



From model simulations towards vegetation properties mapping:

automating, optimizing & simplifying



J. Verrelst EOSS2018 – ESA-ESRIN

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How to quantify vegetation properties?

R



Today we will learn: Semi-automated mapping of vegetation properties from optical RS data



The problem:

Biophysical parameter retrieval is an essential step in modeling the processes occurring on Earth and the interactions with the atmosphere.

The analysis can be done at **local** or **global** scales by looking at bio-geochemical cycles, atmospheric situations, ocean/river/ice states, and vegetation dynamics.

Main parameters: crop yield, biomass, leaf area coverage, chlorophyll content, fraction vegetation cover, GPP,....

Land/vegetation parameters cannot be estimated directly from optical RS data. A model is required!

The objective: Transform measurements into biophysical parameter estimates.

The data:

- Input data: satellite/airborne spectra, in situ (field) radiometers, or simulated spectra by RTMs
- Output results: estimation of a biophysical parameter









Introduction retrieval biophysical parameters



Statistical approaches

Retrieval of biophysical parameters from Remote Sensing (RS) data **always occurs through a model**, e.g. through statistical models or through inversion of physically-based radiative transfer models (RTM).

Physically based RTM approaches





Retrieval of (continuous) vegetation properties

Remote sensing image

Map of a vegetation property



1. Statistical models

- 1. Parametric regression models
- 2. Nonparametric regression models
 - 1. Linear
 - 2. Nonlinear
- 2. Inversion of physically based radiative transfer models
 - 1. Numerical optimization
 - 2. Lookup-table (LUT)-based inversion

Taxonomy of retrieval methods, three main families:

- 1. Statistical: parametric and non-parametric:
 - Parametric models rely on some physical knowledge of the problem and build explicit parametrized expressions that relate a few spectral bands with the biophysical parameter(s) of interest.
 - Non-parametric models are *data-driven* models. They are adjusted to predict a variable of interest using a training dataset of input-output data pairs.
- 2. Physical: try to reverse RTMs.
 - Physically based algorithms are applications of physical laws establishing photon interaction *cause–effect relationships*. Model variables are inferred based on specific knowledge, typically obtained with radiative transfer functions.
- 3. Hybrid:
 - A hybrid-method combines elements of nonparametric statistics and physically based methods. Hybrid models rely on the generic properties of physically based methods combined with the flexibility and computational efficiency of nonparametric nonlinear regression methods.







Retrieval families



Methods of these different families can be combined: hybrid methods



Statistical interpretation of RS

Remote Sensing Data

Statistical relationship

- Parametric regression
- Non-parametric regression

Variable of Interest



- Simple statistical relationships (VIs) constitute the **BULK of RS analysis**.
- These analyses allow to determine **IF** there is a relationship, **not WHY** there is a relationship.
- Linear methods such as VIs are **useful indicators** of biophysical (e.g. structure) or biochemical (e.g. chlorophyll) parameters, however in natural, complex environments indices are **confounded** by additional abiotic and biotic factors.
- VIs lack generality for estimating biophysical parameters.
- Apart from VIs a large number of powerful **alternative statistical retrieval** methods exists (e.g. non-parametric regression methods).

Parametric regression

Parametric regression assume an explicit model for retrieval

- Discrete band methods(VIs):
 - 2-band: SR, NDVI, PRI, OSAVI
 - 3-band: TVI, MCARI, SIPI
 - 4-band: TCARI/OSAVI
- Shape-based methods:
 - Red-edge position (REP)
 - Derivative/Integral indices
 - Continuum removal
 - wavelet



$$PRI = \frac{(\rho 570 - \rho 531)}{(\rho 570 + \rho 531)}$$

$$TCARI / OSAVI = 3 \cdot \left[\left(\rho_{\mu 700} - \rho_{\mu 670} \right) - 0.2 \cdot \left(\rho_{\mu 700} - \rho_{\mu 550} \right) \cdot \right] \\ \left(\rho_{\mu 700} - \rho_{\mu 670} \right) \left(1 + 0.16 \right) \cdot \left(\rho_{\mu 800} - \rho_{\mu 670} \right) / \\ \left(\rho_{\mu 800} - \rho_{\mu 670} + 0.16 \right)$$
(2)



Parametric regression:



Strengths

- Simple and comprehensive regression models; little knowledge of user required.
- Fast in processing
- Computationally inexpensive

- Weaknesses
- Makes only poorly use of the available information within the spectral observation; at most a spectral subset is used. Therefore, they tend to be more noisesensitive as compared to full-spectrum methods
- Parametric regression puts boundary conditions at the level of chosen bands, formulations and regression function.
- Statistical function accounts for one variable at a time.
- A limited portability to different measurement conditions or sensor characteristics
- No uncertainty estimates are provided. Hence the quality of the output maps remains unknown.



Parametric regression



Non-parametric models (1/2):

Data-driven methods: Do not assume explicit feature relations

Linear nonparametric models:

- Stepwise multiple linear regression (SMLR)
- Principal component regression (PCR)
- Partial least squares regression (PLSR)
- Ridge regression (RR)
- Least Absolute Shrinkage and Selection Operator (LASSO)



Non-parametric models (2/2):

Data-driven methods: Do not assume explicit feature relations

Non-linear nonparametric models:

Decision Trees (DT)



Neural networks (NN)



Also:

- Elastic Net (ELASTICNET)
- Bagging trees (BAGTREE)
- Boosting trees (BOOST)
- Neural networks (NN)

Support vector regression (SVR)

Kernel ridge regression (KRR)



 $K(\mathbf{x}_i, \mathbf{x}_j) = \exp(-\|\mathbf{x}_i - \mathbf{x}_j\|^2 / (2\sigma^2)).$

- Extreme Learning Machines (ELM)
- Relevance Vector Machine (RVM)
- Gaussian process Regression (GPR)
- Variational Heteroscedastic Gaussian Process Regression (VHGPR)





Non-parametric regression:

Strengths

- Full-spectrum methods. They make use of the complete spectral information.
- Advanced, adaptive (non-linear) models are built.
- Methodologically, accurate and robust performance is enabled.
- Some MLRAs cope well with datasets showing redundancy and high noise levels.
- Once trained, imagery can be processed time efficient.
- Some of the non-parametric methods (e.g. ANNs, decision trees) can be trained with a high number of samples (typically >1,000,000).
- Some MLRAs provide insight in model development (e.g. GPR: relevant bands; decision trees: model structure).
- Some MLRAs can provide multiple-outputs (e.g. PLRS, ANN, SVR, GPR and KRR)

Weaknesses

- Training can be computational expensive.
- Hypercomplex models can be generated. Their generic potential is limited and hence they do not generalize well, based on the training data (problem of over-fitting).
- Some regression algorithms are difficult (or even impossible) to train with a high number of samples.
- Expert knowledge is required, e.g. for tuning. However, toolboxes exist automating some of the steps in this sub-process.
- Some of the methods can be considered as black boxes.
- Some regression algorithms elicit instability when applied with datasets statistically deviating from the datasets used for training.

• Some MLRAs provide uncertainty intervals (e.g. GPR).

Non-parametric regression

COOKBOOH



Physical interpretation of RS



Radiative transfer models:

- Try to predict RS data based on a function of the RT state variables
- Two categories of RT models:
 - Economically invertible models:



typically designed for simple scenes, have a few number of state variables (e.g. SAIL, RPV)







Background



Radiative transfer models

Leaf RT models



n plate

Compact spheres

Ray tracing

Canopy RT models







layers

N-fluxes

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Multiple models exist with diverse complexity.

Leaf optical models

- A leaf is not opaque but transparent.
- Leaf as composed out of layers and empty spaces







http://rami-benchmark.jrc.ec.europa.eu

Examples of canopy RTMs(1/4)

SAIL model (Verhoef 1984): a 1-D model



Examples of canopy RTMs (2/4)

Canopy models can be coupled with leaf, soil and atmospheric models



Examples of canopy RTMs (3/4)

Ray tracing models

Drat -the aDvanced Radiometric Ray Tracer.

P. Lewis, 1999; Saich et al., 2001. University College, Dept. Geography, London

Vegetation is built using The Botanical Plant Modelling System (BPMS) BPMS is a form of L-systems - the branches of a tree as geometric primitives

ARARAT - the advanced radiometric ray tracer, reverce ray tracing, a variety of camera models implemented



(Dürer, 1525)







Examples of canopy RTMs (4/4)

FLIGHT (North, 1996): A 3-D model

FLIGHT MC ray tracing approach

- Large scale structure by geometric primitives (e.g. cone)
- Foliage within crowns described by volume-averaged parameters
- 3D photon trajectories are simulated, accounting for the probabilities of free path, absorption and scattering
- Individual photon trajectories are traced from a solar source, through successive interactions, to a predetermined sensor view angle.





Biophysical parameters retrieval through RTM inversion:





LUT-based RTM inversion



Hybrid retrieval

COOKBOOK



Summary mapping methods

		LAI
Parametric regression	Calibration & Validation Vegetation indices Shape indices Transformations	on g function g. linear ression)
Non-parametric regression	Training & Validation All bands Band selection or VIs Transformation (e.g. PCA)	-parametric egression
RTM inversion	RTM Regularization &	Validation





Hybrid regression

Verrelst, J., Malenovský, Z., Van der Tol, C., Camps-Valls, G., Gastellu-Etchegory, J.P., Lewis, P., Moreno, J. (2018). Quantifying Vegetation Biophysical Variables from Imaging Spectroscopy Data: A Review on Retrieval Methods. Surveys in Geophysics,

Taxonomy retrieval methods



Optimizing retrieval



31/50



We will learn:

- Using leaf and canopy radiative transfer models (RTMs)
- ARTMO
 - Run forward leaf & canopy RTMS
 - Graphics
 - Sensor
 - Applications
- Retrieval toolboxes
 - LUT-based inversion
 - Machine Learning Regression Algorithms (MLRAs)
 - Spectral indices





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 (GUIs).



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

Model	Reference	Source code
PROSPECT-4	Feret et al., 2008	Matlab
PROSPECT-5	Feret et al., 2008	Matlab
PROSPECT-D	Feret et al., 2017	Matlab
DLM	Stuckens et al., 2009	Matlab
LIBERTY	Dawson et al., 1998	Matlab
FLUSPECT	Vilfan et al., 2016	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:	Matlah®	Leaf RTM
		Canopy RTM
Database:	MySQL®	Combined RTM
Image processing software:	ENVI®	



ARTMO v. 3.24





ARTMO's retrieval toolboxes:

LUT-based inversion toolbox

LUT-	-based Inve	0	9 2	٢		
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Machine learning regression algorithm toolbox (MLRA)

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Spectral indices toolbox

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ARTMO's tools:

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Emulation:

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Sensor Module [v. 1.06]



Global sensitivity analysis:





http://ipl.uv.es/artmo/



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Conceptual architecture ARTMO



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Chlorophyll (Cab - pg/cm³) (0-100)

Dry matter (Cm - g/cm²) (0-0.05)

er-Calr Rasge (0-100)

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Probability density function

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PROSPECT 4

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Leaf Strecture (N) [1-4]

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	104 B	10.1124	10.14**	M 11100	# 1145	-	A. 1003.4.0	. 1.14	4. 1414	14.000.000	W.merta	a put	In manage	# 114
	125-2	10.1001	W.Lett.	A	w Jair	0.000.20	10.074431	0.1104	1.014	A.87178	a.mile	10.000	0.04120	19.15
	1.14.4	IR MALL	48.014.04	4 1805	# 1437	to include	A. Milma	# 11.54	·	10.075.05		10.04.767		4.14
	444.4	a.1997	10.1114	a jarde	m 144m	in meinen	a distant	4.1105	1.01111	in arrists	a	-	0.000	8.14
	443.4	st. Later.	44.1.242	AL INTAKE	8.1444	B. 407103	4.0114.	4.30%	4.40144	10,0001218	A. emeria	10.04134	0.01234	A 14
	110.0	10.2461	10.110	minist	m blen	e.minla	T. Courts	*		10.000		-		* 14
	14.4	10.1.27%	10.14716	4.8/1116	# 1144	W. Maile	8,85152	4.401.04	1.41214	10.05.210	1.46,17	8.8584	0.0141	# 14
	114.5	4.2762	w.raba	A DOTATION OF	m. 144	p. ini. jour	4. 19143	4.00000	0.0.12		a mile			1.14
	600.4	1.1.1.100	a sent	8-81362	# 144	9.45414	6.436.00	4.11458	1.414.68	3.85.86	9.4814	*.43×14	W Wabal	\$ 10
$ \begin{array}{cccccccccccccccccccccccccccccccccccc$	194.2	0.6527	W-12	4.49412	8.1912	8.45743	8,97,71		8-98772	0.00114	D. pasta	0.04135	9.07205	8.17
	\$24	0.8877	9.3195	0.5388	4.1713	5.3453	8,5853	\$ 3441	07.5245	10.49172	9.617	4.0100	0.01010	2.10
1994 - 4.12 4.24 4.24 4.24 4.24 4.24 4.24 4.24	100.0	0.2542	0.2297	6-1787	0.2125	0.1515	415433	4.101	w.10544	9.949	8-8626	W.6187	0.0175	6.02
ter a seret a ter a seret a ter a Let a seret a ter a te	795.4	4.112	W-2067	0.2216	4-2872	6-1967	P. 1844	\$,2437	8.2014	4-21-5	U-Lines.	0.1483	0.1278	# 25
the state while	782	8.0000	9.1132	4.2554	0.3454	8.2441	8.2264	10.0101	4-1728	9.2048	0.2344	0.1000	4.1124	1 22
The standard sector a part of any standard standard standard standard standard standard standard standard stand	738.2	9,4235	0.1495	0.1003	3-3446	4.1771	8.2585	6.1481	8.2375	9.35LA	0.2768	4.1545	8.2127	4.35
	3-	1	- 11c	* 1001		A	a. 3944	1.14	1.131	3.46	8 P.m.	4.154	6	12







Data flow

File Models	Forward Regieval Tools Help	
Project Deser	intion	
Project Name		
Common	d	



44/	′50
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Automated generation of spectral data



Spectral data can be reflectance, transmittance, fluorescence

Automated mapping of vegetation properties

LCC [µg/cm²] 0 5 10 15 20 25 30 35 40 45 50 55 60 65





Simulated data



File	Models	Forward	Retrieval	Tools	Help	Plugins	Y
Proj	ject Desci	iption					
P	roject Nam						
	Comme						
	Comme						-
	Senso	NO SENS	OR				•





LAIb

3.75

ן_בשו_זשן 2.50

AI Bro

1.25

0.00

LAIg

5,25

LAI Green [m²/m²]

1.75

0.00

Lectures for following days

goo.gl/5DzDkx



1. Forward running leaf and canopy radiative transfer models (RTMs)



2. Machine learning regression algorithms for vegetation properties mapping



3. Optimizing vegetation indices for vegetation properties mapping



4. Optimizing RTM inversion for vegetation properties mapping

5. Global sensitivity analysis of RTMS



6. Emulation of RTMs



7. Synthetic scene generation



Lectures for following days

goo.gl/5DzDkx

