



# From SAIL simulations towards automated remote sensing applications:

# *an overview of 6 years of ARTMO developments*

🛃 ARTMO (v. 3.19)
File Models Forward Retrieval Tools Help
Project Description
Project Name:
Comment
Sensor: NO SENSOR
DB: test_si3

J. Verrelst, J.P. Rivera & J. Moreno

SAIL35 - 27 Sept 2016

### Background



### **Radiative transfer models**

#### Leaf RT models







### **Canopy RT models**







 $I_e \bigvee^{J_e} \stackrel{I_d}{\longleftrightarrow} \stackrel{I_d}{\longleftrightarrow} \stackrel{\overset{I_d}{\longleftrightarrow}}{\overset{\overset{W}}{\Longrightarrow}} I_d$ 

JLT

Various models exist with different complexity.

RTMs are important tools in EO research but for the broader community these models are perceived as complicated. Only very few of them offer user-friendly interfaces.



Only very few offer a GUI.

- No interface exists that brings multiple RTMs together in one GUI.
- None of existing (publicly available) GUIs provide post-processing tools.

## To fill up this gap:



### > To develop a GUI toolbox that:

- operates various RTMs in an intuitive interface
- provides a comprehensive visualization of model outputs
- works both for **multispectral and hyperspectral** data
- enables to retrieve biophysical parameters through various retrieval methods
- takes different land cover classes into account.

### **Toolbox for EO applications:**





# Selection RTMs & programming language

### language

### Accessibility

v.1	Model	Reference	Source code
	PROSPECT-4	Feret et al., 2008	Matlab
	PROSPECT-5	Feret et al., 2008	Matlab
	DLM	Stuckens et al., 2009	Matlab
_	LIBERTY	Dawson et al., 1998	Matlab
	4SAIL	Verhoef et al., 2007	Matlab
	FLIGHT	North, 1996	Executable file
	INFORM	Atzberger, 2000	Matlab
	SCOPE	Van der Tol et al., 2009	Matlab

### **Software packages:**

Programming language:





Database:



# <sup>2012</sup> ARTMO v. 3: modular design

ARTMO					
Load Project New Proje	ect DB Administration		*		
- Project Description					
Project Name:					
Comment		J		r	
Sensor: No Se	insor .			ſ	🛃 ARTMO (v. 3.19)
		Image Class User Class			
Leaf Model	Run Panel	Tools Panel			File Models Forward Retrieval Tools Help 🛛 🛥
PROSPECT 4	PROSPECT 4	SENSOR			Project Description
PROSPECT 5	PROSPECT 5	GRAPHICS			
FluorMODieat	E FluorMODIeaf	INVERSION			Project Name:
Canopy Model	FLIGTH				
FLIGTH	345AIL				Comment:
4SAJL	FluorSAIL	Settings			
FluorSAIL	SLC	Save Load			Sensor: NO SENSOR
Combined Model					
SLC	RUN				DB: test_si3
, ·					



### **Conceptual architecture ARTMO**



10/49

# Forward



File Models	orward Retri	ieval Tools	Help	3
- Project Descr	ption			
Project Name:				
Comment				
Sensor:	NO SENSOR			•



### RTM outputs only a few clicks away...

-101×

Chiorophyll (Cab - µg/cm') [0-100]

Dry matter (Cm - a/cm<sup>2</sup>) (0-0.05)

ab Range: (0-100)

-5 F Bange FT Tan

50 (Seo -

Pr.5 PY.0

🛃 ARTMO (v. 3.19)
File Models Forward Retrieval Tools Help 🏻 🛥
Project Description
Project Name
Comment
Sensor: NO SENSOR
DB: test_si3

ICT 4

Select L17 Class Commencement

1.5 E Range E

Water thickness (Cw., cm) (0.0.05)

E Range E Latte











Data flow

- Project Deser	intion	
Project Name	[	
Common	e[	
Sensor	NO SENSOR	-

0.034 0.001 0.517 00 0.17 00 0.17

#### Radiative Transfer Models

### Entering data: e.g. PROSPECT-4

### 1. A single value

📣 PROSPECT 4	
File Load external data	لا ا
PROSPECT 4 MODEL	
Select LUT Class Generic class	
Leaf Structure (N) [1-4]	Chlorophyll (Cab - µg/cm²) [0-100]
1.5 🗖 Range 🗖 Table	-5 🗖 Range 🗖 Table
Water thickness (Cw - cm) [0-0.05]	Dry matter (Cm - g/cm² ) [0-0.05]
0.03 Range Table	0.012 Range Table
	ОК

### 2. User data (e.g. field data)

	Leaf bioch	iemical paramet	ers							
Control delimeter character or	Lear Dic	DitrahaialAPTh		5 d files)enecti	al libr	Process	at A y Elemen	and but	Browner	
booderlinee	TOAT ING	D. drabajo vercin	io_cuisur_suppo	n mesispeci	ai imi	nya-tospe	cr = y o drost	-	Didwoei	
neader lines	- Option text	t file			1					
	Delimiter	character	HeaderLine	is or	-	1	2	3		Selected
	Tab	*		- UN	2	CaD 31.408	0.020	0.005	-	input data
	- Mary	1000			3	21 574	0.008	0.005	-	
A sample of the	CabCwCm	ine			4	11.809	0.013	0.004		
A dample of the	21.5740.0080	005			5	15.051	0.015	0.004		
input text file is	11.8090.0130.	004			6	26.619	0.013	0.005		
visualized.	15.0510.0150	004			7	26.789	0.013	0.005		
	26.7890.0130	005			8	30.466	0.013	0.006		
;	30.4660.0130. 76.8910.0160.	006			9	76.891	0.016	0.008		
Other services of										Convert units
Cnosen Input										if needed
parameter and	Paramete			Column			Co	nversion fac	tor 🗲	
corresponding	sin: Dry ma	tter content - Gree	n Leat 🔄	Column 3	_		3		Add	
column		Param	ter	G	olumo	C	onversion f			
	1 Cett: C	hlorophyll AB - Gre	en Leaf	Column 1			1			
	2 Cw: W	later content - Gree	n Leaf	Column 2			1			
1	3 Cdm E	iry matter content -	Green Leaf	Column 3			1			
Availableinput										
narameters										
parameters	1									
									Import	

3. A range of multiple values:

### I) steps



**II) distribution:** (e.g., uniform, normal, exponentional)



### **III)** Multiple input values



## Filling in a canopy model: SAIL

• Filling in SAIL: single or multiple values

Radiative Transfer Models

- Soil spectra is required. Default spectra are provided or own spectra can be imported.
- Usually coupled with a leaf model. When not coupled then leaf spectra is required.

📣 45AIL MODEL	
File Leaf Spectrum Dry Soil Spectrum Wet	Soil Spectrum 🛛 🕲
4SAIL MODEL	
Select LUT Class Generic class	-
- LAI [0-10]	Hot spot effect [0 - 1]
3 Range Table	0.01 Range Table
– Average leaf angle (% [0 - 90]	– Solar zenith angle (°) [0 - 90]
30 Range Table	0 Range Table
— Diffuse/Direct radiation [0 - 100]—	Observer zenith angle (°) [-75 -75]
10 Range Table	0 Range Table
– Soil coefficient [0 - 1]	Azimuth (°) [0 - 180]
0 Range Table	O Range Table
	ОК



#### Input soil spectra (refl.)



# Sensor

	📣 ARTMO [v.	3.19]						X	
ſ	File Models	Forward	Retrieval	Tools	Help			ĸ	
	Project De	scription—							
	Project Na	me:					- C		
	Comr	nent:						🣣 Sensor	
	Sens	sor: NO SENS	SOR	>				Import	
	DB: test_si3				LUT Class	by map	Class	Senso	)
-								Contino	i

- New sensor settings can be imported by clicking on the 'Import' button in the top bar.
- Existing band settings can be modified or new ones can be added by clicking on the 'Edit' button.
- Also a spectral filter of a sensor can be imported or viewed by clicking on the 'Spectral Filter' button.

## Simulations can be generated according to band settings of a selected sensor.

📣 Sensor Module	[v. 1.04	]						
Import Edit S	pectral	Filter	Help					3
Sensor Infor	matic	on						
Sentinel-2						🗕 🗖 S	pectral filter	
Unit wavelength		Band	details					
Micrometers	-		Band name	Min	Max	Center	FWHM	
Nanometers		1	Band1	433	453	443	20	
GHz		2	Band2	457.5000	522.5000	490	65	
MHz		3	Band3	542.5000	577.5000	560	35	
Index		4	Band4	650	680	665	30	E
Unknown		5	Band5	697.5000	712.5000	705	15	
	-	6	Band6	732.5000	747.5000	740	15	
		7	Band7	773	793	783	20	
		8	Band8	784.5000	899.5000	842	115	
		9	Band8a	855	875	865	20	
		10	Road0	025	055	0.45	20	
								OK

### **Default sensors:**

- Landsat 7 TM
- Landsat 7 ETM+
- SPOT-4 VMI
- SPOT-4 HRVIR
- CHRIS Mode-3
- MODIS
- MERIS

- Sentinel-2
- Sentinel-3 OLCI
- Sentinel-3 SLSTR
- Landsat 8
- Pleiades-1A
- Quickbird

# Graphics

Graph	nics Mo	odule [v. 1.01]			
rap	hic	s Module			
Selec	t Proje	ect			
	I	Model: scope		-	]
Gr	roup C	Output: Reflectance		]	
utpu	ıt Parı	meter: fraction of radiation in ok			
Cotti	nac of	innut parametere			
Mod	lel:	scope		¥	Parameter 1 (Hue)
		PARAMETER	MIN	MAX	Cab:Chlorophyll AB content [ug cm 💌
1	Cab:0	Chlorophyll AB content [ug cm	1	80 🔺	Parameter 2 (Saturation)
2	Cw:le	eaf water equivalent layer [cm]	0.0010	0.0300	LALL eat area index [m2 m-2]
3	Cdm:	Dry matter content [g cm-2]	0.0010	0.0300	
4	LAIL	eafarea index [m2 m-2]	0.1000	7	Z Label curve
5	Veme	o:maximum carboxylation cap	1	200	Empty
Ь	m:Ba ∎	II-Berry stomatal conductance	2	20 •	
					ADD
400		ЕСТВА			
ADD					Add Spectrum
	Draw	Description		Color	
1	M	scope - traction of radiation in obs	servation direction	[1,1,1]	Delete selected
					Delete all
					Export selected
					ОК

#### **Visualization options**







#### Spectral data

	CONTRACT	Algebraid.	istina kunija	Distante.	1. Harry	inhericit.	effectives	det.							
		1.7	2.3	Bullet	8.8	3.3	1.7	1	5.50	1.3	3.7.	1.3	2020	1.3	
		32.46	5.8.25	10.04	13,42	35.00	16,44	14,21	10.0	25.21	24.28	25.32	24,14	26.67	21
		0.0793	0.054	g.erks	#.#233	0.0382	8.4287	0.002	8.9117	#. 0255	8.418	0.0047	0.0393	0.034	
		0.041		0.0201	8.991	B. B285	8.8288	10.007	10.01.00	#. OF L	8.8575	******	0.0200	W- 000 L	
		1.428	2.942	3.492	1.047	3.710	1.437	1.042	1.253	1.710	1.012	8.332	2.102	10.31.70	- 2
		Air .	4.00	-	44		40	4.0	-			40		-	
		0.75	4.25	0.5	4.1	8.22	8.5	4.25	0.25	1	0.25	0.75	0.2	0.01	
		4.46		4.5	w. 0%	4.15		4.4	4.2	· · ·	0.45	4.5.	0.05	4.15	
	10.0	8.03647		0.02544	4. 021-m1	0.03544	8.03178		10.0023-25	4.01744	H. (8-2401)	0.0100	0.01714	0.04776	
	143.1	0.00711	4.016.78	a.atria.	0.01045	4. 407 911	0.02515	0.03556	the sections.	8.00550	0.03026	0.00125	0.01075	0.05257	
	155.5	0.04400	49,001071	0.02912	0.00072	0.03010	0.025.93	0.03095	10.0111.54	4.00644	0.035.64	0.00124	0.0106.3	0.06127	6
		0.64720	0.01154	0.03176			0.02750	0.01092	0.4370			6.02213		0.04435	
	174	0.01010	0.04255	9.91129		8.82754	0.03014		10.02000	B. 04 784	8.833	0.02220	0.01005	0.00000	
	82.7	0.05272	0.01000	9.93479	#. \$4771	8.42843	9.927-92	0.04137	0.02012	4.02040	0.01020	9,91223	0.01007	9.97170	4
	4.14	0.01122	0.01101	0.01444			0.03222	0.04112	0.015		0.04244	A.82124	0.030114	4.4757	
	40.4	0.07341	0.00458	0.01007	0.00375	* *****	0.03952	0.01748		4.02043	0.04000	4.03685	0.02241	4.44455	
	111.0	m	-	0.07278	a. minted a	a anima	0.055115		101003-008	a. (411.44)		*	at a high a	in and in	1
	2.2	8.1175	0.172	0.1047	8,1257	F. POSIA	8,88254	0.00181	0.04744	4.0765	0.02385	0.09975	0.04042	0.1075	
	6.22.8	10.264.5	0.1472	10.1.1.00	#.1525	@.15.95	0.2834	8.1276	10.1000	#,1025	0.09575	0.07303	m. dd.40m	18.1016	
	6 C 4	m. habia	m. homi	10.1.1.1.1.1.1	m. Lon Y	a. 1.2 hr.	m. h1.4.8	M. 1.0412	m. 1.8		m.Land.A	****		m. 1.844	
		0.1815	. 1047	#-14M	4.1704	8.1.583	8.11.88	m. Lond	8.1755		0.13.54	0.00334	0.017017	8.1447	
	53.2	10.2828	9.1554	9.1.844	8.175.2	8.1216	H-1153	8.1014	8.1.84	P. 1154	B. 18.82	8.08.000	9.97185	9-1409	
	73.0	0.2834	0.1108	9.1122	P. 160	8.11.34	8.2455	#.1875	18.1141	. 1040	8.1892	0.071.02	10.00075	18.13.03	
	4.4	4.1744	4.115	0.1.040	. 11.27	4.1.845	0.00754	4.1244	8.1479	a beach		4.04353	0.05344	4.1912	
	10.1 M	0.1748	0 1404		4.154.1		8.05418	0.1744	1.1.44	# 00140	10.1884		A AMOTT		
		0.1720	8.1475	0.1174	B. 13.8.2		0.001.00	m. Litin	10.1000	10.0007.000	-	*	a manuta	8.1556	
	1.82	0.1451	0.1404	0.1492	8.1467	8. 65524	0.00433	8.1164	0.09144	4.07978	0.49554	0.05432	0.04119	0.1587	
	124.4	0.1611	10113-04100	0.1015	8.1424	a altres	10.0001.0	8,1114	in ministry	8.07575	at maxim	10.000	H . (1973) 1 (1	10.110.000	-
		a that		a labor	B. built B.							a ment		d lash	
	4.1.1			IL MARKET	A. 1314					-	-	A		8.7011	- 2
				1.00.00	8.1228		10.00.000	a point	in a line	* #5.9.25	A	******	or other a	W.LANK	-
	14.3.5	0.1173	0.1070	0.07313	4.11.14		0.00717		8.47331	4.01145	0.00101	0.01101	0.03471	0.1054	
ALI, S.         A. 1210         A. 1210 <t< td=""><td>174 1</td><td>0.1010</td><td>8.1574</td><td>0.04371</td><td>8.147</td><td>4.45244</td><td>0.25347</td><td></td><td>8.65571</td><td># #5414</td><td>0.00154</td><td>4.531.53</td><td>0.03464</td><td>4.1655</td><td></td></t<>	174 1	0.1010	8.1574	0.04371	8.147	4.45244	0.25347		8.65571	# #5414	0.00154	4.531.53	0.03464	4.1655	
484.2 0.1527 0.11 0.00012 0.155 0.022/0 0.0717 0.100 0.0007 0.00010 0.0000 0.0100 0.070 0.0077 0.0070 0.100 0.1000 0.100 0.100 0.000 0.0010 0.001 0.0000 0.000 0.0000 0.000 0.0000 0.0000 0.0000 0.0000 0.00	12.2.1	0.1289	0.1005	0.07943	P.110		0.05524	0.00141	0.07455				0.03018	8.1492	
044 0.1977 0.1002 0.1002 0.1002 0.1700 0.1002 0.1012 0.1013 0.1175 0.0077 0.117 0.027 0.0007 0.0001 0.101 0844 0.1559 0.1979 0.1770 0.1700 0.100 0.1115 0.1013 0.101 0.1010 0.100 0.100 0.0000 0.0001 0.101 0844 0.1517 0.1001 0.100 0.000 0.1115 0.1000 0.000 0.017 0.1000 0.0111 0.100 0.0000 0.101 0.101 0.1000 0.101 0.1000 0.100 0.100 0.000 0.017 0.1000 0.0110 0.1000 0.1000 0.0000 0.101	44.7	0.1527	10.12	0.00011	8.135.1		8.07178	M. 1004	10.000772	10.000.14	a bisto	de la la la la la la	m. orbites.	0.1771	
698.0 0.2543 0.2167 0.2767 0.2500 0.1115 0.2433 0.1073 0.2610 0.266 0.255 0.29000 0.0035 0.277 205.0 0.2117 0.2007 0.2560 0.0772 0.1003 0.004 0.2077 0.2008 0.2121 0.1000 0.1443 0.125 0.257 71 0.240 0.0101 0.1212 0.2001 0.2101 0.2100 0.2200 0.2077 0.2000 0.2011 0.200 0.2001 0.2000 0.2000	194	0.3977	9.1092	0.1540	8,1764	8.1856	0.1012	0.1423	0.1175	4,9173	0.117	9,55293	9.00005	0.1979	
201.0 0.1117 0.2107 0.2100 0.2017 0.1001 0.2001 0.2017 0.2005 0.2125 0.1000 0.1015 0.2018 0.215 712 0.2019 0.2222 0.2009 0.2019 0.2010 0.2010 0.2007 0.2017 0.2011 0.2009 0.2022 0.1000 0.201	10.0	0.7563		10.7784	6 2326	10. 1 515	10.2422		10.744.10	A 144	# 15.ML	of strategy	IR COLLEGE		
714 0.2000 0.2012 0.2000 0.2010 0.2010 0.2000 0.2007 0.2000 0.2011 0.2000 0.2012 0.2000 0.201		4.111.2	4.304.7	A	m. 24YP	8.1851			4.1445	1. 21.24	- 1. mar	*. 1441	8.1256	8.2530	-
THE THE TRACE THE TRACE THE TRACE THE TRACE THE TRACE	110			H. Dank	m. philm		m. home		9.2530		8.2000		W. Links	10.2057	-
718.2 0.0131 0.0001 0.0001 0.0001 0.0001 0.0001 0.0004 0.0071 0.0114 0.0700 0.0001 0.0127 0.000	128.2	9-0125	8.2255	9.2002	8.2685	8.2775	8.2585	9.2484	9.2974	8. 2114	8.2786	8.2285	9.2127	8.2224	-
the run	T.	1	9.9442	A	*****	8. 18.27	8 1885	A	A \$150	A			A 1101	A 1415	â

#### Associated metadata

the dat mert	the Mark Sales De	rutet Opimen Sent	101	
10 4 40 - 5	220.01	ROCORI	1 1 1 1 1 1 T + O - O - 4 - O	
13 Have alterial	(idiatania, mda.ht	I showing the set of	adaptace in the second s	×
CLASS: Sener's PADDOCT: PADD COMPARY: DATE: 2452-80 EDMDON: D-8025 # RANDON: 52-00 File simulation fi	-is -is PODEL -is PODEL -is -is -is -is -is -is -is -is -is -is	0613/28/26 Time:	18-13-17	4
1.1mm 11 10		migral J. Londo	simula b	
1.84# 21 Cab	min1 0.1486	Auro 74,2545	1000011 89	
13mm 31.5m		P#11 8.0500	countr 50	
Liter AL Co	HEAL 0.0038	max) 8.0700	6.000E1-20	
LANE ST LAR	M041 0-1020	MAXY 2.8295	E04043 49	
True of suits	ML-1 00.0000	##11 HP.0000	counts a	
the states		and # 1000	CONTRACT OF	
time is the state.				
Column. Sr. manor	length Column	\$2 mestigne	licit_reflections	
Nodels Heids Hysicister Reid Historier Reid Historier Ver Historier Ang Historiet Ang Historiet Ang Historiet Ang	rert ligns: Augle: 39.500 ell Augle: be a anno ell Gets:	1.0000 24.1598 1.0000		
11	180	e// #(_1	-0558 -082 -	ي ا
Bages 117 Lam	Same Abarta Gam -	the last test plus		



# Retrieval







### Methods of these different families can be combined: hybrid methods



# **ARTMO's retrieval toolboxes:**



Optimizing and generating maps of vegetation properties only a few clicks away...

# **General structure:**



### **Spectral indices toolbox:**

🛃 Spec	tral Indice	s Toolbox [v. 1	.17]		•	×
Input	Settings	Assessment	Retrieval	Tools	Help	З





#### **Properties:**

- Calculates all possible band combinations.
- For index formulations with up to 10-band indices (#b<sup>10</sup>, for a 10 band sensor that would be 10 billion combinations)
- Includes multiple fitting functions (linear, exponential, logarithmic, power, polynomial)
- Noise & Cross-validation options
- Results stored in MySQL
- Top-performing indices per formulation and fitting function are given.
- Can process both image or individual spectra.

#### PROSAIL (100# @ 10 nm; Cab, LAI) ND linear regr.



Best-performing index can be applied to an image.

R

### Machine learning regression algorithm toolbox



#### Simpler to execute than SI: no band selection needed.



#### Properties:

• About 15 MLRAs implemented

Input Settings Validation Retrieval Tools Help

• Single-output & multi-output

MLRA Toolbox [v. 1.16]

- Noise & Cross-validation options
- Dimensionality reduction options
- Results stored in MySQL
- GPR properties: band relevance & uncertainties
- Can process both images or individual spectra.
- Active learning, GPR-BAT, dim. reduction

#### Non-parametric models:

- SimpleR [Camps-Valls et al., 2013]
- <u>http://www.uv.es/gcamps/code/simpleR.html</u>

#### <u>Also:</u>

- Elastic Net (ELASTICNET)
- Bagging trees (BAGTREE)
- Boosting trees (BOOST)
- Neural networks (NN)
- Extreme Learning Machines (ELM)
- Support Vector Regression (SVR)
- Relevance Vector Machine (RVM)
- Variational Heteroscedastic Gaussian Process Regression (VHGPR)

#### GPR in Bayesian framework also provides:

- Band relevance
- Uncertainty esitmates

(kernel-based) MLRAs are adaptive and can be very powerful. However that goes a computational cost. This can be problematic for hybrid (e.g. PROSAIL) retrieval methods. 22/33

- -

Solutions to deal with large datasets applicable to *hybrid* approaches (e.g., PROSAIL + GPR): 2/4

- 1. Reducing spectral data: I) band selection (GPR-BAT), II) dimensionality reduction
- 2. Samples reducing : Active learning

### I) Band selection: GPR-BAT

Ĭ



Sequential Backward Band Removal: remove band with highest sigma (least informative)

#### Best-performing method can be applied to an image. 23/33

### **II)** Dimensionality reduction: SIMFEAT

#### 9 dimensionality reduction methods implemented.

Sel	File				
11 12	Featu	re Extra	ction Algorithms		
13		Select	Band reduction methods	Kernel	type
14	1	-	Principal component analysis (PCA)	Empty	~
Select al	2	-	Partial least squares (PLS)	Empty	~
Para	3	✓	Ortho-normalized PLS (OPLS)	Empty	~
e.,	4	✓	Canonical correlation analysis (CCA)	Empty	~
3.	5	-	Minimum Noise Fraction (MNF)	Empty	~
RTM data [>	6	✓	Kernel Principal Component Analysis (KPCA)	rbf	~
Trai	7	-	Kernel partial least squares (KPLS)	rbf	~
Only tr	8	✓	Kernel Orthonormalized Partial Least Squares (KOP	rbf	~
	9	-	Kernel Canonical Correlation Analysis (KCCA)	rbf	~
		# Featu	re [max:125] 5 Clustering User V	5	ОК



#### **Experimental setup:**

#### **PROSAIL: 500 random samples**

Variable	Min	Max
N	1	4
Cab	1	80
Cw	0.02	0.05
psoil	0	1
LAI	0.01	7



directional reflectance (2101 bands)



Best-performing method can be applied to an image.

24/33

### 2) Sample reduction: Active learning (AL)



Active learning (AL) searches for new samples from a data pool based on *uncertainty* (PAL, EQB, RSAL) and *diversity* (ABD, CBD, EBD).

 AL method search more efficiently for relevant samples than random sampling or when using all data.

4/4

## Background LUT-based inversion <sup>1/2</sup>



### **LUT-based inversion toolbox:**

🛃 LUT-	-based Inve	rsion Toolbo	к [v. 1.06]		•	×
Input	Settings	Validation	Retrieval	Tools	Help	ъ

**/** 



#### **Properties:**

- LUT ARTMO RTMs or external LUT ٠
- **Over 60 different cost functions** ۰
- Noise & multiple solutions
- **Results stored in MySQL** •
- **Top-performing inversion strategies** ٠ are given.
- Can apply inversion to both image or individual spectra.



Best-performing method can be applied to an image.

Noise (%)

27/33

2/2

# Tools



실 ARTMO [v. 3.1	9]				×
File Models	Forward Retrieval	Tools H	elp		ч
- Project Descr	ription				
Project Name:					
Comment	t				
Sensor:	NO SENSOR				-
DR test si2			UT Class by map	LUT Class by L	Jser



28/33

# Global sensitivity analysis

# <u>Global sensitivity analysis</u>: explores the full input parameter space, i.e. all input parameters are changed together.

Variance-based methods: the output variance is decomposed to the sum of contributions of each individual input parameter and the interactions (coupling terms) between different parameters.

Based on the work of Sobol', variance-based sensitivity measures are represented as follows:

$$1 = \sum_{i} S_i + \sum_{i} \sum_{j>i} S_{ij} + \cdots + S_{12,\dots,k}$$

in this equation,  $S_i$ ,  $S_{ij}$ ,..., $S_{12,...,k}$  are **Sobol's global sensitivity indices**.:

The <u>first order sensitivity index</u>  $S_i$  measures and quantifies the sensitivity of model **output** Y to the input parameter  $X_i$  (without interaction terms), whereas,  $S_{ij},...,S_{12,...,k}$  are the sensitivity measures for the higher order terms (interaction terms).

The <u>total effect sensitivity index</u>  $S_{Ti}$  measures the whole effect of the variable  $X_{i}$ , i.e. the first order effect as well as its coupling terms with the other input variables:

$$S_{T1} = S_1 + S_{12} + S_{13} + S_{123}$$

# **GSA toolbox**

Save Load Project PRO4SAIL_1000 Type SI Satelli RT model	subsamples 1000
4SAIL-Prospect 4    Default	NO SENSOR
Group Canopy  Parameter Total Leaf Area Index Extremal Parameters Empty Range min max Distribution 0 10 Sobol	Select     Parameter     m       1     Leaf Structural Parameter     2       2     chlorophyll a+b content i     3       3     equivalent water thickne     1.000       4     dry matter content in g/c     1.000       5     Total Leaf Area Index       6     Leaf angle distribution       7     Diffuse/direct light       V     III
RTM outputs Group Canopy Parameter Directional reflectance Add output	Select Parameters Gr Directional reflectance Canopy Canopy Delete selected Delete all

- E X

### Properties:

ARTMO [v. 3.19]

- ARTMO RTMs
- Saltelli 2010 GSA method
- Various sample distributions
- Results stored in MySQL
- First order or total order Sobol Sensitivity indices
- Can process multiple RTM outputs.





## **Emulation**

Emulators are regression models that are able to approximate the processing of an RTM, at a fraction of the computational cost:



1/2



making a statistical model of a physical model

### **Emulators applied to RTMs:**

• In principle any nonlinear, adaptive machine learning regression algorithms (MLRAs) can serve as emulators.



• To emulate RTMs, the emulator should have the capability to reconstruct multiple outputs, i.e. the complete spectrum: resolved with **dimensionality reduction** techniques (e.g. PCA).



### **500 TOC reflectance simulations according to Sentinel-3 (13 bands)**



In Emulation, physical models go hand in hand with machine learning

2/2

# **Conclusions**

