

# Optimizing LUT-based RTM inversion for retrieval of biophysical parameters

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# Outline

I: Principles of RTM inversion

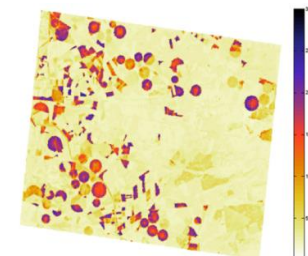
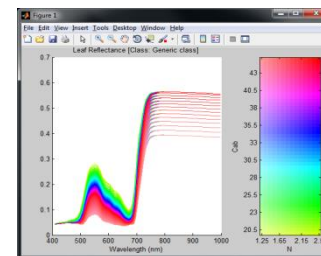
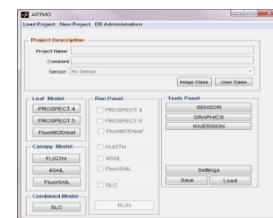
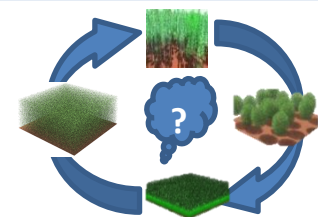
II: ARTMO toolbox

- Design
- Modules
- Inversion strategy

III: LUT-based inversion using CHRIS data

- Optimizing inversion through regularization strategies
- Class-based inversion

VI: Outlook



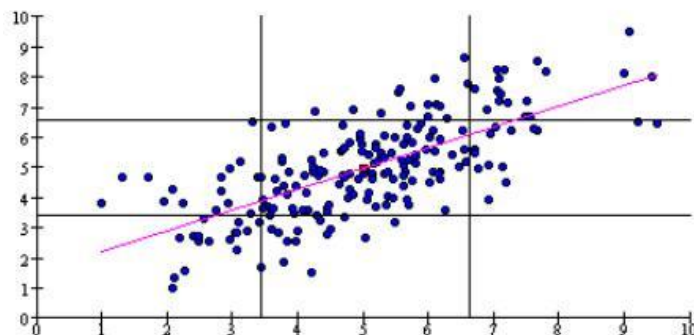
# Basics biophysical parameter retrieval



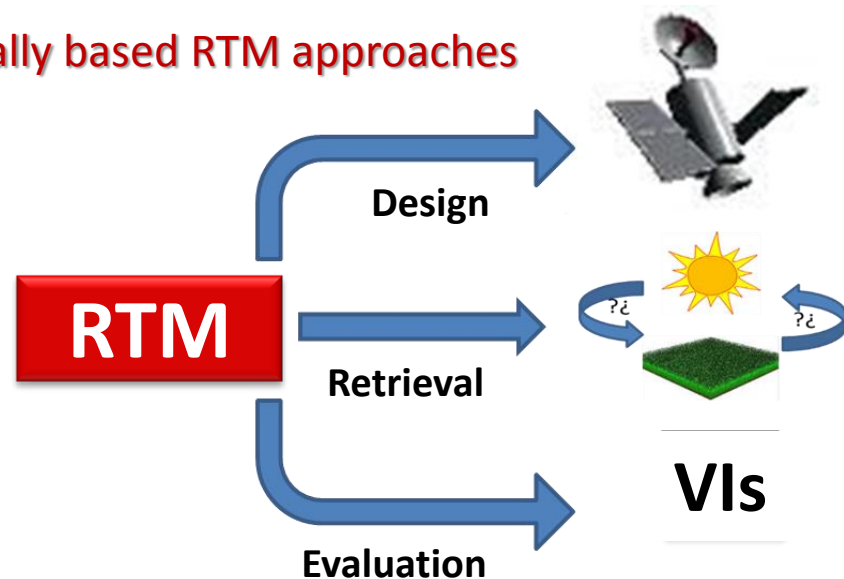
Retrieval of biophysical parameters from optical EO data **always occurs through a model**; e.g. through **statistical models** or through **inversion** of physically-based **radiative transfer models (RTM)**.

## Statistical approaches

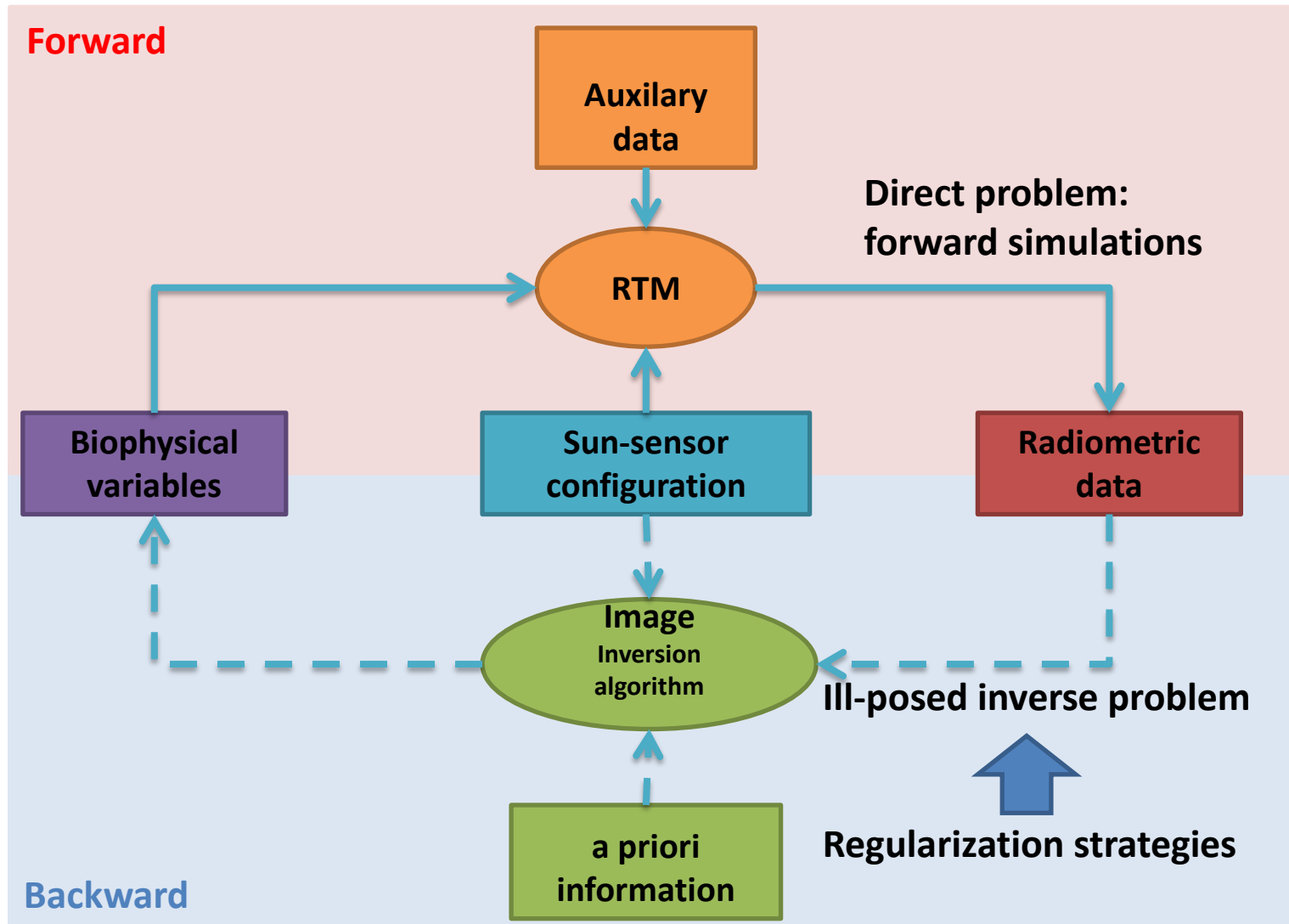
Scatter, Correlation, and Regression



## Physically based RTM approaches



# Retrieval of biophysical parameters through RTM inversion:



# RTMs

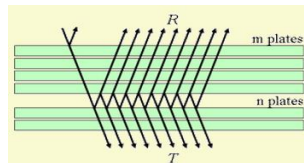
## Leaf RTMs



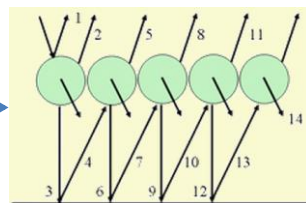
## Canopy RTMs



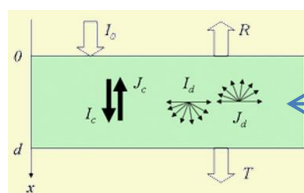
layers



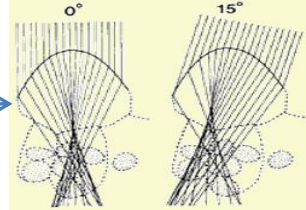
Compact spheres



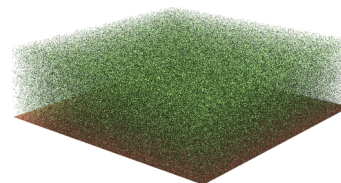
N-fluxes



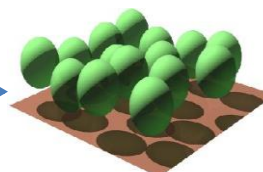
Ray tracing



Turbid medium



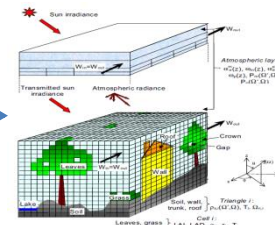
Geometric



Hybrid



Volumetric

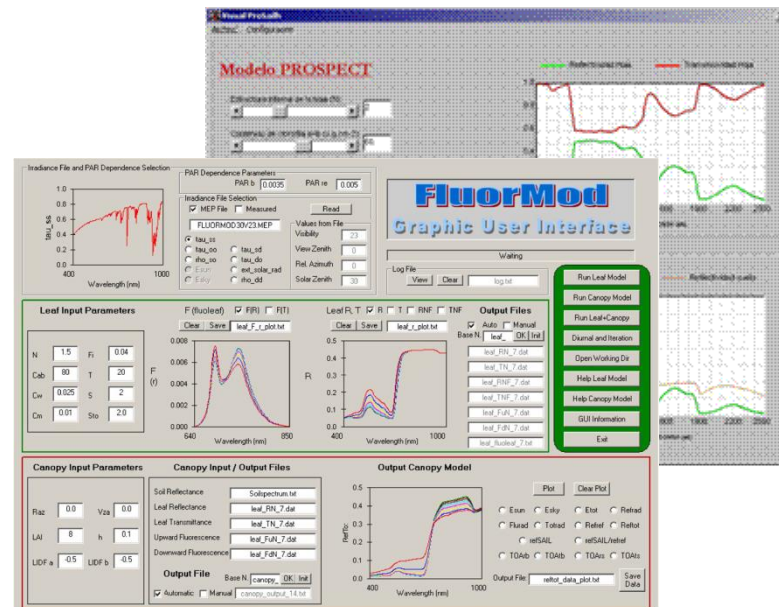
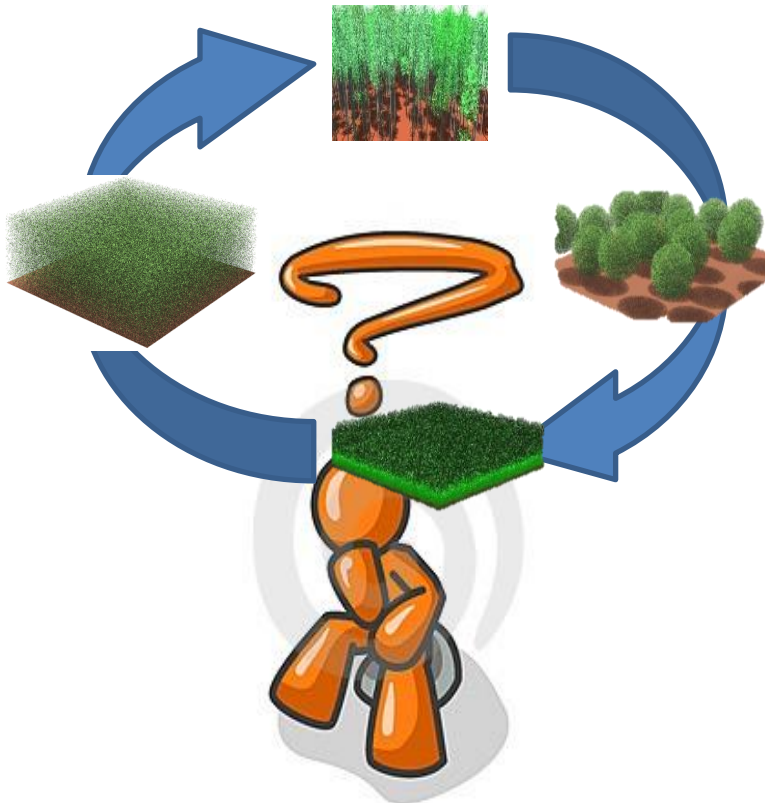




RTMs are important tools in EO research but for the broader community these models are perceived as complicated.

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.

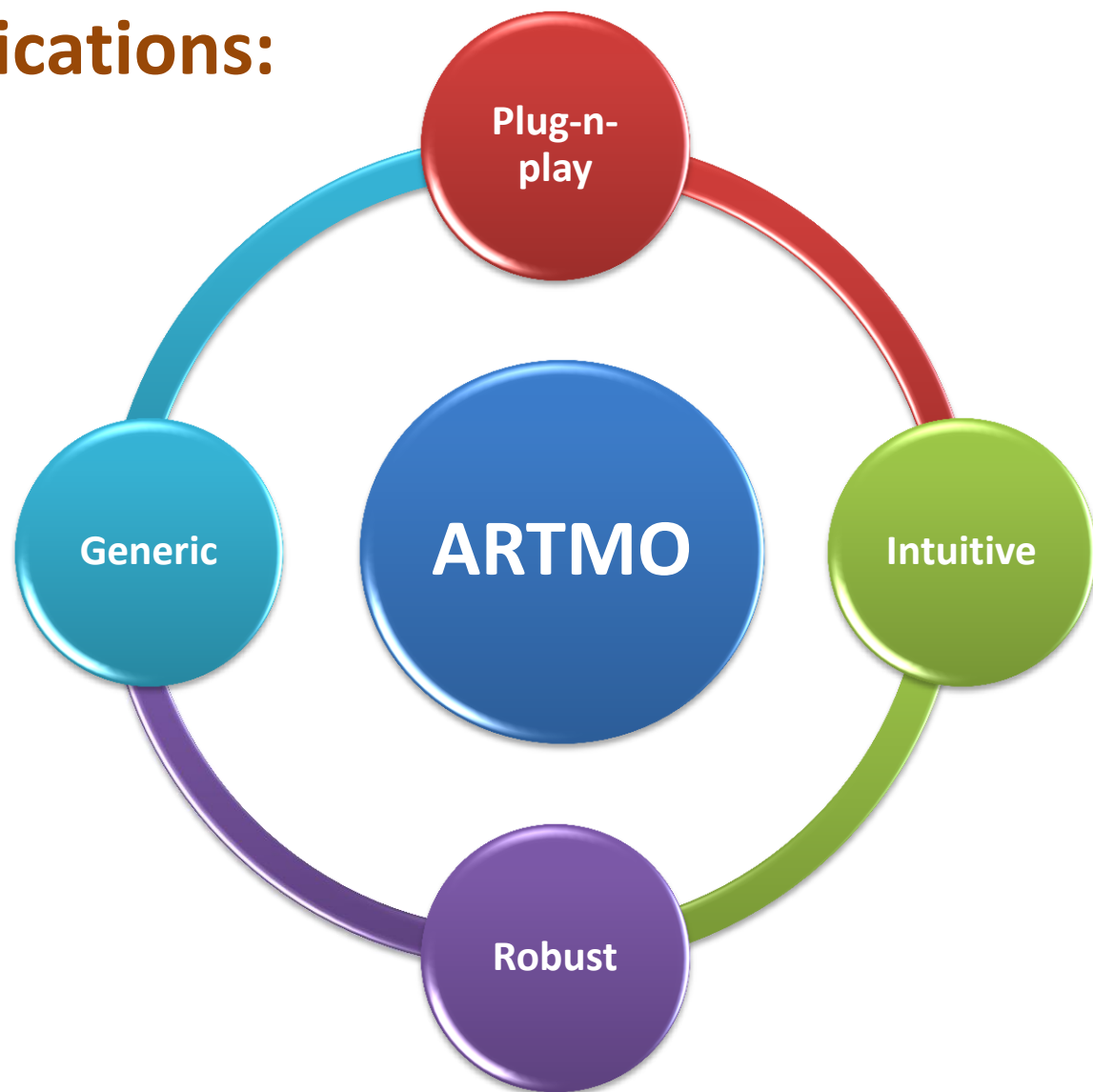
## Objective:

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

## Toolbox for EO applications:

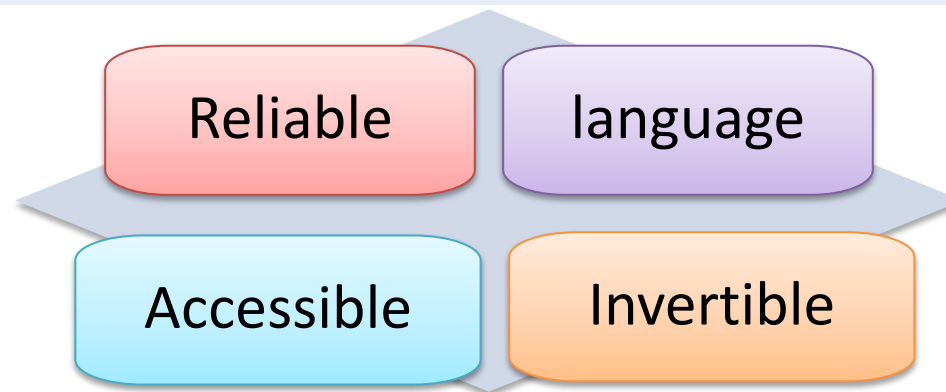
# ARTMO:

Automated  
Radiative  
Transfer  
Models  
Operator

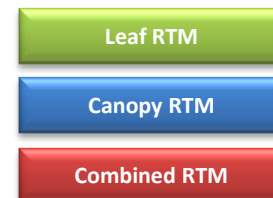




## Selection RTMs:



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)



## Software packages:

Programming language:

Matlab<sup>®</sup> (R2009b)

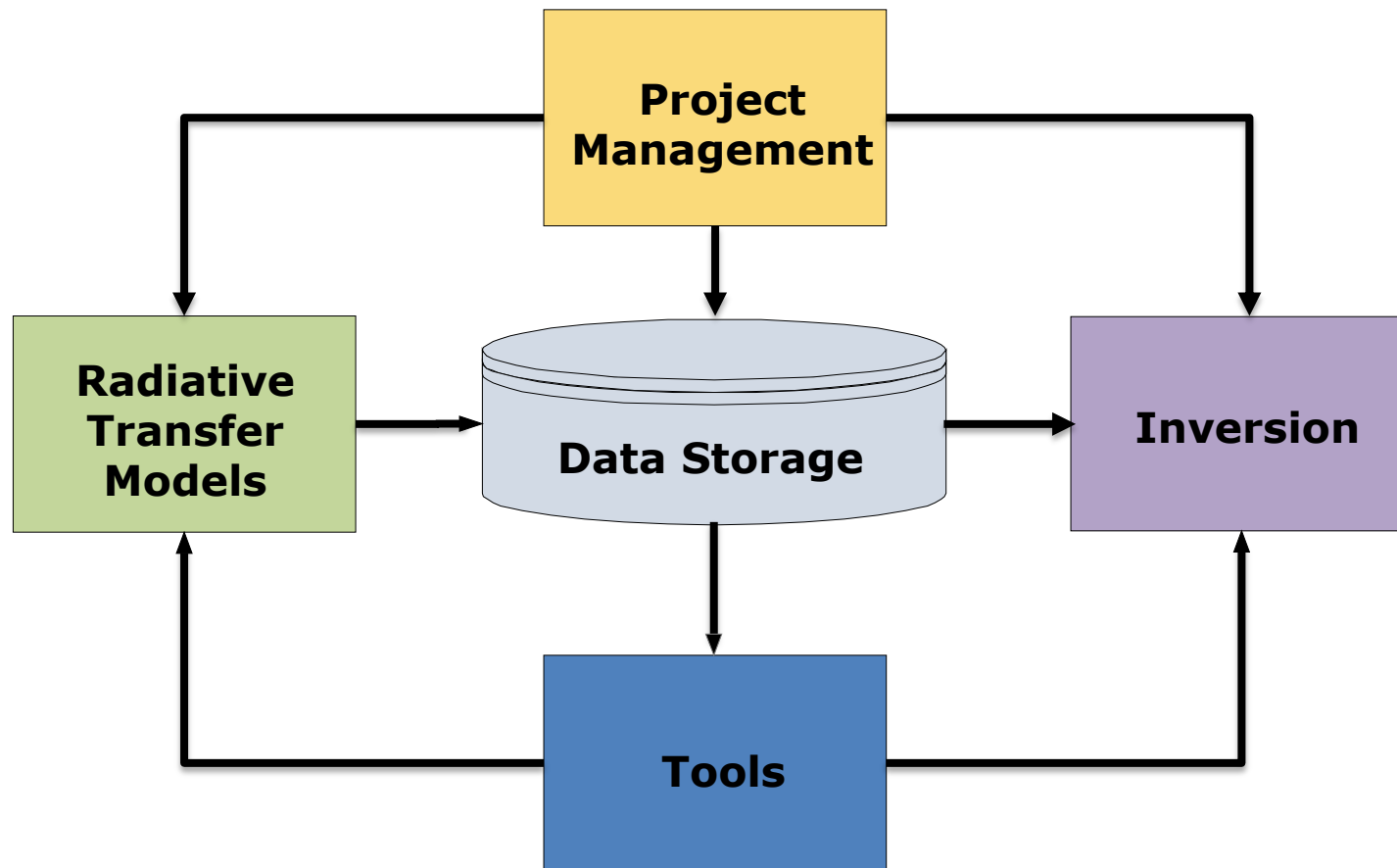
Database:

MySQL<sup>®</sup> (5.5.8)

Image processing software:

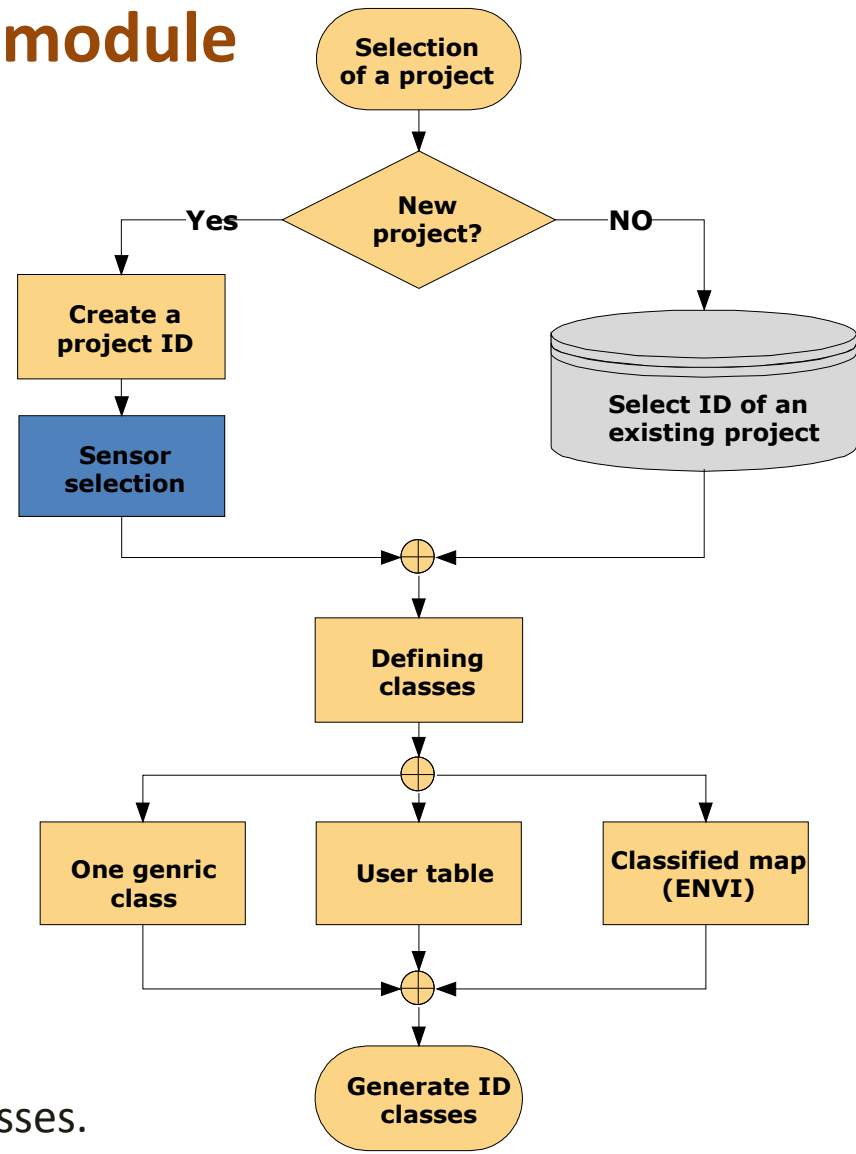
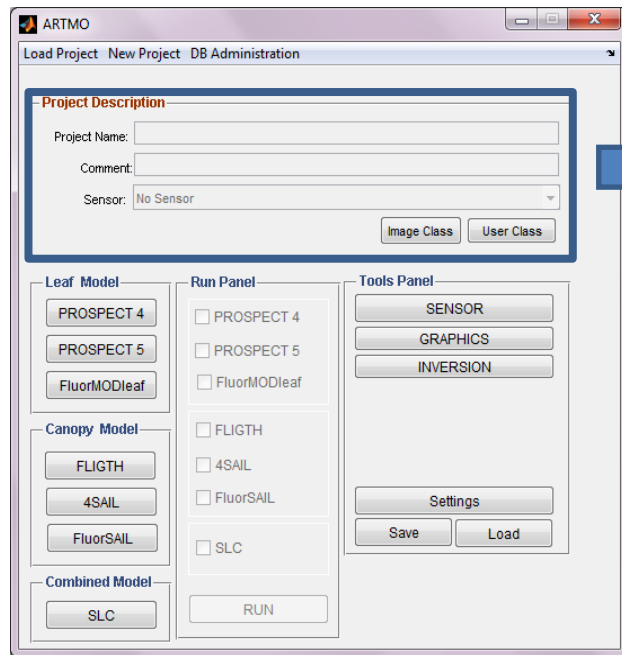
ENVI<sup>®</sup> 4.5

# Conceptual Architecture ARTMO



**Project Management**

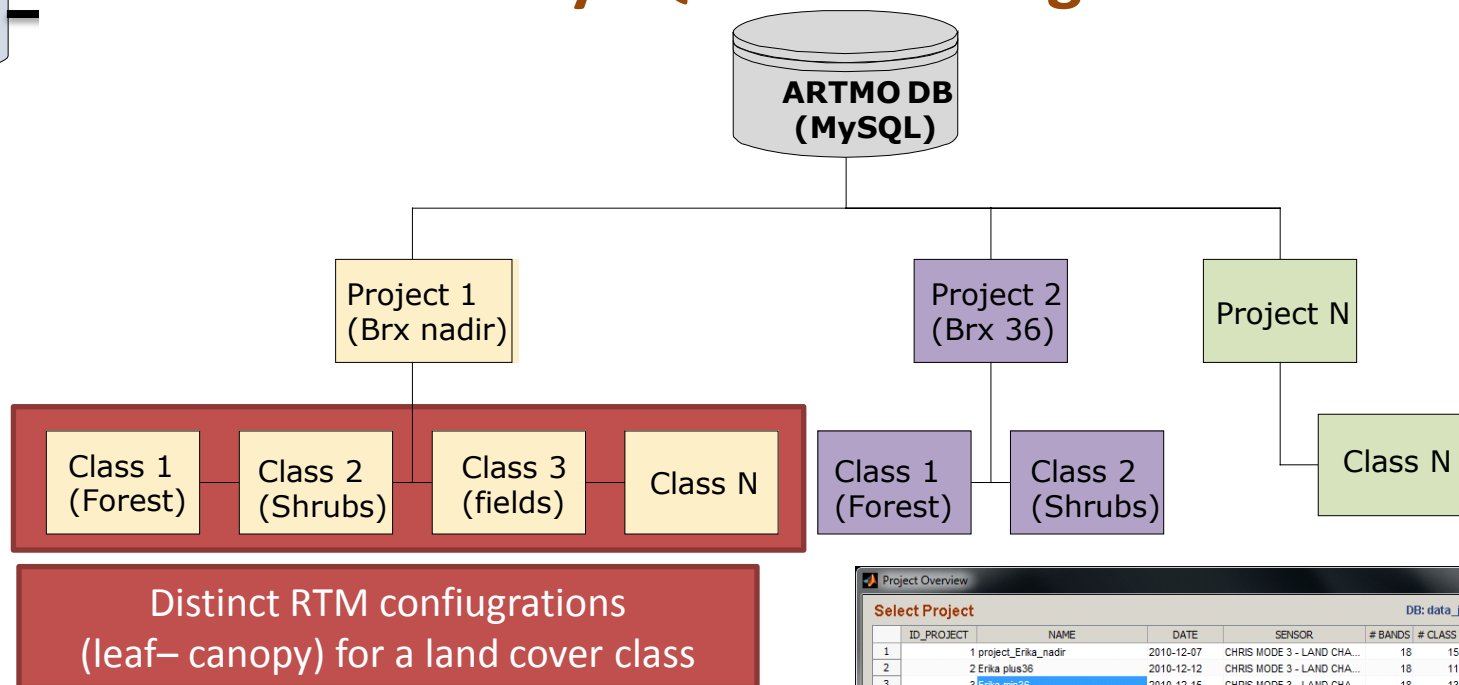
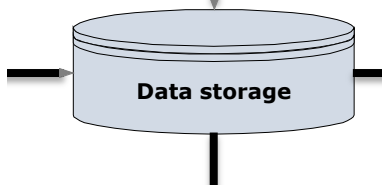
# Project management module



### 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.

**Select Project**

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	FLIGHT	shrubs min36 final	2196
7	21	3 2011-01-18	FLIGHT	min36 forest final normal	2196
8	22	3 2011-01-19	FLIGHT	forest min36 bg-50oc	1098
9	23	3 2011-01-20	FLIGHT	forest min36 final bg-25pc	1098
10	45	3 2011-01-24	FLIGHT	forest min36 3D test	1792
11	52	3 2011-02-02	FLIGHT	forest min36 3D bg-25 fcover wide...	5440
12	58	3 2011-02-04	FLIGHT	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 psol	0,500,0,500,0,000
4 skyf	0,000,0,000,0,000
5 hspot	0,100,0,100,0,000
6 lts	24,000,24,000,0,000

Radiative Transfer Models

# RTM module

FLIGHT - Green Leaf Spectrum - Senescent Leaf Spectrum - Soil Spectrum - Bark Spectrum

Select LUT Class: Generic class

**Input Parameters**

Dimension:  1D  3D

Mode of operation:  REVERSE

Number of photons: Photons: 10000

Number of bands: Bands: 62

**Solar Angle**

Zenith: 24  Range  Table

Azimuth: 162.8  Range  Table

**View Angle**

Zenith: 21.21  Range  Table

Azimuth: 315.20  Range  Table

**AOT @ 550 nm**

0.08  Range  Table

**Soil roughness index [0-1]**

0  Range  Table

**Leaf size [0-1]**

0.01  Range  Table

**LAI**

1  Range  Table

**FVC**

0.2  Range  Table

**Crown Shape**

Ellipsoid  Cones  Field data

**Crown geo parameters**

Crown radius: 0.880

Centre to top distance: 4.929

Height to first branch: Min: 4.1 Max: 9.9

Trunk DBH: 0.179

**FGL**

Fraction of green leaves: 0.2  Range  Table

% Fraction of 'senescent/shoot': 50

Remaining fraction will go to 'bark'

**LAD**

Planophile

[0-10]: 0.22	[10-20]: 0.207
[20-30]: 0.182	[30-40]: 0.149
[40-50]: 0.111	[50-60]: 0.073
[60-70]: 0.04	[70-80]: 0.015
[80-90]: 0.003	

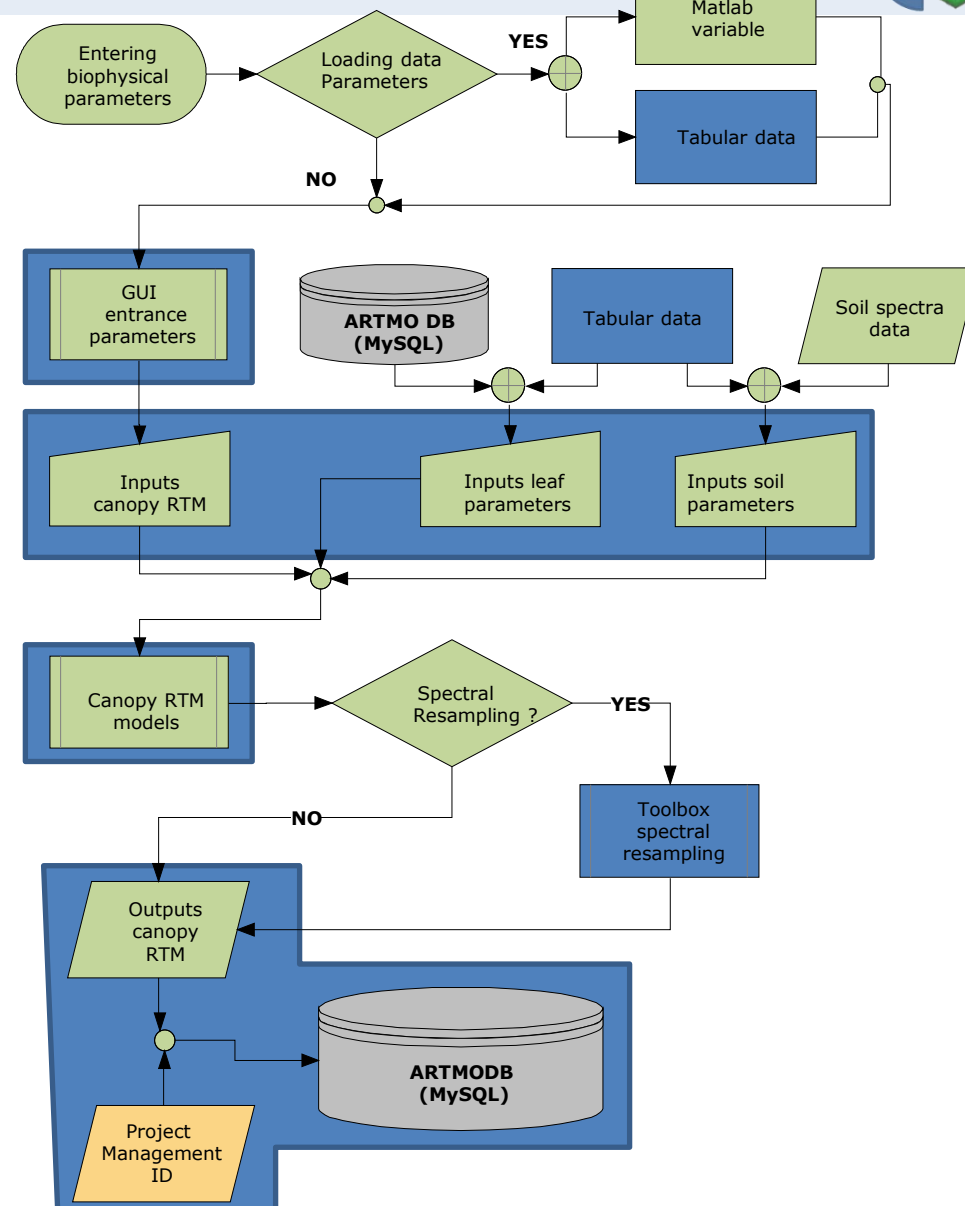
30  Range  Table

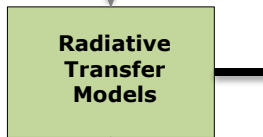
OK

GUI of the FLIGHT model

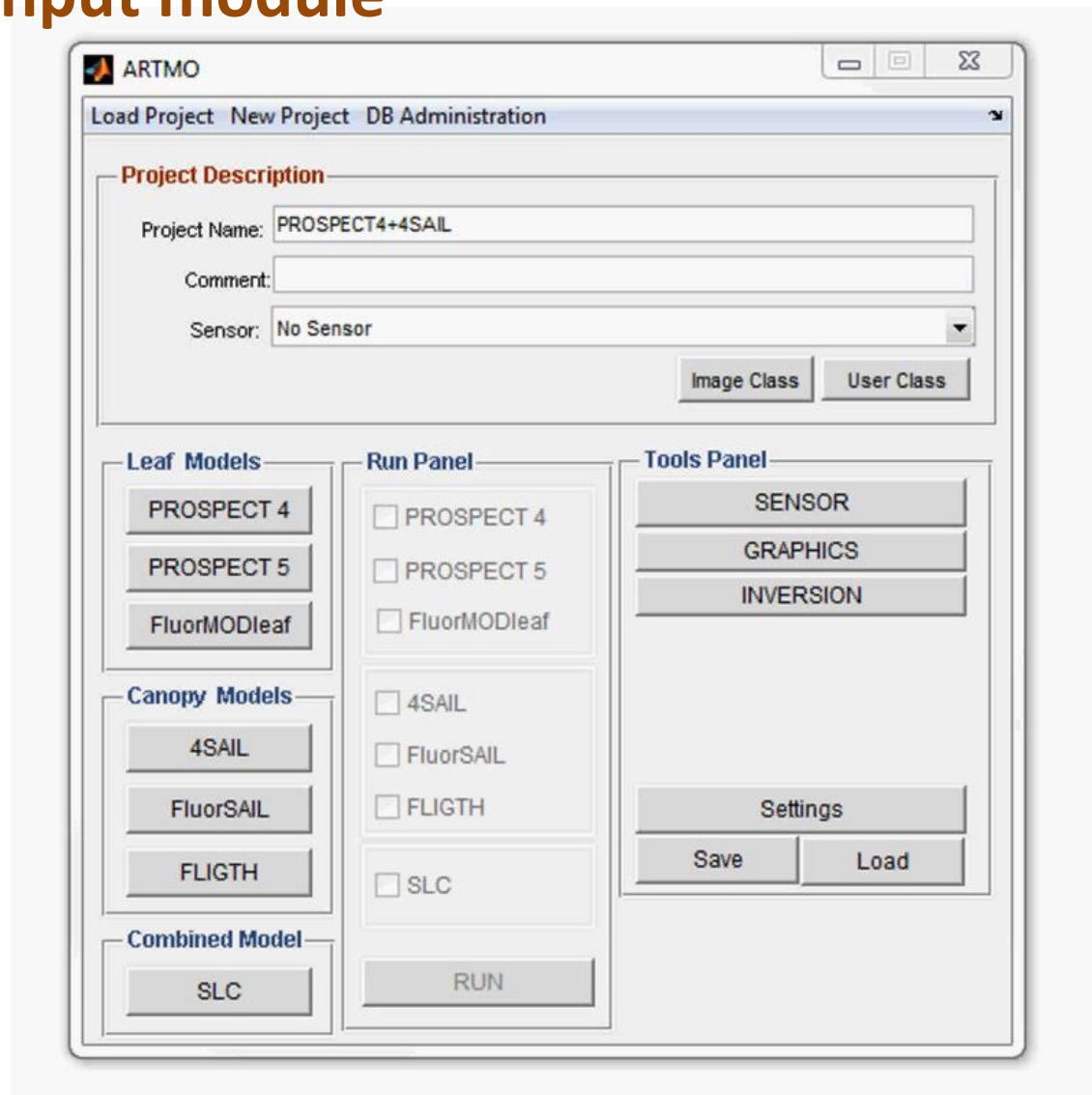
## Important features:

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

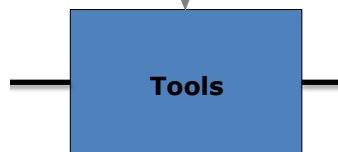




# RTM input module



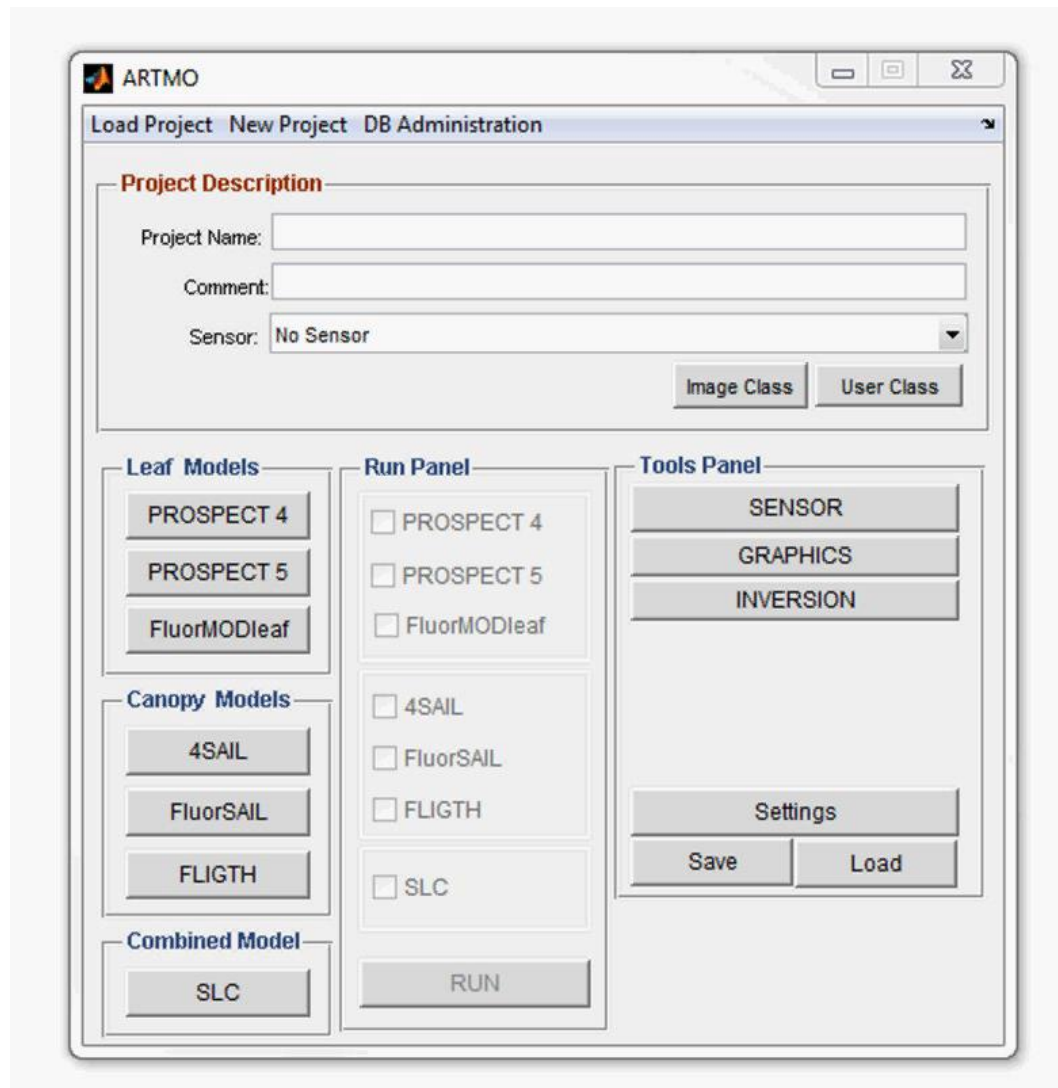




# Tools

TOOLS

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





# Plotting examples

**Graphics Module**

Select Project

**LEAF PARAMETERS**

Figure 1 Leaf Reflectance

Figure 2 Empty

PARAMETER	MIN	MAX	#	STEP	Parameter 1 (Hue)
1 Cab: Chlorophyll a+b	30.0348	79.0874	100	NaN	Cab: Chlorophyll a+b
					Parameter 2 (Saturation)
					Empty

**CANOPY PARAMETERS**

Figure 1 Directional reflectance

Figure 2 Empty

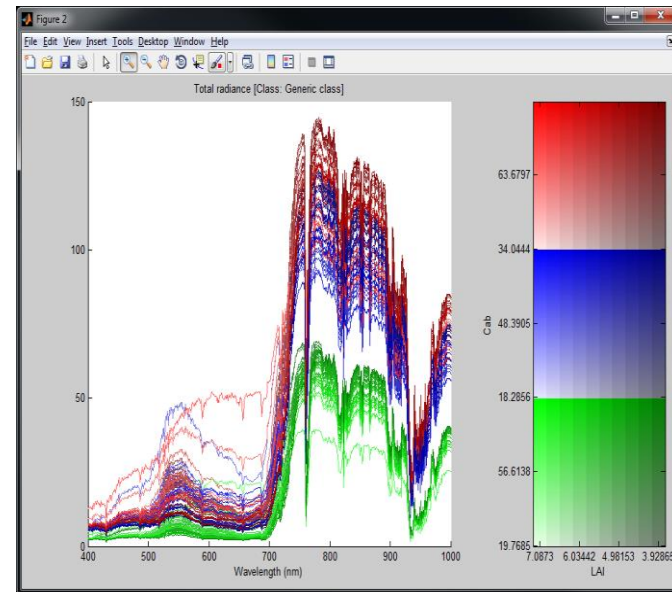
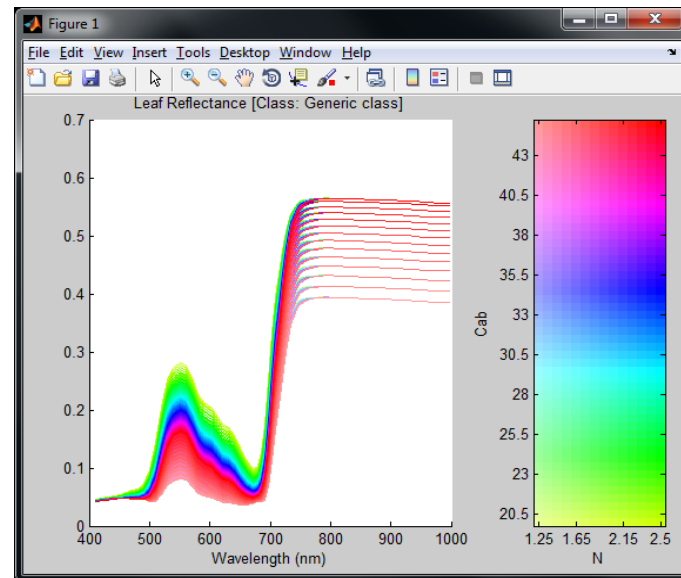
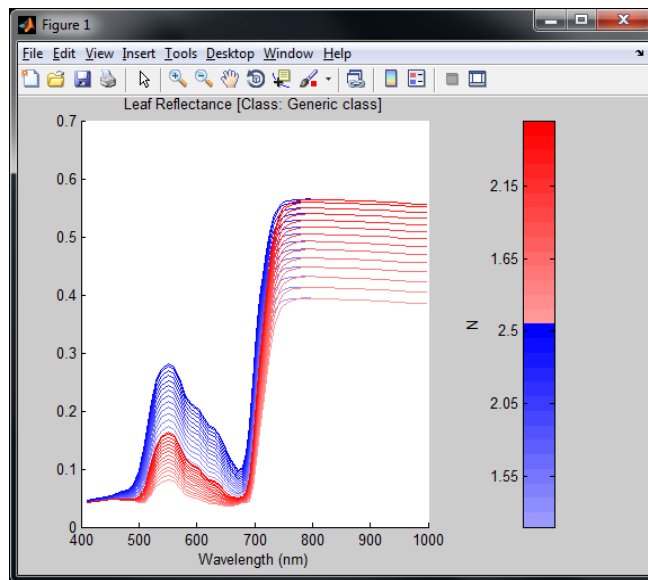
PARAMETER	MIN	MAX	#	STEP	Parameter 1 (Hue)
1 lat: Leaf area index	2.0085	4.9830	100	NaN	Cab: Chlorophyll a+b
					Parameter 2 (Saturation)
					lat: Leaf area index

**ADDED SPECTRA**

Draw	Description	LUT Class	#Sm...	#Sm...	Color
1	Cab: (30.0348-79.0874) lat (2... Class2 (0.35-0.75) 27828 pol...	100	5000	[1,1,1]	

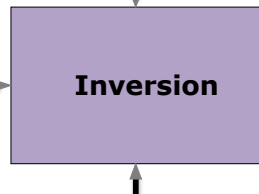
Add spectra from file

OK



## 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.

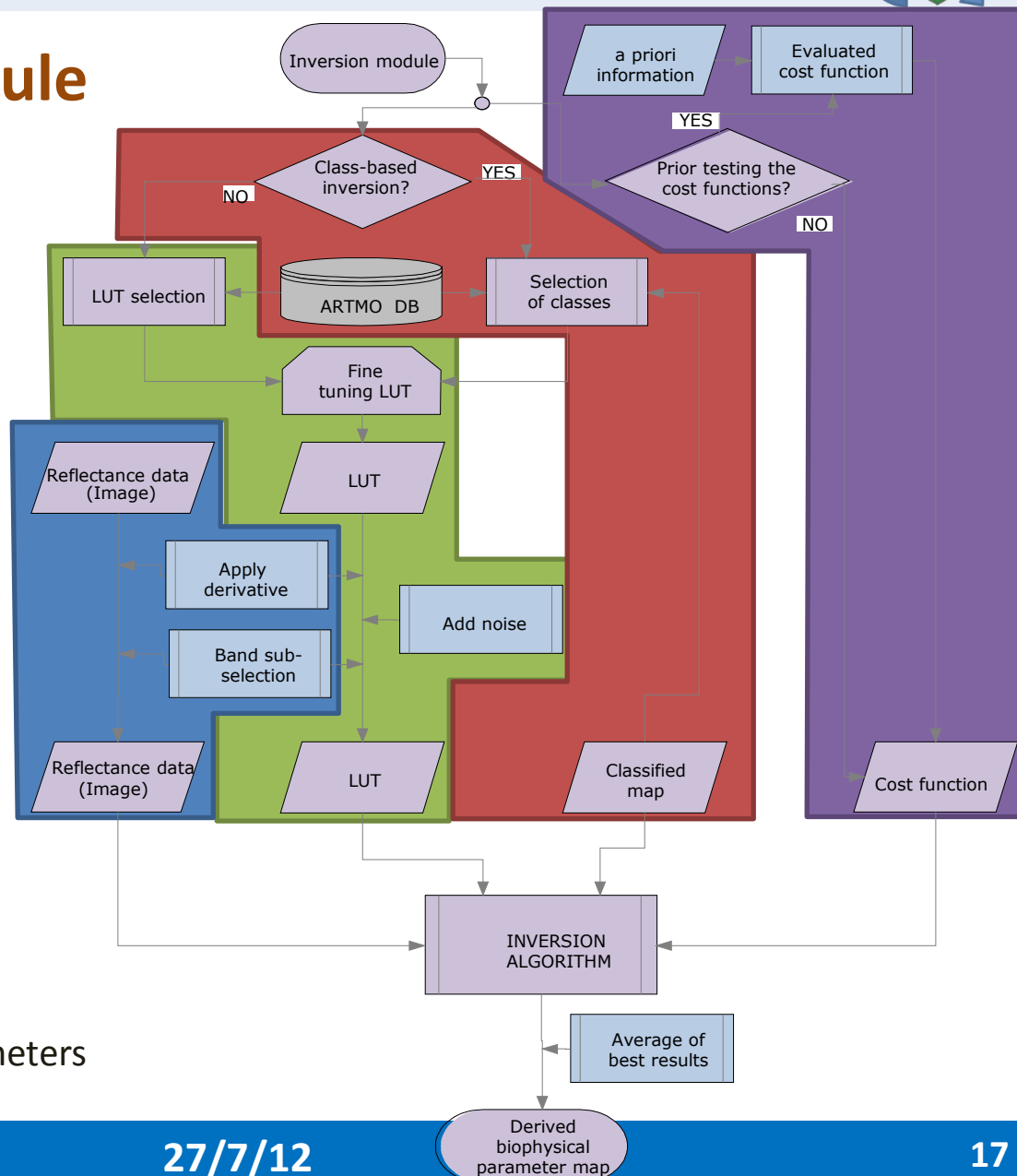


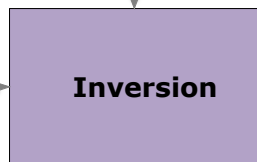
# Inversion module



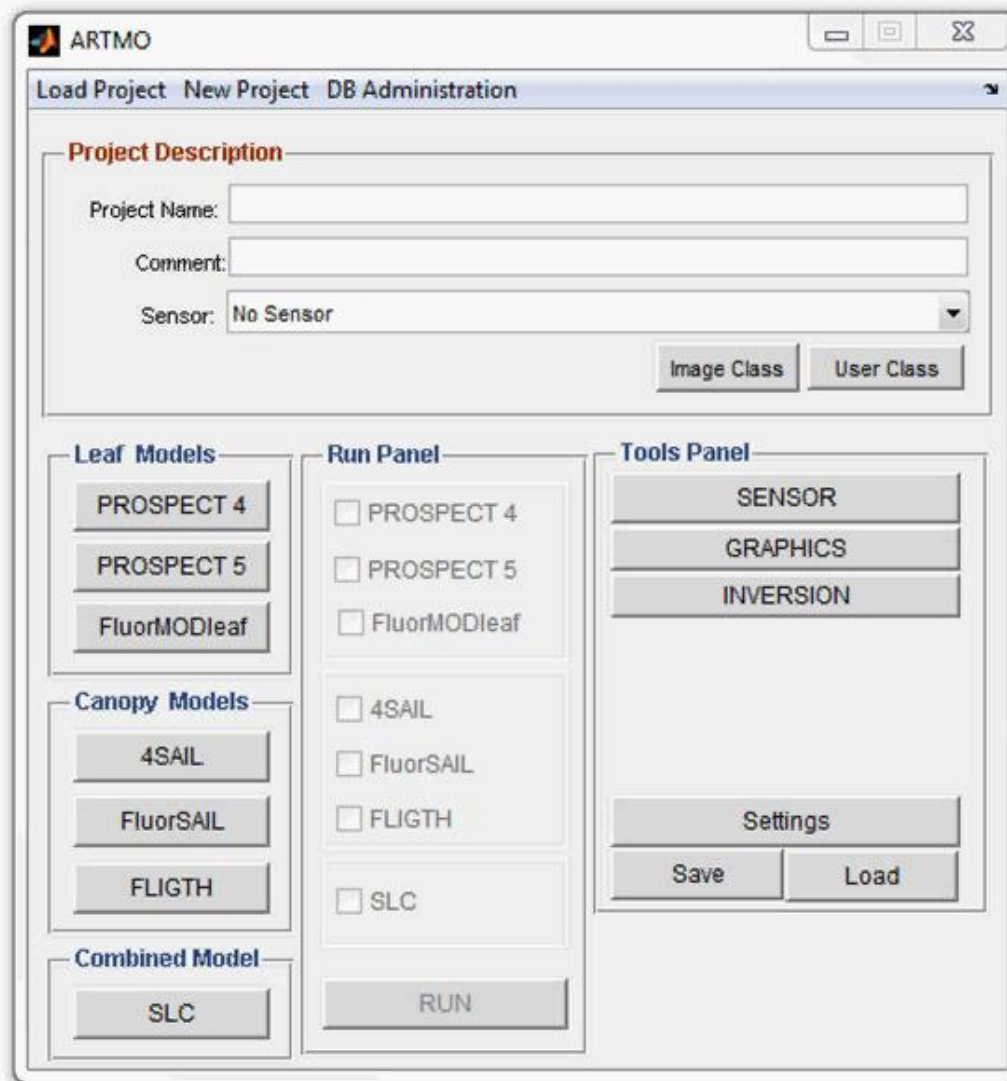
### Important features:

- ✓ 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 referred 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**.

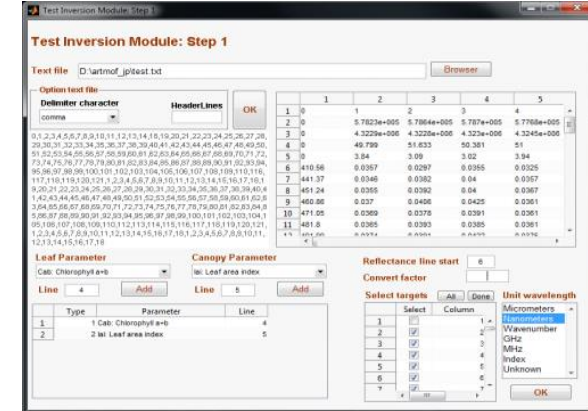
- Root Mean Squared Error (RMSE): 
$$D[P, Q] = \sqrt{\sum_{\lambda_i=1}^{\lambda_n} \frac{(p(\lambda_i) - q(\lambda_i))^2}{n}}$$
- Trigonometric : 
$$\rho(x) = v \left( x \arctan(sx) - \frac{\log(s^2 x^2 + 1)}{2s} \right), s, v > 0.$$

3. Third family of **minimum contrast estimates** represents **distances in the spectral domain**. In this case **reflectance is considered as spectral density function**.

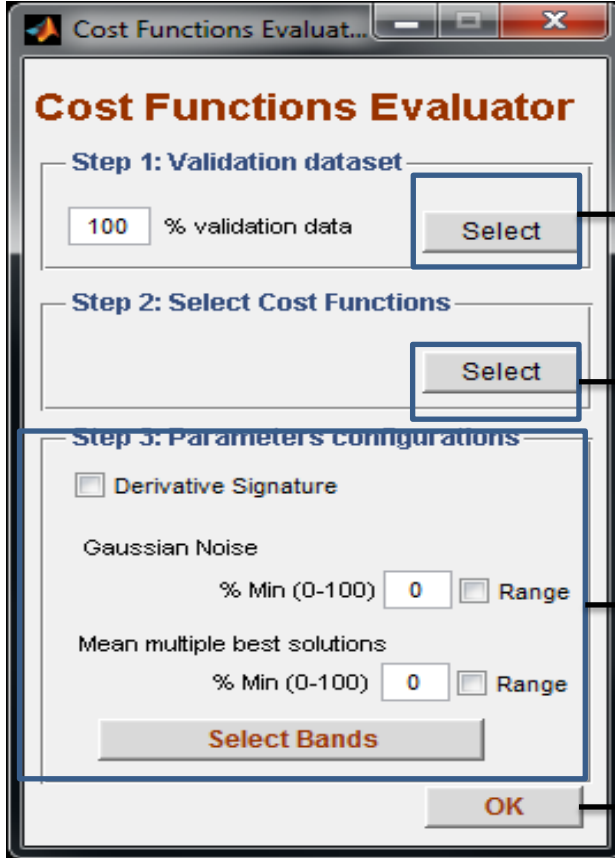
- Contrast function  $K(x) = -\log(x) + x$ : 
$$D[P, Q] = \sum_{\lambda_i}^{\lambda_n} \{-\log(q(\lambda_i))/p(\lambda_i) + q(\lambda_i)/p(\lambda_i)\}.$$

Inversion

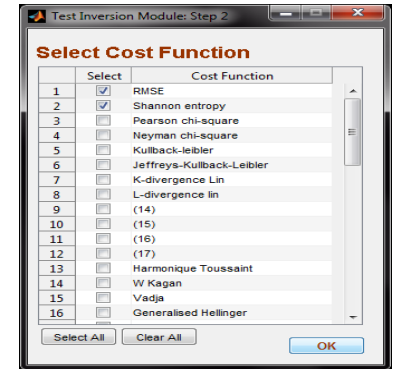
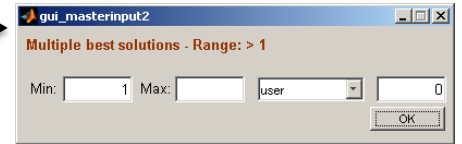
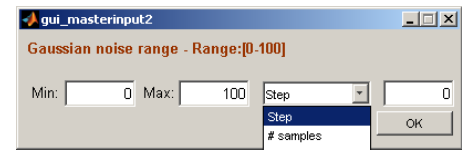
# Inversion strategy evaluator



Validation/  
*a priori* data



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



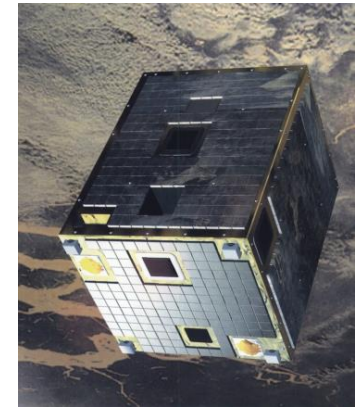
All inputted regularization combinations is evaluated against the validation dataset. Results are stored in a MySQL table.



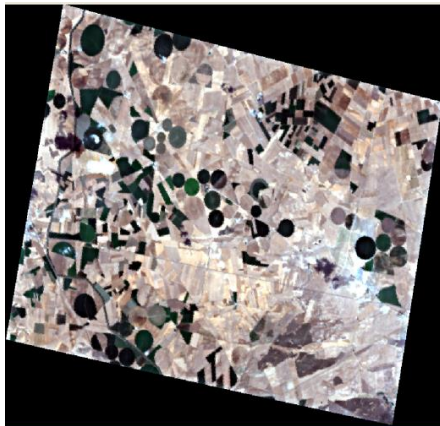
# Hyperspectral Satellite data:

## 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 different 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<sup>2</sup>
- **LAI** values between 0 and 6.5

Validation

# Evaluating cost functions:

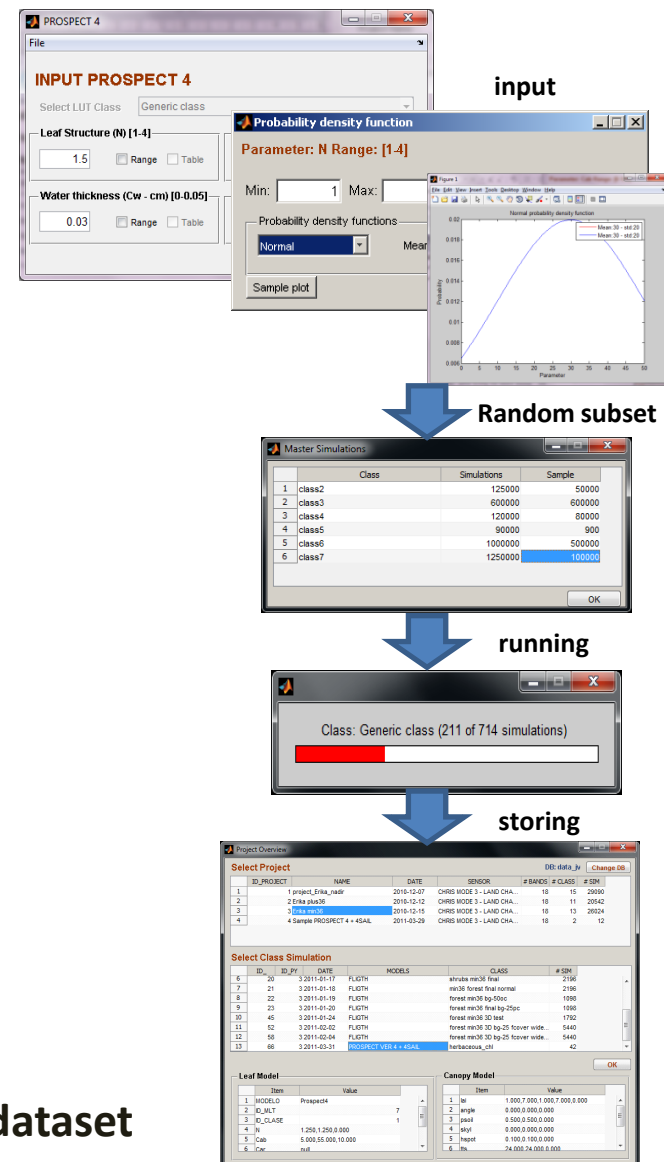
- **RMSE**
- 3 alternatives, from each family one.

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

## LUT easily created (here with PROSAIL)

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

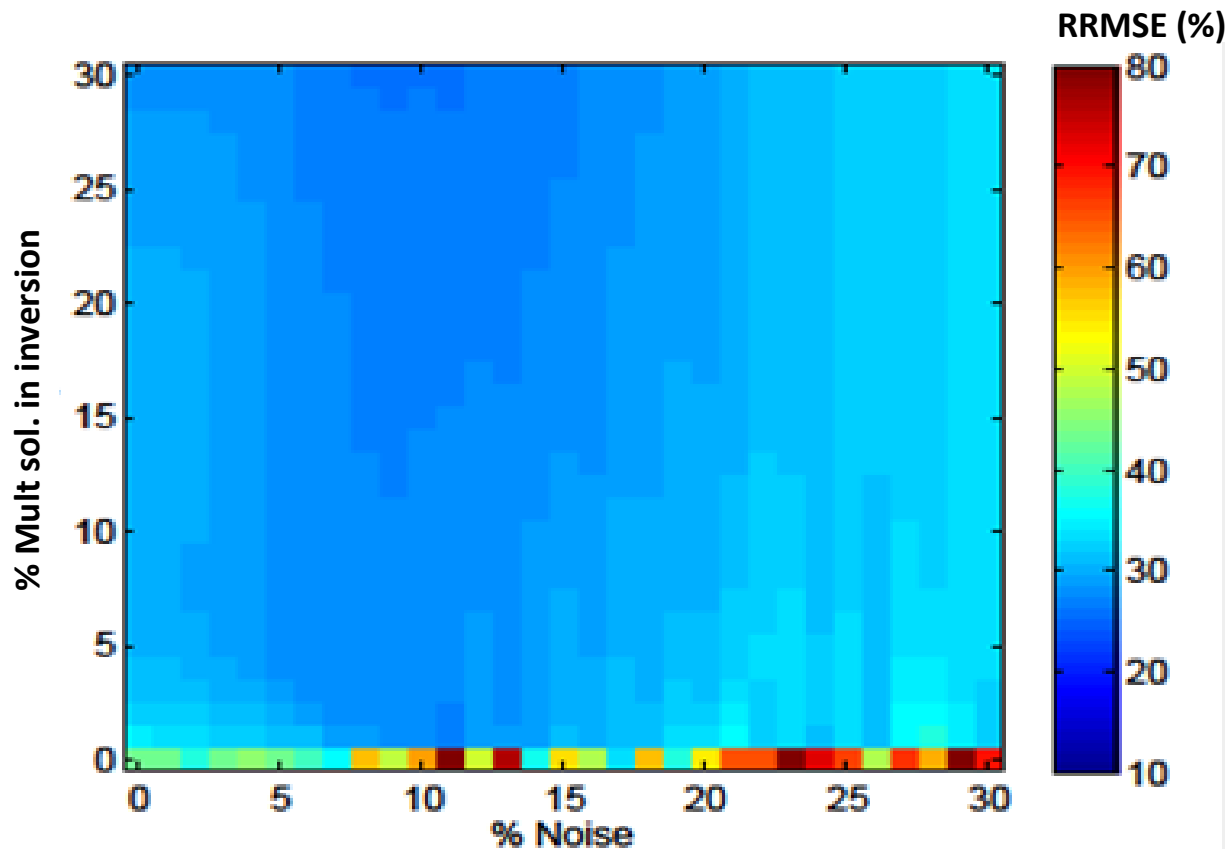
	Model Parameters	Units	Range	Distribution
<i>Leaf parameters: PROSPECT-4</i>				
<i>N</i>	Leaf structure index	unitless	1.3-2.5	Uniform
<i>Chl</i>	Leaf chlorophyll content	[ $\mu\text{g}/\text{cm}^2$ ]	5-75	Gaussian ( $\mu$ : 35, SD: 30)
<i>C<sub>m</sub></i>	Leaf dry matter content	[ $\text{g}/\text{cm}^2$ ]	0.001-0.03	Uniform
<i>C<sub>w</sub></i>	Leaf water content	cm	0.002-0.05	Uniform
<i>Canopy variables: 4SAIL</i>				
LAI	Leaf area index	[ $\text{m}^2/\text{m}^2$ ]	0.1-7	Gaussian ( $\mu$ : 3, SD: 2)
ALA	Average leaf angle	[°]	40-70	Uniform
$\alpha_{soil}$	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	-
$\theta_s$	Sun zenith angle	[°]	22.3	-
$\theta_v$	View zenith angle	[°]	20.19	-
$\phi$	Sun-sensor azimuth angle	[°]	0	-



Evaluating the role of inversion strategies against validation dataset

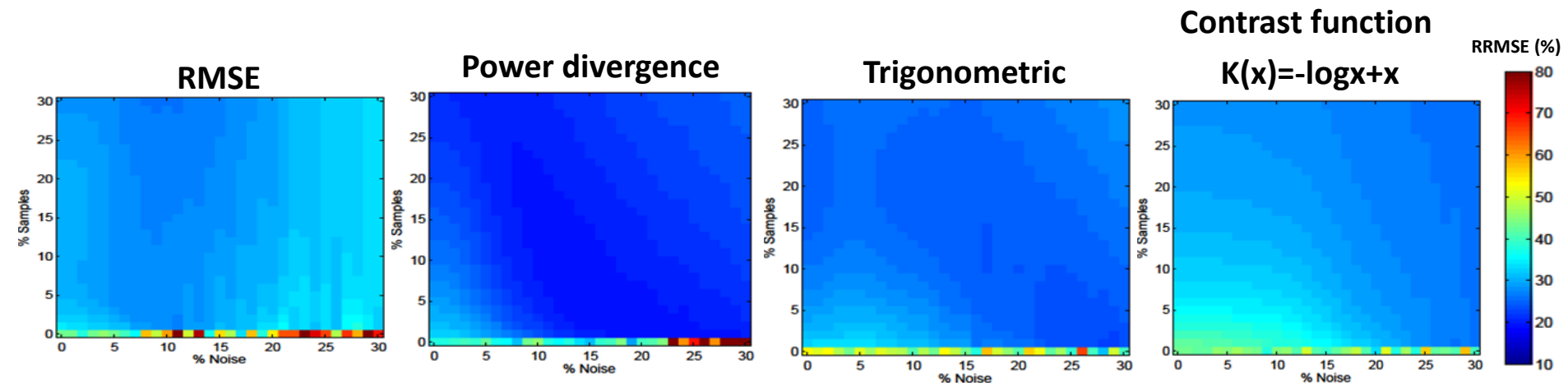
# Chl retrieval using CHRIS 62 bands - Validation

## RMSE



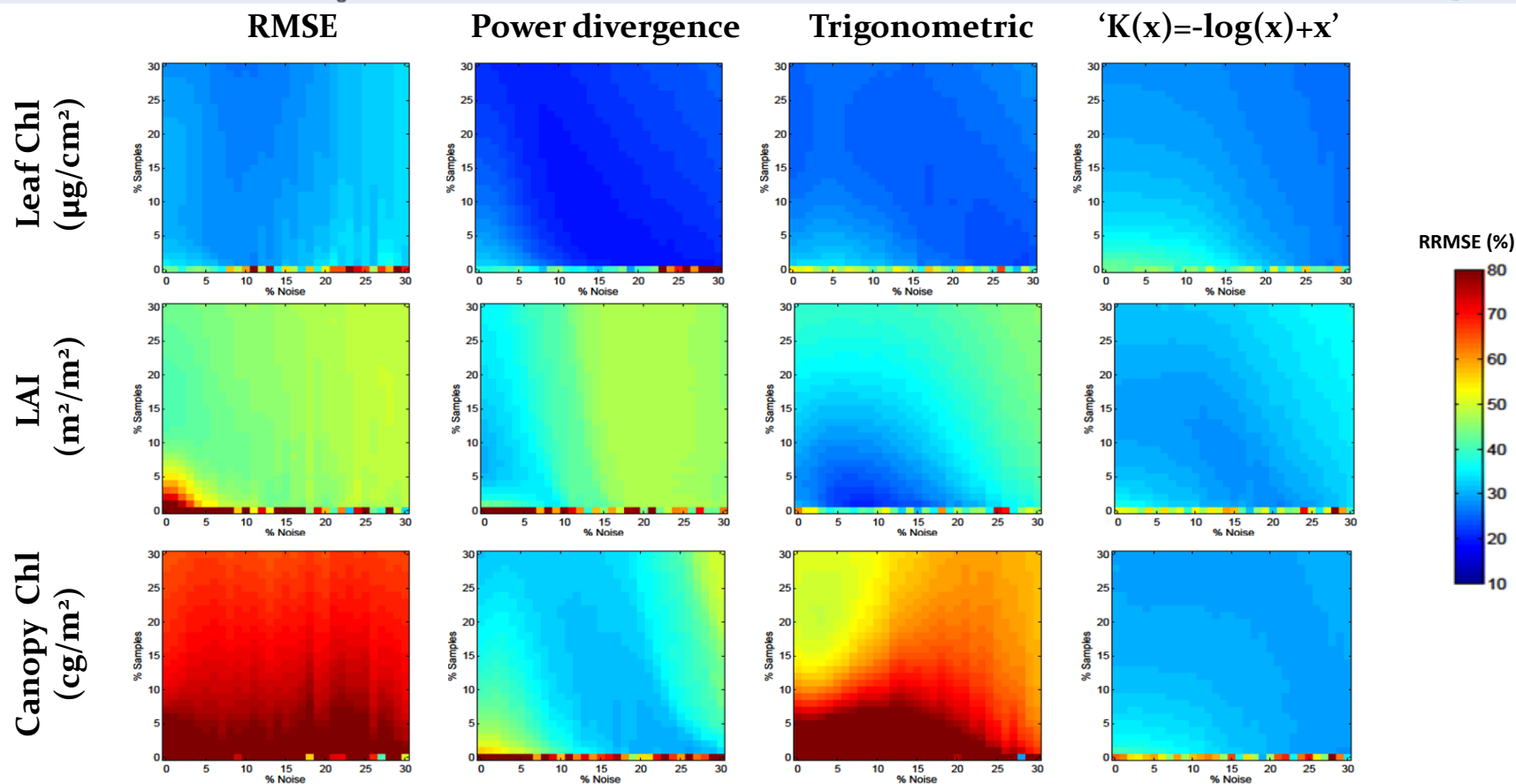
- Single best solution never the best choice.
- Regularization options improved retrievals: from 43% to 26%.

# 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 ( $\alpha$ ,  $\beta$ ).



- 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 ' $K(x)=-\log(x)+x$ ' yielded overall best results. Most useful for simultaneous retrieval of multiple parameters (21% noise, 1% mult. solution).

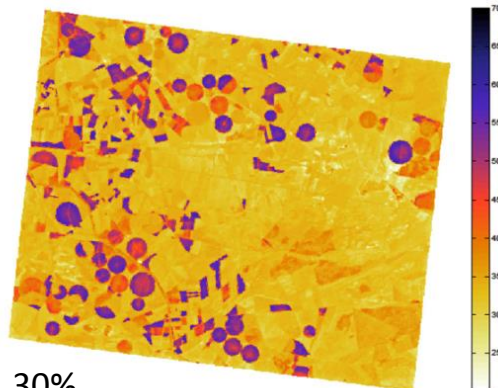


Final maps through optimized LUT-based inversion:

## Mean estimation

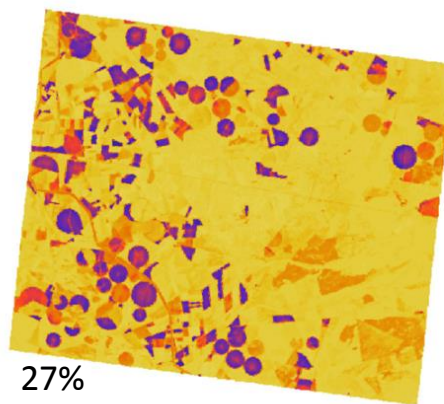
Contrast function  $K(x) = -\log(x) + x$   
(21% noise, 1% mult. solution)

Leaf Chl ( $\mu\text{g}/\text{cm}^2$ )



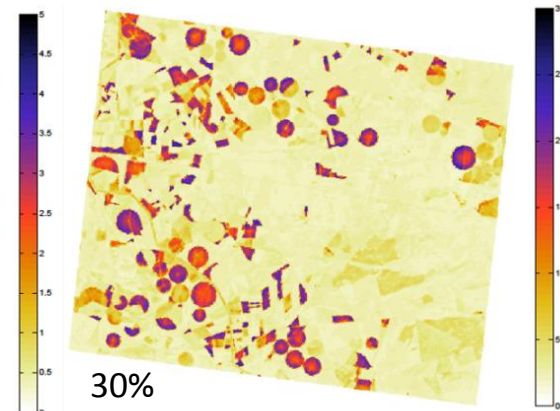
RRMSE: 30%

LAI ( $\text{m}^2/\text{m}^2$ )



27%

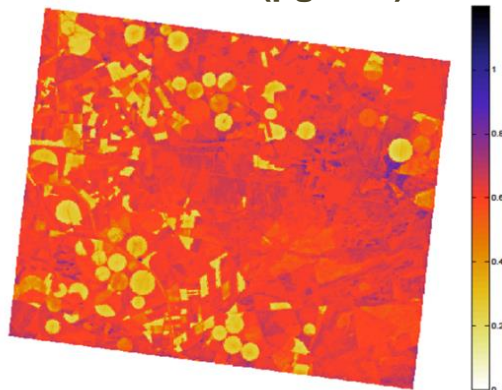
Canopy Chl ( $\text{cg}/\text{m}^2$ )



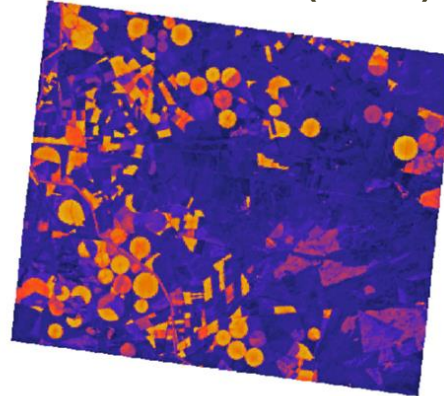
30%

## Coefficient of Variation

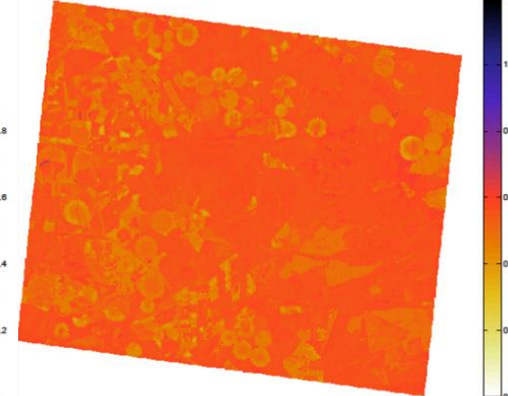
CV Leaf Chl ( $\mu\text{g}/\text{cm}^2$ )



CV LAI ( $\text{m}^2/\text{m}^2$ )



CV Canopy Chl ( $\text{cg}/\text{m}^2$ )

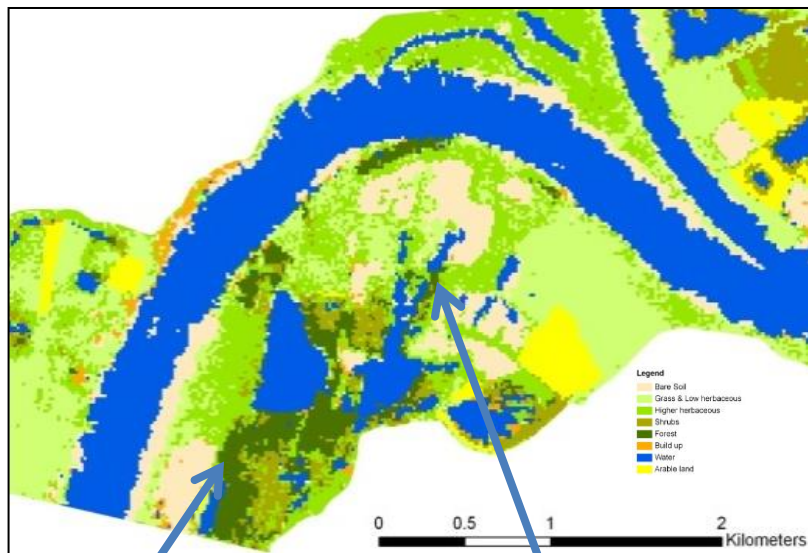




# Example class-based inversion: combining 1D and 3D models within same image

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

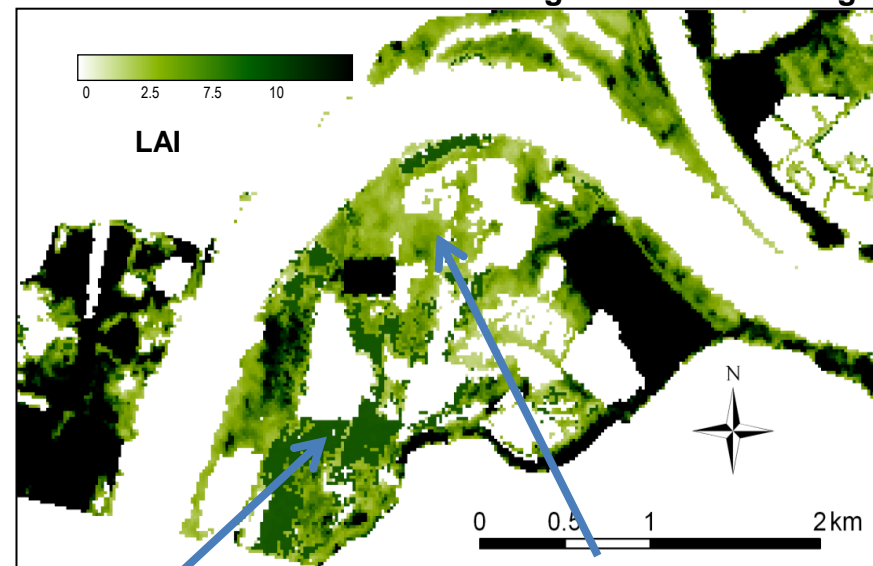
Input: Land cover map



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**

**ARTMO**

Atmospheric models

MODTRAN

Vegetation indices

Time series analysis

Ray tracing model

RPV model

Neural nets

Support vectors

Gaussian Processes

BRDF apps

Spectral unmixing

Classifiers

# 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 7<sup>th</sup> SIG-Imaging Spectroscopy Workshop 2011*, 11-13 April, Edinburgh, UK.