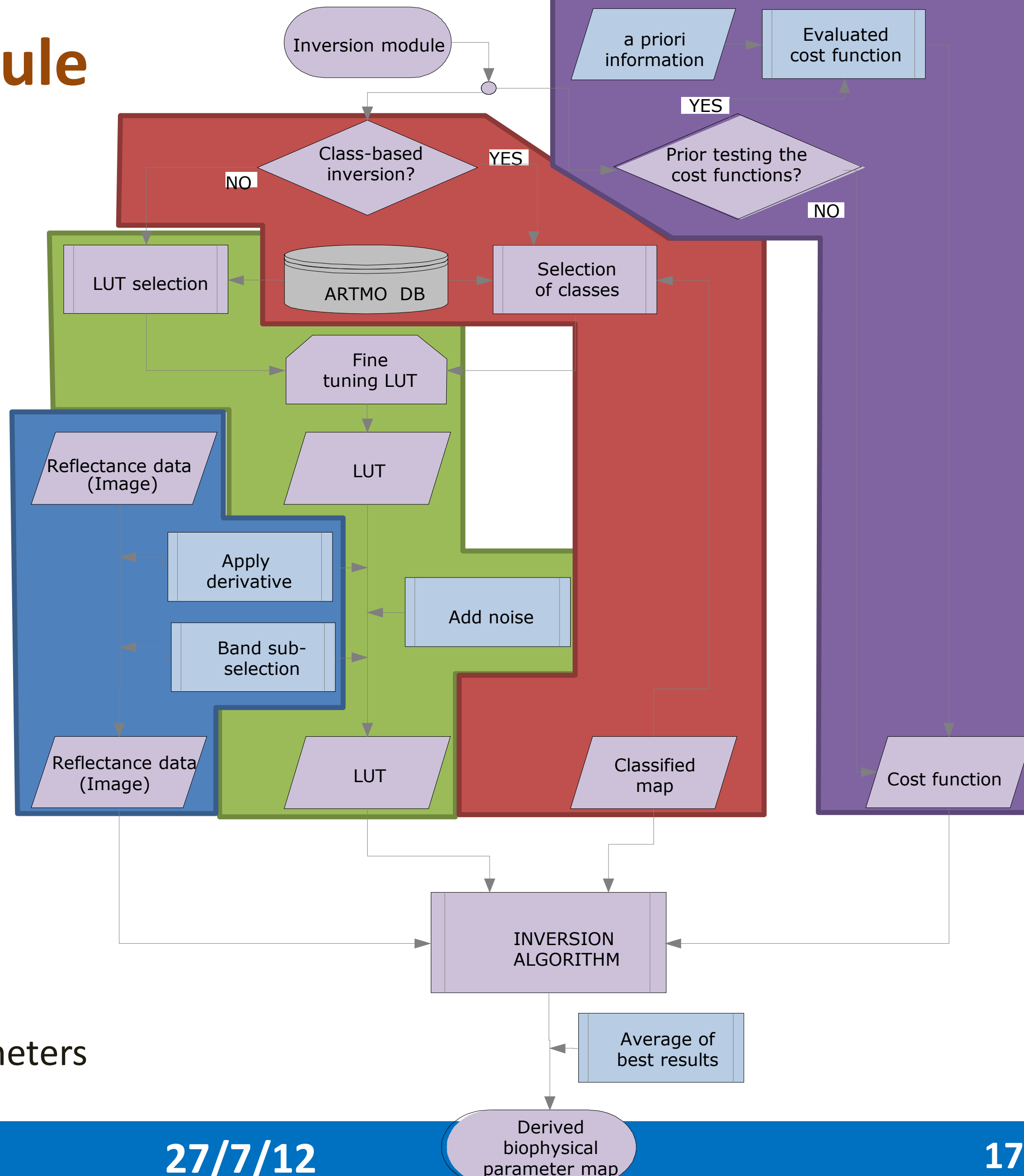
Inversion module

Image

Land cover map

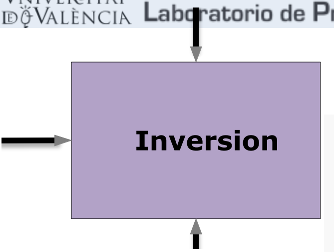
LUT selection

Inversion strategy

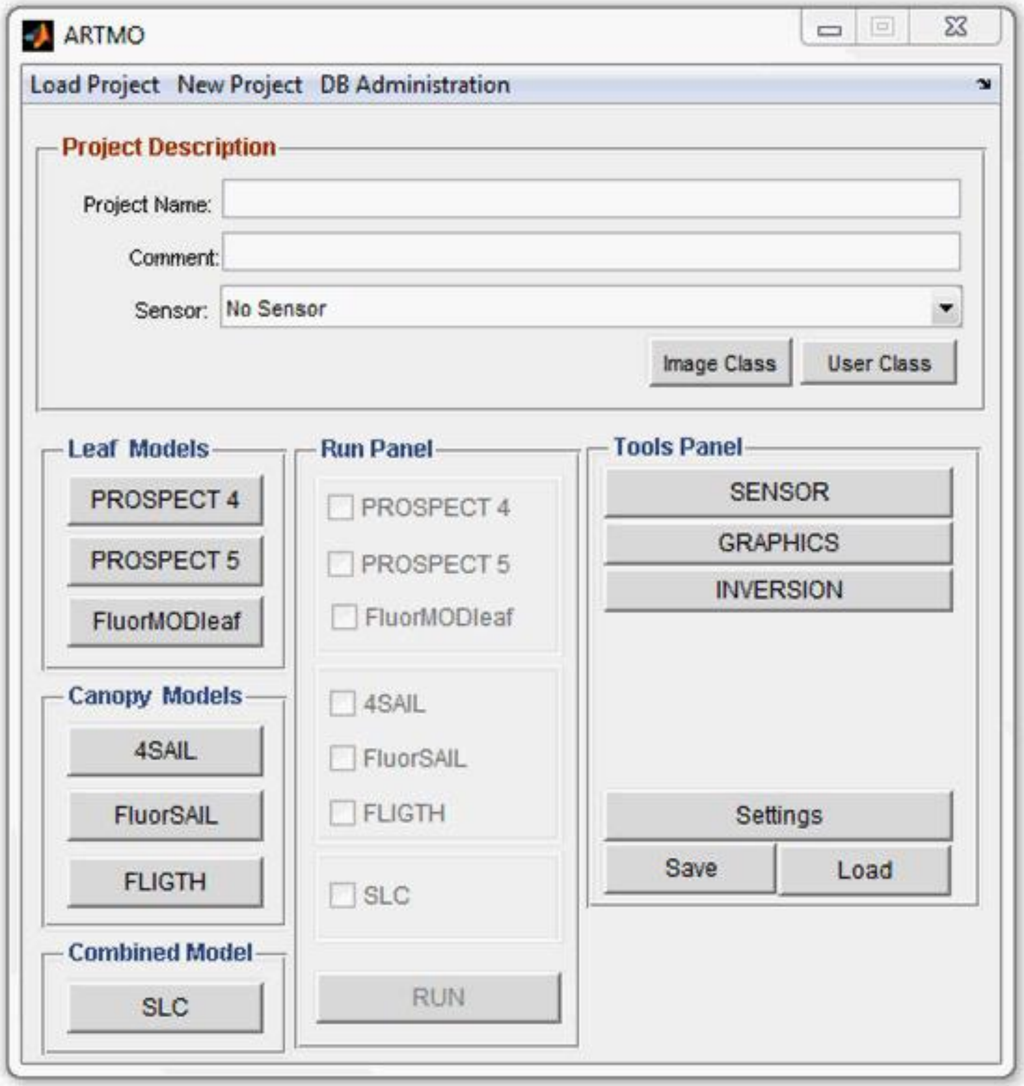


Important features:

- ✓ Generic or class-based inversion
- ✓ Select form multiple cost functions
- ✓ Select inversion optimization tools
- ✓ Retrieve simultaneously multiple parameters



Inversion module



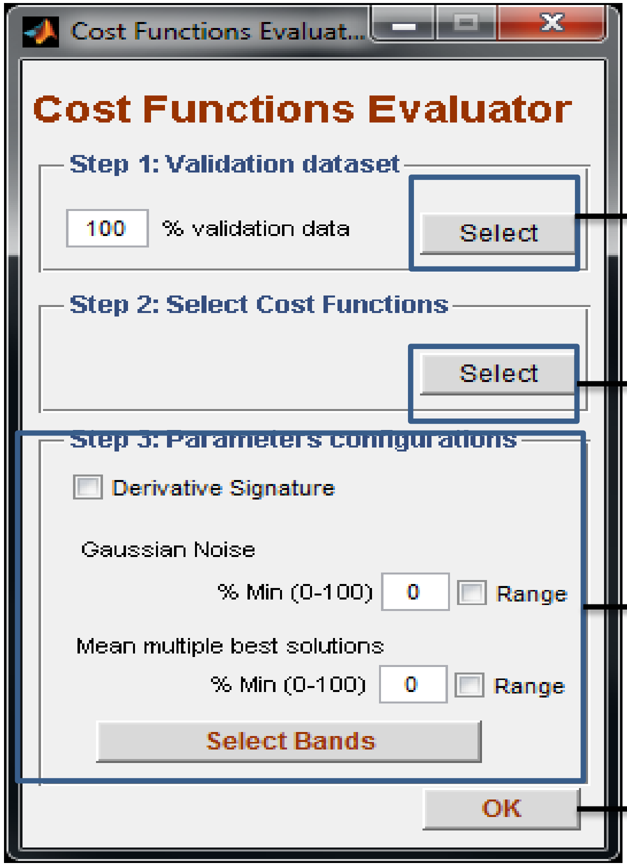
ARTMO's cost functions: minimizing distances between observed and modeled spectra

More than 60 different cost functions (also known as **metrics, distances, or divergence measures**) have been implemented (Leonenko et al, 2012). They can be grouped into three families:

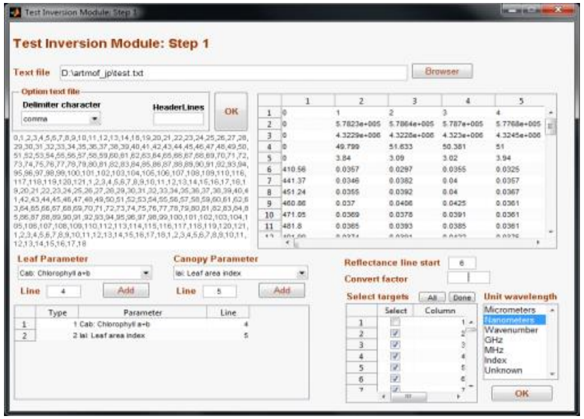
1. First family is reffered to **information measures** and describes **distances between two probability functions**.
   - Power divergence measure: $$D[P,Q] = \sum_{\lambda_i=1}^{\lambda_n} p(\lambda_i) \frac{\{[p(\lambda_i)/q(\lambda_i)]^\alpha - 1\}}{\alpha(\alpha+1)}, \alpha \in (-\infty, +\infty)$$
2. Second family is called **M-estimates**, and in this case **reflectance is considered as a nonlinear regression function**.
   - Root Mean Squared Error (RMSE): $$D[P,Q] = \sqrt{\sum_{\lambda_i=1}^{\lambda_n} \frac{(p(\lambda_i) - q(\lambda_i))}{n}}$$
   - Trigonometric $: \rho(x) = \nu\left(x \arctan(sx) - \frac{\log(s^2x^2+1)}{2s} \right), \quad s, \nu > 0.$
3. Third family of **minimum contrast estimates** represents **distances in the spectral domain**. In this case **reflectance is considered as spectral density function**.
   - Contrast function K(x)=-log(x)+x: $$D[P,Q] = \sum_{\lambda_i}^{\lambda_n} \{-log(q(\lambda_i))/p(\lambda_i)) + q(\lambda_i))//p(\lambda_i)\}.$$

Inversion

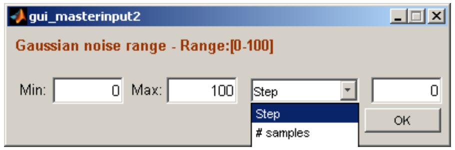
Inversion strategy evaluator

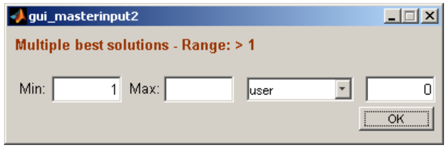


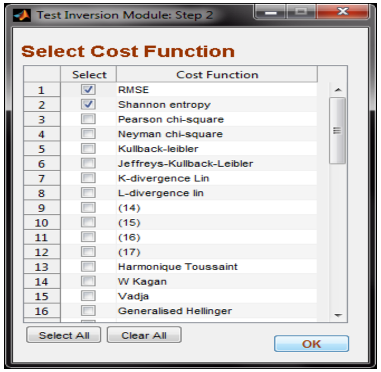
Validation/
a priori data



$$\Gamma_f^h(P,Q) = \left(\frac{1}{1-\alpha}\right)\left[\left(\sum_{l=1}^{n}\left(\frac{p_l+q_l}{2}\right)^{\beta}\right)^{\frac{\alpha-1}{\beta-1}} - \frac{1}{2}\left(\left[\sum_{l=1}^{n} {p_l}^{\beta}\right]^{\frac{\alpha-1}{\beta-1}} + \left[\sum_{l=1}^{n} {q_l}^{\beta}\right]^{\frac{\alpha-1}{\beta-1}}\right)\right], \begin{cases}\alpha > 0, \neq 1\\ \beta > 0, \neq 1\end{cases}$$

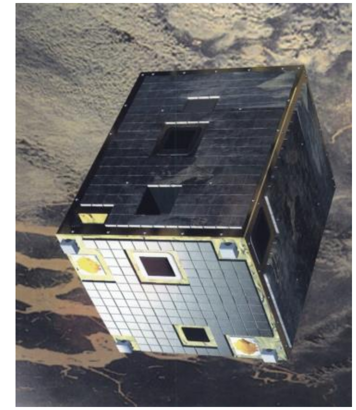






All inputted regularization combinations is evaluated against the validation dataset. Results are stored in a MySQL table.

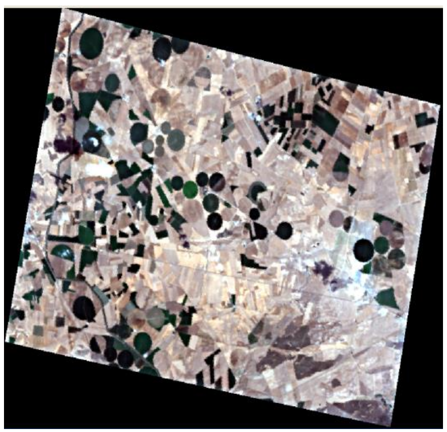
Hyperspectral Satellite data:



CHRIS (Compact High Resolution Imaging Spectrometer)

- Acquisition angle: **Nadir**
- **Mode 1**: 62 bands (410-1040 nm), 37 m
- Geometrically and atmospherically corrected

Field measurements for validation:



SPectra bARrax Campaign (SPARC 2003):

- >100 elementary sample units on agricultural fields
- **Rich dataset:** 9 differents crops (corn, sugarbeet, onion, garlic, potato, alfalfa, wheat, sunflower, vine)
- In situ: Ch, LAI, fCOVER, Biomass, Water content,…
- **Leaf Chl** values between 0 and 55 mg/cm^2
- **LAI** values between 0 and 6.5

} **Validation**

Evaluating cost functions:

- **RMSE**
- 3 alternatives, from each family one.

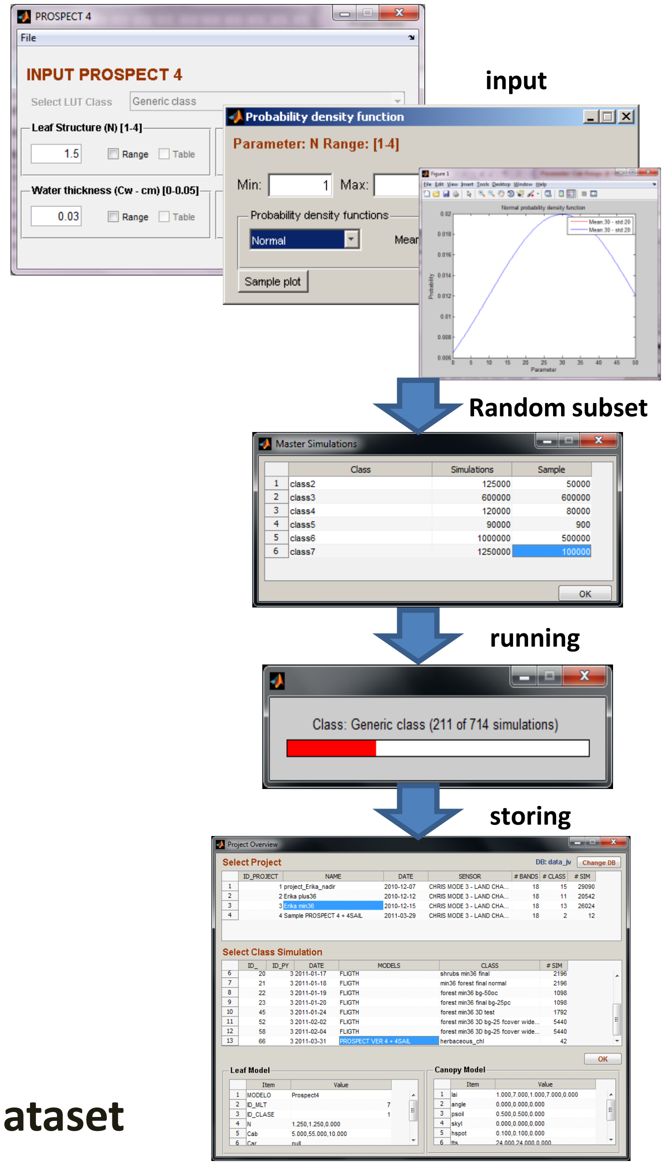
{
- **Power divergence**
- **Trigonometric**
- **Contrast function K(x)=-log(x)+x**

Laboratorio de Procesado de Imágenes

LUT easily created (here with PROSAIL)

- ✓ 100000 spectra generated
- ✓ Spectra automatically resampled to CHRIS mode 1

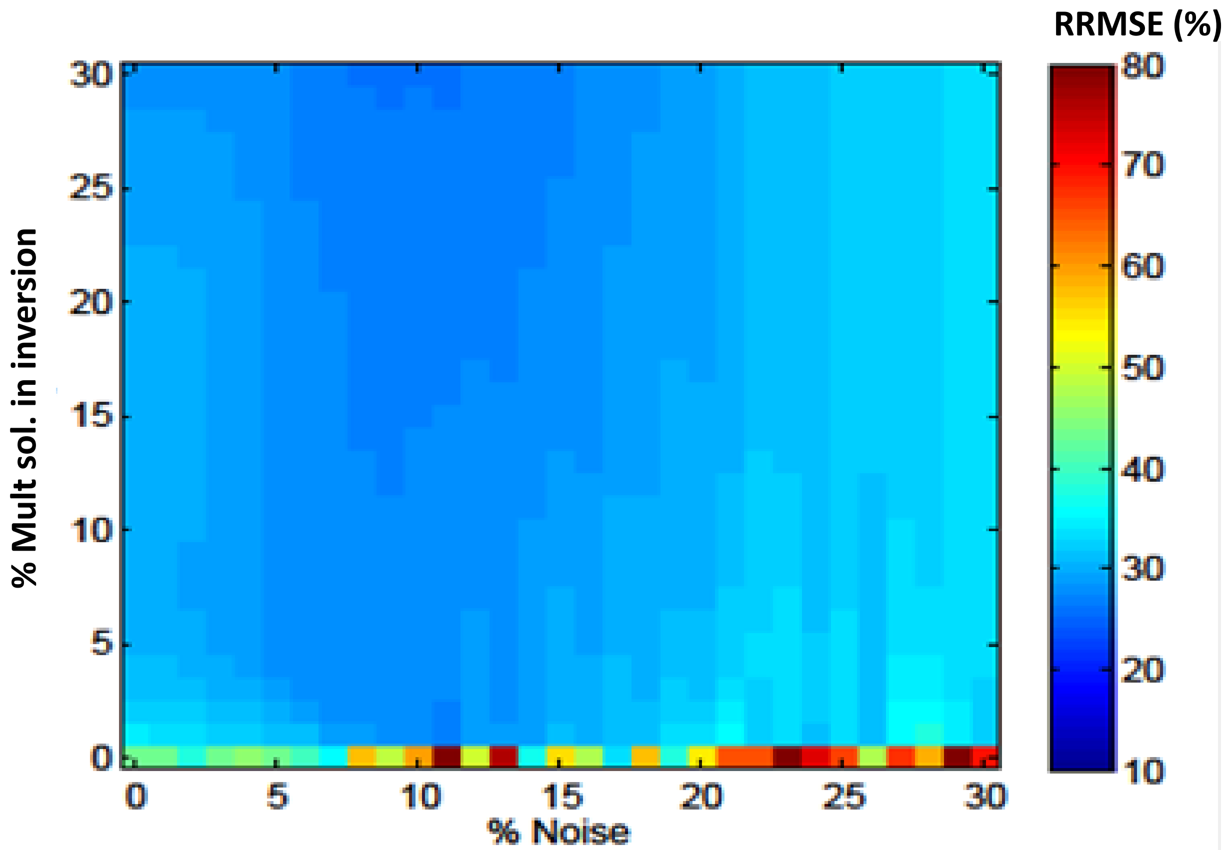
	Model Parameters	Units	Range	Distribution
Leaf parameters: PROSPECT-4				
N	Leaf structure index	unitless	1.3-2.5	Uniform
Chl	Leaf chlorophyll content	[μg/cm^2]	5-75	Gaussian (μ: 35, SD: 30)
C_m	Leaf dry matter content	[g/cm^2]	0.001-0.03	Uniform
C_w	Leaf water content	cm	0.002-0.05	Uniform
Canopy variables: 4SAIL				
LAI	Leaf area index	[m^2/m^2]	0.1-7	Gaussian (μ: 3, SD: 2)
ALA	Average leaf angle	[º]	40-70	Uniform
α_{soil}	Soil scaling factor	unitless	0-1	Uniform
HotS	Hot spot parameter	[m/m]	0.05-0.5	Uniform
skyl	Diffuse incoming solar radiation	[fraction]	0.05	-
θ_s	Sun zenith angle	[º]	22.3	-
θ_v	View zenith angle	[º]	20.19	-
ϕ	Sun-sensor azimuth angle	[º]	0	-



Evaluating the role of inversion strategies against validation dataset

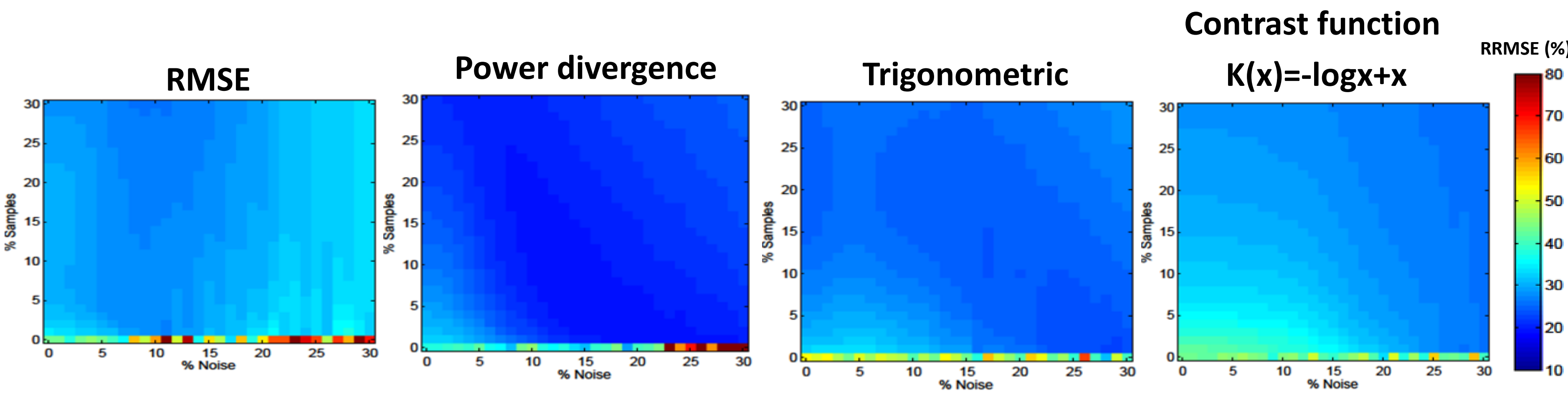
Chl retrieval using CHRIS 62 bands - Validation

RMSE



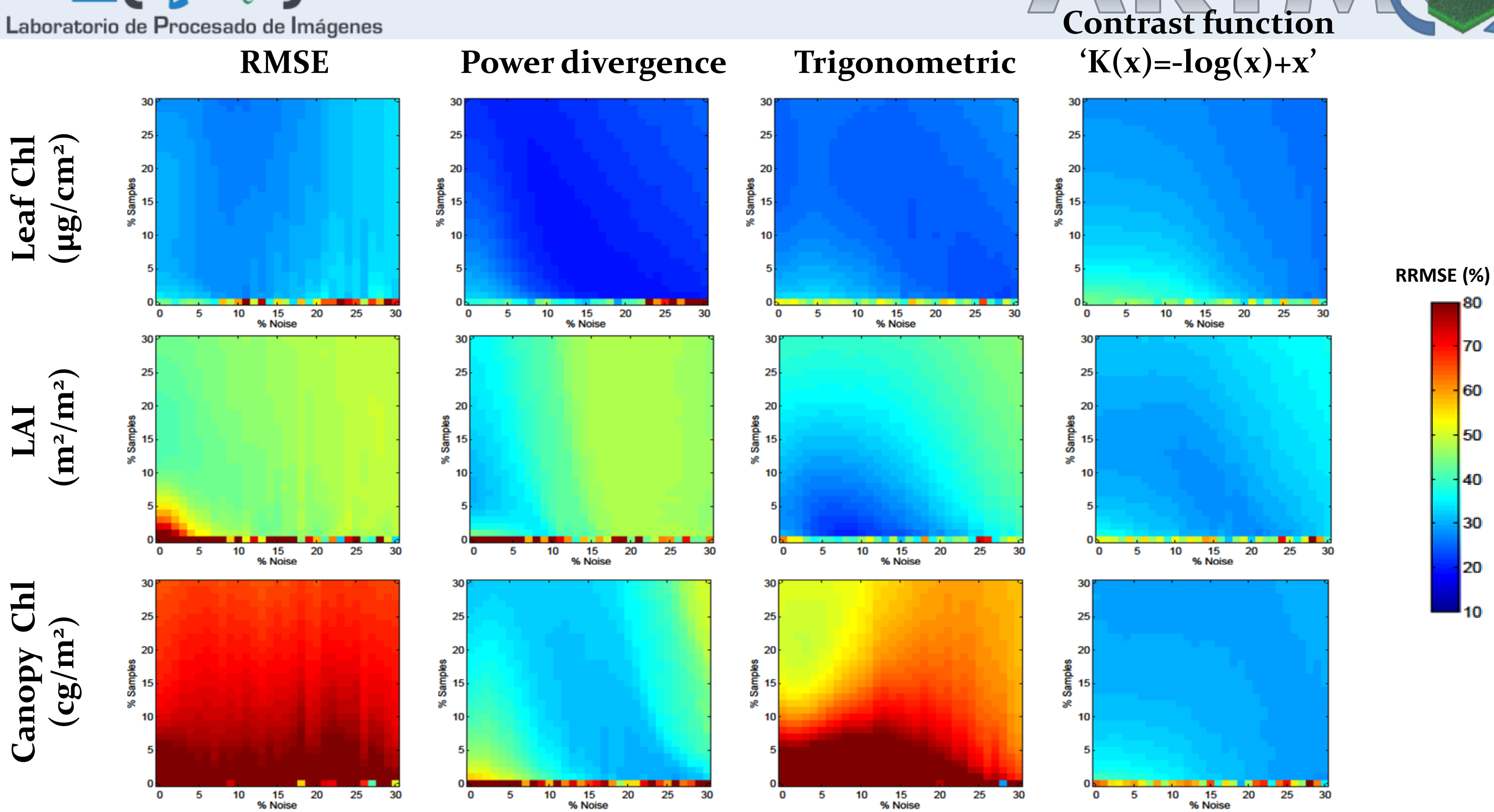
- Single best solution never the best choice.
- Regularization options improved retrievals: from 43% to 26%.

Chl retrieval using CHRIS 62 bands



RMSE suboptimal cost function – other cost functions perform superior!

- The single best solution is never the best choice.
- Regularization options different impact on CFs (because of different interpretation on data distribution).
- ‘Power divergence’ and ‘Trigonometric’ best performing but they need to be tuned (*α, β*).



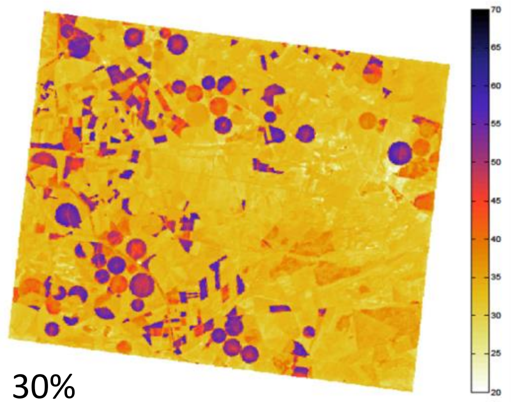
- **Different patterns for different biophysical parameters.**
- **RMSE is performing poorly** for LAI and extremely poor for canopy chl.
- LAI best retrieved by 'Trigonometric'.
- Given the three biophysical parameters, **the Contrast function 'K(x)=-logx(x)+x'** yielded overall best results. Most useful for simultaneous retrieval of multiple parameters (**21% noise, 1% mult. solution**).

Final maps through optimized LUT-based inversion:

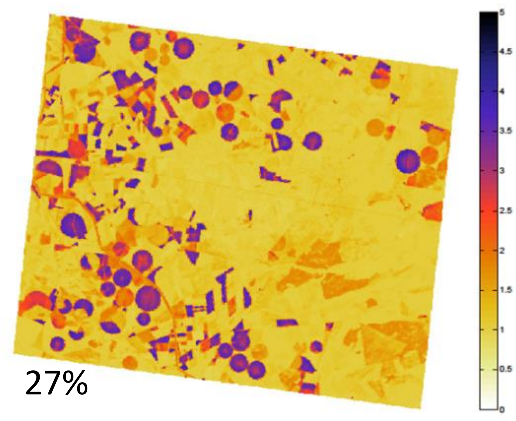
Contrast function K(x)=-log(x)+x
(21% noise, 1% mult. solution)

Mean estimation

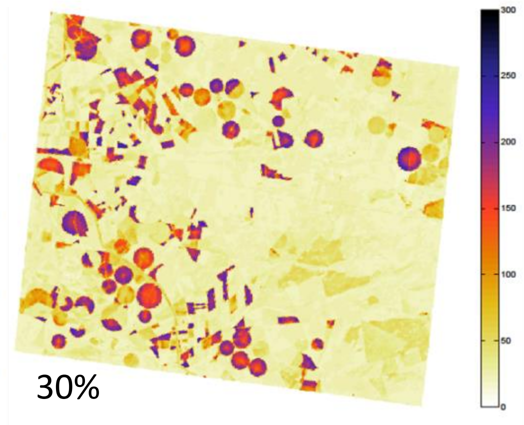
Leaf Chl (µg/cm²)



LAI (m²/m²)



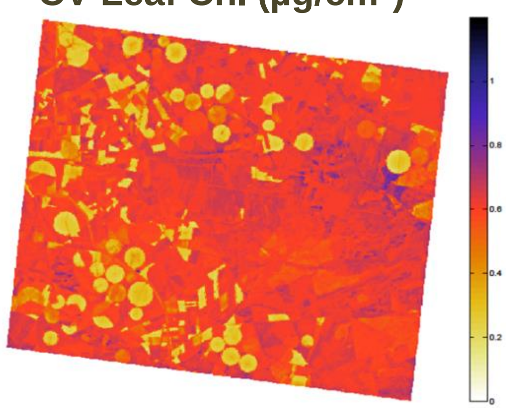
Canopy Chl (cg/m²)



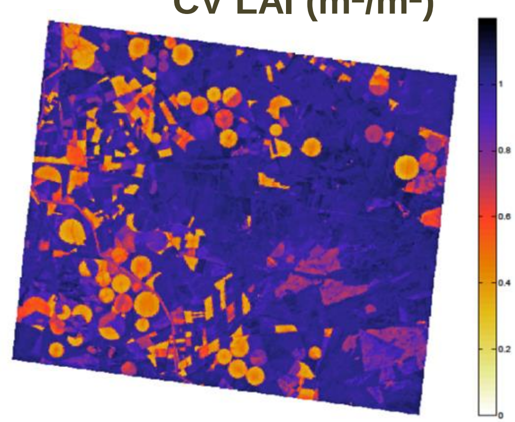
RRMSE: 30% | 27% | 30%

Coefficient of Variation

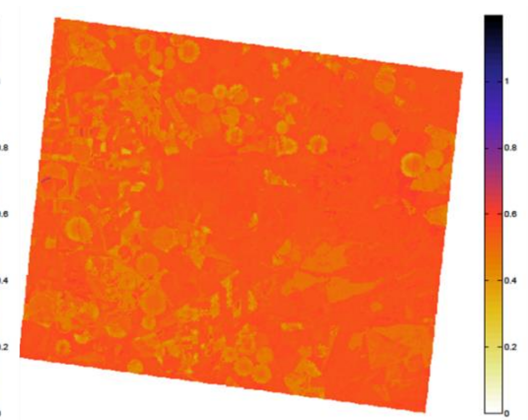
CV Leaf Chl (µg/cm²)



CV LAI (m²/m²)



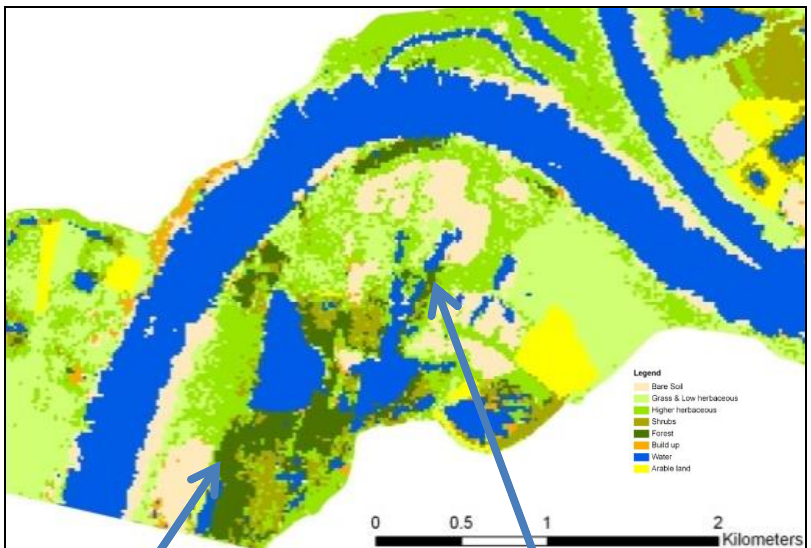
CV Canopy Chl (cg/m²)



Example class-based inversion: combining 1D and 3D models within same image

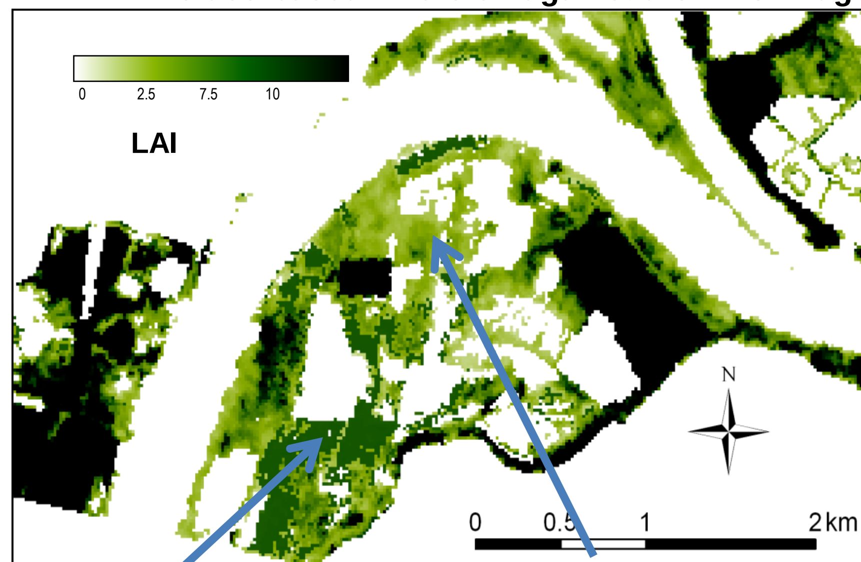
Landscapes are typically patchy. With class-based inversion a whole image can be instantly processed.

Input: **Land cover map**



Trees
Grassland

Class-based inversion against a CHRIS image



3D model (FLIGHT)
1D model (4SAIL)

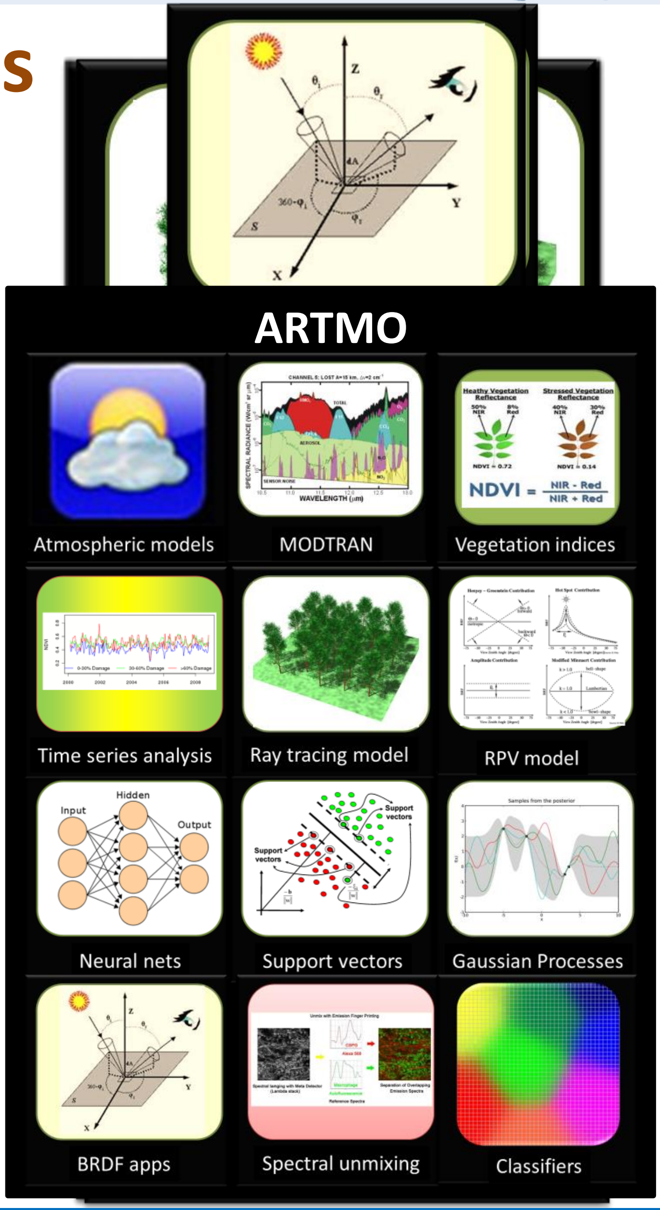
Models can be combined. As such, more realistic representations of patchy landscapes can be achieved

Outlook ARTMO – towards addings 'apps'

Various new modules and apps can be added to ARTMO:

- Atmospheric correction models
- Module with Vegetation Indices apps
- New RTMs: e.g., GeoSAIL, RPV, FRT, SCOPE, …
- Module with Nonparametric models (e.g. neural nets, SVR,..)
- Module with BRDF apps
- Unmixing app
- Classifier apps

We encourage colleagues to develop apps for easier working with EO data



Thanks

VERRELST, J., RIVERA J.P., ALONSO, L., MORENO, J. (2011). ARTMO: an Automated Radiative Transfer Models Operator toolbox for automated retrieval of biophysical parameters through model inversion. In: *EARSeL 7th SIG-Imaging Spectroscopy Workshop 2011*, 11-13 April, Edinburgh, UK.