Earth observation in the optical/infrared spectral domain for Land science and applications

Jose F. Moreno
University of Valencia, Spain
Jose.Moreno@uv.es

9 September 2013

- Information content of optical data: retrievable information
- Forward modelling of surface reflectance: soil, leaf and canopy models
- Pre-processing aspects: from raw data to surface reflectance
- Information retrieval techniques, validation and interpretation
- Data usage as inputs to Land models and applications
- Perspectives: new data, new science and new applications
Understanding the actual information content of the optical data: forward modelling of the signal

OPTICAL SYSTEMS:
- Visible
- Near infrared
- Shortwave infrared
- Thermal infrared

0.4 μm – 14 μm
OPTICAL SYSTEMS:

- **Panchromatic:**
  - mapping in very high spatial resolution

- **Multispectral:**
  - “colour” imaging

- **Hyperspectral:**
  - chemical composition

- **Multi-angular:**
  - structure

**Available Signal**

- **surface reflected radiance**
- **surface emitted radiance**

![Graph](image)

- Atmosphere
  - Solar 1.0 Reflectance
  - Earth 300 K, 1.0 Emisivity

**Wavelength (nm)**

0 2000 4000 6000 8000 10000 12000 14000

0.0 0.2 0.4 0.6 0.8 1.0 1.2 1.4 1.6 1.8 2.0

**Solar Radiance (µW/cm²/nm/sr)**
Signatures of natural targets:
- Spectral signatures
- Angular signatures
- Spatial signatures
- Temporal signatures
- Other signatures (i.e., emissivity, fluorescence, polarization)

What we measure is always radiance, either reflected and/or emitted by the land surface, which variations depend on the optical properties of land targets (and illumination conditions).

Optical properties of elementary constituents determine the spectral reflectance of land elements.
VEGETATION MATERIAL

SCATTERING

High variability!

Are all pigments separable in the signal?
TUTORIAL: Earth observation in the optical/infrared spectral domain for Land science and applications

Senescent / dry leaves

TUTORIAL: Earth observation in the optical/infrared spectral domain for Land science and applications

green vegetation (alfalfa)

senescent vegetation (barley)
TUTORIAL: Earth observation in the optical/infrared spectral domain for Land science and applications

---

**TUTORIAL**: Earth observation in the optical/infrared spectral domain for Land science and applications

**Jose F. Moreno**
University of Valencia, Spain

---

**Dynamics of vegetation reflectance**

- **viologlanthin**
- **zeaxanthin**

**Xanthophyll cycle**

- **Carotenoids**
  - Cinnamic acids
  - Chlorophyll

---

**living planet symposium** 9–13 September 2013 | Edinburgh, UK

**Jose F. Moreno**
University of Valencia, Spain
TUTORIAL: Earth observation in the optical/infrared spectral domain for Land science and applications

**Canopy Reflectance**

- Wavelength (nm)
- Absorption (a.u.)

**Red-Edge Dynamics**

- Sunlight absorption and fluorescence emission

**Chlorophyll Fluorescence**

- Energy levels: $S_0, S_1, S_2$
- Light absorption and fluorescence emission

Jose F. Moreno
University of Valencia, Spain

Living Planet Symposium | 9–13 September 2013 | Edinburgh, UK
Chlorophyll fluorescence as an indicator of usage of the absorbed light by vegetation.

Energy budget at the leaf level:
- Incident light
- Reflectance
- Absorption
- Chlorophyll fluorescence
- Heat (5-17.5%)
- Transmittance

De-excitation pathways:
- Photosynthesis
- Photochemistry
- Constitutive heat dissipation
- Regulated heat dissipation
- Fluorescence

THERMAL INFRARED

\[ L_\lambda(T) = \varepsilon_\lambda B_\lambda(T) \]

\[ \varepsilon_\lambda = 1 - \rho_\lambda \]

\[ \tau_\lambda \sim 0 \]
TUTORIAL: Earth observation in the optical/infrared spectral domain for Land science and applications

THERMAL INFRARED: Temperature versus emissivity effects

\[
L_{\text{sat}} = [\varepsilon B(T) + (1-\varepsilon) L_{\text{atm}}^\uparrow] \tau + L_{\text{atm}}^\uparrow \\
L_{\text{atm}}^\uparrow \approx (1-\tau_\theta) B(T_a) \\
L_{\text{atm}}^\downarrow = (1-\tau_{53}) B(T_a)
\]

“Split-window” / Dual-angle approaches

\[
T = T_b + \frac{1-\varepsilon}{\varepsilon} \left( L'(T_b) - [1-\tau_{53}] [T_a + L'(T_b) - T_b] \right) + \frac{1-\tau(\theta)}{\varepsilon \tau(\theta)} (T_b - T_a)
\]

Degree of polarization:

\[
P_{\text{deg}} = \frac{\sqrt{Q^2 + U^2 + V^2}}{I}
\]

POLARIZATION EFFECTS
- Mostly due to atmosphere
- Surface also introduces polarization effects

Reflectance spectra and polarization spectra in four directions at the principal plane (60° forward, 30° forward, nadir, 30° backward)

Measured polarized reflectance at 865 nm

living planet symposium 9–13 September 2013 | Edinburgh, UK

Jose F. Moreno
University of Valencia, Spain
TUTORIAL: Earth observation in the optical/infrared spectral domain for Land science and applications

Jose F. Moreno
University of Valencia, Spain

living planet symposium 9–13 September 2013 | Edinburgh, UK

ANGULAR EFFECTS

Scan across the principal plane 
\( \theta_{\text{scan}} = -16.8^\circ \)
TUTORIAL: Earth observation in the optical/infrared spectral domain for Land science and applications

A rather Lambertian surface

Spectral versus angular information

A highly anisotropic surface

CHRIS/PROBA DATA

62 spectral bands
34 m resolution
5 view angles
Spatial information in the images
- Textures
- Higher order statistics

TEMPORAL SIGNATURES
Time series and data assimilation will be common strategies with future GMES Sentinel data
TUTORIAL: Earth observation in the optical/infrared spectral domain for Land science and applications

FORWARD MODELLING

Leaf

Canopy

Environment

simple leaf models

complex leaf models

multiple canopy models

BARE SOIL REFLECTANCE

Soil chemistry / roughness as key parameters

SOIL MODEL

ACTUAL DATA (HYMAP)
TUTORIAL: Earth observation in the optical/infrared spectral domain for Land science and applications

How well the spectral reflectance signal is understood?

simulation & inversion software tools

living planet symposium 9–13 September 2013 | Edinburgh, UK
Data processing methods for optical remote sensing data and information extraction
Pre-processing steps:

- Radiometric calibration
- Noise removal
- Cloud screening
- Geometric correction
- Atmospheric correction
- Data integration

Cloud screening:

- Very dependent on the available spectral information
- Many different algorithms (from simple thresholds up to sophisticated techniques)
Atmospheric effects

Transmittance vs. Wavelength (nm)

- $O_3$
- Molecular scattering
- Aerosol
- Total

$O_3$, $H_2O$, $CO_2$

TOA, BOA

living planet symposium 9–13 September 2013 | Edinburgh, UK

Jose F. Moreno
University of Valencia, Spain
$p'(\theta_s, \theta_v, \phi_v) = t_g(\theta_s, \theta_v) (p_d(\theta_s, \theta_v, \phi_v) + \frac{T(\theta_s)}{1 - <\rho(M) > S} (p_c(M)e^{-\tau/\mu_v} + <\rho(M) > t_d(\theta_v)))$
Effects introduced by topography:

A - Vertical geometric distortion (horizontal displacement due to relief)

B - Variation of atmospheric (optical) properties with height

C - Relative changes in slope and orientation of surface introduce variations in illumination conditions:

Direct irradiance:
- illuminated areas
- self-shadowed areas
- cast-shadowed areas

Diffuse irradiance:
- directional distribution
- modeling of sky view factors

Surface reflectance model:
- non-Lambertian effects
- modeling of direct/diffuse components

D - Adjacency effects (additional contributions)

E - Additional multiple reflections
OUTPUT OF THE ATMOSPHERIC/TOPOGRAPHIC CORRECTION FOR QUANTITATIVE COMPARISONS IN MULTITEMPORAL STUDIES

a.- reflectance

\[ \rho(\theta_s, \phi_s; \theta_v, \phi_v) \]

- no comparison is possible among different dates
- no comparison is possible among different points of an image

b.- spectral albedo

\[ \alpha(\theta_s, \phi_s) = \int \int_\Omega d\Omega \rho(\theta_s, \phi_s; \theta_v, \phi_v) \]

- comparison is possible within an image but not among different dates
- results are model-dependent (!)

c.- 'normalized' spectral albedo

\[ \alpha(\theta_0, \phi_0) = \alpha(\theta_s, \phi_s) \left|_{(\theta_s=\theta_0, \phi_s=\phi_0)} \right. \]

- comparison is possible within an image and among different dates
- strongly model-dependent (!)

Every sensor is a subset of the whole possible spectral-angular information.
TUTORIAL: Earth observation in the optical/infrared spectral domain for Land science and applications

SPECTRAL INDICES AS PROXIES

EMPIRICAL APPROACHES

living planet symposium 9–13 September 2013 | Edinburgh, UK

Jose F. Moreno
University of Valencia, Spain

\[
\frac{R_{\text{green}} - R_{\text{red}}}{R_{\text{green}} + R_{\text{red}}}
\]
Optimized spectral indices

Leaf chlorophyll

Canopy water

SURFACE MODEL PARAMETERISATION:

(a) Leaf inputs:
- Leaf effective thickness
- Total leaf chlorophyll (a+b)
- Ratio Ca/Cb
- Fraction of Ca in LHC
- Leaf carotenes content
- Leaf water content
- Specific leaf weight
- Cellulose content
- Lignin content

(b) Canopy inputs:
- LAI
- fCover
- Clumping parameter (H/D)

(c) Soil inputs:
- Soil wetness parameter
Water, pigments and non photosynthetic elements drive the spectral variability + soil + vegetation structure

Signal composed by multiple contributions (soil+vegetation)

Multiple scattering effects play a major role
MODEL INVERSION STRATEGIES

The problem of model inversion can be considered from different perspectives:

(a) Root finding of a given function

(b) Solving non-linear set of equations

(c) Function minimisation

(d) Non-linear least-squares modeling of data

Root finding and solving non-linear set of equations would require that the function is “exact”, and for this reason function minimisation is normally preferred.

Merit function:
Incorporation of the uncertainties in the inversion process

\[ \chi^2 = \left[ R_{\text{mes}} - R_{\text{mod}}(V) \right]^T W^{-1} \left[ R_{\text{mes}} - R_{\text{mod}}(V) \right] + \left[ V - V_p \right]^T C^{-1} \left[ V - V_p \right] \]

Use of constrained minimization procedures that guarantee the minimal variation of model variables to produce the same output, and a robust initialization procedure of such variables (consistency even if model has global bias).
- Numerical inversion methods are computationally expensive (and subject to unstable results)
- Functional approximations often used as practical solution:
  (a) Empirical approaches based on regression using many EO data points and field measurements (incomplete / biased sampling in most cases)
  (b) Alternative (or complement) use of forward model outputs to produce a simple mathematical relationship which is then used for retrievals (complete sampling)
Neural network methods

Network design and training become critical issues

Signal decomposition or multiple linear/non-linear regression approaches:
- Partial least squares regression, Kernel regression, Multivariate adaptive regression, Stepwise regression, Segmented regression
- Spectral unmixing, Principal components / SVD decompositions
- Support Vector Machines, Gaussian processes, ...

Spectral fitting methods are especially useful because we can use the well-known shape of spectral features.

Requires rather high spectral resolution.
TUTORIAL: Earth observation in the optical/infrared spectral domain for Land science and applications

Leaf Water Content (cm)

- 0.001
- 0.002
- 0.004
- 0.006
- 0.010
- 0.015
- 0.020
- 0.040
- 0.060
- 0.080
- 0.100

living planet symposium 9–13 September 2013 | Edinburgh, UK
Jose F. Moreno
University of Valencia, Spain
Decoupling of atmospheric effects when retrieving leaf / canopy biochemical information (i.e., coupled water absorptions)

Transmittance & reflectance (relative units)

Atmospheric water vapour
Surface liquid water

Wavelength (μm)

TUTORIAL: Earth observation in the optical/infrared spectral domain for Land science and applications

MULTI-STEP PROCEDURES

A general multi-step procedure

- Explicit separation of almost pure pixels from spectral mixtures
- Use of several retrieval techniques for each step
- Produce different adequate outputs for each retrieval procedure

Such methods are used in practice for real images
SCALING ASPECTS

Comparison among different sensor products

MERIS FR

CHRIS/PROBA

Intensive field campaigns
Ground validation data:
- vegetation properties
- soil properties
- solar radiation
- atmospheric status
- surface fluxes

Exploitation of optical remote sensing data for land science and applications
LAND SCIENCE AND APPLICATIONS

- Mapping applications:
  - Cartography
  - Thematic mapping

- Monitoring applications:
  - Ecosystem dynamics
  - Natural hazards (fires, floods, desertification)

- Research about Land Surface Processes:
  - Heat and mass exchange at land / atmosphere interface
  - Photosynthesis and carbon assimilation by terrestrial vegetation
  - Hydrological processes
  - Land/atmosphere/ocean coupling and biochemical exchanges

Usage of the derived information:

- Tendency: from proxies to quantitative information
- Multi-resolution spatial inputs and time series

- **First approach:** Land cover mapping, classification and tables of biophysical variables assigned to each class
- **Second approach:** Retrievals of biophysical variables as direct inputs to models
- **Third approach:** direct assimilation of radiances/reflectances into models
GLOBAL MAPS

Land cover maps derived from ENVISAT / MERIS data

Disturbances described by multi-annual classifications

REGIONAL MAPS

Application of specific retrieval methods for each land surface class

More accurate classifications exploiting high spatial resolution and multitemporal coverage
TUTORIAL: Earth observation in the optical/infrared spectral domain for Land science and applications

LAI FROM LANDSAT DATA:

MULTITEMPORAL SERIES

RESOLVED SPATIAL SCALES

<1 - 300 meters
Local site

global
Global sampling

living planet symposium 9–13 September 2013 | Edinburgh, UK
Jose F. Moreno
University of Valencia, Spain
TUTORIAL: Earth observation in the optical/infrared spectral domain for Land science and applications

RESOLVED TIME SCALES

few days

several years

RESOLVED TIME SCALES

- Photosynthesis and leaf respiration.
- Growth respiration and stem and root maintenance respiration.
- Allocation
- Phenology
- Nitrogen cycle
- Competition between plant functional types (PFTs).

Extent to which vegetation acts as a dynamic component

- Stomata respond to variability in environmental conditions and CO₂ concentration when coupling between photosynthesis and stomatal conductance is explicitly modeled.
- Estimating respiration allows us to model NPP. \( \text{NPP} = \text{GPP} - \text{R}_d - \text{R}_m \).
- Biomass allocation to leaves determines LAI. LAI thus varies with change in climatic conditions from year to year, and the seasonal cycle of LAI can be simulated rather than being prescribed.
- The timing of leaf onset and offset is modeled rather than being prescribed.
- Explicitly modeling N cycle and plant N uptake implies that N availability does not have to be assumed constant. The effect of variability in N availability on plant productivity can thus be modeled.
- Vegetation reacts to long-term changes in climate, and PFTs which are best suited for a given region and climate succeed.

Timescale at which processes are modeled

- Minutes to months
- Minutes to months
- Daily to annual
- Daily to monthly
- Monthly to annual
- Decades to centuries

Requires very large time series

LSM model

HEAT, MASS AND MOMENTUM TRANSFER

biogeochemical fluxes

- photosynthesis, temperature
- \( T_h, T_v, \text{vap}, \text{CO}_2, \text{O}_2, \text{S} \_	ext{down}, \text{L} \_	ext{down} \)

biophysical fluxes

- radiative transfer
- sensible/latent heat
- stomatal physiology
- momentum flux
- soil heat/snow melt
- temperatures

HYDROLOGICAL PROCESSES

- interception
- throughfall/stemflow
- snow hydrology
- infiltration/surface runoff
- soil water redistribution
- capillary rise/drainage
- irrigation
- lateral inflow

water

- vegetation/snow/soil
- wetland/lake/glacier
- groundwater
- river

LAI model

biomass

- vegetation
- soil
- type
- height
- foliage/stem/root

lateral outflow

hydrologic transport

surface/sub-surface transport
- river flow
- lake/wetland/glacier dynamics

ECOSYSTEM DYNAMICS

- CO₂ fluxes
- \( \text{CH}_4, \text{NMHC, } \text{N}_2\text{O} \)

chemicoecological fluxes

- maintenance respiration
- growth respiration
- microbial respiration
- net primary production

vegetation dynamics

- phenology
- growing season
- monthly foliage
- regeneration
- mortality
- soil processes
- decomposition
- mineralization

living planet symposium 9-13 September 2013 | Edinburgh, UK
Jose F. Moreno
University of Valencia, Spain
TUTORIAL: Earth observation in the optical/infrared spectral domain for Land science and applications

Water cycle

Carbon cycle

Integration with other data sources (in a GIS environment)

from local measurements to global models...

living planet symposium 9–13 September 2013 | Edinburgh, UK

Jose F. Moreno
University of Valencia, Spain
Perspectives for the coming years: new data, new science and new applications

NEW GENERATION OF SENSORS

- Well calibrated (more suitable for multitemporal studies)
- Increased spatial resolution (0.5 m PAN now available)
- Increased spatial coverage (global mapping in high spatial resolution (as ESA GMES/Sentinel-2)
- New type of information (i.e., vegetation fluorescence)
- Time series: gap filling using multi-sensor data, better temporal resolution also with high spatial resolution
- Integration of multi-resolution data with diverse spectral information in common temporal databases
TUTORIAL: Earth observation in the optical/infrared spectral domain for Land science and applications

SENTINEL-2

"cloud removal" and generation of synthetic daily composites

Reflectance Data
Assimilation approaches into dynamical Land surface models

365 days cloud-free synthetic dataset
PERSPECTIVES IN DATA EXPLOITATION

- Adequate exploitation of the different data sources: multi-source (multi-resolution data integration).
- Focus on systematic data assimilation approaches exploiting the time-series concept and synergy among simultaneously available satellite systems.
- Consistent incorporation in the modelling approaches of processes covering time scales from weeks to decades and exploiting spatially distributed inputs.
- Accounting for spatial variability and temporal dynamics as the main contributions.

EO Applications
- Calibration & Validation
- Vegetation monitoring
- Agriculture
- Forestry
- Water quality
- Climate change
- Damage Assessment
- Cartography

Methods
- Physical models
- Instrument design
- Image processing and analysis
- Automatic classification
- Analysis of time series
- Biophysical parameter estimation
- Data fusion
Thank you for your attention!

Questions?