Advanced Earth Science Products using APEX

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2012 HyspIRI Science Workshop
NASA Decadal Survey Mission
Short update on APEX
Product suite

– Level 1
  – Constraint priors directional effects correction
  – Large scale simulation (ESA Sentinel-2)

– Level 2 (≈ HyspIRI Level 4)
  – Mapping biospheric variables from radiance data using Bayesian optimization and coupled models
  – GPP estimates based on $F_{s\text{yield}}$ retrieval
  – Improved LUE estimates using pigments
  – Scale invariant retrieval of vegetation properties

– Level 3
  – Alpine ecosystem services (agronomic, cultural, pollination, soil C)
  – Using $\text{NO}_2$ vertical column density for policy validation

– Outlook
APEX – Airborne Prism Experiment
Short update on APEX

Successful and increasing data acquisition in Europe since 2009

Image data from 2011 (142 flight lines), and 2012 (116 flight lines) online
(quicklooks on apex-esa.org)

Improvements in calibration, APEX (physically based) model, data processing, and archiving

Prospects for 2013ff are doubling to tripling data acquisition in Europe (and beyond)

APEX is outperforming much of the models and technologies currently available: next generation models and hardware are urgently needed (e.g., APEX can calibrate its Calibration Home Base, ASD FieldSpecs do not have sufficient spectral resolution for vicarious calibration, certain absorption features seen by APEX are not yet represented in models, etc.)!
Level 1: Constraint priors directional effects correction

Idea

– Minimize impact of directional effects on airborne imaging spectrometer data
– Normalize airborne acquisition observation/sun-angle geometries to nadir (later: predefined) geometries (‘aNBAR’) 
– Minimize directional effects using image based information (‘BRDF-correction’)

Methods

– Select scattering \( (BRDF_{iso, vol, geo}) \) abundance classes from image data and correct image data using these classes as prior information to a kernel driven approach

Results


Outlook

– Implement operational approach, base prior estimates on RPV model inversion
Vegetation product differences on directional effects

Across-track gradient for bright green vegetation

Chl a/b

CDM

Weyermann et al. (2012), in review
Level 1: Large scale simulation (ESA Sentinel-2)

Idea
- Simulate a ‘full’ ESA GMES Sentinel-2 tile

Methods
- Next slide

Results
- Sentinel-2 scene, with almost realistic sun/observation angles (Laurent, et al. (2012). RSE, submitted)

Outlook
- Generating real data format (JPEG2000, NEdL ≈ compression noise & level)
- Normalization of geometrical-optical scattering
- Multitemporal simulation
Sentinel-2 simulation: methods

- **Anisotropy correction** (aNBAR) by Weyermann et al., 2012
- **Spectral convolution** (334 to 13 bands) by D’Odorico et al., 2012
- **Geocoding (PARGE)** (7 flight lines) by Schläpfer et al., 2002
- **At-sensor to Top-of-atmosphere modelling** by Guanter et al., 2009
- **Mosaicking** (7 lines to 1 image)
- **Spatial resampling** (2m to 10m)
- **Band-by-band spatial resampling** (10, 20, 60m)
- **Ground validation** (Vicarious calibration, MODTRAN)

**Sentinel-2 scene**
- (June 26, 2011)
- 1’608 x 2’238 pix @ 10m
- 13 spectral bands
- 10/20/60m spatial resolution

**APEX flight lines**
- (June 26, 2011)
- 7 APEX flight lines
- 334 spectral bands
- 2 m spatial resolution
- 7 x (1’000 x 24’000 pix)
- 5000 m fl. altitude
- >3 APEX bands for each Sentinel-2 band
Department of Geography

Sentinel-2 simulation

B1 443nm 20nm 60m
B2 490nm 65nm 10m
B3 560nm 35nm 10m
B4 665nm 30nm 10m
B5 705nm 15nm 20m
B6 740nm 15nm 20m
B7 775nm 20nm 20m
B8 842nm 115nm 10m
B8a 865nm 20nm 20m
B9 940nm 20nm 60m
B10 1375nm 20nm 60m
B11 1610nm 90nm 20m
B12 2190nm 180nm 20m

RGB B4 B3 B2
RGB B12 B11 B8
RGB B11 1610nm 90nm 20m
RGB B8 B4 B3
RGB B10 B9 B1
Level 2: Mapping biospheric variables from radiance data using Bayesian optimization and coupled models

Idea
– Use coupled models to retrieve as many free vegetation parameters from radiance data as possible

Methods
– Next slide

Results

Outlook
– Ground truthing within spatial neighborhood
– Cost of *a priori* knowledge to be determined
– Estimates of probability distribution functions to be used as priors
– Estimate effects of biased and informative priors
‘Conventional’ inversion (LUT approach from refl. data)

- Chlorophyll: 10 - 80 [µg cm\(^{-2}\)]
- Water: 0.01 - 0.03 [g cm\(^{-2}\)]
- Dry Mater: 0.001 - 0.01 [g cm\(^{-2}\)]
- Leaf Area Index: 0 – 7 [m\(^2\) m\(^{-2}\)]
**Methods**

**Model coupling**
- SLC: PROSPECT & 4SAIL2 with canopy clumping
- MODTRAN 4: between ground level and APEX flight height

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**A priori data** for each crop type
- Bayesian optimization of 6–7 variables for each field

**Spatial constraint** at field level
- Field-specific LUT inversion for LAI and Cab

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\[
\chi^2 = \frac{1}{2} (L_o - L)^T C_o^{-1} (L_o - L) + \frac{1}{2} (v_a - v)^T C_a^{-1} (v_a - v)
\]

- Radiometric cost
- A priori cost
Variation of costs, variables, and damping factor

![Graph showing variation of costs, variables, and damping factor](graph.png)
Map of crop type, estimated LAI and Cab for the fields in the study area.
Bayesian optimization for agricultural fields

High model costs
Results: Field-specific LUT inversion of LAI and Cab

Laurent et al., (2012), RSE, in review
Level 2: GPP estimates based on $F_{s_{\text{yield}}}$ retrieval

Idea

– Improve GPP estimates ($\text{PAR} \times f_{\text{APAR}} \times \text{LUE}$) using $F_{s_{\text{yield}}}$ (in place of $\text{LUE}_{\text{land_cover=const}}$)

Methods

– Next slide

Results

– Large scale mapping of GPP using $F_{s_{\text{yield}}}$

Outlook

– Further refine method by including pigments
**APEX products – fluorescence**

Approach (adapted from Guanter 2010 JGR):

- MODTRAN5 to simulate LUT’s of \(L_{\text{Path}}, E, T, S\)
- 3FLD method to relate \(R\) in- / outside of the band
- Use of reference targets (bare soil) to constrain FS retrieval

\[
\begin{align*}
L_i &= L_i^p + \frac{(E_i^0 \cdot \frac{R_i}{\pi} + F S_i) \cdot T_i}{1 - S_i \cdot R_i} \\
L_o &= L_o^p + \frac{(E_o^0 \cdot \frac{R_o}{\pi} + F S_o) \cdot T_o}{1 - S_o \cdot R_o}
\end{align*}
\]

GPPv = F_{yield} \times APAR

GPPc = LUE_{const} \times APAR

Difference GPPv, GPPc
APEX fluorescence mosaic
Laegeren test site

Fluorescence
0.0 – 0.15 [W m\(^{-2}\) sr\(^{-1}\) nm\(^{-1}\)]
Level 2: Improved LUE estimates using pigments

Idea
– Improve GPP estimates (PAR x fAPAR x LUE) using pigments

Methods
– Improving LUE by using PRI in combination with pigments

Results
– Work in progress

Outlook
– Diurnal and phenological cycles measurements of pigments and pigment pool shifts
– Use light acclimation of leaf traits with time kinetics (long: LMA & N; medium: Chl a/b, Car/Chl; short: fluorescence ($F_v/F_m$)) (cf Hallik et al. (2012), Plant Biology)
Pigment retrieval (modified after Gitelson)
Towards improved pigment estimates

- False color pigment composition
- Chlorophyll/Carotenoid relation
- Fractions of Chl/Car, Chl/Ant, Car/Ant
Level 2: Scale invariant retrieval of vegetation properties

Idea
– Use ecological concepts of catastrophic shifts, criticality, and scale invariance in combination with physical models in remote sensing

Methods
– Next slide

Results
– Retrieval of vegetation parameters in all relevant dimensions (spectral, spatial, temporal, directional) at their typical length scale.
– First results are very promising! Validation requires spatially extended ground truth

Outlook
– High dimensional data only available with HyspIRI, EnMap, etc.!
– Coupling of physical approaches (ecology and Earth observation)
Combining concepts of Earth observation with ecology

Catastrophic shifts
- Sudden and drastic change in the state of the system in space or time

Criticality
- State of the system is critical, if poised at a phase transition

Scale invariance
- Distribution characterized by a power law is said to be scale invariant

Scheffer et al., Nature, 2001; Rietkerk et al., Science, 2004; Pascual et al., Trends in EE, 2005
Dimensionality of remote observations

Optical remote observations are dependent on spatial, spectral, temporal, angular, and polarization sampling approaches.

Often, methods are implemented functioning at scale independence in a certain range of the dimensions observed (spectral invariants (Knyazikhin et al., 2010), BRDF kernels (GlobAlbedo, Lewis et al., 2012), etc.)

If processes are observed at inappropriate scales, scale mismatches will occur and may lead to feedback omissions.

Assessing new feedback mechanisms substantially increases our understanding of the functioning of the system Earth (shrub shading (Blok et al., 2012); increased light absorption (Pinty et al. 2012)).
Field 16 Grass
Effects of scale: regionalization

Much change is driven by feedback mechanisms that take place at spatial and temporal scales that are smaller than those currently incorporated in global models (e.g. characteristic length scale is mixed).

This severely limits our ability to predict, mitigate and adapt to environmental change at local and regional scales.

Global modelling, reference sites and data will gradually converge to spatial and temporal scales where processes at their characteristic length scale can be compared (scale invariance is the goal).

However, spatio-temporal homogeneity is a concern (53 of 138 FLUXNET sites correspond ($r^2=.82$) well wrt. satellite observations and ground measurements (Cescatti et al., 2012, RSE)).
Vegetation structure

Vegetation structure at shoot (canopy) level is very poorly defined (eg is not well expressed in single/multiple SI variables) and therefore is its measurement tricky!
3DVegLab

Reconstruct vegetation canopies using TLS/ALS
Measure LOP (Leaf Optical Properties) and reconstruct trees
Collect ‘all’ (!) Earth observation data above sites
Implement toolbox using 1D and 3D RTM approaches (BEAM: librat, DART)
Make everything open source (ca. spring 2013)
(ESA STSE project: UZH, UCL, TU Vienna, CESBIO, Netcetera AG)
Canopy structure models based on laser scanning

Tree structure characterization based on ALS (leaf-off/-on, 300 pts/m\(^2\))
Level 3: Alpine ecosystem services (agronomic, cultural, pollination, soil C)

Idea

Methods
– Replacing modeled continuous traits and services (using GLM) by spectroscopy. Derive land cover in a continuous fashion from spectroscopy data

Results

Outlook
– Improve pollination estimates by using multitemporal remote sensing data
French Alps – Ecosystem Services

Photos: L. Homolova
**Department of Geography**

**Approach of Lavorel et al. (2011)**

- **Field data (collected during 2003-2008)**
  - Continuous Abiotic data: ALT, RAD, WHC, Soil NNI, PNI
  - Continuous Land use (LU)
  - Traits per plot: LDMC, LNC, LPC, FO
  - EP per plot: Green mass GM, Litter mass LM, Crude protein CPC, Soil carbon SC, Species rich SR, Flower. onset FO

- **Modelled continuous trait data using GLM**
  - LDMC, LNC, LPC, FO = f(LU, ALT, RAD, WHC)

- **Modelled continuous ecosystem properties using GLM**
  - EP = f(traits + LU + abiotic)

- **GLM based proxies of EP scaled between 0-1 (low-high)**

- **Estimation of ecosystem services**
  - Agronomic = GM + CPC + ½ CWM_FO + ½ FD_FO
  - Cultural = FD_FO + SR – LM
  - Pollination = CWM_FO + FD_FO
  - Soil carbon = soil carbon

  - **TOTAL ES = agronomic + cultural + pollination + soil carbon**

**RS Approach of Homolova et al. (2012)**

- **AISA RS data & processing**
  - AISA RS images (raw DN)
  - Processing (Radiometric, geometric, atmospheric corr.)
  - AISA RS images (HDRF)

- **RS proxies of EP (table 1)**
  - RS calibrated by field EP data
  - Based on RS only

- **Spatial comparison**
  - **Comparison of e. properties (#1)**
  - **Comparison of e. services (#2)**

- **RS proxies of EP scaled between 0-1**
  - RS calibrated by field EP data
  - Based on RS only

- **Estimation of ES (Lavorel et al. 2011)**
  - RS calibrated by field EP data
  - Based on RS only
Total ecosystem services = Agricultural + Cultural + Pollination + Soil C
Level 3: Using NO$_2$ vertical column density for policy validation

Idea
– Use unbinned APEX acquisition for NO$_2$ vertical column density retrieval and policy validation

Methods
– Differential optical absorption spectroscopy (DOAS) and air mass factor calculations using radiative transfer approaches

Results
– Detection of NO$_2$ emission sources, NO$_2$ emission modelling, and linking in-situ and satellite observations (Popp et al. (2012) AMT).

Outlook
– Combined estimates of NO$_2$ emission/deposition using transport models
Measurements and policy implementation

a) 

b) 

Conclusions

Pushing the limits: 4th generation spectroscopy pushes much of the current models and technology to a higher level.

We move from predominantly observational & empirical approaches to

- radiance based approaches (instead of reflectance based) using coupled models
- coupling the physics of the observations to the physics of the environment
- implementing spectral databases providing ‘informative priors’ allowing the prediction of spectral signatures representing the dynamics of the process observed
- direct radiance data assimilation into process models (of photosynthesis)

Combined suborbital and orbital spectroscopy is the only way assessing many relevant processes of the Earth system simultaneously and at unprecedented accuracy!
Thank you for your attention!