Remote sensing of soil properties and soil patterns: Current research and perspectives

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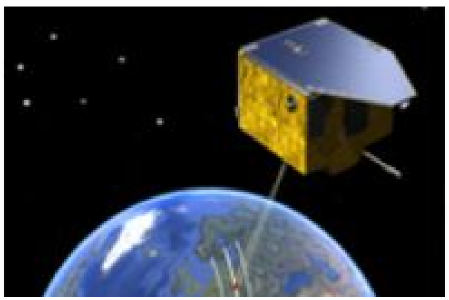
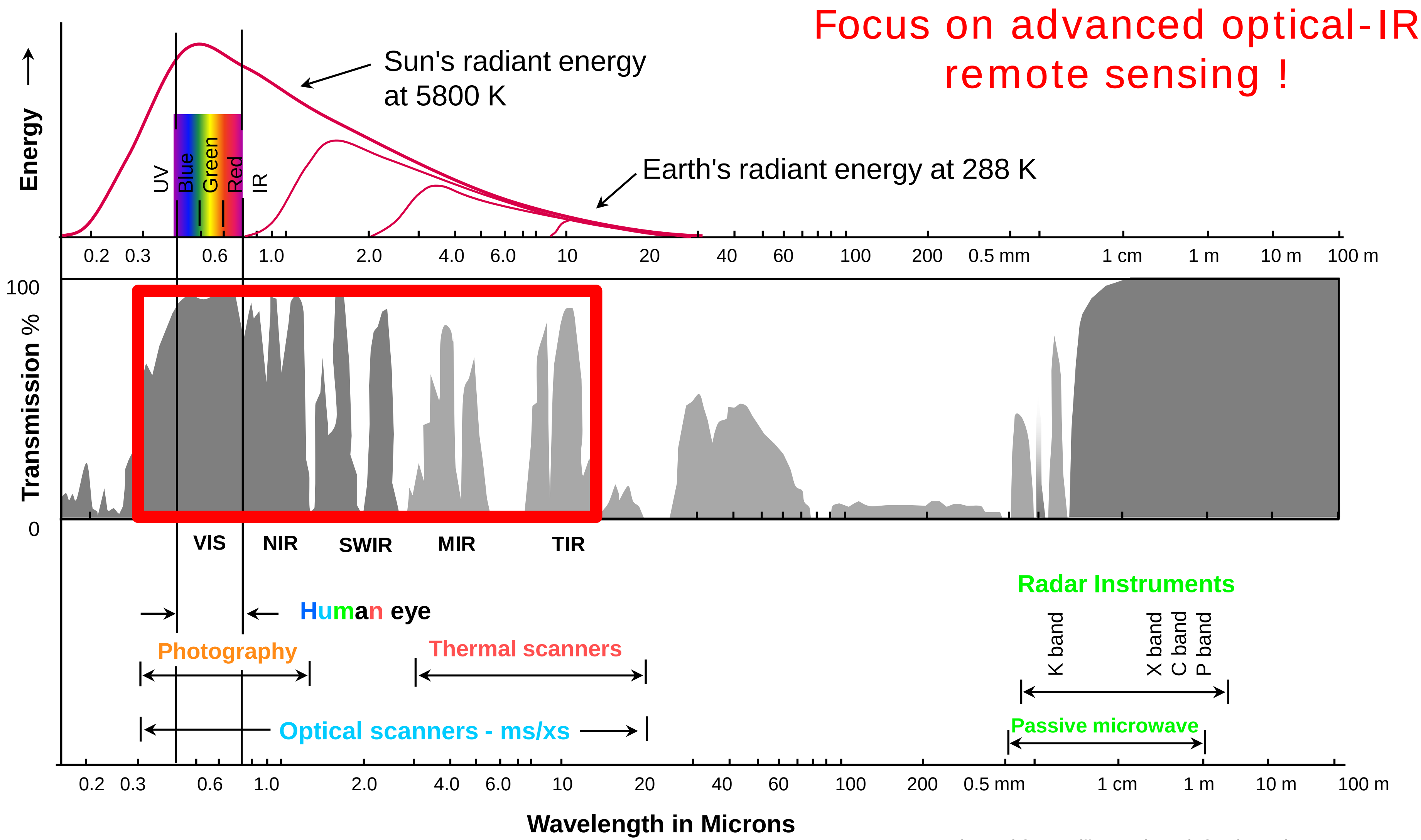



GFZ German Research Center for Geosciences
Section 1.4: Remote Sensing
Potsdam, Germany

Introduction



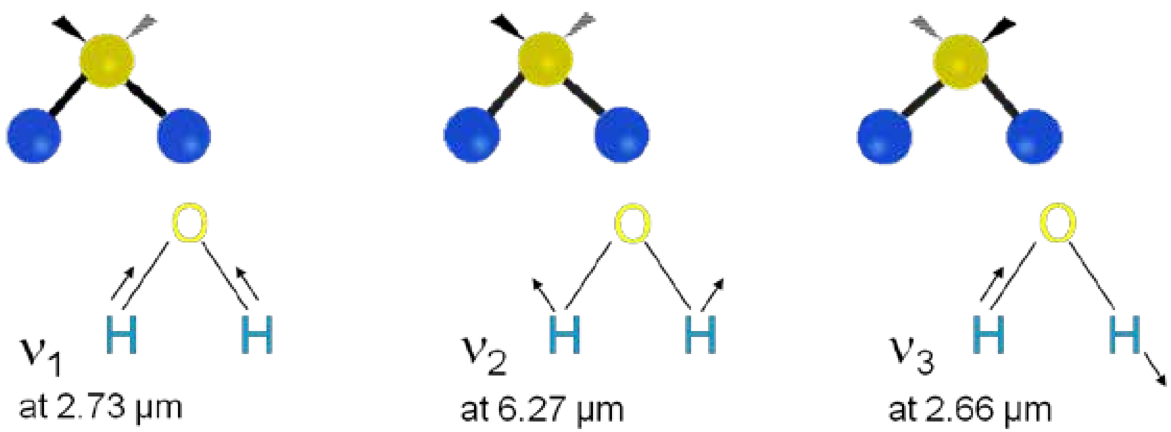
adapted from Lillesand & Kiefer (1994)

Quo Vadis imaging spectroscopy

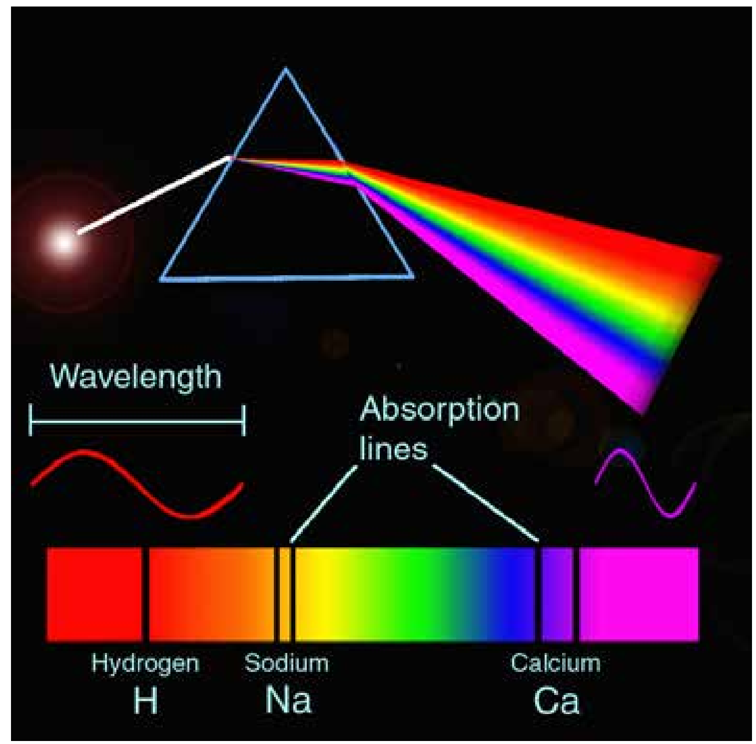
v **Reflectance spectroscopy à** Reflectance spectroscopy is the study of light as a function of wavelength that has been reflected or scattered from a solid, liquid, or gas in the optical domain

v **Absorption bands** due to electronic, vibrational or rotational energy transitions in atoms and molecules that **characterize material**

Water molecule: 3 fundamental modes of vibration



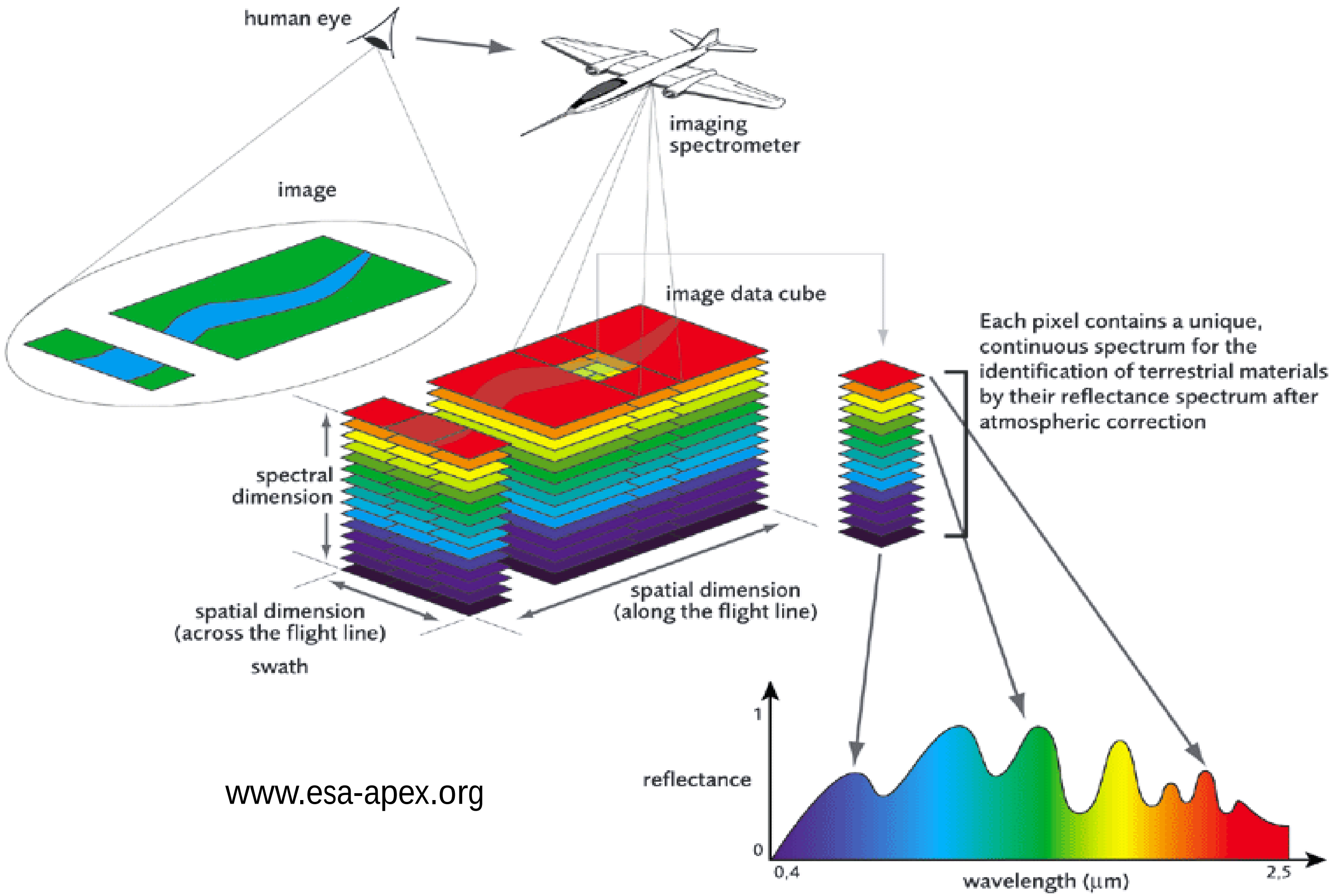
v **Imaging spectroscopy à** Study of solar electromagnetic radiation reflected by Earth materials in the spatial domain



Airborne or spaceborne Imaging Spectroscopy (IS)

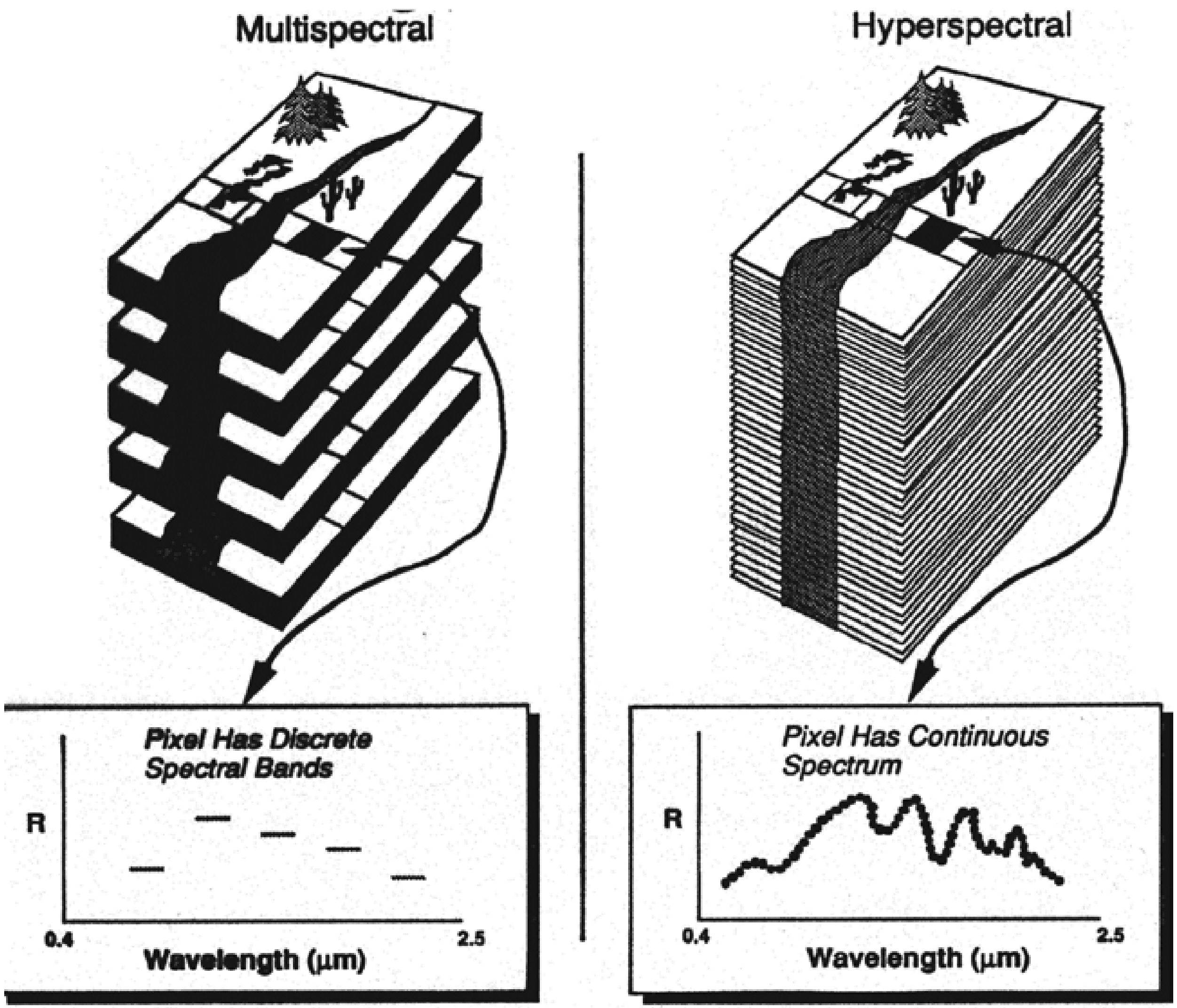
Also named: Hyperspectral Remote Sensing (HRS)

Each image is acquired in >~100 narrow contiguous spectral bands



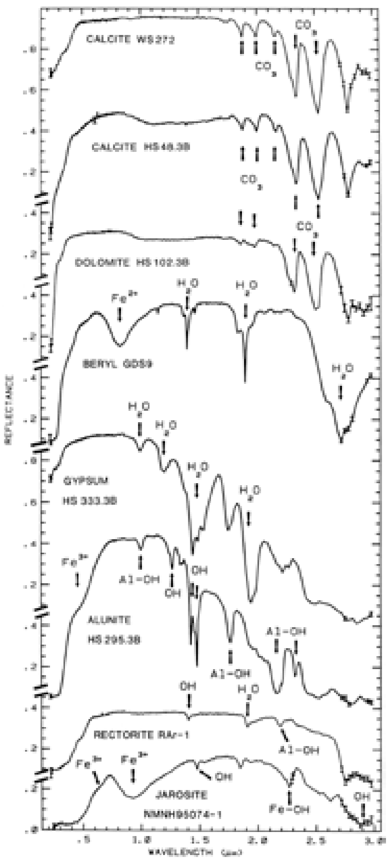
www.esa-apex.org

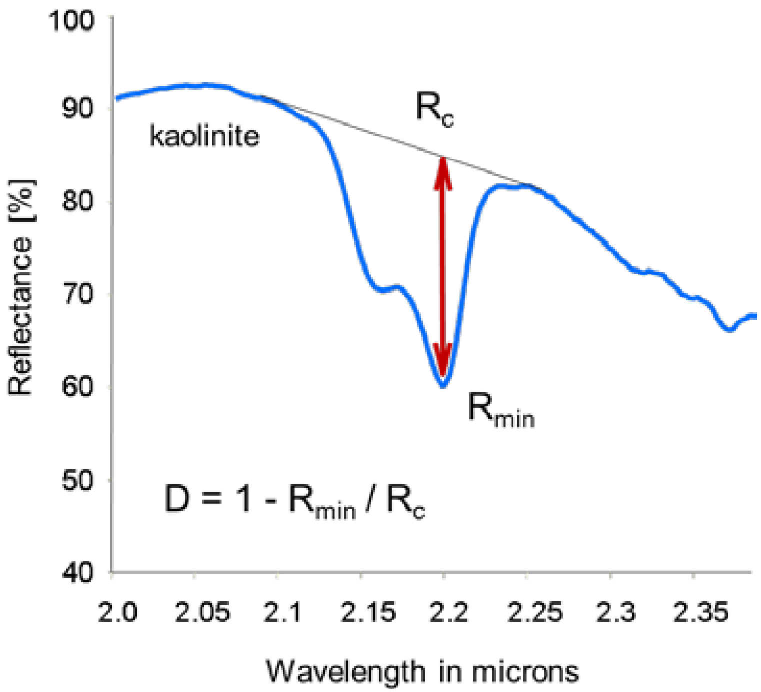
Comparison multispectral - hyperspectral



From absorption bands to material identification & quantification

Absorption bands à spectral features in the spectrum of reflected radiation





Each material on the Earth‘s surface has a unique spectral characteristic

Pigments, Minerals, Man Made Objects

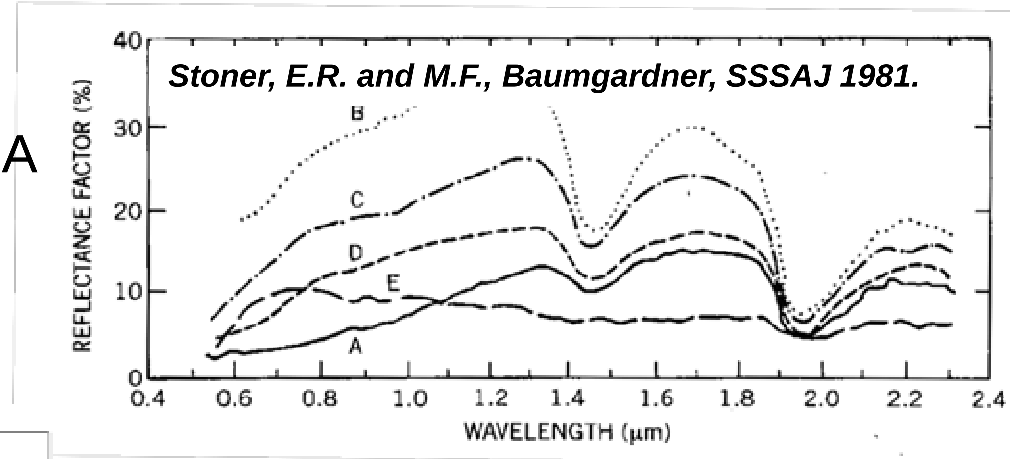
Shape
Position → Identification

Depth → Quantification

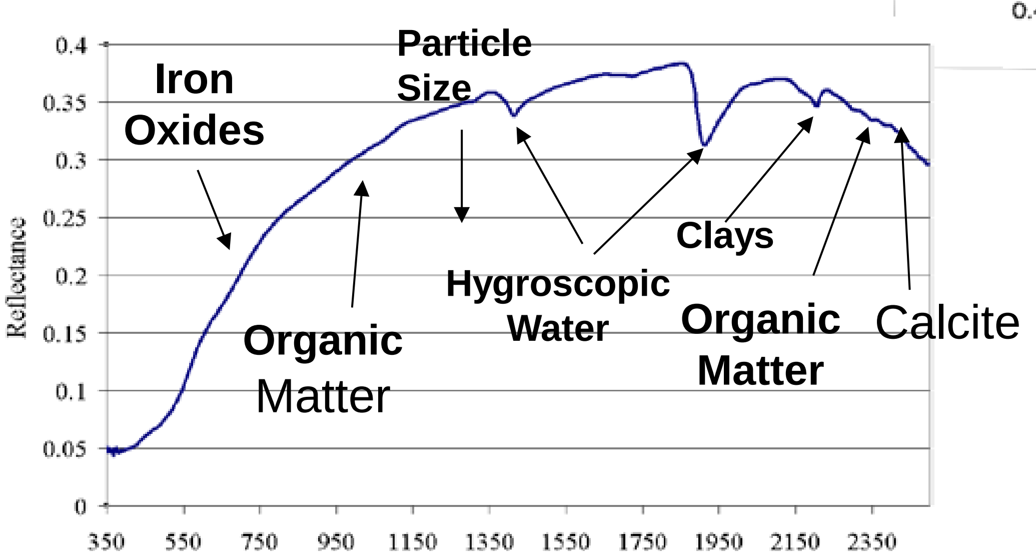
Soil spectroscopy

Absorption features in the reflectance spectrum due to mineral and water constituents can be exploited to map soil conditions

5 spectral types in USA



7 Main Soil Chromophores



Ben-Dor E., and A. Banin 1995b, Soil Science

Soil Spectroscopy: An Alternative to Wet Chemistry for Soil Monitoring

Nocita et al., white paper, Adv. Agr. 2015

In the laboratory

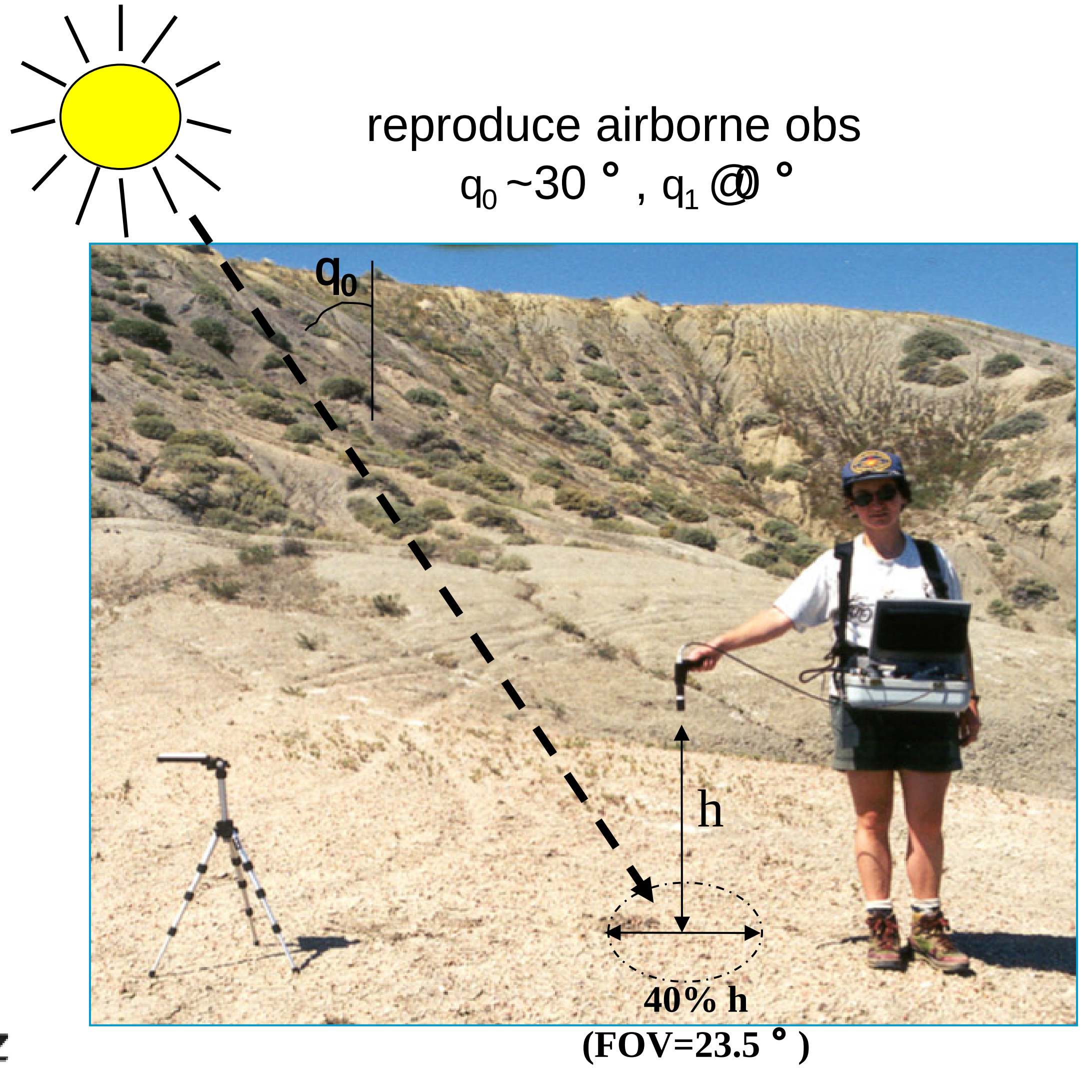
Soil attribute	Spectral region	Spectral range (nm)	Multivariate metho
Acid (exch.); cmol/kg	VIS–NIR	400–2498	PCR
Al (exch.); cmol/kg	MIR	2500–25,000	PLSF
Biomass (N); mg/kg	NIR	1100–2300	PLSF
Biomass (N); mg/kg	NIR	1100–2498	PLSF
Biomass; g/kg	MIR	2500–25,000	PLSF
Biomass; mg/kg	VIS–NIR	400–2498	PCR
C (inorg.); g/kg	MIR	2500–25,000	PLSF
C (inorg.) g/kg	NIR	1100–2498	PLSF
C (inorg.); g/kg	VIS–NIR	400–2498	PLSF
C (total); g/kg	MIR	2500–25,000	PLSF
C (total); g/kg	NIR	1100–2498	PLSF
C (total); g/kg	NIR	1100–2498	PLSF
C (total); g/kg	VIS–NIR	400–2498	PLSF
C (total); g/kg	VIS–NIR	400–2498	PCR
C; %	UV–VIS–NIR	250–2450	PLSF
C:N ratio	VIS–NIR	400–2498	PLSF
CEC; cmol(+)/kg	MIR	2500–25,000	PLSF
CEC; cmol(+)/kg	NIR	1000–2500	MRA
CEC; mmol(+)/kg	NIR	700–2500	PCR
CEC; cmol(+)/kg	VIS–NIR	400–2498	PCR
CEC; cmol(+)/kg	VIS–NIR	350–2500	MAF
CEC; mmol(+)/kg	UV–VIS–NIR	250–2500	PCR
Σ exch. cations; cmol(+)/kg	MIR	2500–20,000	PLSF
Ca; cmol/kg	MIR	2500–25,000	PLSF
Ca; mmol(+)/kg	NIR	700–2500	PCR
Ca; g/kg	VIS–NIR	400–2500	modi
Ca (exch.); cmol(+)/kg	VIS–NIR	350–2500	MAF
Ca (exch.); cmol(+)/kg	VIS–NIR	400–2498	PCR
Ca; mmol(+)/kg	UV–VIS–NIR	250–2500	PCR
Carbonate; %	MIR	2500–20,000	PLSF
Carbonate; %	NIR	1000–2500	MRA band
EC; mS/cm	UV–VIS–NIR	250–2500	PCR
Fe (DTPA); mg/kg	MIR	2500–25,000	PLSR
Fe (free); %	NIR	700–2500	PCR
Fe; mg/kg	VIS–NIR	400–2500	modified
Fe (Mehlich III); mg/kg	VIS–NIR	400–2498	PCR (9)
Fe (free); %	UV–VIS–NIR	250–2500	PCR
K; g/kg	VIS–NIR	400–2500	modified
K; mmol(+)/kg	UV–VIS–NIR	250–2500	PCR
K (exch.); mg/kg	MIR	2500–25,000	PLSR
K (avail.); mg/kg	VIS–NIR	400–1100	NN
K (exch.); cmol/kg	VIS–NIR	400–2498	PCR (13)
LR; t/ha	MIR	2500–25,000	PLSR
LR; t/ha	NIR	700–2500	PLSR
Mg (exch.); cmol/kg	MIR	2500–25,000	PLSR
Mg; mmol(+)/kg	NIR	700–2500	PCR

Soil attribute	Spectral region	Spectral range (nm)	Multivariate method[a]	n_{calib} | n_{valid}[b]	RMSE	R^2	Authors
Mg; g/kg	VIS–NIR	400–2500	modified PLSR	315		0.90	Cozzolino and Moron (2003)
Mg (exch.); cmol(+)/kg	VIS–NIR	350–2500	MARS	493|246	11	0.81	Shepherd and Walsh (2002)
Mg (exch.); mg/kg	VIS–NIR	400–2498	PCR (9)	30|119	12.8	0.68	Chang et al. (2001)
Mg; mmol(+)/kg	UV–VIS–NIR	250–2500	PCR	121|40		0.63	Islam et al. (2003)
Mn (DTPA); mg/kg	MIR	2500–25,000	PLSR	183		0.57	Janik et al. (1998)
Mn (exch.); cmol/kg	MIR	2500–25,000	PLSR	183		0.66	Janik et al. (1998)
Mn (Mehlich III); mg/kg	VIS–NIR	400–2498	PCR (12)	30|119	56.4	0.70	Chang et al. (2001)
OC; %	MIR	2500–20,000	PLSR			0.92	Janik and Skjemstad (1995)
OC; %	MIR	2500–25,000	PLSR	188		0.93	Janik et al. (1998)
OC; g/kg	MIR	2500–25,000	PLSR (17)	177|60		0.94	McCarty et al. (2002)
OC; (acidified soil) g/kg	MIR	2500–25,000	PLSR (19)	177|60		0.97	McCarty et al. (2002)
OC; %	NIR	1100–2500	MLR (1744, 1870, 2052)	72|48		0.93	Dalal and Henry (1986)
OC; %	NIR	1100–2500	RBFN	140|60	0.32	0.96	Fidêncio et al. (2002)
OC; %	NIR	700–2500	PCR	121|40		0.68	Islam et al. (2003)
OC; g/kg	NIR	1100–2498	PLSR (18)	177|60		0.82	McCarty et al. (2002)
OC; mg/kg	NIR	1100–2300	PLSR (8)	180 x-val		0.94	Reeves and McCarty (2001)
OC (acidified soil); g/kg	NIR	1100–2498	PLSR (17)	177|60		0.80	McCarty et al. (2002)
OC; g/kg	VIS–NIR	400–2498	PLSR (6)	76|32	0.62	0.89	Chang and Laird (2002)
OC; g/kg	VIS–NIR	350–2500	MARS	449|225	0.31	0.80	Shepherd and Walsh (2002)
OC; dag/kg	VIS–NIR	350–1050	PLSR (5)	43|25	0.36		Viscarra Rossel et al. (2003)
OC; %	UV–VIS–NIR	250–2500	PCR	121|40		0.76	Islam et al. (2003)
OM; %	MIR	2500–25,000	PLSR (4)	31 x-val	0.72	0.98	Masserschmidt et al. (1999)
OM; %	NIR	1000–2500	MRA (30 bands)	39|52		0.55	Ben-Dor and Banin (1995)
OM; %	VIS–NIR	400–1100	NN	41		0.86	Daniel et al. (2003)
OM; %	VIS–NIR	400–2400	SMLR (606, 1311, 1238)	15|10		0.65	Shibusawa et al. (2001)
P (avail.); mg/kg	MIR	2500–25,000	PLSR	186		0.07	Janik et al. (1998)
P (avail.); mg/kg	VIS–NIR	400–1100	NN	41		0.81	Daniel et al. (2003)
pH	MIR	2500–20,000	PLSR			0.72	Janik and Skjemstad (1995)
pH	NIR	1100–2300	PLSR (8)	180 x-val		0.74	Reeves and McCarty (2001)
pH	NIR	1100–2498	PLSR (11)	120|59		0.73	Reeves et al. (1999)
pH	VIS–NIR	350–2500	MARS	505|253	0.43	0.70	Shepherd and Walsh (2002)
pH_{Ca}	MIR	2500–25,000	PLSR	183		0.67	Janik et al. (1998)

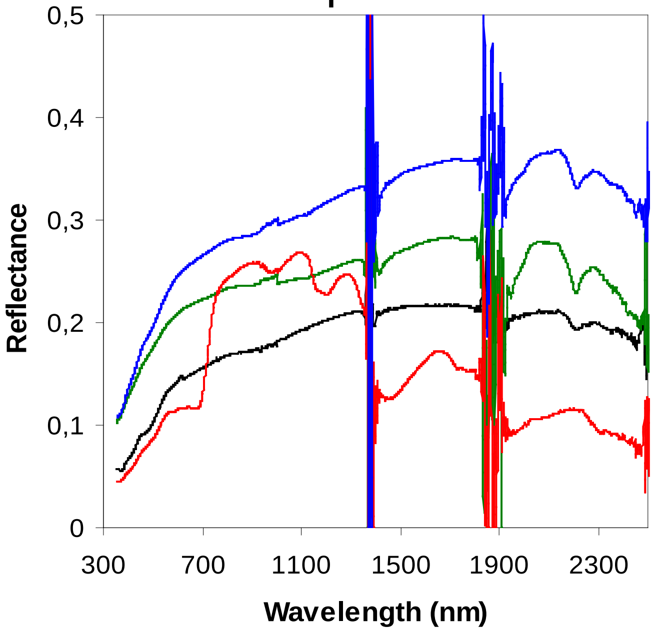
R.A. Viscarra Rossel et al. / Geoderma 131 (2006) 59–75

Field spectroscopy with portable instruments

reproduce airborne obs
q0 ~30 ° , q1 @0 °



Field spectra



Soil profile mapping

Soil profile classification using an optical head device

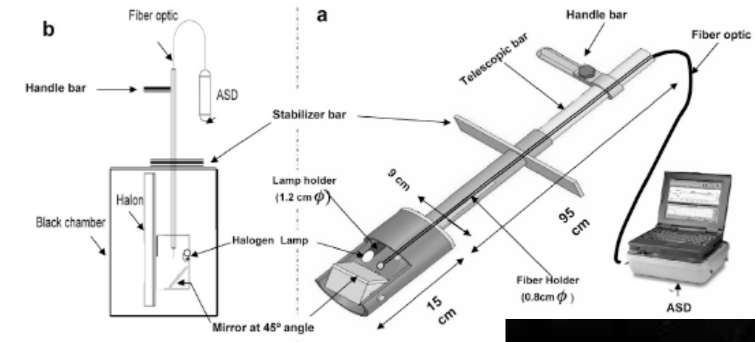


Fig. 2. (a) A sketch describing all parts of the in-soil 3S-HeD probe and the connection betwee
inner fore-optics. (b) Also given is a schematic configuration of a dark chamber showing
measured for the spectral optimization and reading.

BenDor et al., 2008, SSSAJ

Direct Soil Profile Spectral Mapping

Ben Dor et al., 2010

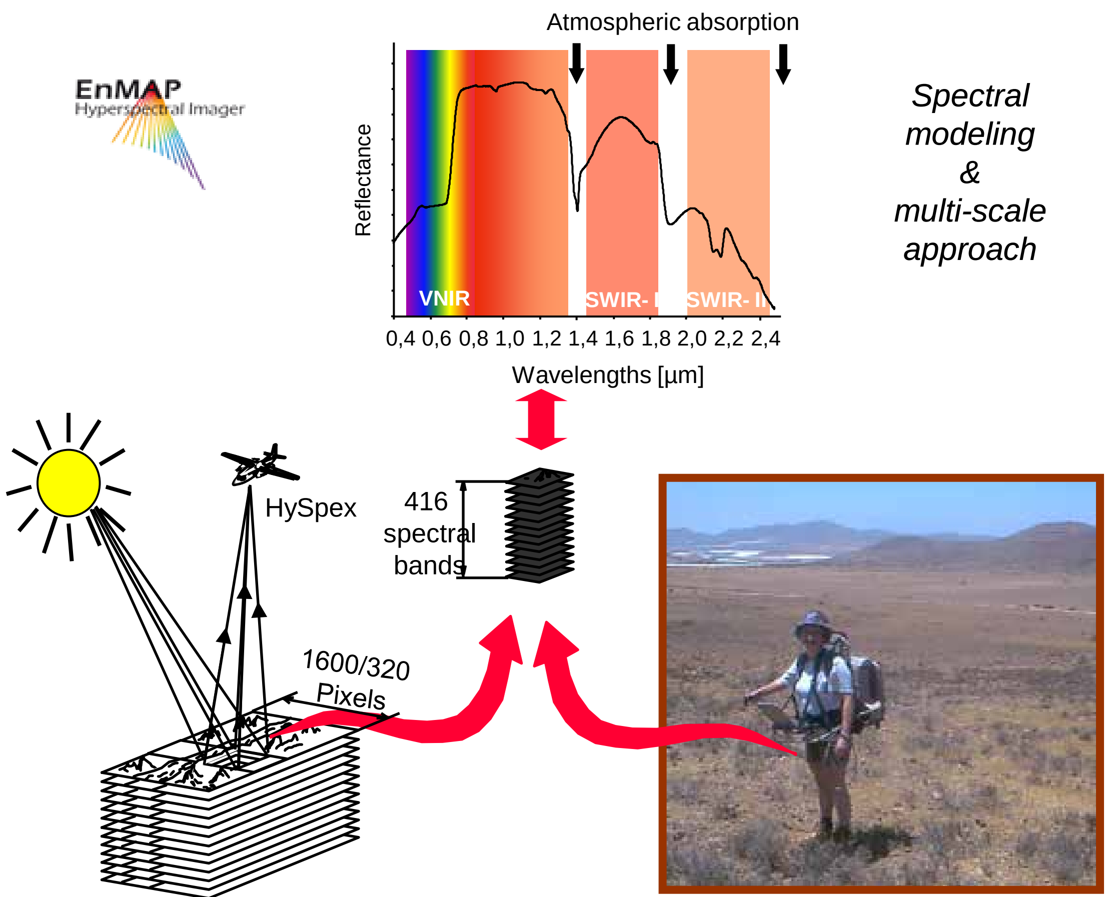
THE REMOTE SENSING AND G.I.S. LABORATORIES

POS – Penetrating Optical Sensor ltd.

Soil spectroscopy from the field to airborne platforms

Advanced optical-IR remote sensing methodology

Imaging spectroscopy or hyperspectral imagery



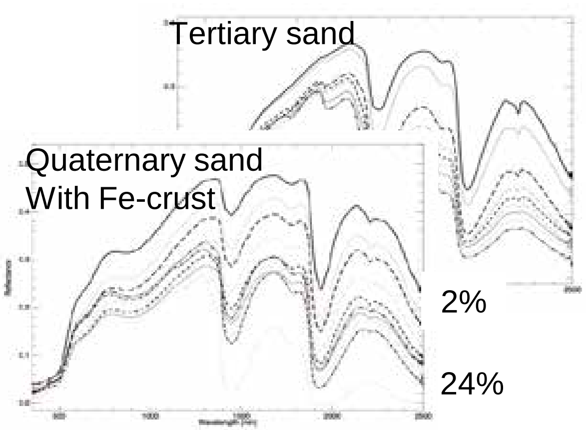
Research objectives:
Improved surface characterization and accurate retrieval of soil surface properties

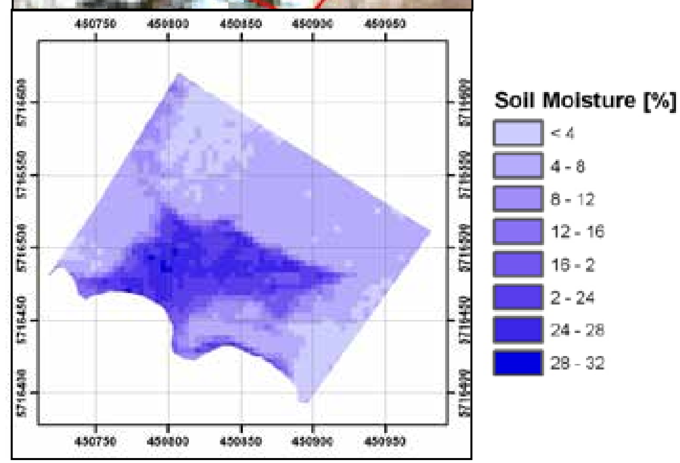
- Enhanced quantification of soil water content
- Enhanced quantification of soil variables and surface cover
- HYSOMA Toolbox for the derivation of soil maps
- Support for soil erosion modeling and monitoring

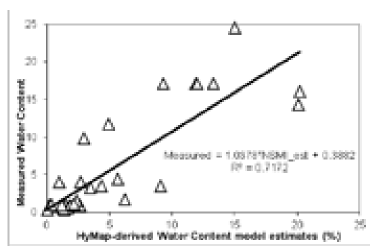
Soil water content

- Development of a new approach for surface soil moisture estimation: The **N**ormalised **S**oil **M**oisture **I**ndex (**NSMI**)

HyMap image and related surface soil water map







Prediction model of gravimetric water content

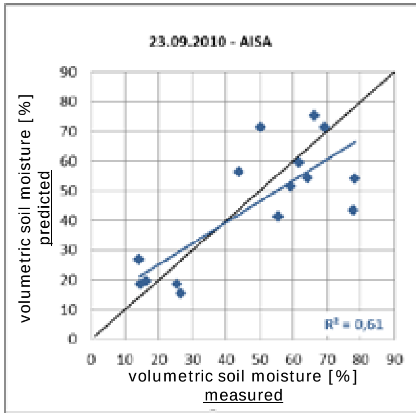
Haubrock et al., 2008, J.Applied Rem.Sen.

Soil water content

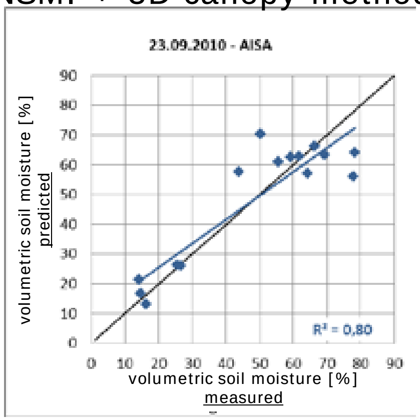
- Soil moisture quantification of vegetated areas in agriculture
- Enables determination of soil moisture up to vegetation cover of about 70%

Prediction model of surface soil moisture (Vol %) integrating artificial 3D canopy models

NSMI method



NSMI + 3D canopy method

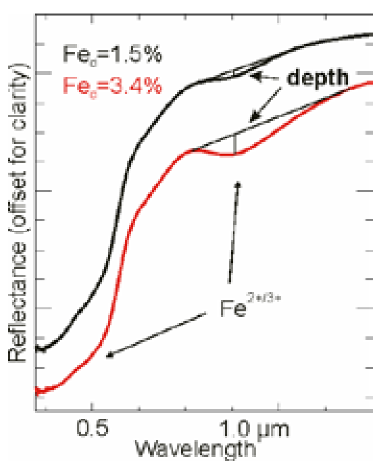


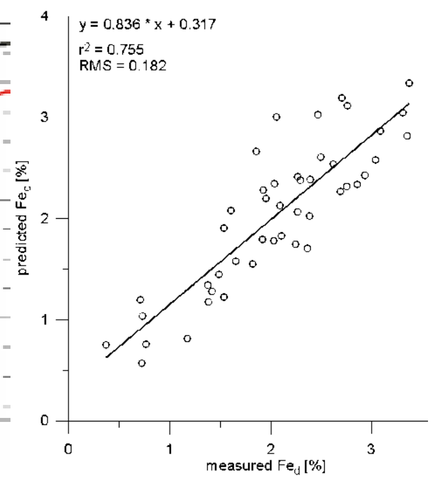
Spengler et al., 2013

Enhanced soil parameters determination

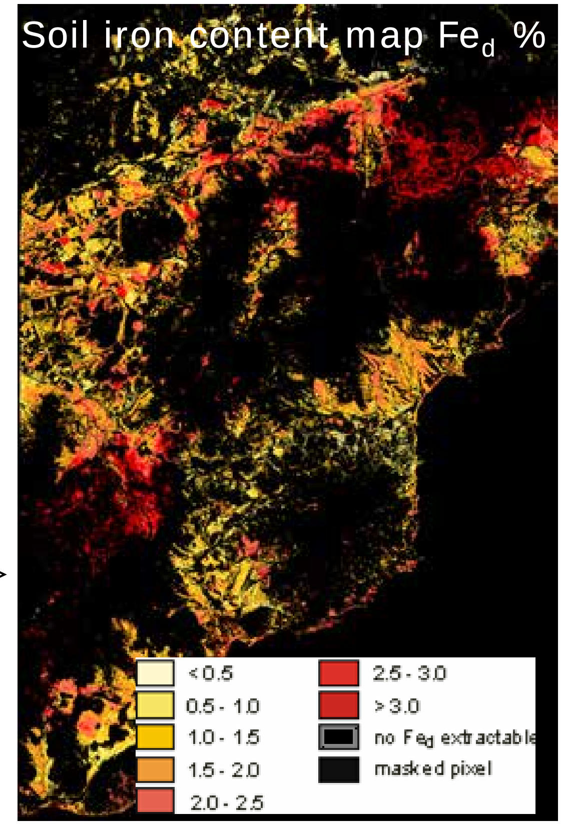
- Quantification of free iron surface content using spectral modeling techniques

- Support for identification of degraded areas





Prediction model of free iron oxide content



Richter et al., 2009, SSSAJ

HYSOMA toolbox for operational soil properties mapping

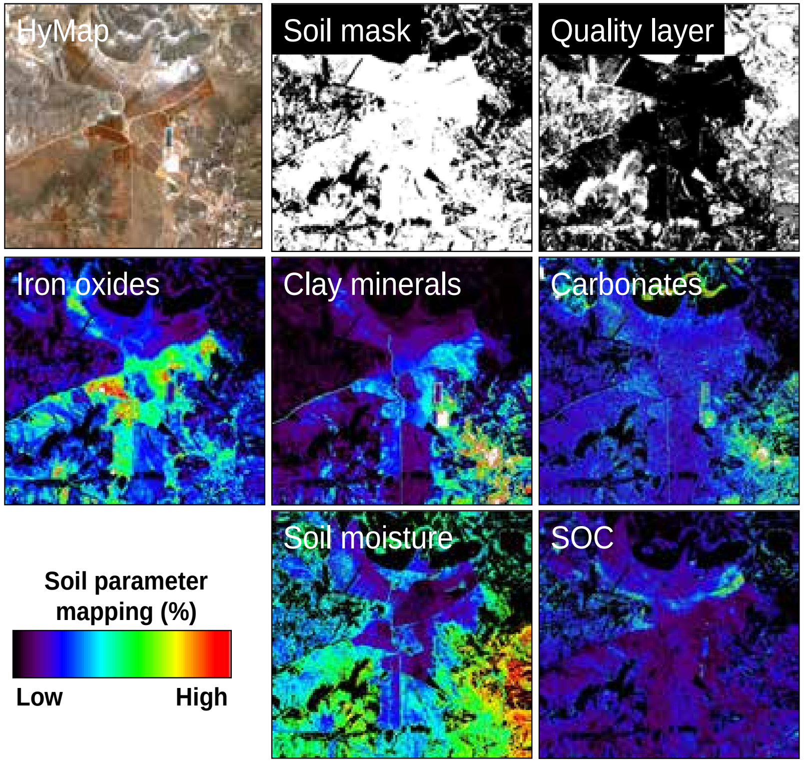
- Development of higher performing soil algorithms as demonstrators for end-to-end processing chains with harmonized quality measures

- **Automatic generation of semi-quantitative soil maps** (Soil moisture content, organic carbon, iron oxides, clays, carbonates content) + quality layer map

- **Fully quantitative soil mapping** based on field calibration

- Currently distributed for airborne users: www.gfz-potsdam.de/hysoma

- >100 users worldwide!



Chabrillat et al., 2012

Software download: www.gfz-potsdam.de/hysoma

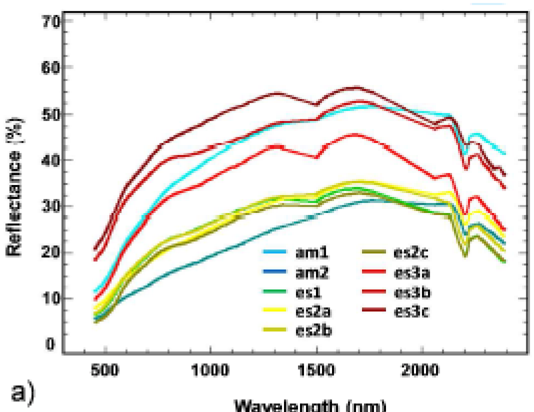
Soil erosional states mapping in agricultural semi-arid spain

- Characterisation of soil erosion indicators in a Mediterranean rainfed cultivated region (Camarena, Central Spain)

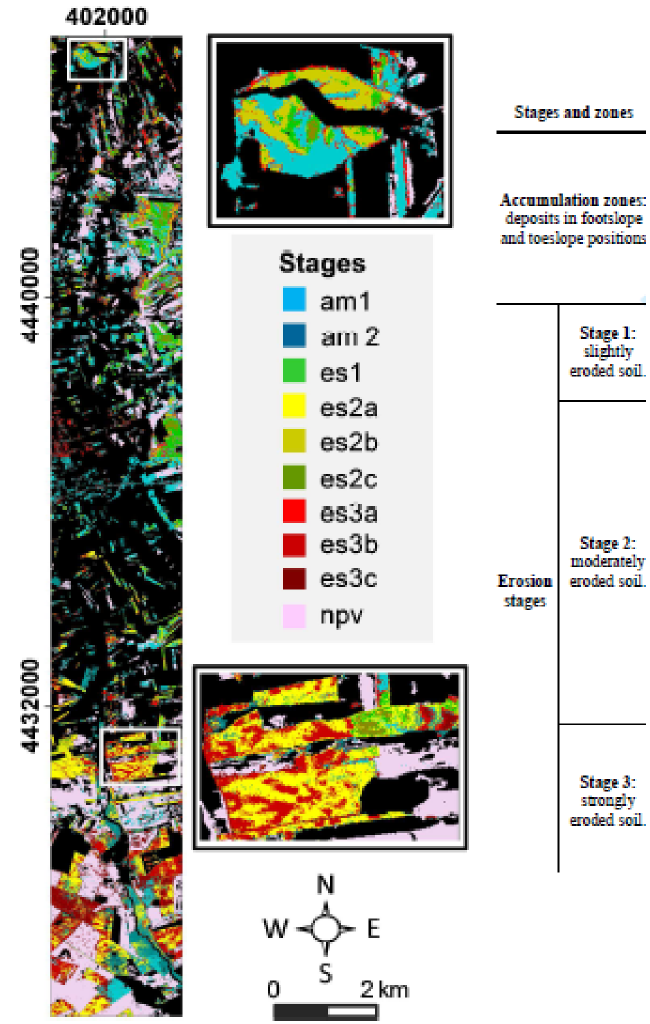
SU location: Carbonatic area

SU test site in fallow (08.Aug.11) and with wheat cultivation (23.Mar.12)

Mean field spectra of the different erosion and accumulation stages

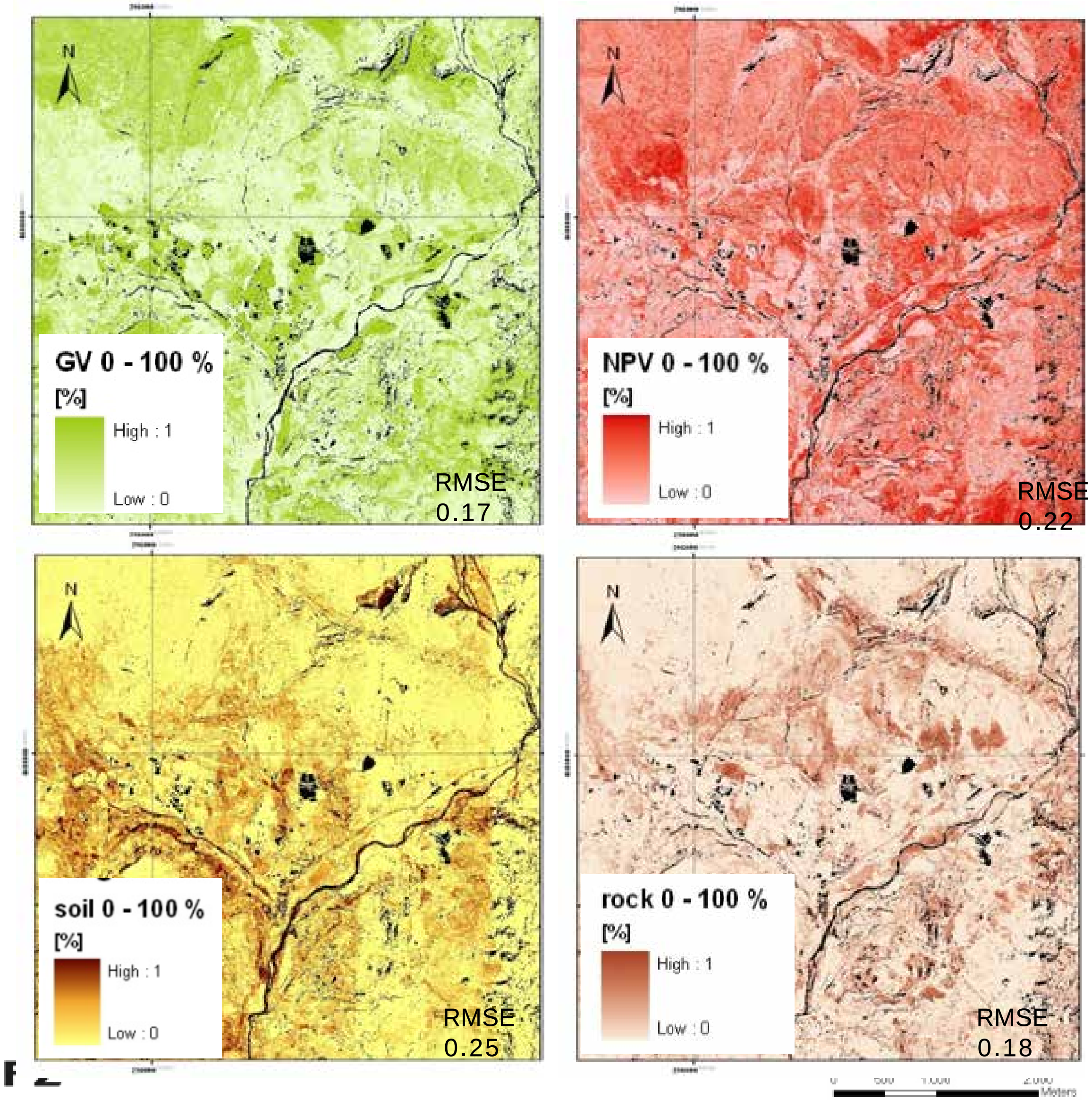


Distribution of soil erosion stages and accumulation zones using the SVM classifier, AISA Eagle/Hawk data @3m



Schmid et al., 2015, JSTARS

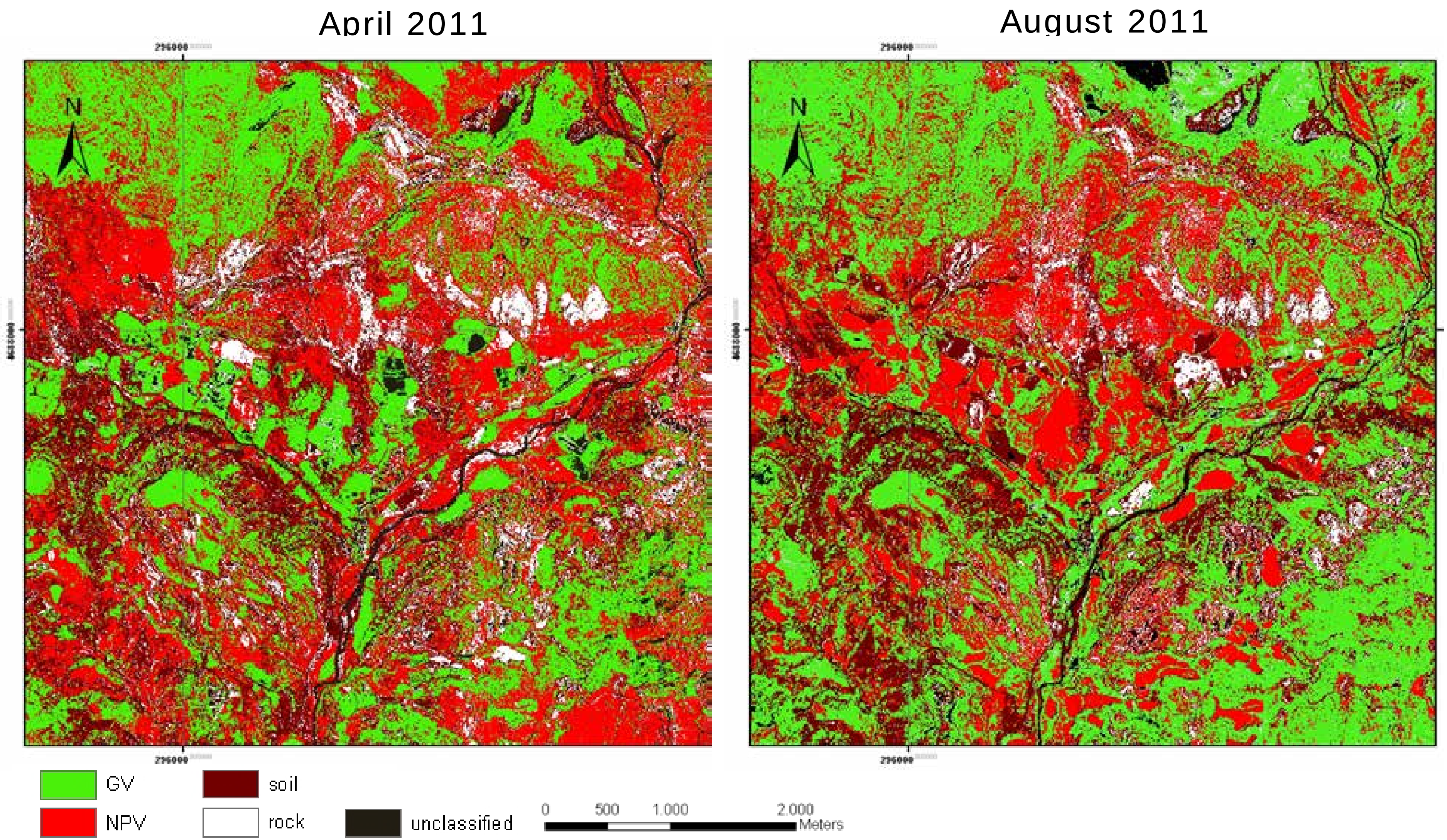
Enhanced derivation of fractional ground cover for hydrological model parameterization



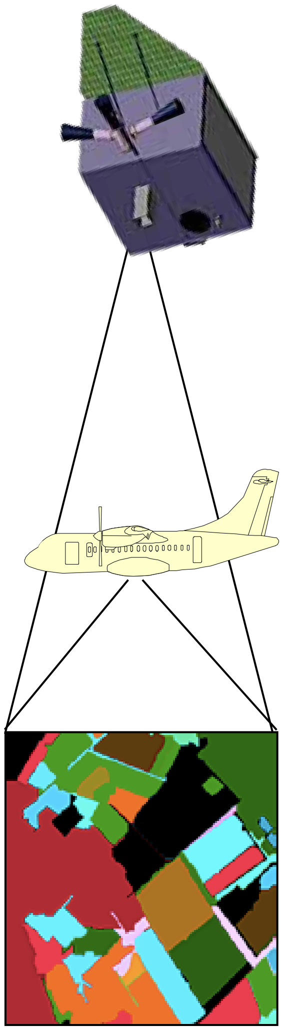
Airborne hyperspectral imagery (April 2011) Isabena catchment, northern Spain

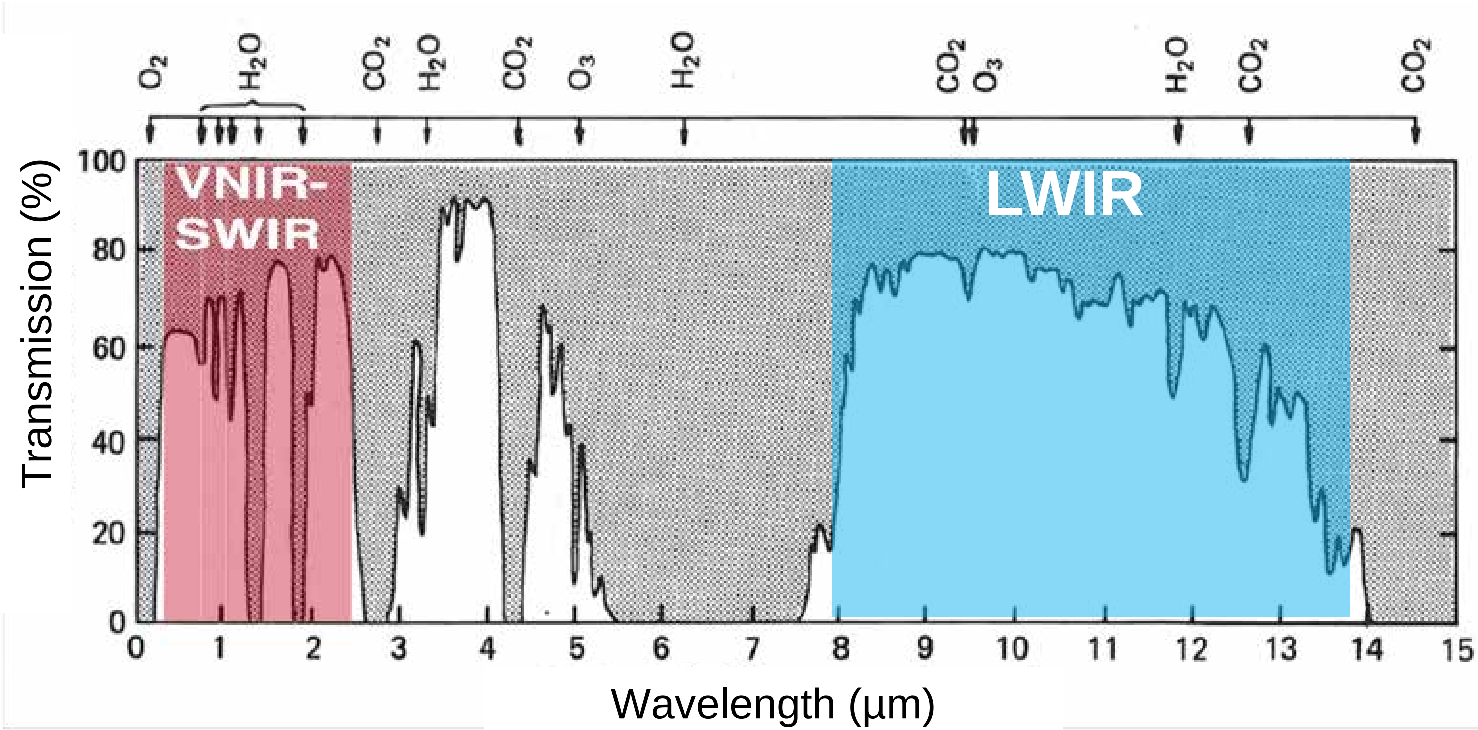
Foerster et al., 2013

Enhanced derivation of fractional ground cover for hydrological model parameterization



Thermal IR remote sensing: Potential for soil studies





Example: PLSR prediction models for common soil properties based on VNIR-SWIR and Thermal IR (TIR) spectroscopy

- Retrieval of soil erosion relevant parameters in the Western Australia Wheatbelt region

VNIR (0.4-1.0 µm, Electron Transitions)
iron oxides and hydroxides (hematite, goethite)

SWIR (1.0-2.5 µm: Vibration Transitions - overtones and combinations)
- OH bearing silicates (kaolinite, smectite)
- Chlorites, Calcite, etc..

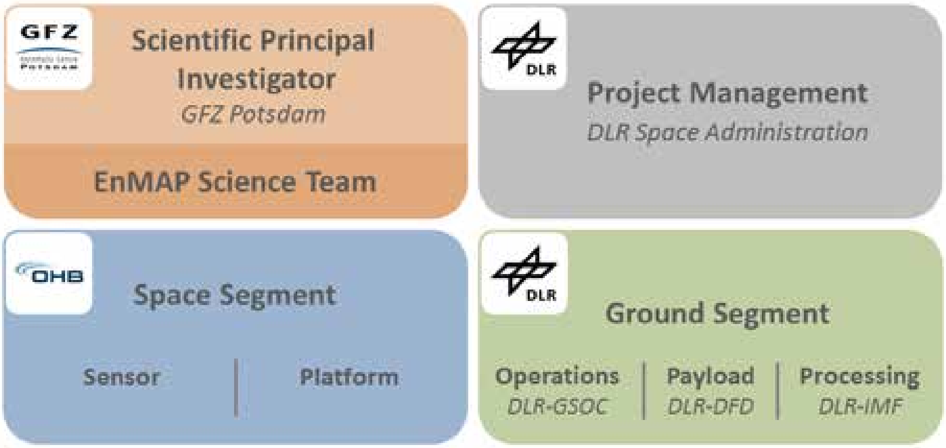
TIR (*3-5* and 7-12 µm: Fundamental Vibrations of Si-O bonds)
- non-OH-bearing silicates (e.g.: Qz, feldspars, garnets, pyroxenes and olivine)
- distinguish silica, quartz, mafic, carbonate mineral groups

Y	Spectral range	n	f	PLSR prediction models		
				R^2_{adj}	RMSEP	expl. Y var.
% clay	VNIR-SWIR	88	5	0.87	3.98	86.68 %
	TIR	88	4	0.87	3.23	87.29 %
	VNIR-SWIR-TIR	87	5	0.91	2.89	90.67 %
% sand	VNIR-SWIR	87	5	0.84	4.85	83.95 %
	TIR	88	3	0.947	3.5	94.72 %
	VNIR-SWIR-TIR	87	5	0.94	3.1	93.57 %
% OC	VNIR-SWIR	84	6	0.79	0.13	78.67 %
	TIR	83	7	0.75	0.14	75.41 %
	VNIR-SWIR-TIR	83	5	0.85	0.1	84.55 %

Eisele et al., 2013, 2015

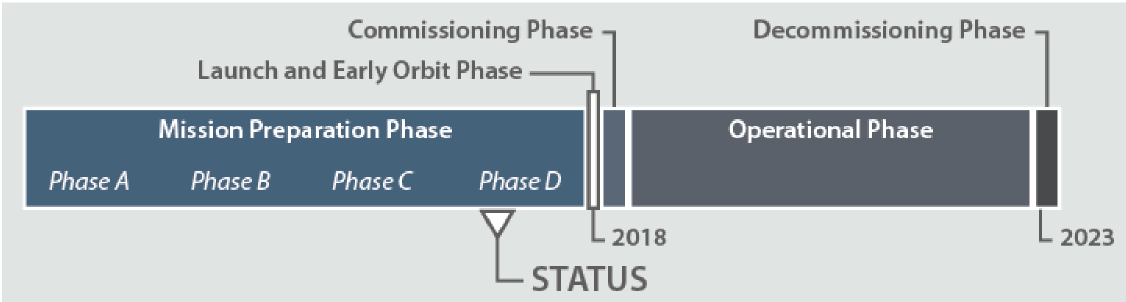
Hyperspectral imagery and soil science studies

- Main field of applications
  - Soil mapping and classification
  - Soil genesis and formation
  - Soil water content
  - Soil degradation (salinity, erosion, deposition), soil contamination
- Global increasing interest
  - Soil protection (EU directive 2006 21/EC)
  - Evaluation and monitoring of soil quality and quantity
  - Soil function (e.g. water storage, carbon storage) and threats (e.g. acidification, soil erosion)
  - Demand for digital soil mapping (www.globalsoilmap.net)
- Optical RS benefits: upper surface sensing (<50 mm), can map SM & a wide range of soil properties



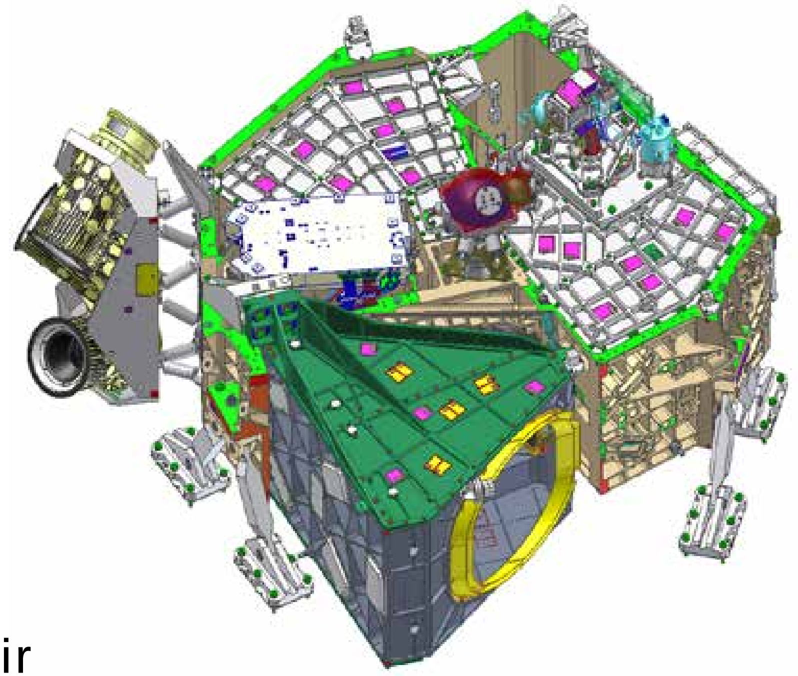
- Environmental Mapping and Analysis Programme (GFZ/DLR)
- Full range VNIR/SWIR satellite imaging spectrometer for quantitative surface parameter retrieval at 30m scale
- Frequent coverage for monitoring on global basis
- Open data policy

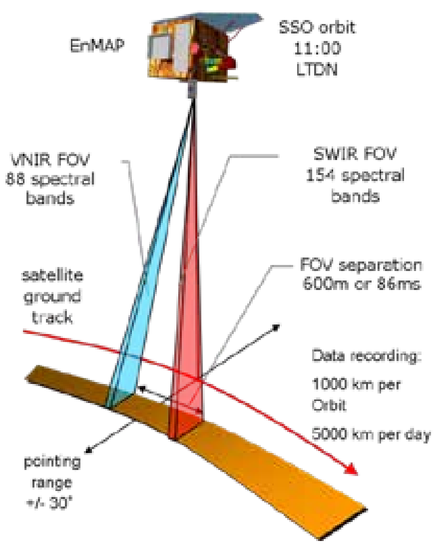
- Core funding from Germany's Federal Ministry Economics and Technology
- Currently under construction phase, launch ~mid 2018
- GFZ – soil/geology applications



EnMAP mission and instrument overview

- Push-broom imager
- Spectral range from 420 nm to 2450 nm (**VNIR-SWIR**)
- **high spectral resolution** of 6.5 nm (VNIR) and 10 nm (SWIR); ~ 240 bands
- **high SNR** of 500 @ 495 nm; 180 @ 2200 nm





- Swath width **30 km**
- Pixel size **30 m** at nadir
- Repeat cycle of **27 days**
- ± 30° off-nadir pointing for frequent revisit (≤**4 days**)
- **5000 km** total swath length acquisition per day
- Mission Life Time of **5 years**
- Currently in construction phase, launch **~mid-2018**

Current research: Potential from spaceborne platforms

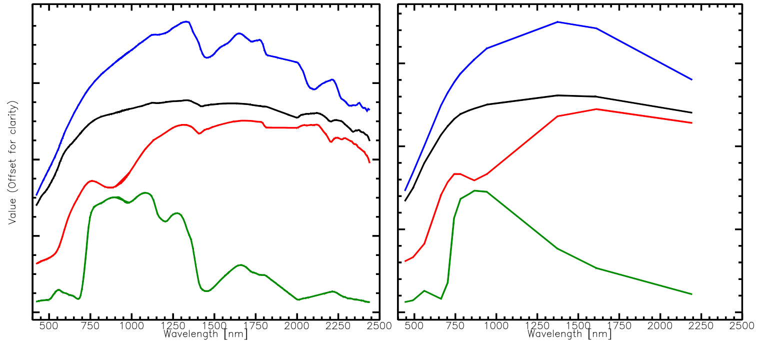
v **Upcoming high-quality imaging spectroscopy data expected from next generation orbiting sensors to be launched soon,** e.g. EnMap (2018), HISUI (2018), Shalom (2020), HyPXIM (>2023), HypSRI (>2023)

v **From local à regional à global scale**

- § Support to soil related EU policy areas and different stakeholders
- § Global soil mapping and monitoring

v **Demonstration of potential of hyperspectral imagery for soil mapping applications from airborne to satellite scale**

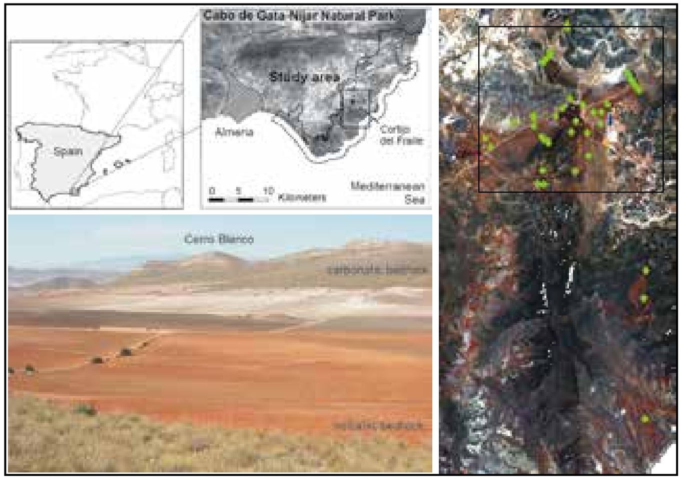
- § Simulation of satellite images based on existing datasets
- § Algorithm development
- § Feasibility and expected accuracy for delivery of soil products



EnMAP simulation S-2 simulation

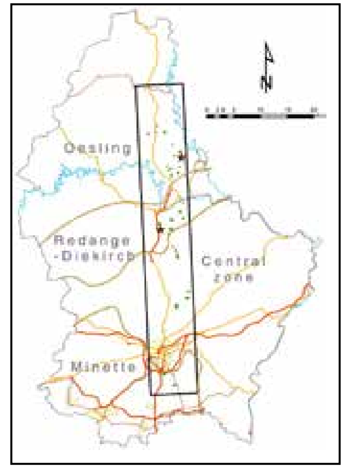
Case study : Soil properties mapping in bare crops

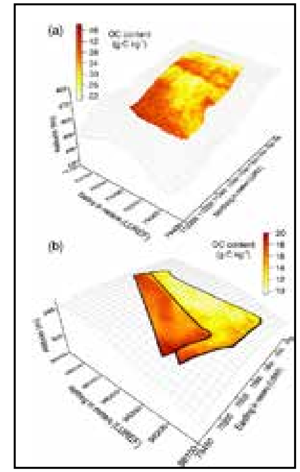
Semi-arid Mediterranean Spain



- Parameters of interest: Mineralogy (Clay, iron oxide, $CaCO_3$ content)
- In-situ validation dataset: 50 samples
- Airborne HyMap imagery: 126 sp. bands ~400-2450nm, SSD 12-17 nm. GSD 4.5m

Luxembourg



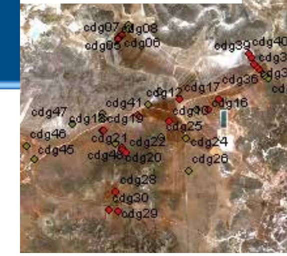


- Parameter of interest: Soil organic carbon (SOC) content
- In-situ validation dataset: 81 samples
- Airborne AHS-160 imagery: 20 sp. bands ~442-1019nm, SSD 27-30 nm. GSD 2.6m

⇨ **EnMAP end-to-end scenes simulation** of (i) EnMAP-like TOA radiance images and (ii) L2 surface reflectance after pre-processing (Segl et al., 2012): 244 sp. bands ~450-2450 nm, SSD 6.5-10nm. GSD 30m

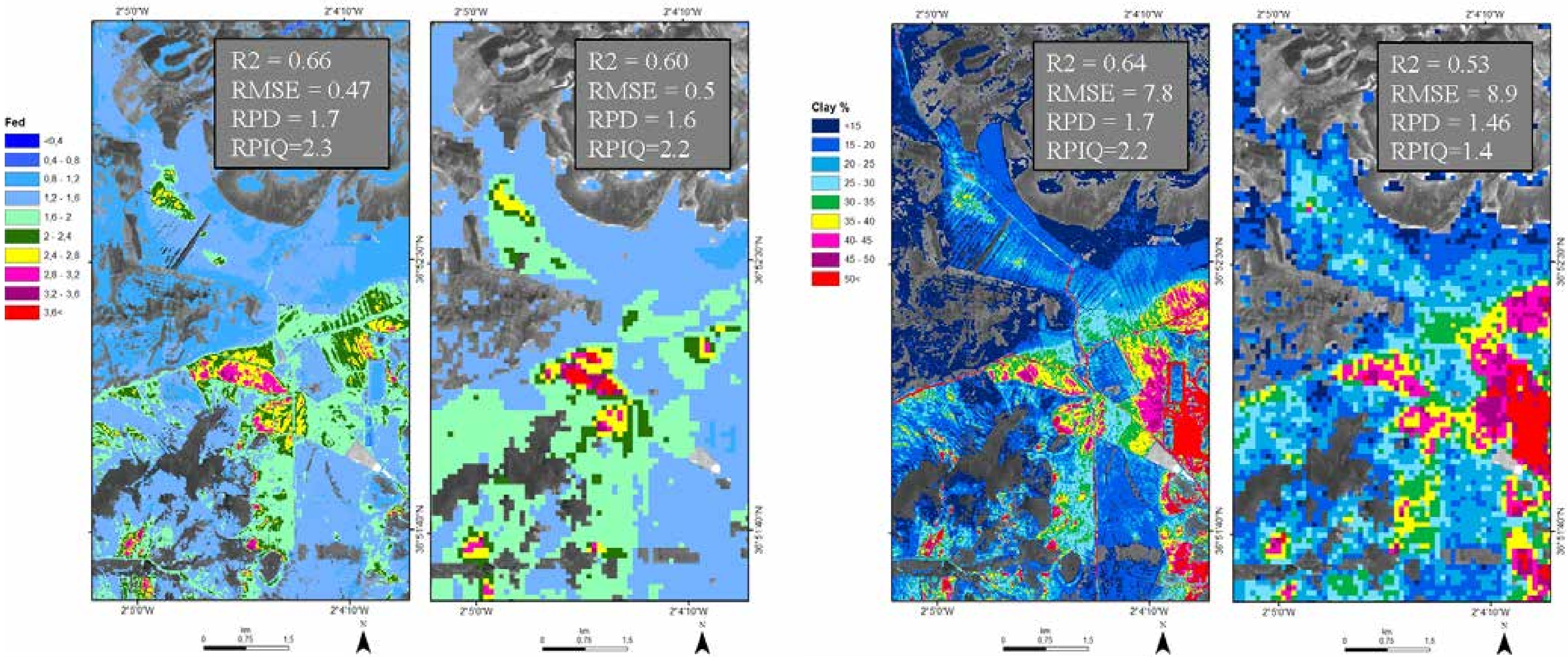
Spaceborne soil mineralogical mapping

Ground-truth



Retrieval of soil mineralogical content (AutoPLSR): Soil maps and prediction model performances vs. Ground-truth data

Airborne HyMap (4m) | Simulated EnMap (30m) | Airborne HyMap (4m) | Simulated EnMap (30m)



Steinberg et al., 2015, Rem. Sens.

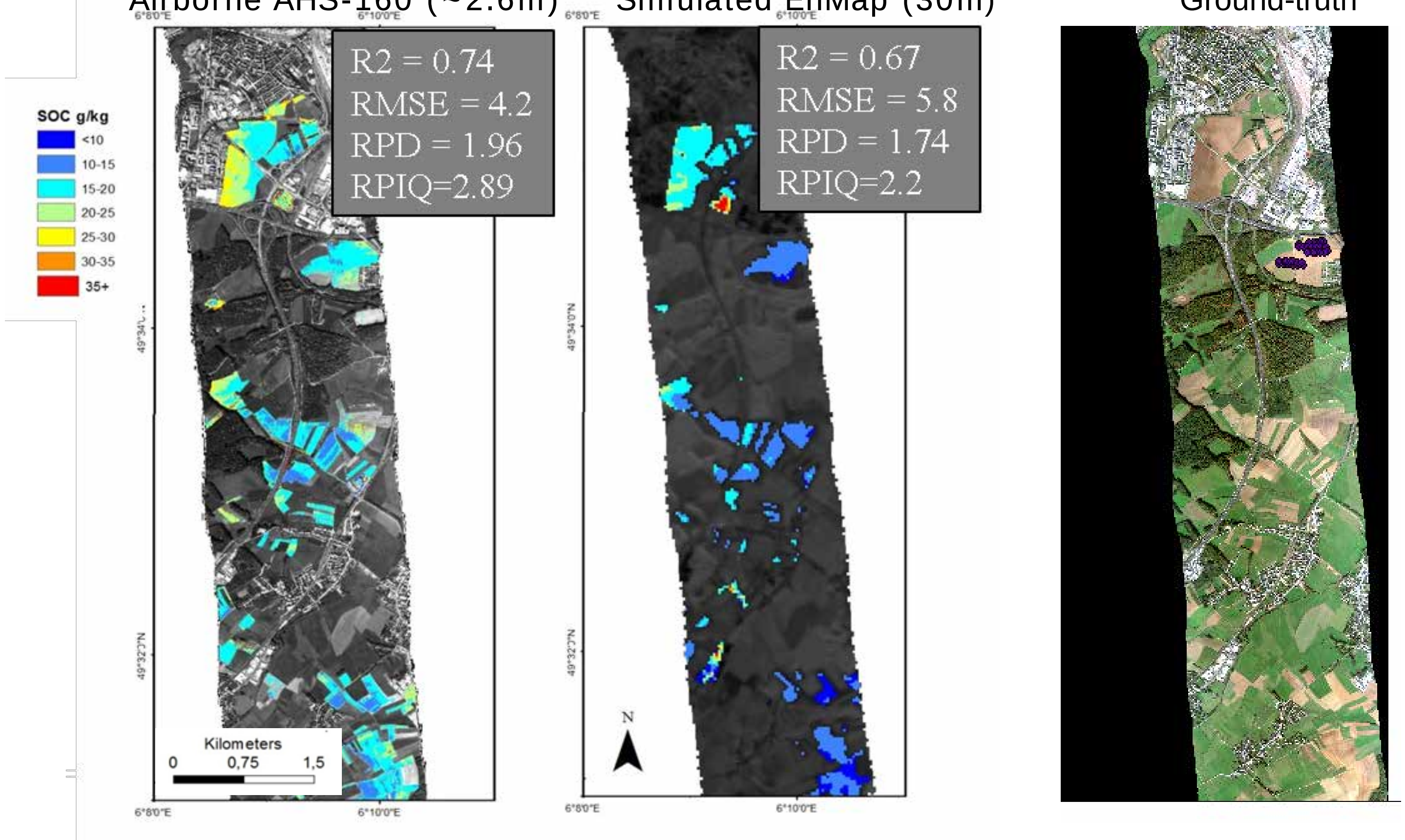
GFZ Helmholtz Centre Potsdam

HELMHOLTZ ASSOCIATION

Spaceborne soil organic carbon mapping

Retrieval of soil OC content (AutoPLSR): Soil maps and prediction model performances vs. Ground-truth data

Airborne AHS-160 (~2.6m) Simulated EnMap (30m) Ground-truth



Overall agreement from airborne to spaceborne

Slighly reduced prediction accuracy at spaceborne level

Digital soil mapping from space: Opportunities and challenges

- Optical surface soil prediction models: Good accuracy depending on soil parameter, observational and environmental conditions

- Validation with field data

- But: Is this enough?
  - User requirements are very variable !

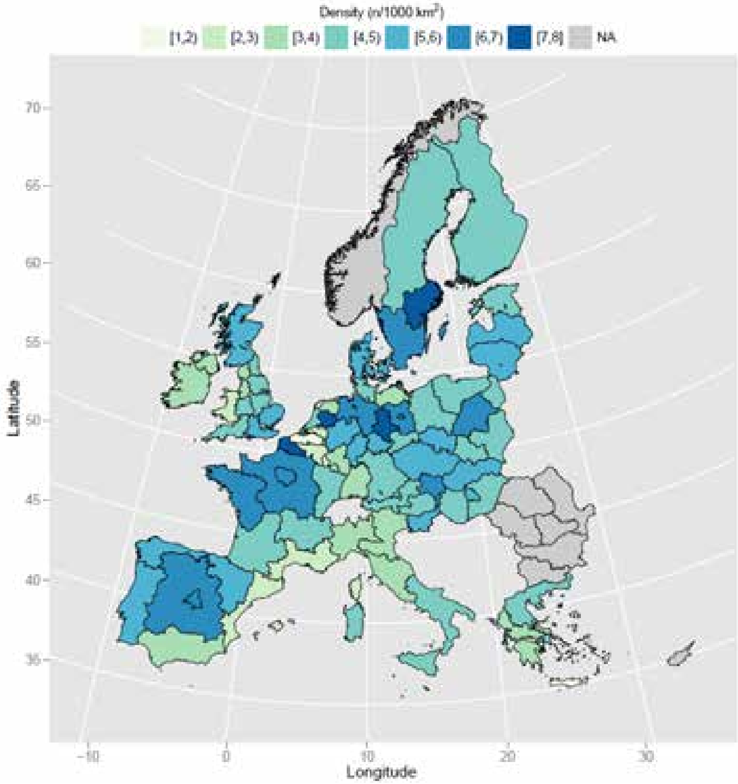
    → Global soil maps vs. quantitative requirements (JRC 3% OC g/kg)

  - Models are dependent on local observations

    → Need of large soil spectral database for model stability

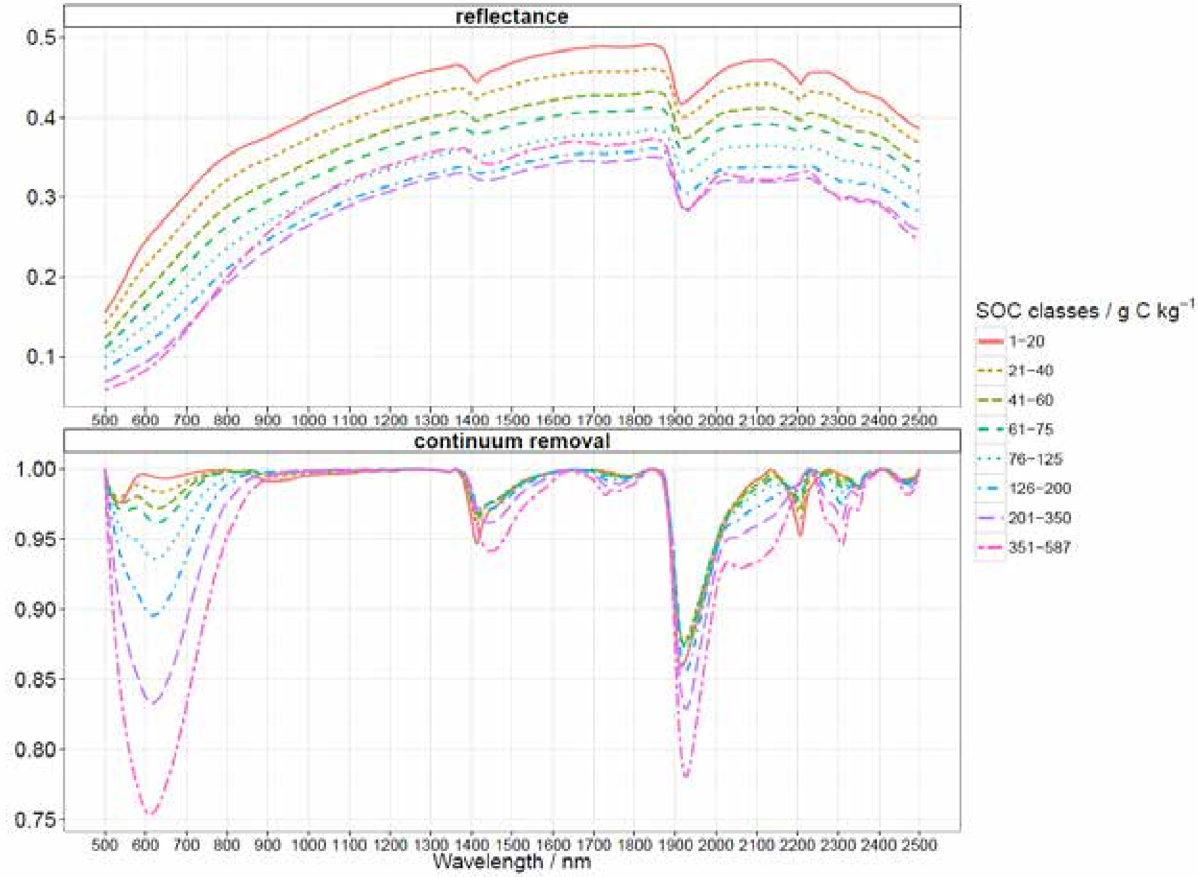
  - Models are influenced by state of surface (Soil moisture is a problem!)

Perspectives: The LUCAS spectral library



Current status:

- § 23 European countries
- § ~20,000 high quality spectral readings
- § Metadata: Clay, silt, sand, OC, pH, CEC, $CaCO_3$, Geographical coordinates, land use, etc



Perspectives: Demmin - TERENO Northeastern German Lowland Observatory database

Objectives

- calibration and validation of national / international remote sensing missions
- supplying environmental data for developing of new algorithms in remote sensing and environmental modelling
- practical test for the integration of remote sensing data in agricultural practice

Demmin - permanent data infrastructure

Data infrastructure

Agrarian meteorological network:
40 weather stations (GFZ: 20, DLR: 20)

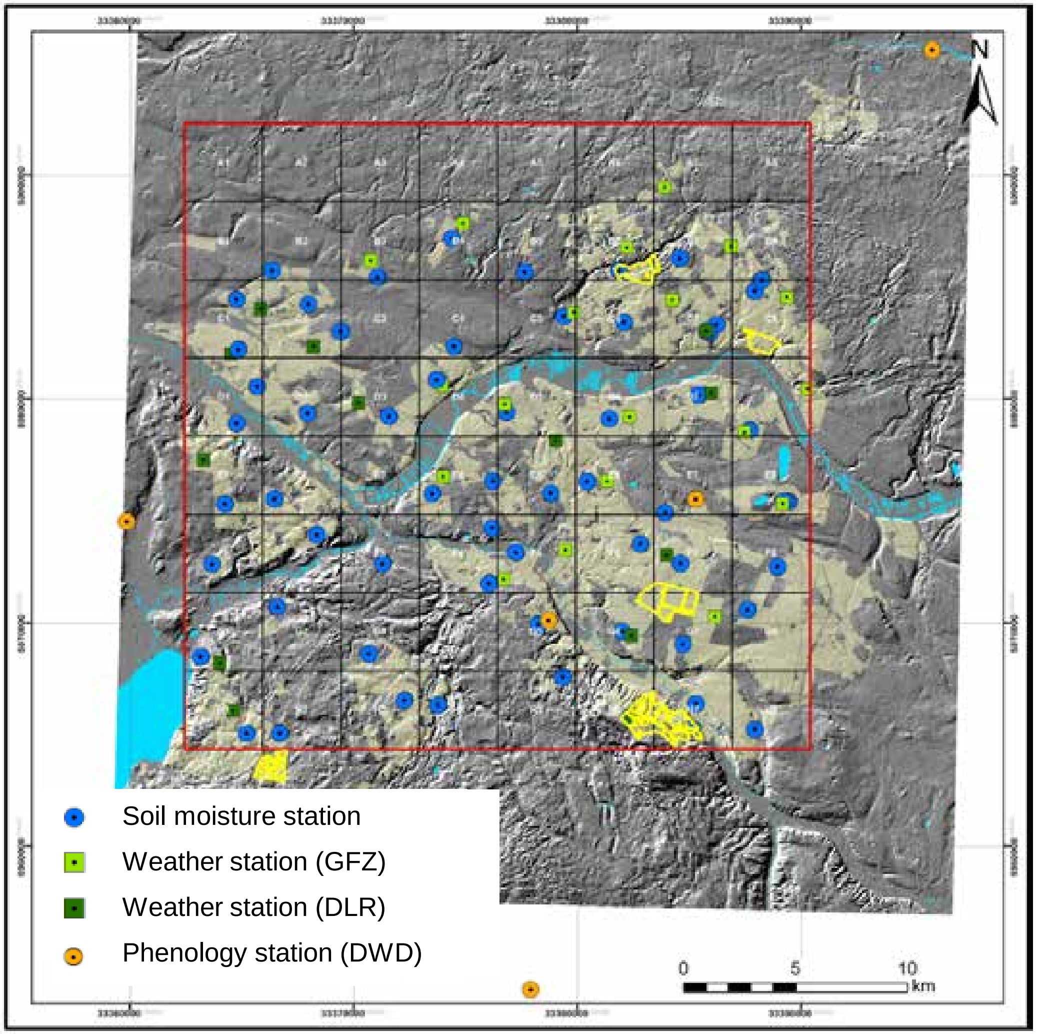
Soil moisture measuring network:
62 gaging stations

Soil documentation & soil analysis at each soil moisture station:
~110 soil profiles , ~1 m depth;
Parameter: texture, pH, CaCO3, OM

Crop data from association of local agricultural companies (IG Demmin), Yield Mapping

Phenology data:
5 observation stations (German Meteorological Service)

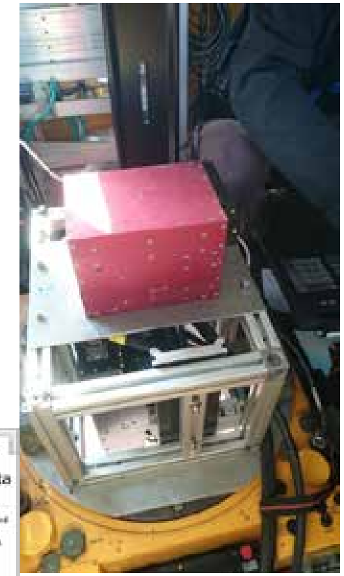
Demmin soil spectral library & soil analyses: ~850 soil samples, chemically and spectral analysed



Demmin – Field and flight experiments

Multiscale observations

Multitemporal airborne acquisitions (2015)



GFZ HySpex VNIR/SWIR installed in aircraft of FU Berlin

EnMAP-flight campaigns

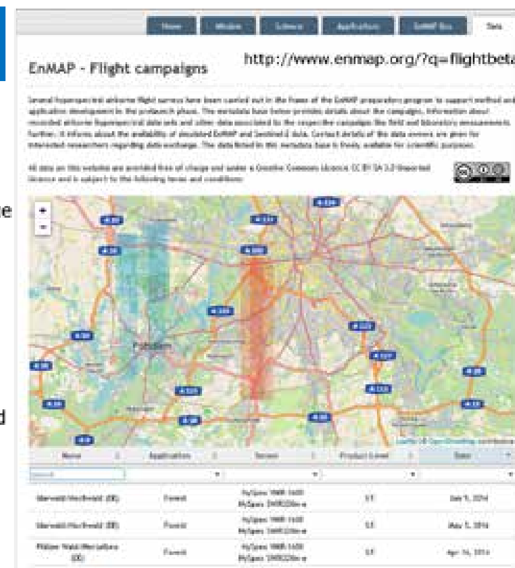
Airborne hyperspectral images and associated in-situ data

provided free of charge to science community under CC BY-SA Licence

Search **metadata portal** at www.enmap.org → data

Datasets published as **data publications** (with DOI)

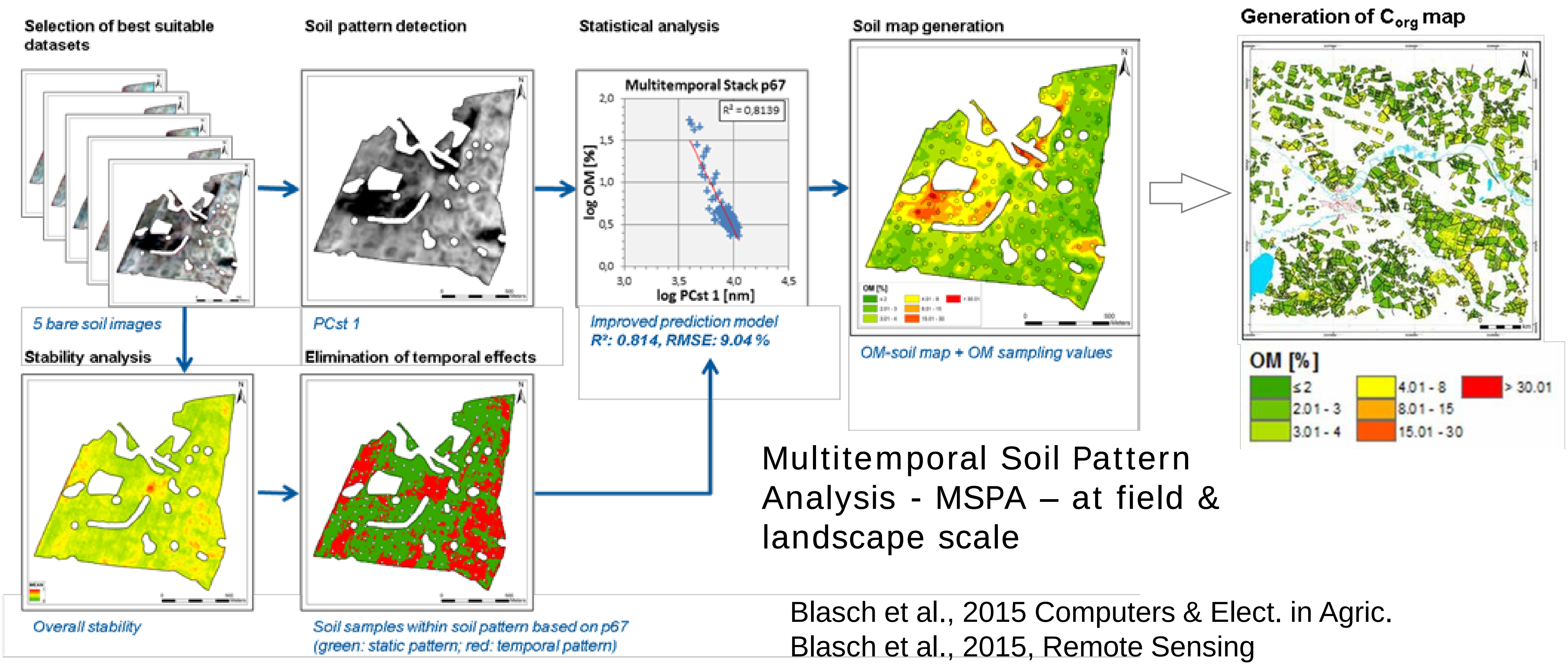
Technical Report will be provided with each dataset (documentation of data acquisition, processing, quality etc.)



Demmin – Soil patterns

Demmin - Soil pattern analysis for the determination of organic matter based on multispectral data at field and landscape scale

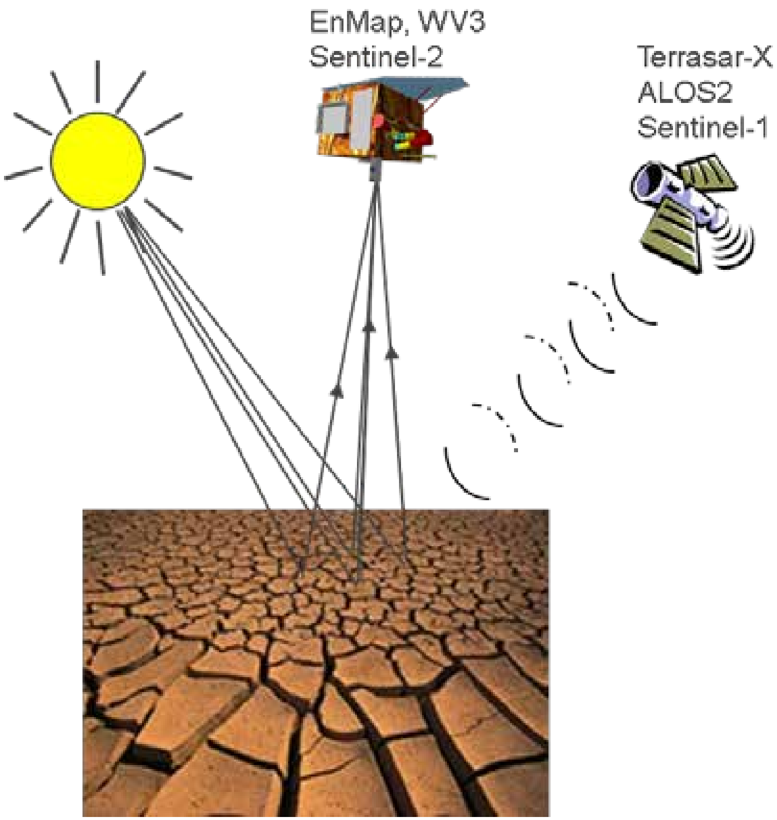
Result: OM determination at the field-scale using local prediction model



Multitemporal Soil Pattern Analysis - MSPA – at field & landscape scale

Blasch et al., 2015 Computers & Elect. in Agric.
Blasch et al., 2015, Remote Sensing

Outlook: Global soil mapping and monitoring



- Future developments
  - Spectral model improvements
    - Link with soil database (Demmin, EU LUCAS)
    - Simulation/correction of disturbing factors (vegetation, soil moisture, illumination)
  - Use of combined optical and radar RS for additional soil information
  - Potential of thermal IR remote sensing for soil studies
  - Use of multitemporal information combined with hyperspectral