Data assimilation to improve retrievals of land surface parameters

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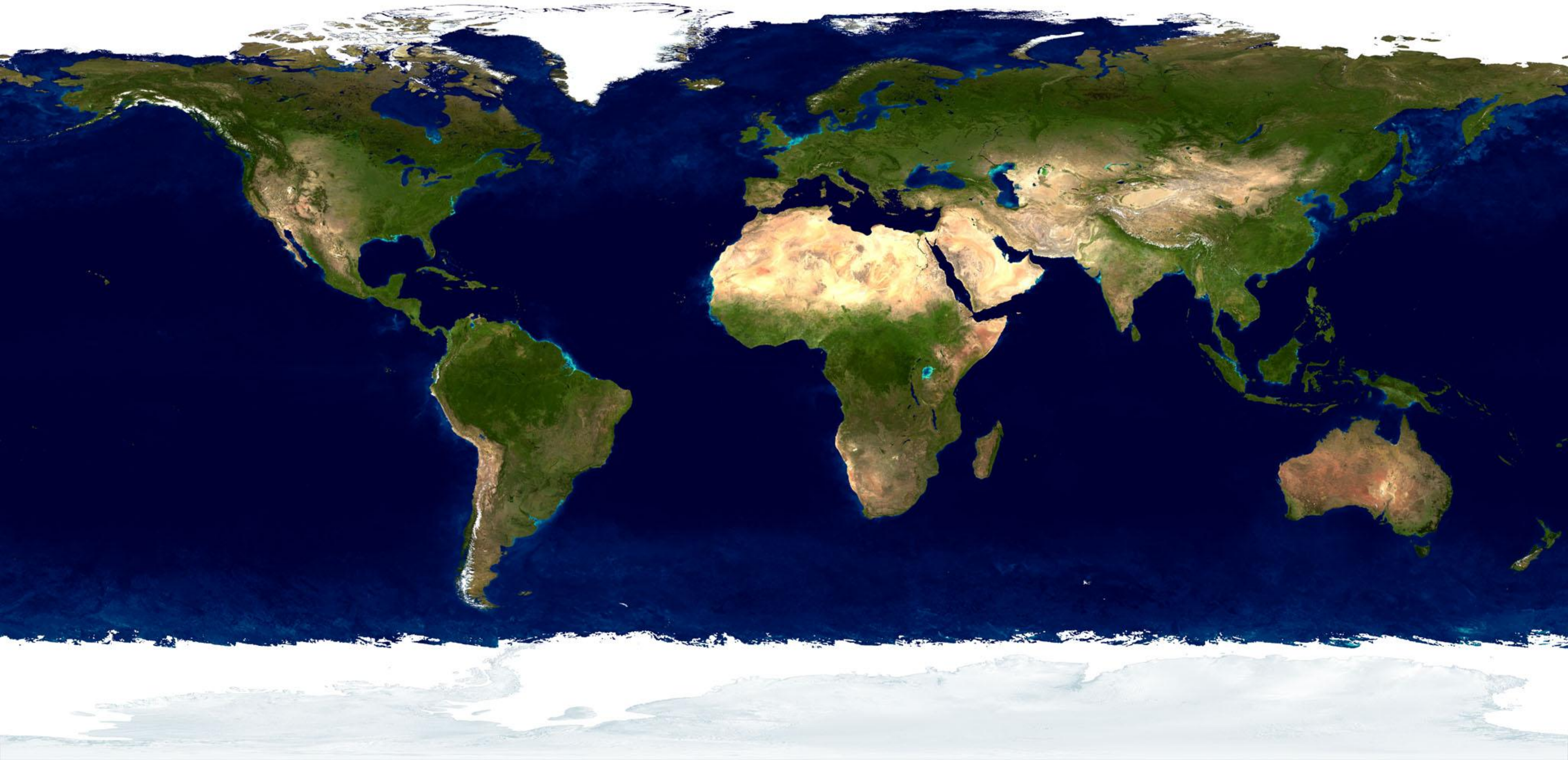
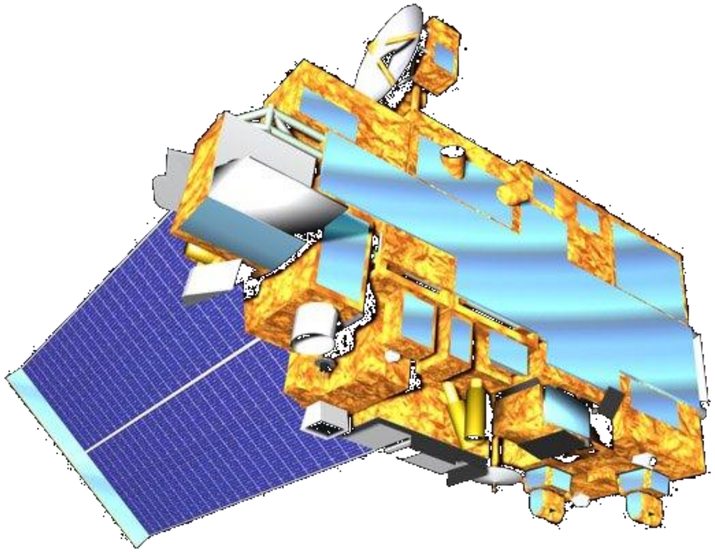


MODIS:
Moderate Resolution Imaging Spectrometer



- Two in orbit (onboard Terra and Aqua)
- Since 2000
- Daily global coverage
- 250m → 1km resolution
- Various spectral channels

Some definitions - BRF

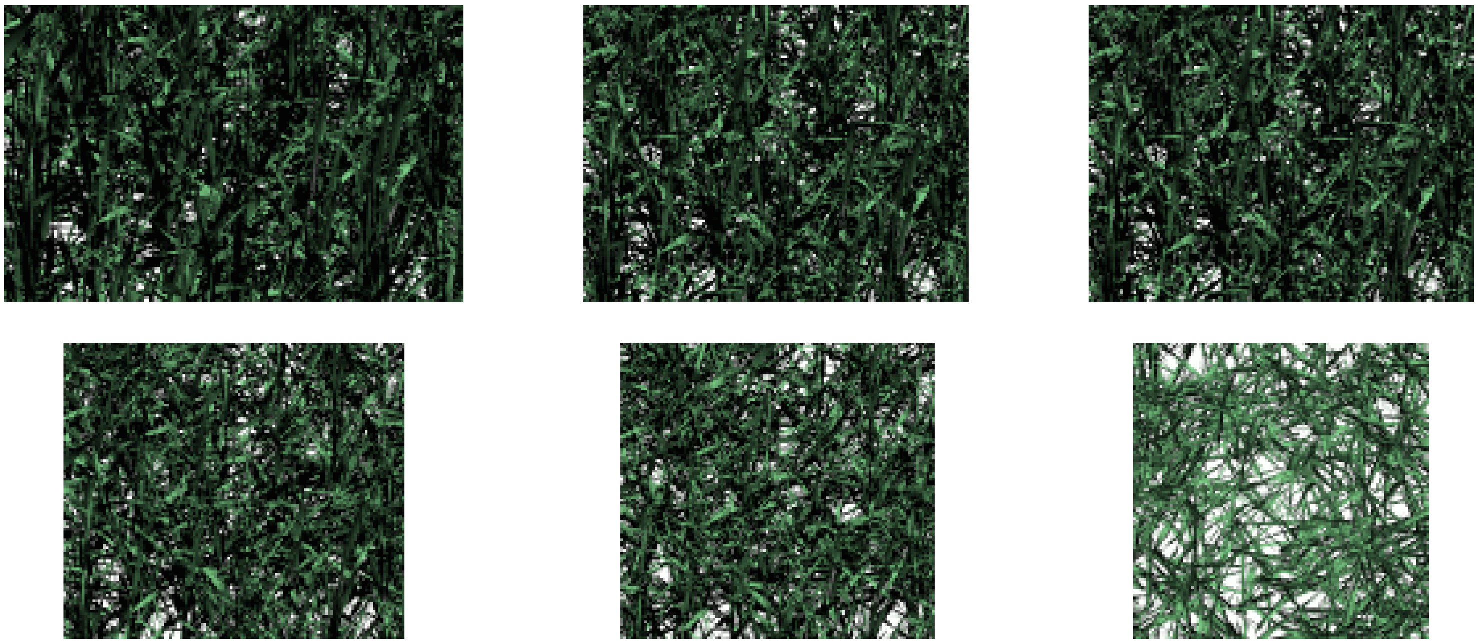
- Bidirectional reflectance factor
  - The ratio of the radiance reflected into a finite solid angle and the radiance reflected into the same angle (under the same illumination conditions) from a perfect Lambertian reflector
  - This is what is reported as “reflectance” from passive optical sensors (MODIS, Landsat, LISS etc) which observe the top of atmosphere radiance

Some definitions - BRDF

- Bidirectional reflectance distribution function
  - ratio of incremental radiance, dL_e, leaving surface through an infinitesimal solid angle in direction $\mathbf{\Omega}(\theta_v, \phi_v)$, to incremental irradiance, dE_i, from illumination direction $\mathbf{\Omega}'(\theta_i, \phi_i)$

$$BRDF(\mathbf{\Omega}, \mathbf{\Omega}') = \frac{dL_e(\mathbf{\Omega}, \mathbf{\Omega}')}{dE_i(\mathbf{\Omega}')} \left[sr^{-1}\right]$$

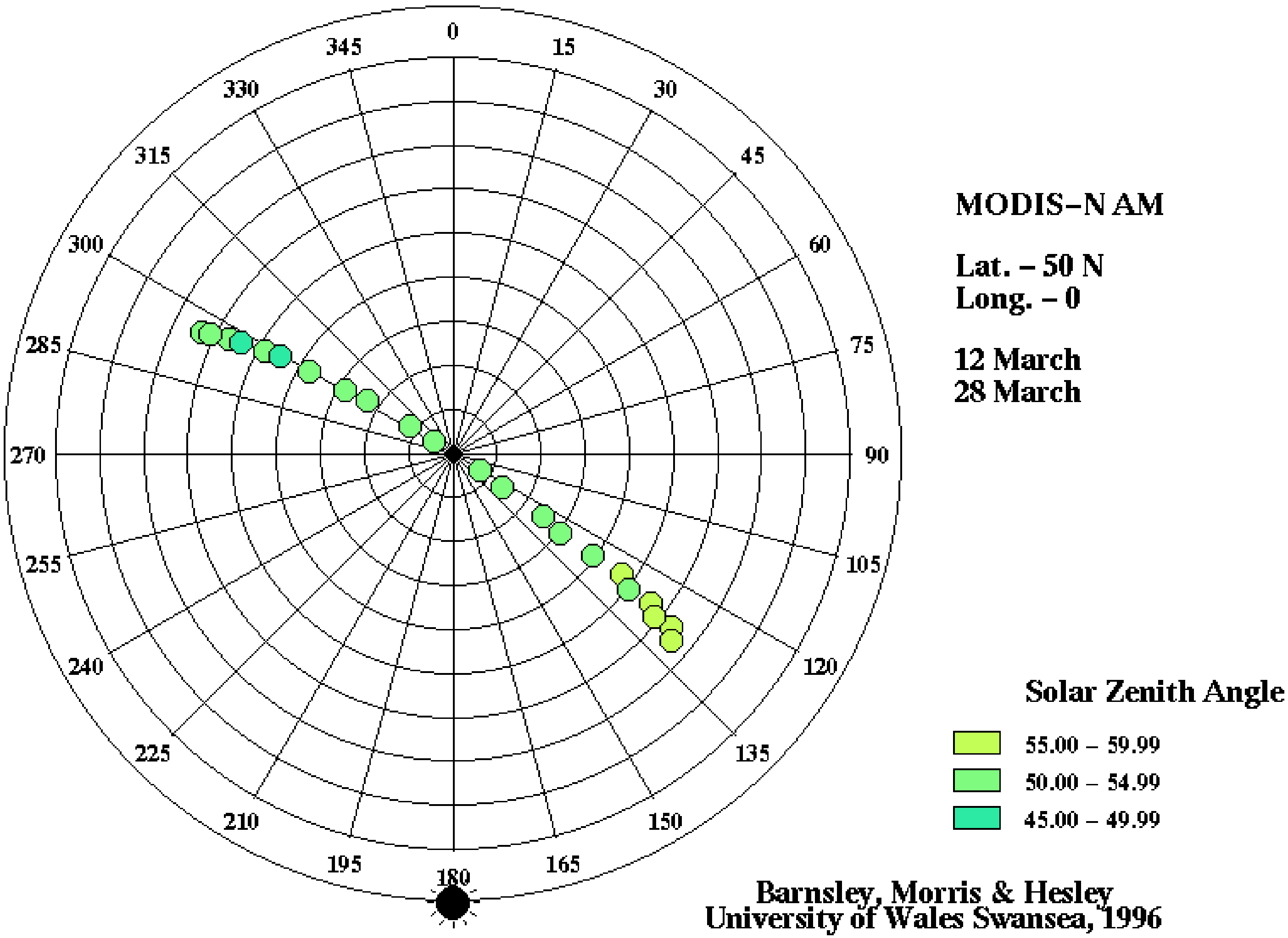
BRDF example



Modelled barley reflectance, θ_v from –50° to 0° (left to right, top to bottom).

BRDF example

MODIS BRDF sampling



Some definitions – spectral albedo

- Spectral albedo
  - The integral of the BRDF, at one wavelength, over the viewing hemisphere with respect to the illumination conditions. Two commonly used forms:

DHR = $$\overline{\rho}(\mathbf{\Omega}'; 2\pi) = \frac{1}{\pi}\int^{2\pi} BRDF(\mathbf{\Omega}, \mathbf{\Omega}')\,d\mathbf{\Omega}$$

BHR = $$\overline{\overline{\rho}}(2\pi;2\pi) = \int^{2\pi} \overline{\rho}(\mathbf{\Omega}')\,d\mathbf{\Omega}' = \frac{1}{\pi}\int^{2\pi}\int^{2\pi} BRDF(\mathbf{\Omega}, \mathbf{\Omega}')\,d\mathbf{\Omega}\,d\mathbf{\Omega}'$$

Some definitions – albedo

- Albedo (or “broadband” albedo)
  - The spectral albedo integrated over the desired wavelength range:

$$\alpha = \int p(\lambda)\alpha(\lambda)d\lambda$$

  - p(λ) is the proportion of incoming radiation at the given wavelength and α(λ) is the spectral albedo

From data to information...

- The key to understanding the remote sensing signal is to understand how the target modifies the EMR distribution
- To begin with, assume the canopy is filled with randomly positioned ‘plate’ absorbers (i.e. leaves)...

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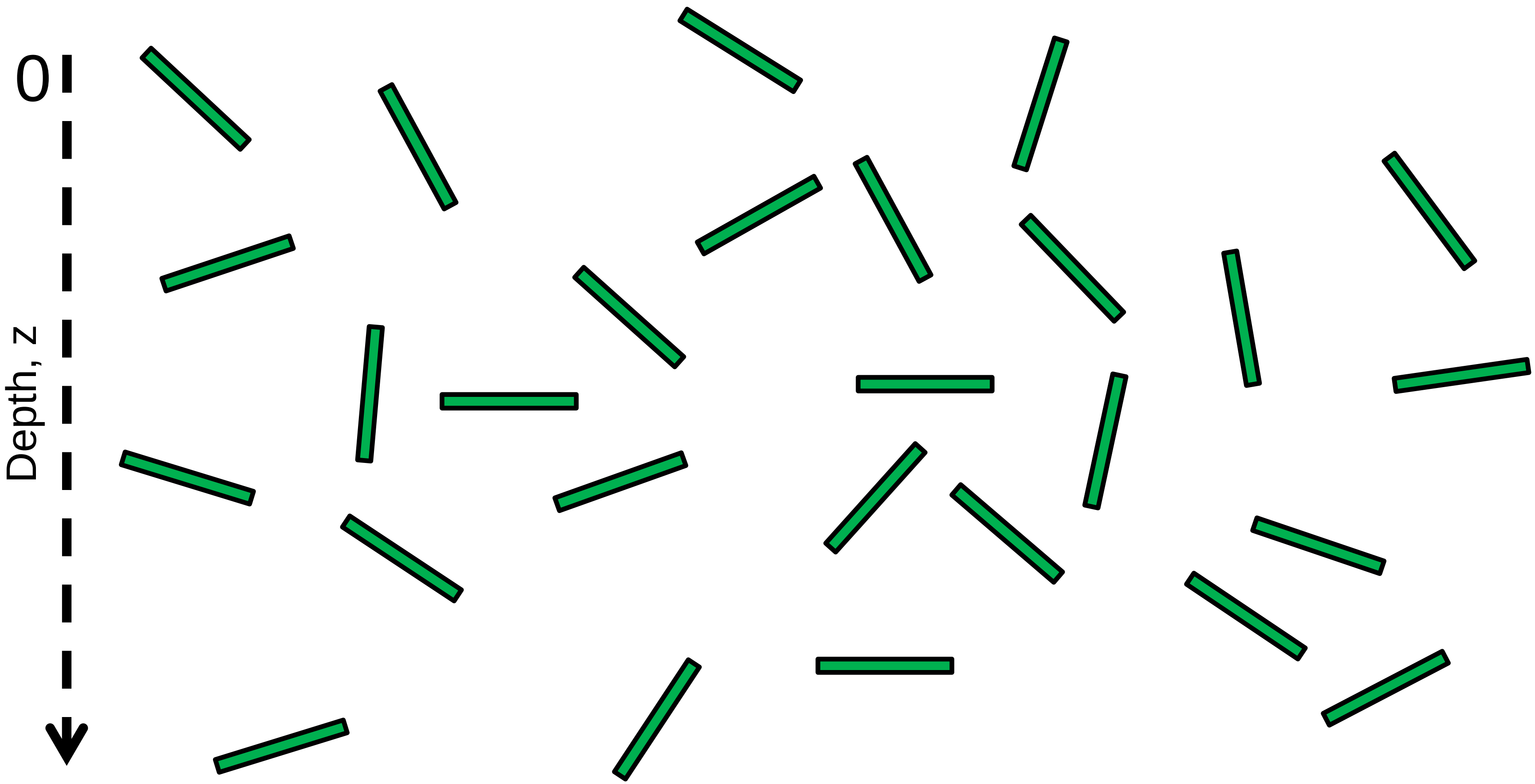
1-D plane-parallel semi-infinite turbid medium



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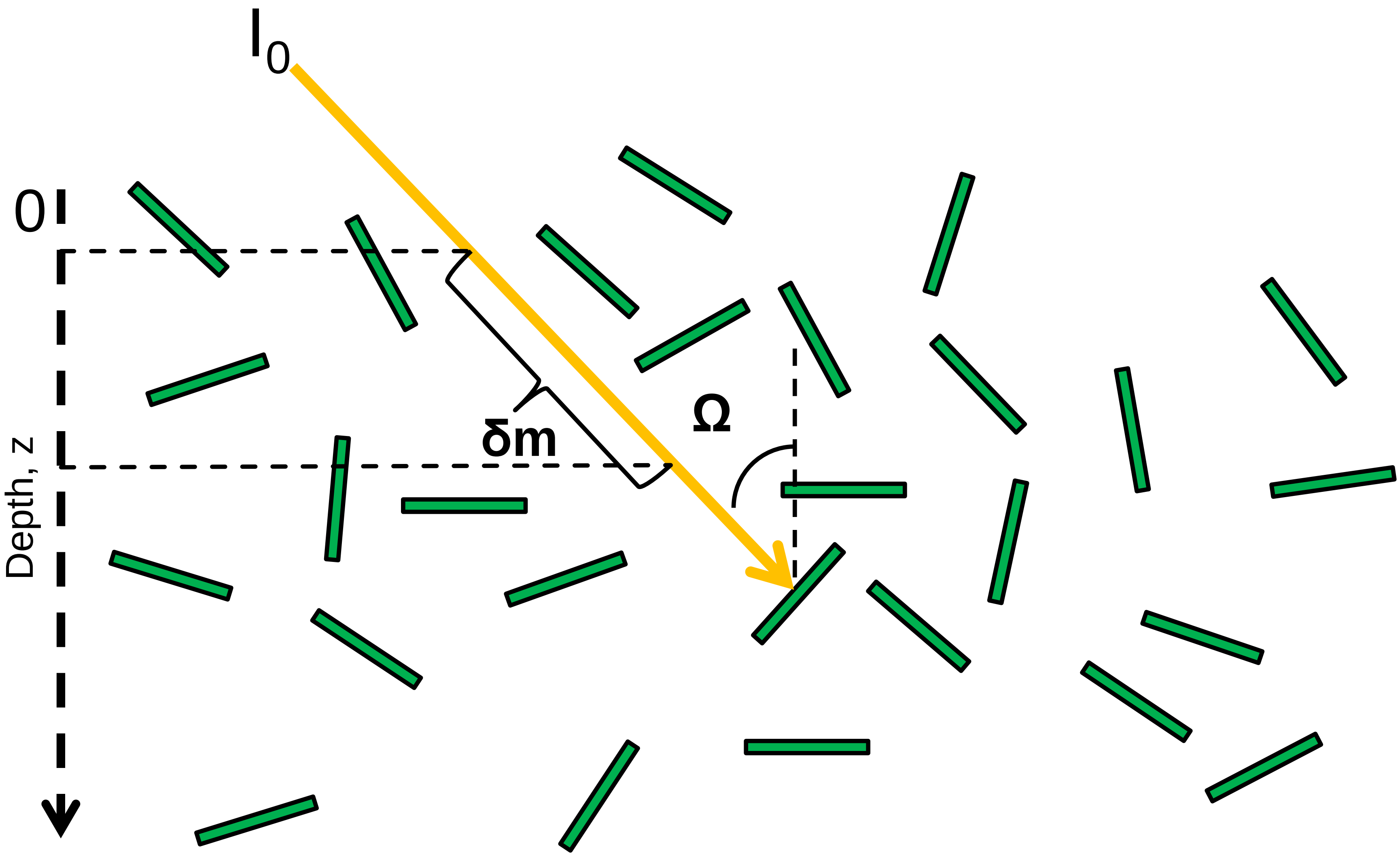

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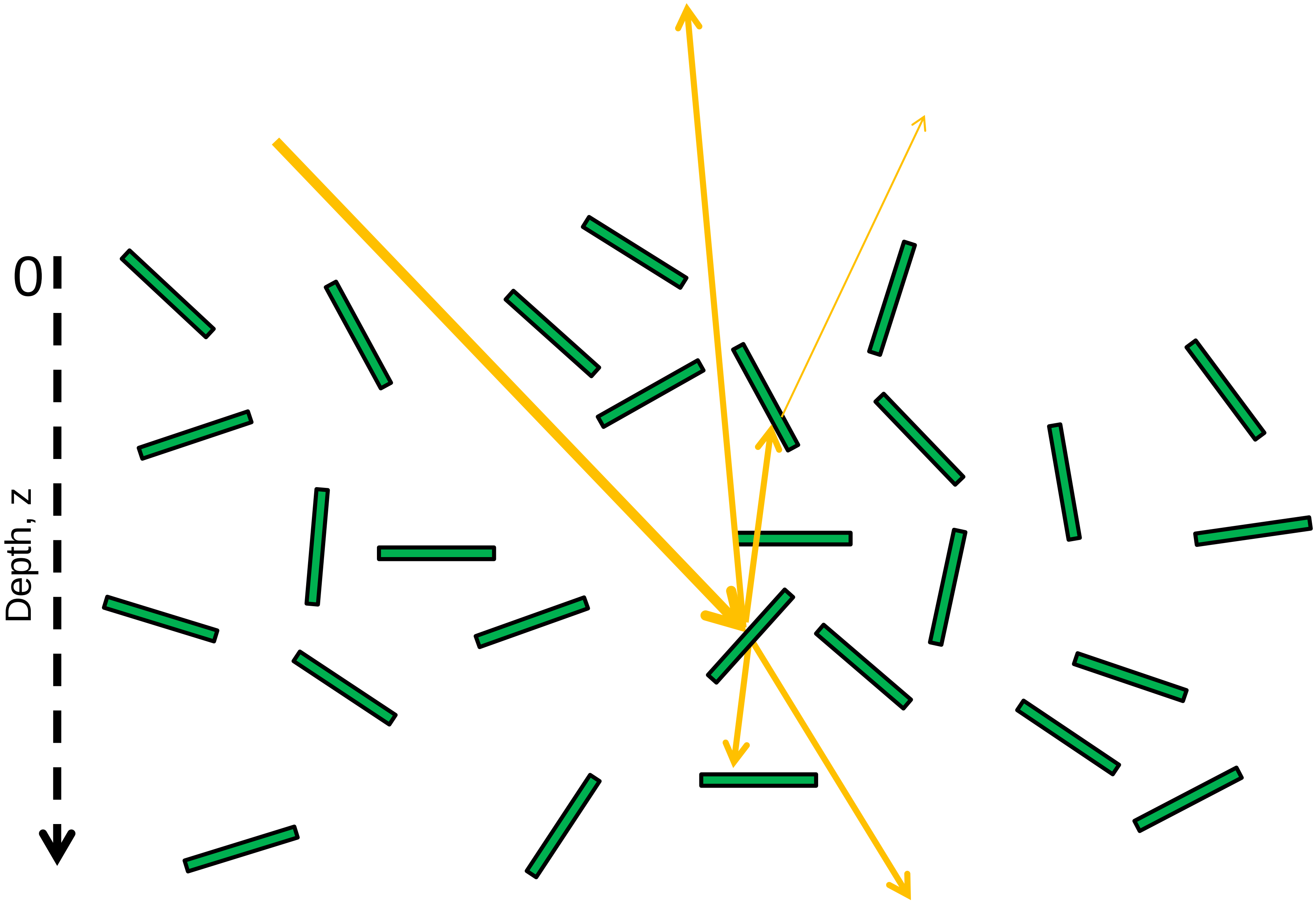


1-D Scalar Radiative Transfer Equation

- for a plane parallel medium (air) embedded with a low density of small scatterers
- change in specific Intensity (Radiance) $I(z,\underline{\Omega})$ at depth z in direction $\underline{\Omega}$ with respect to z:

$$m\frac{\partial I\left(z,\underline{\mathrm{W}}\right)}{\partial z} = - k_e I(\underline{\mathrm{W}}, z) + J_s\left(\underline{\mathrm{W}}, z\right)$$

- Requires either numerical techniques or fairly broad assumptions to solve

A [relatively] simple semi-discrete solution

Gobron, N., B. Pinty, M. M. Verstraete, and Y. Govaerts (1997), A semidiscrete model for the scattering of light by vegetation, *J. Geophys. Res.*, 102(D8), 9431–9446, doi:10.1029/96JD04013.

$$\rho^{0}(z_0, \Omega, \Omega_0) = \gamma_s(H, \Omega, \Omega_0) \cdot \left[1 - \lambda \frac{G(\Omega_0)}{|\mu_0|}\right]^{K} \left[1 - \lambda \frac{\|\mathcal{V}_{\bullet}\|}{\|\mathcal{V}_2\|} \frac{G(\Omega)}{\mu}\right]^{K}$$

Single scattered soil reflectance

$$\rho^{1}(z_0, \Omega, \Omega_0) = \frac{\Gamma(\Omega_0 \to \Omega)}{\mu|\mu_0|} \sum_{i=K}^{1} \lambda \left[1 - \lambda \frac{G(\Omega_0)}{|\mu_0|}\right]^{i} \cdot \left[1 - \lambda \frac{\|\mathcal{V}_{\bullet}\|}{\|\mathcal{V}_2\|} \frac{G(\Omega)}{\mu}\right]^{i}$$

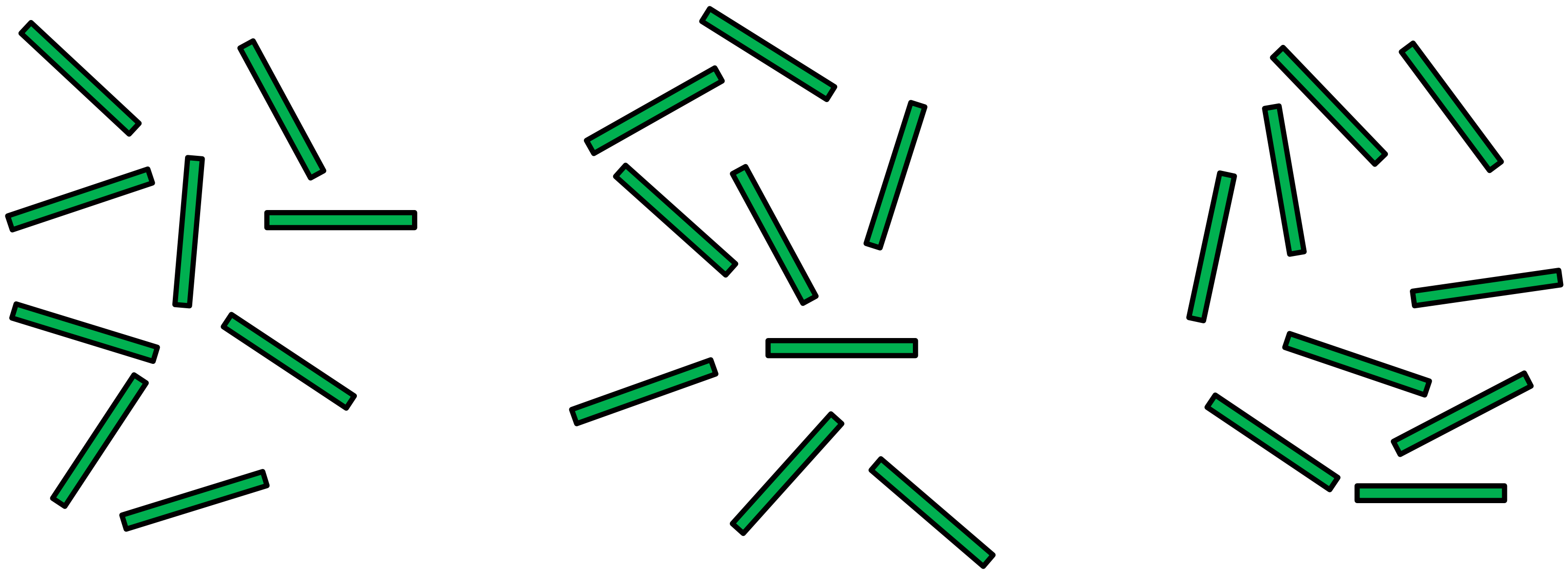
Single scattered canopy reflectance

$$\rho^{M}(z_0, \mu_0, \mu) = \frac{I^{M}(z_0, \mu_0, \mu)}{(|\mu_0|/\pi) \int_0^{2\pi} I_s \, d\phi} = \frac{I^{M}(z_0, \mu_0, \mu)}{2 I_s |\mu_0|}$$

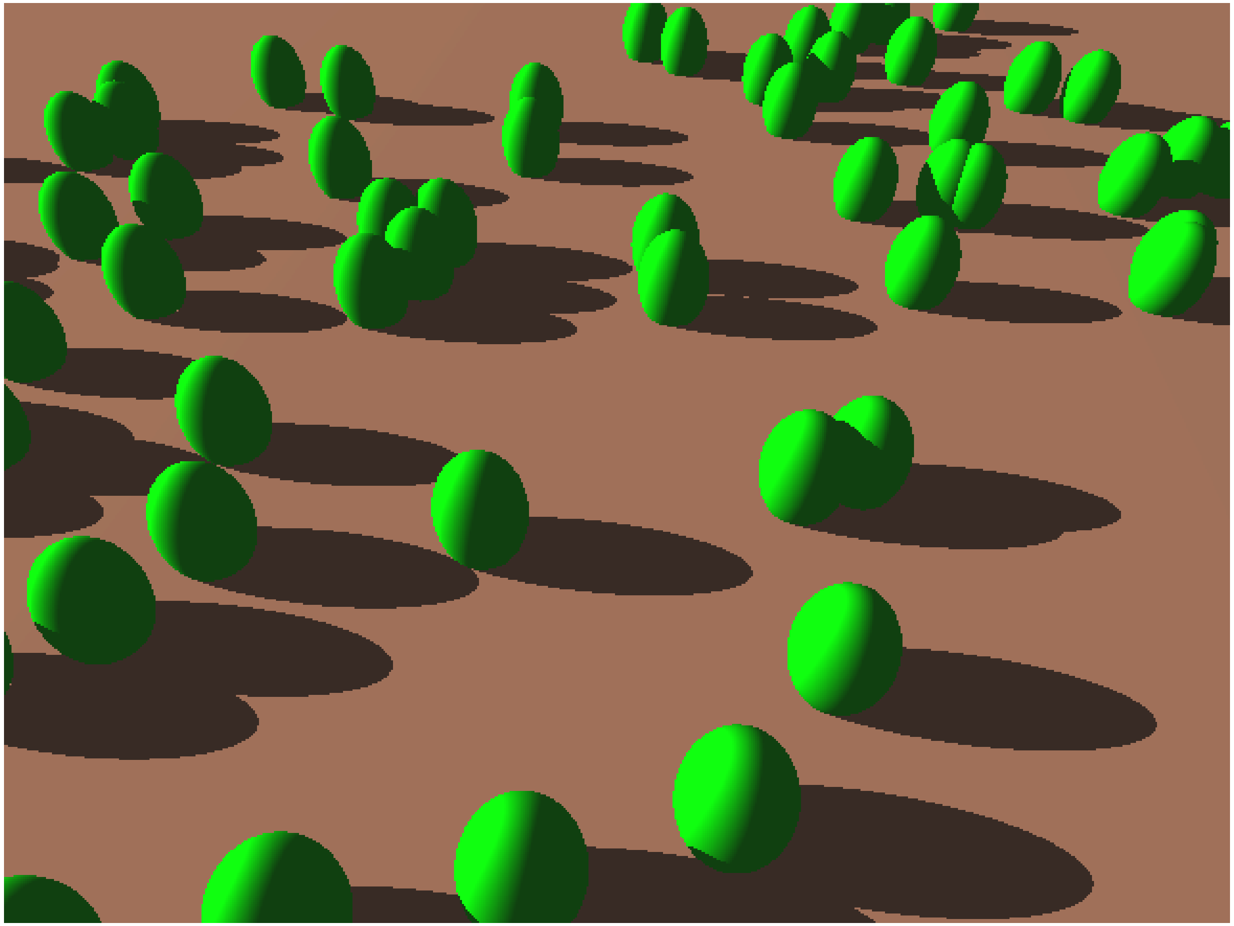
Multiply scattered reflectance

(requires numerical solution)

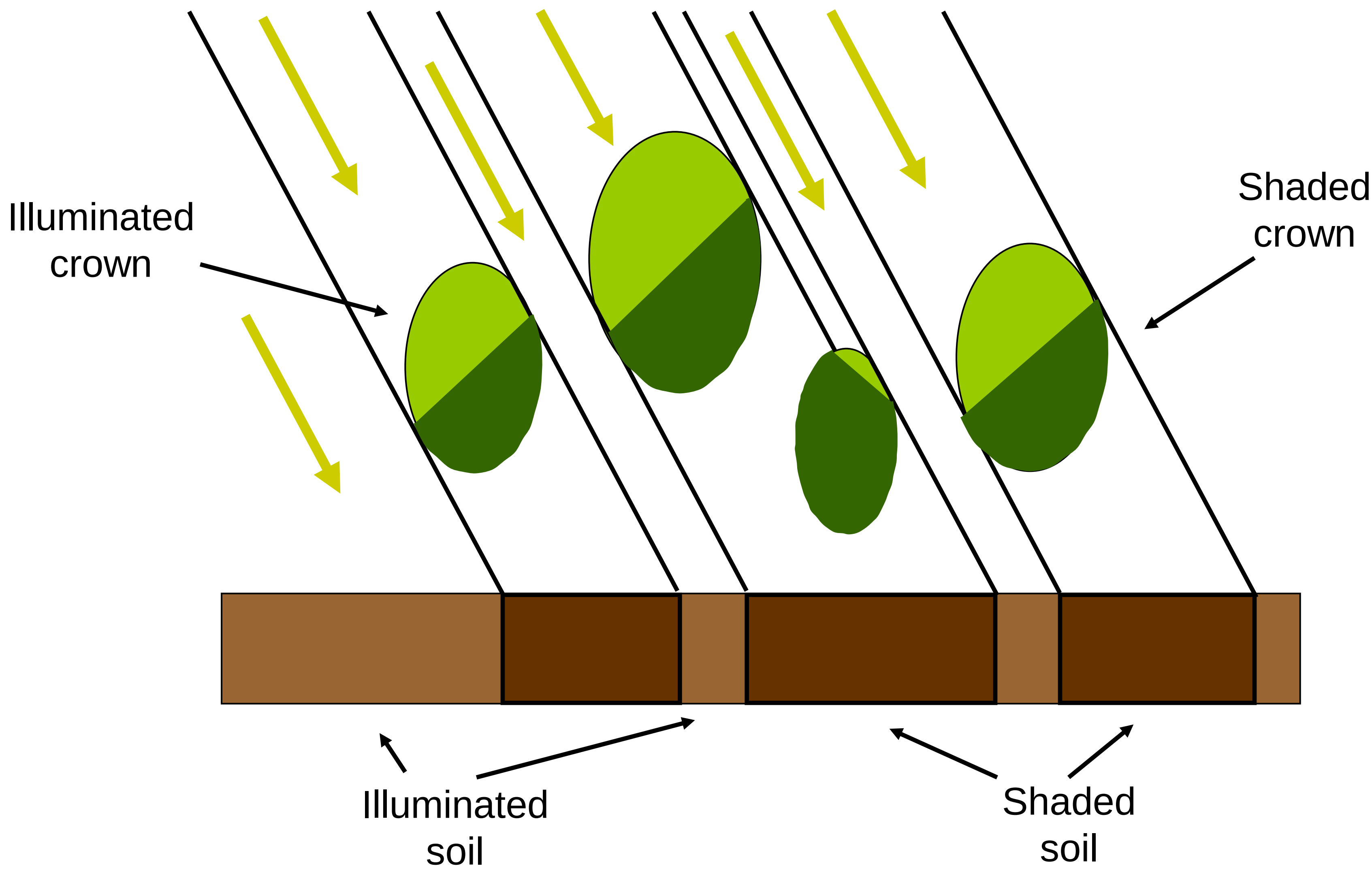
Clumping



Shadowing



Geometric optics

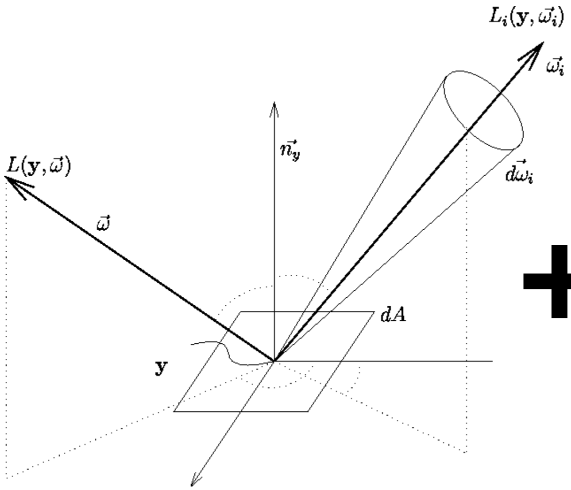


Operational models

- Probably the minimum model required to be general enough to work for most vegetation types requires some element of radiative transfer and geometric optics
- However such models are typically very difficult and/or time consuming to invert

Kernel driven BRDF model

surface BRDF =



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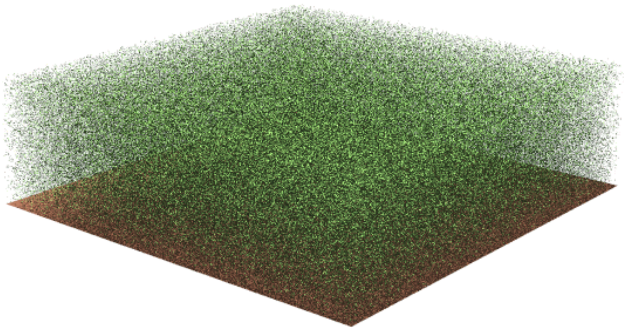

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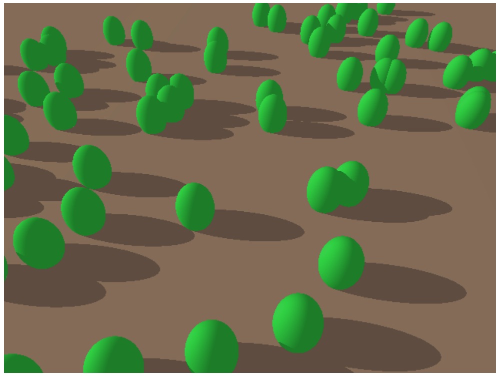


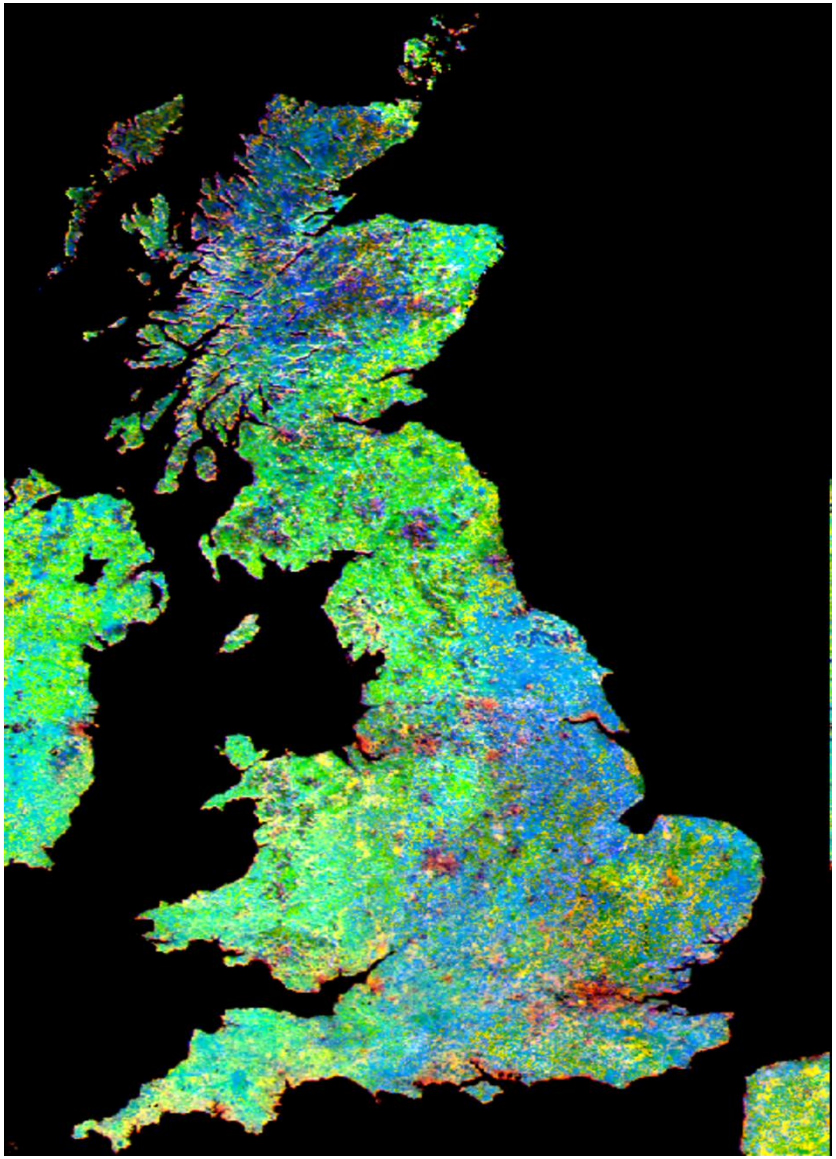
ISOTROPIC **VOLUMETRIC** **GEOMETRIC**

Kernel driven BRDF model

$$\rho(\Omega, \Omega', \lambda) = \sum_{j=1}^{n} f_j(\lambda) K_j(\Omega, \Omega')$$

f = kernel weight
K = kernel value
n = number of kernels

λ = wavelength
ρ = BRF
Ω = view geometry
Ω' = illumination geometry



Dominant scattering map (near infra red):

Red = Geo
Green = Iso
Blue = Vol

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Kernel driven BRDF model

$$y=Hx$$

H is known for any given geometry, so if **y** can be determined this enables:

- Calculation of integral terms (e.g. albedo)
- Normalisation of data to common geometries
- Higher level data processing (e.g. burn scars)

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Kernel driven BRDF model - albedo

$$\alpha = \mathbf{a}\mathbf{x}$$

- Where **a** is a vector of (pre-computed) integrals of the BRDF kernels
- N.B. α is a spectral albedo in this case

Formulation of H

$$H = \begin{pmatrix} K_{iso}(\Omega_1; \Omega'_1) & K_{vol}(\Omega_1; \Omega'_1) & K_{geo}(\Omega_1; \Omega'_1) \\ K_{iso}(\Omega_2; \Omega'_2) & K_{vol}(\Omega_2; \Omega'_2) & K_{geo}(\Omega_2; \Omega'_2) \\ K_{iso}(\Omega_3; \Omega'_3) & K_{vol}(\Omega_3; \Omega'_3) & K_{geo}(\Omega_3; \Omega'_3) \\ K_{iso}(\Omega_4; \Omega'_4) & K_{vol}(\Omega_4; \Omega'_4) & K_{geo}(\Omega_4; \Omega'_4) \\ K_{iso}(\Omega_5; \Omega'_5) & K_{vol}(\Omega_5; \Omega'_5) & K_{geo}(\Omega_5; \Omega'_5) \\ \vdots & \vdots & \vdots \\ K_{iso}(\Omega_n; \Omega'_n) & K_{vol}(\Omega_n; \Omega'_n) & K_{geo}(\Omega_n; \Omega'_n) \end{pmatrix}$$

Formulation of y

$$
y = \begin{pmatrix} \rho(\Omega_1; \Omega'_1; \lambda) \\ \rho(\Omega_2; \Omega'_2; \lambda) \\ \rho(\Omega_3; \Omega'_3; \lambda) \\ \rho(\Omega_4; \Omega'_4; \lambda) \\ \rho(\Omega_5; \Omega'_5; \lambda) \\ \vdots \\ \rho(\Omega_n; \Omega'_n; \lambda) \end{pmatrix}
$$

Formulation of x

$$x = \begin{pmatrix} f_{iso}(\lambda) \\ f_{vol}(\lambda) \\ f_{geo}(\lambda) \end{pmatrix}$$

Least squares (over determined case)

$$x = (H^T R^{-1} H)^{-1} H^T R^{-1} y$$

- Formulation used for the MODIS BRDF/albedo product (MCD43)
- Requires an 16 day window

Observation errors

$$\mathbf{R} = r\mathbf{I} = \begin{pmatrix} r & 0 & 0 & \cdots \\ 0 & r & 0 & \cdots \\ 0 & 0 & r & \cdots \\ \vdots & \vdots & \vdots & \ddots \end{pmatrix}$$

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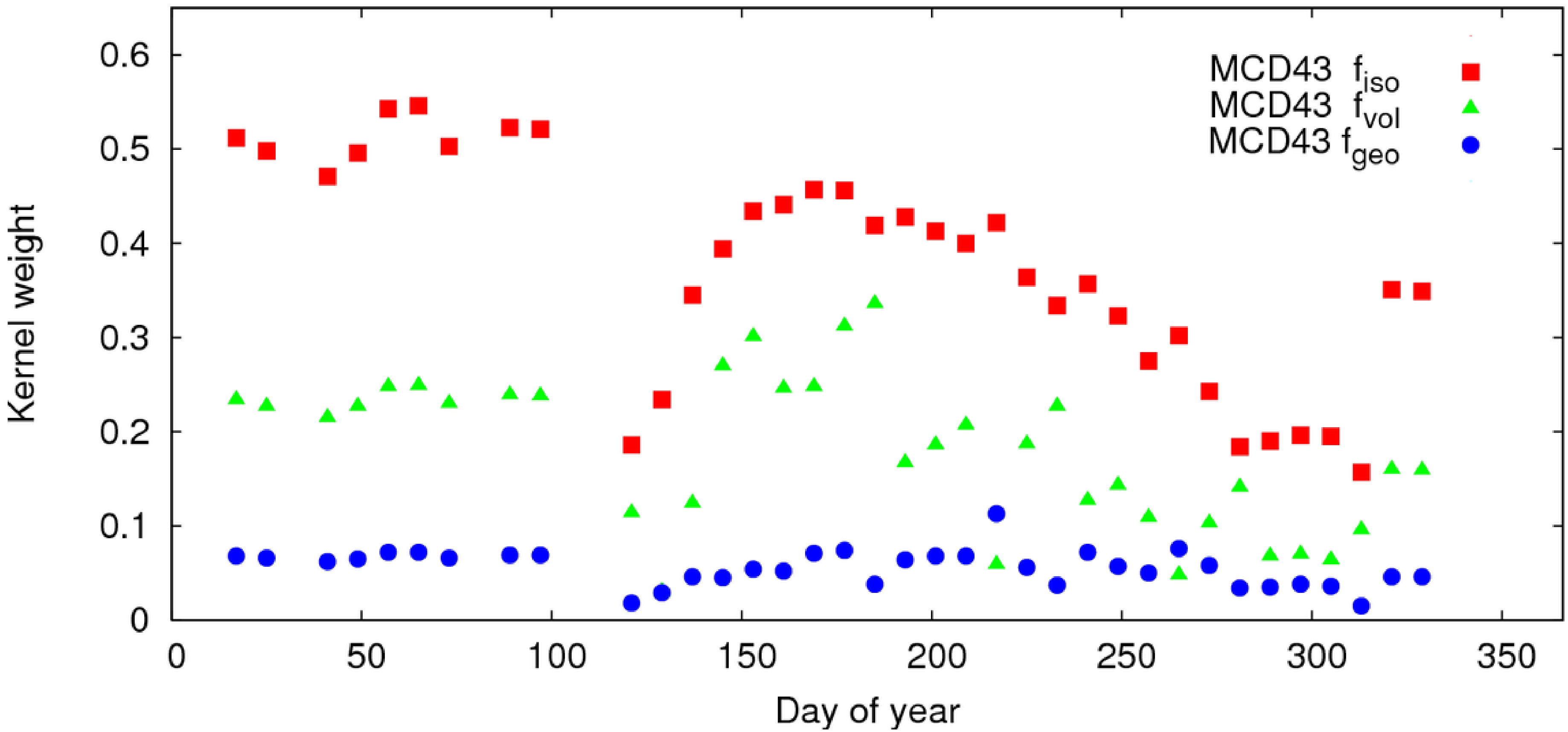
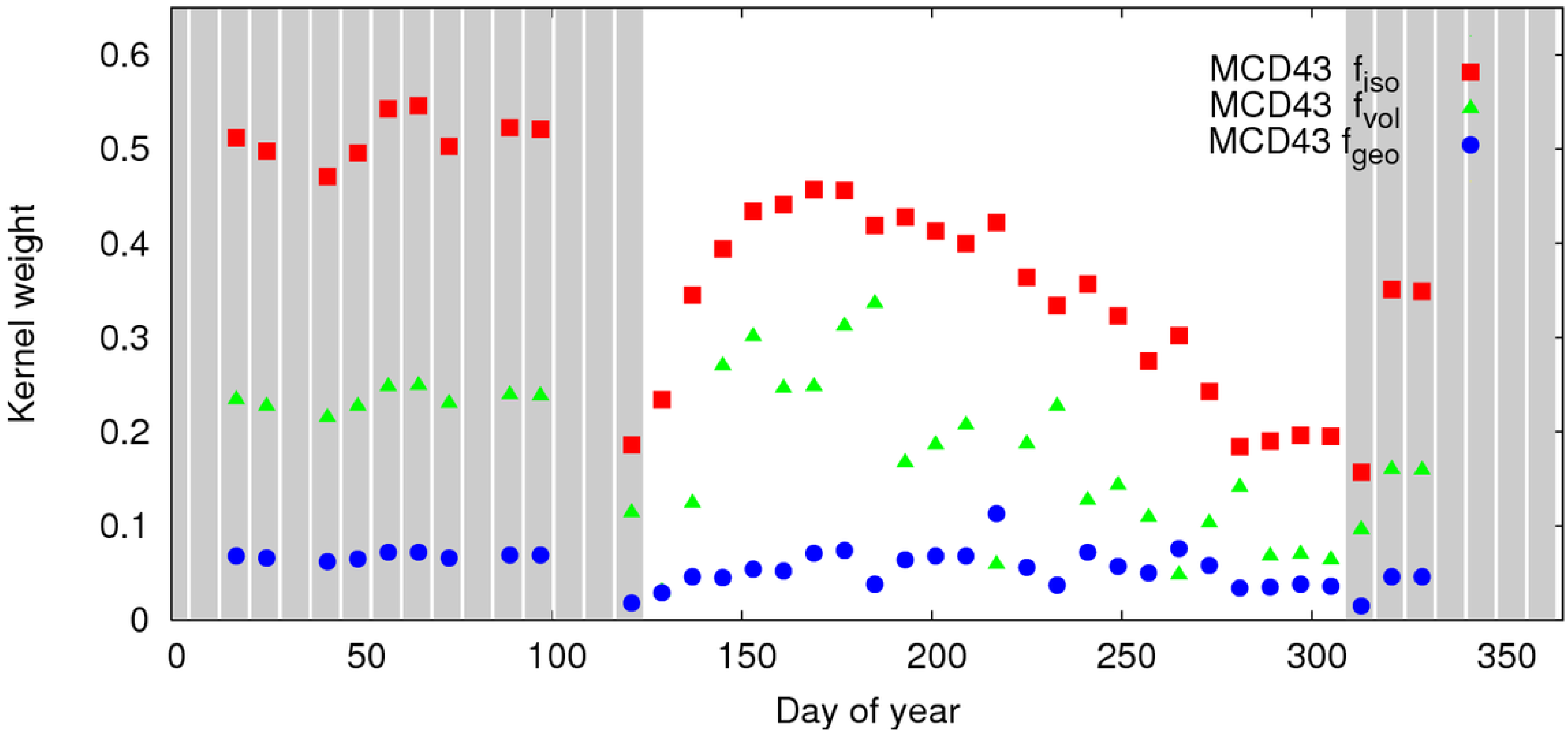
MODIS data product (MOD43)



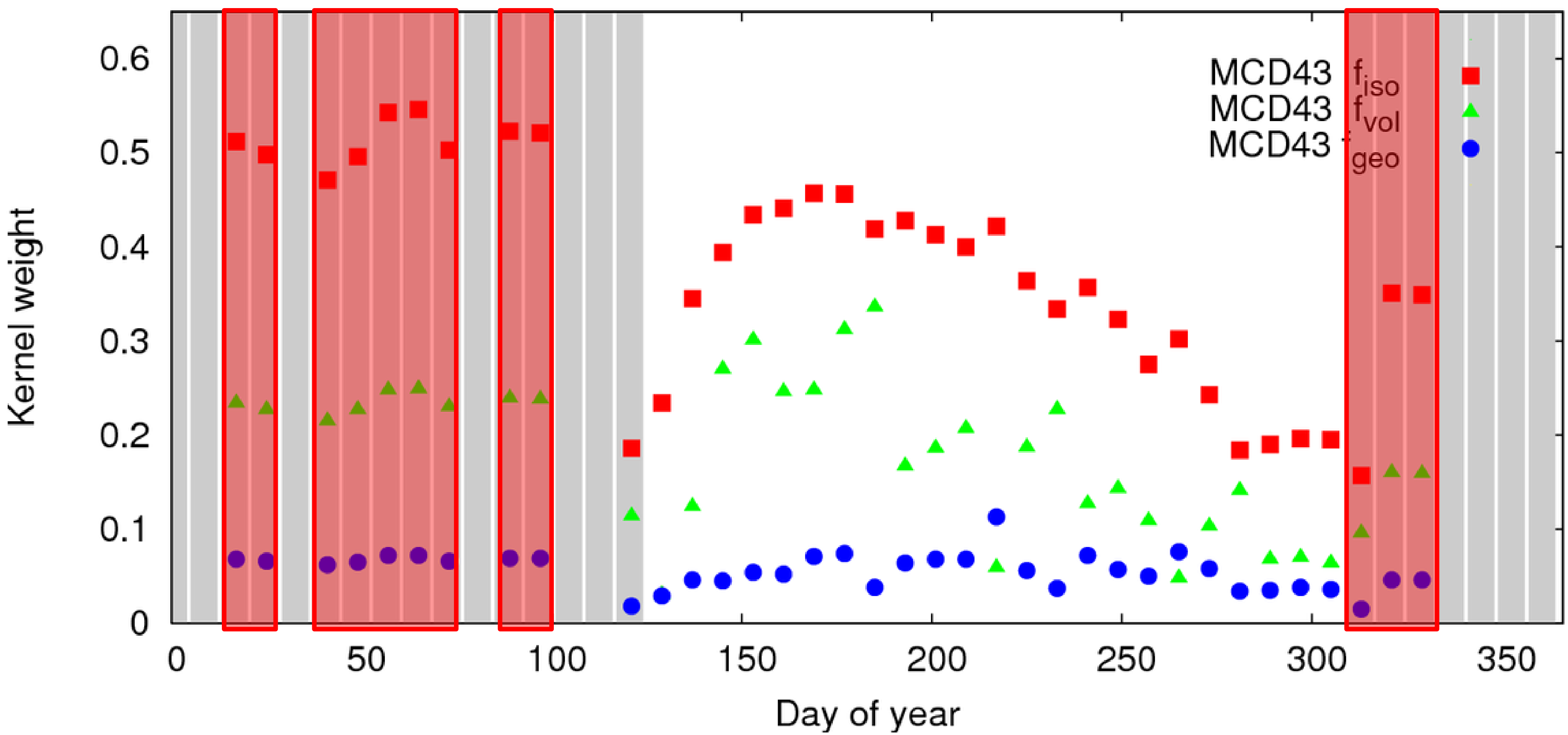
MODIS band 2: NIR

MODIS data product (MOD43)



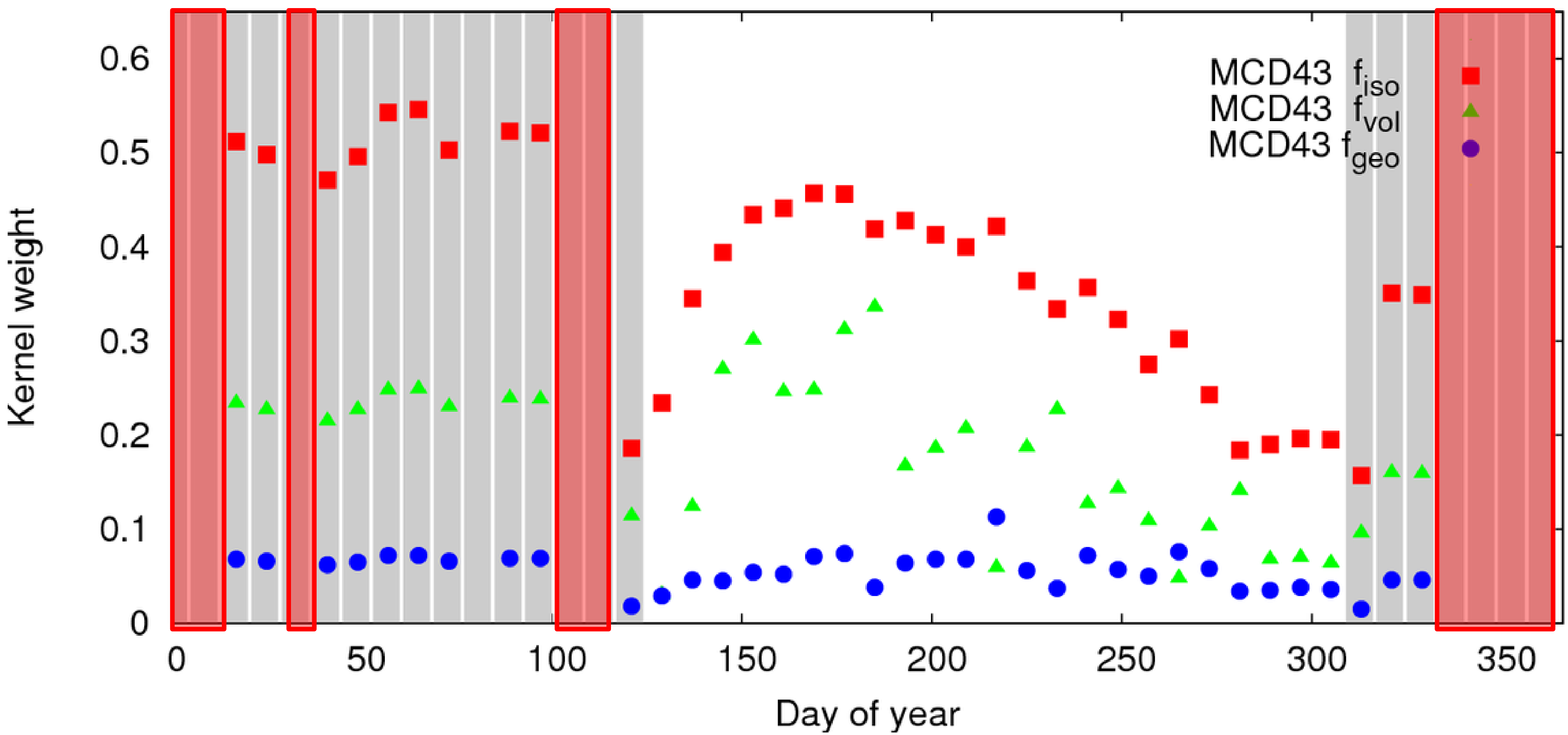
MODIS band 2: NIR

MODIS data product (MOD43)



Backup inversion algorithm used

MODIS data product (MOD43)



No inversion!

Potential improvements

- Eliminate use of the backup algorithm
- Produce daily estimates of kernel weights
  - to improve timing of events
  - best estimates where no data
- Reduce noise in parameters

Data assimilation

- A key weakness of the NASA algorithm is that the inversions are not constrained in anyway by the preceding inversion results
- This is a clear opportunity to apply data assimilation techniques…

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Kalman filter

$$x^a = x + K(y - Hx)$$

- Additional requirements:
  - Dynamic model (M)
  - Model covariance (P) and forcing (Q)
  - Estimate of initial state

For simplicity…

$$M = I = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

For simplicity…

$$P = pI = \begin{pmatrix} p & 0 & 0 \\ 0 & p & 0 \\ 0 & 0 & p \end{pmatrix}$$

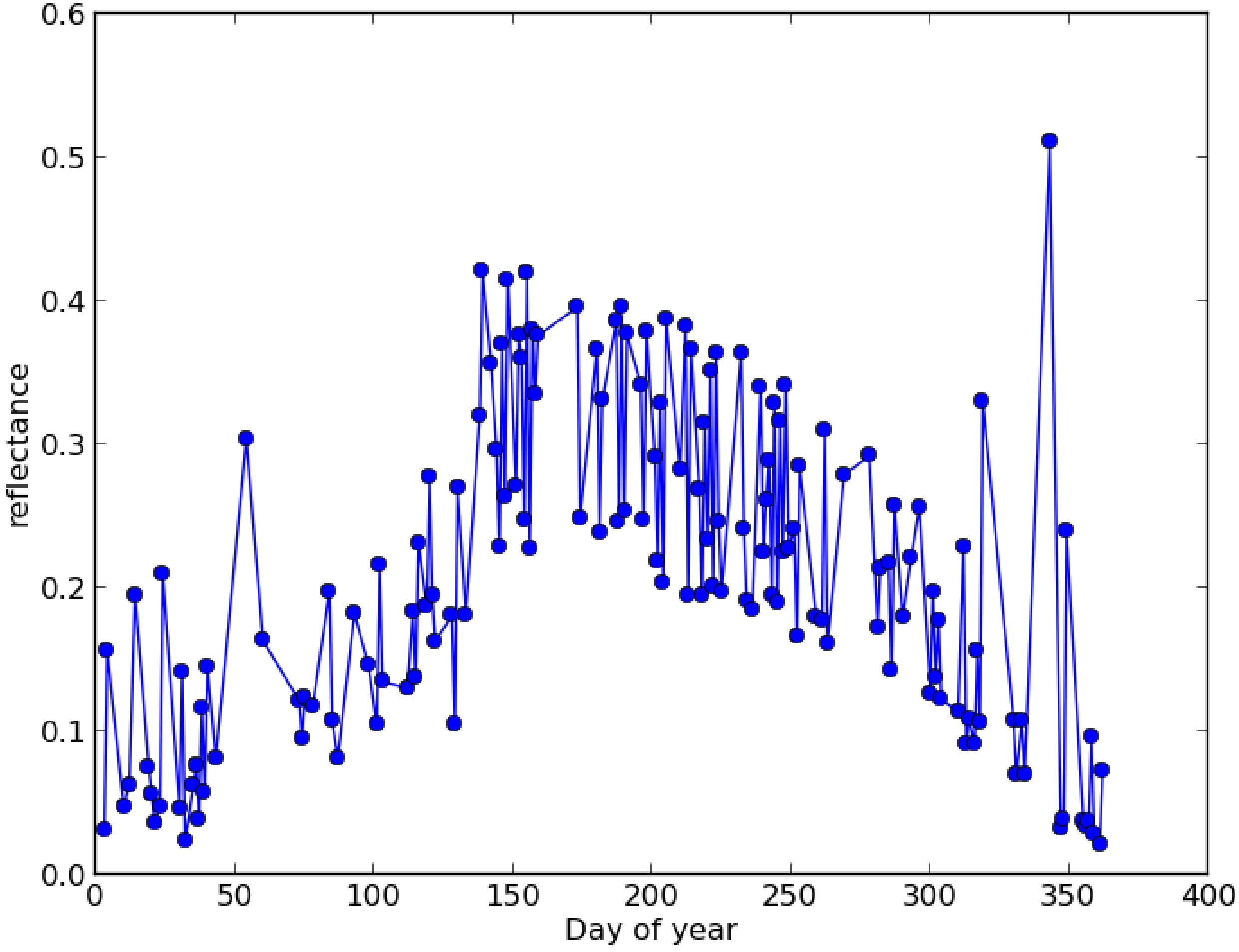
Peculiarities of the system 1

- Each observation is a linear combination of all state vector elements, and…
- …the dynamic model is not really dynamic
- Consequently small numbers of observations in the analysis window will produce odd state estimates (which still fit the observations well)

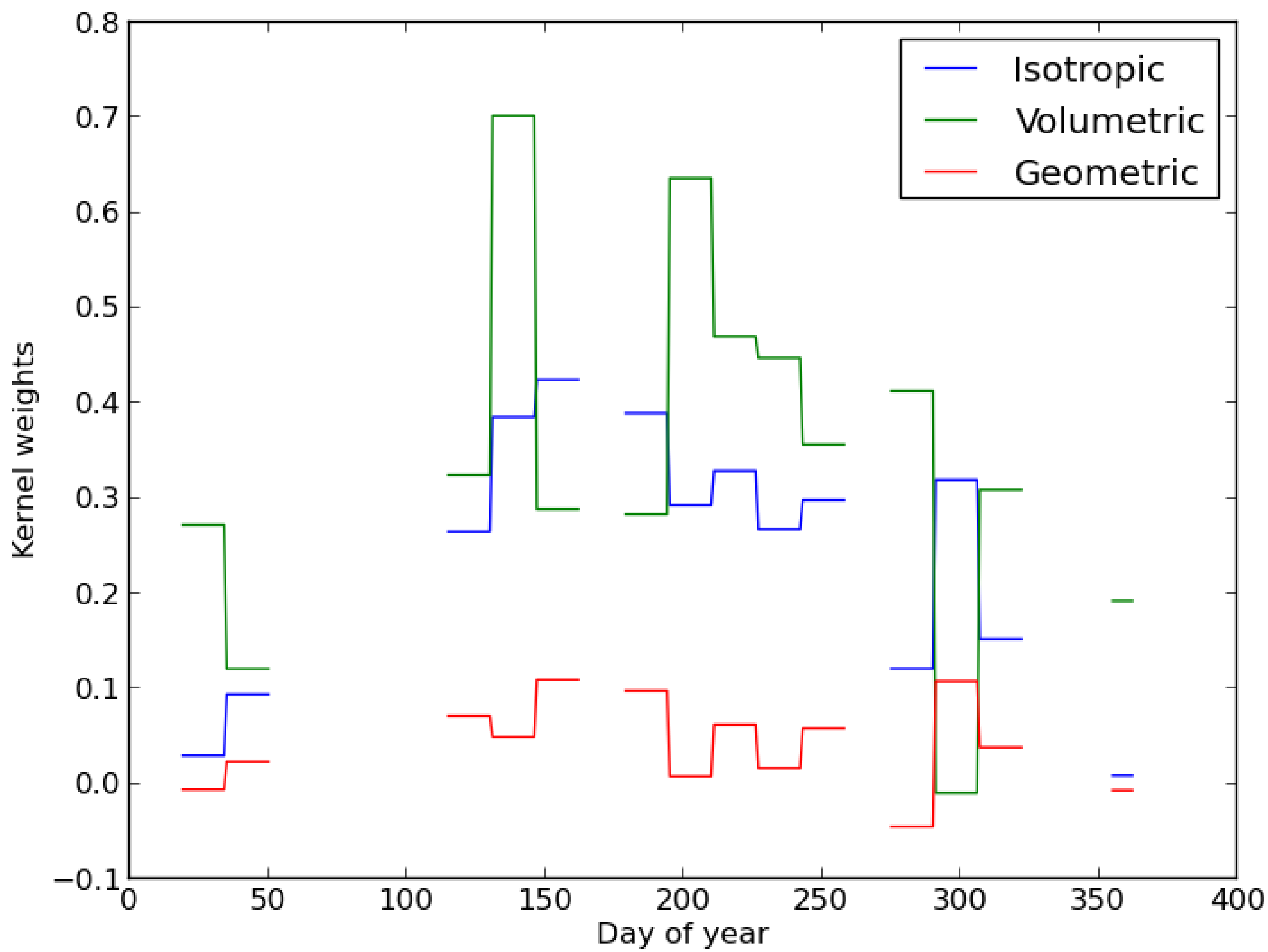
Peculiarities of the system 2

- The values of the state elements are unitless and not readily interpreted in terms of things we can observe on the ground
  - Sometimes qualitative analysis used
- Consequently validation of the state vector values is more-or-less impossible and we have to resort to comparing y and Hx^a

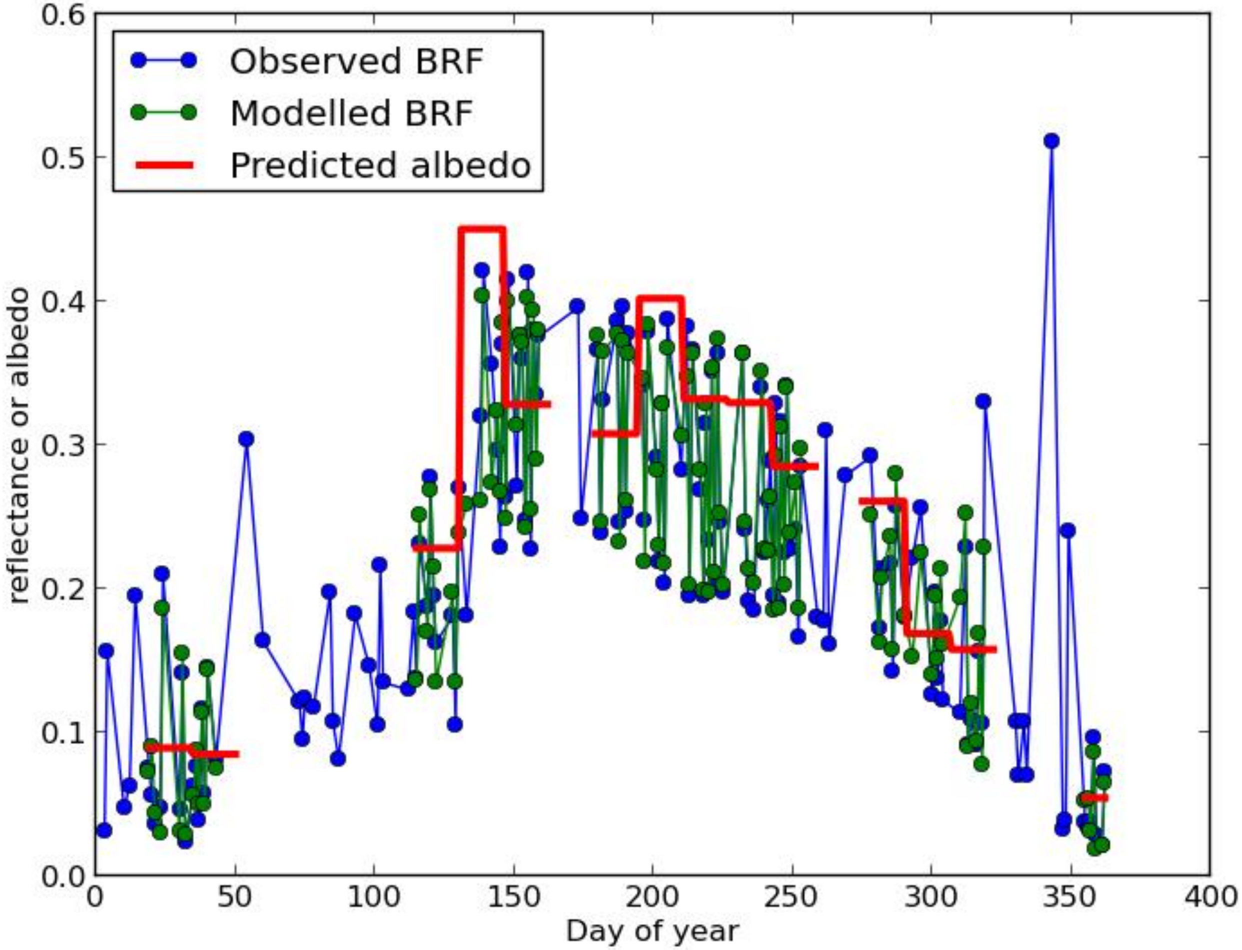
Example – reflectance data



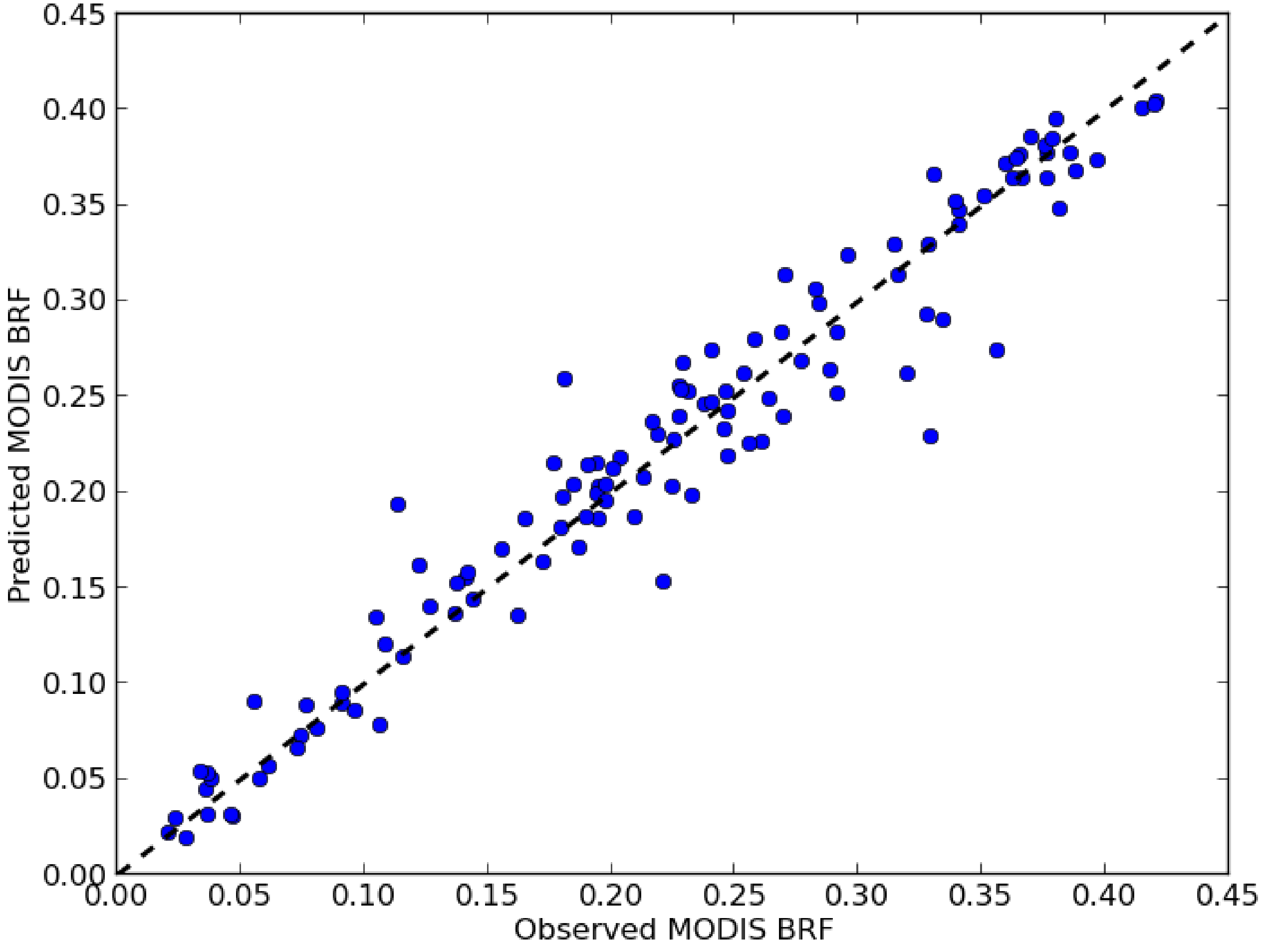
Example – retrieved kernel weights



Example – predictions of BRF & albedo



Example – predicted vs. observed BRF



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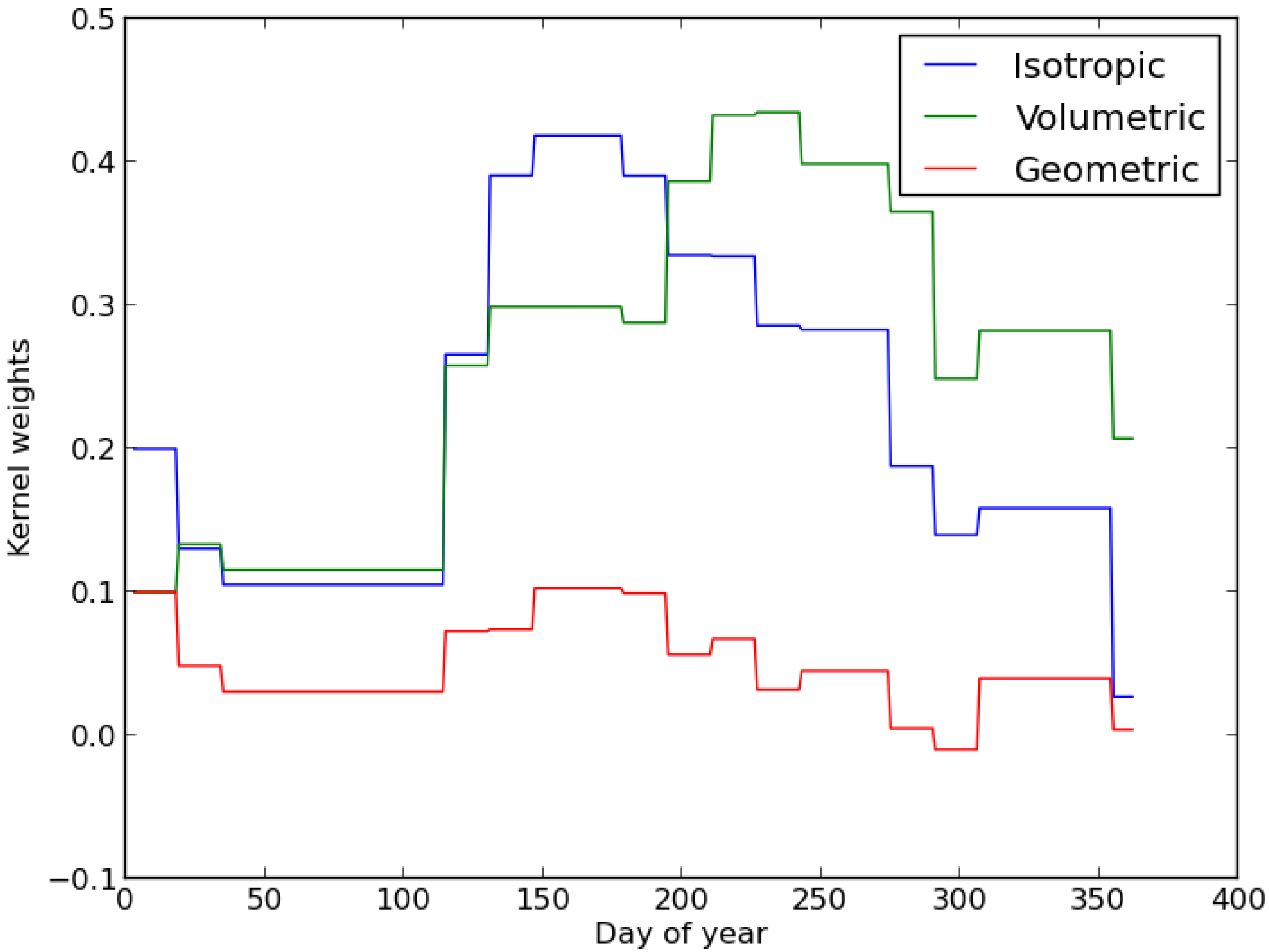

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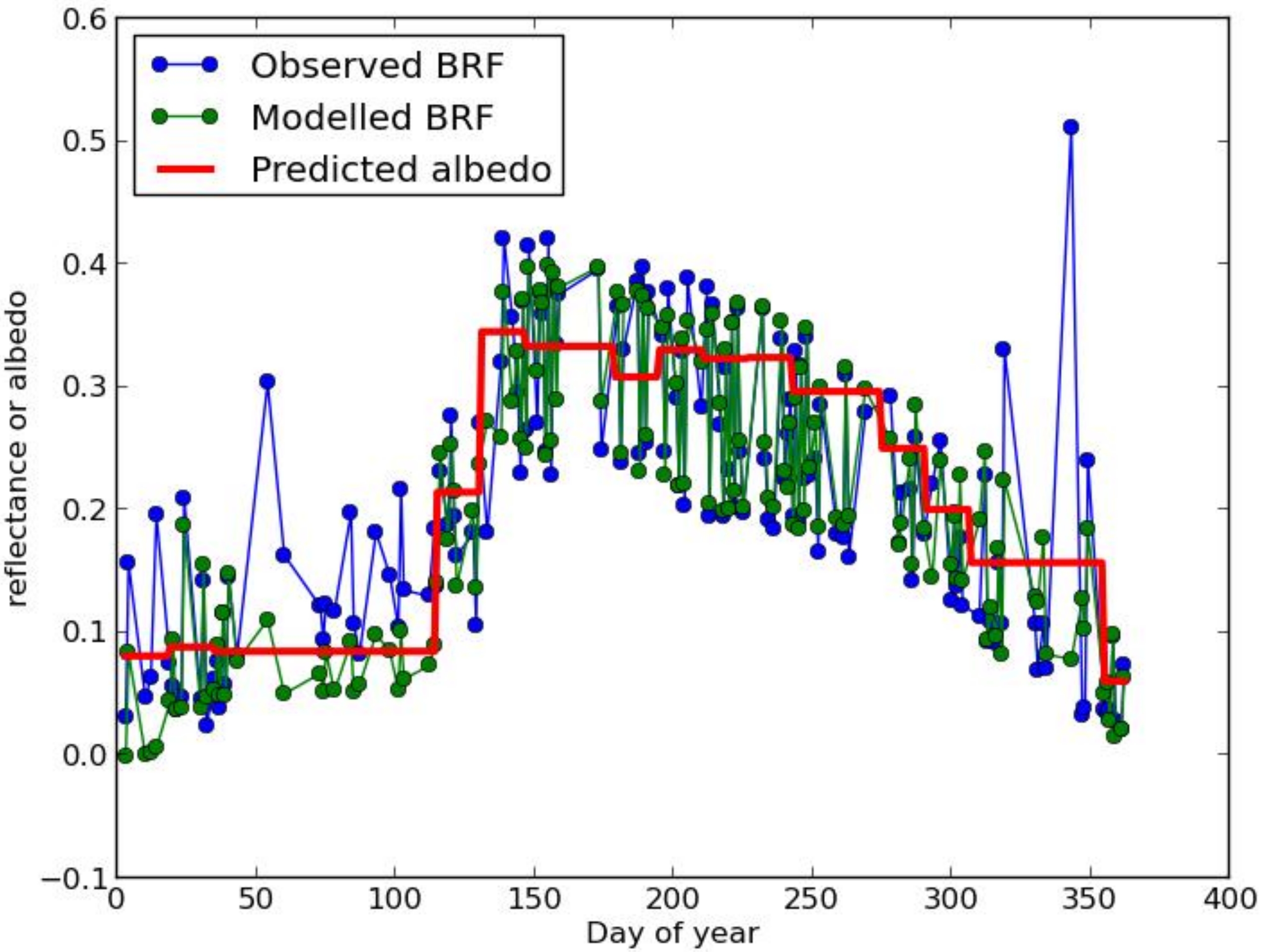

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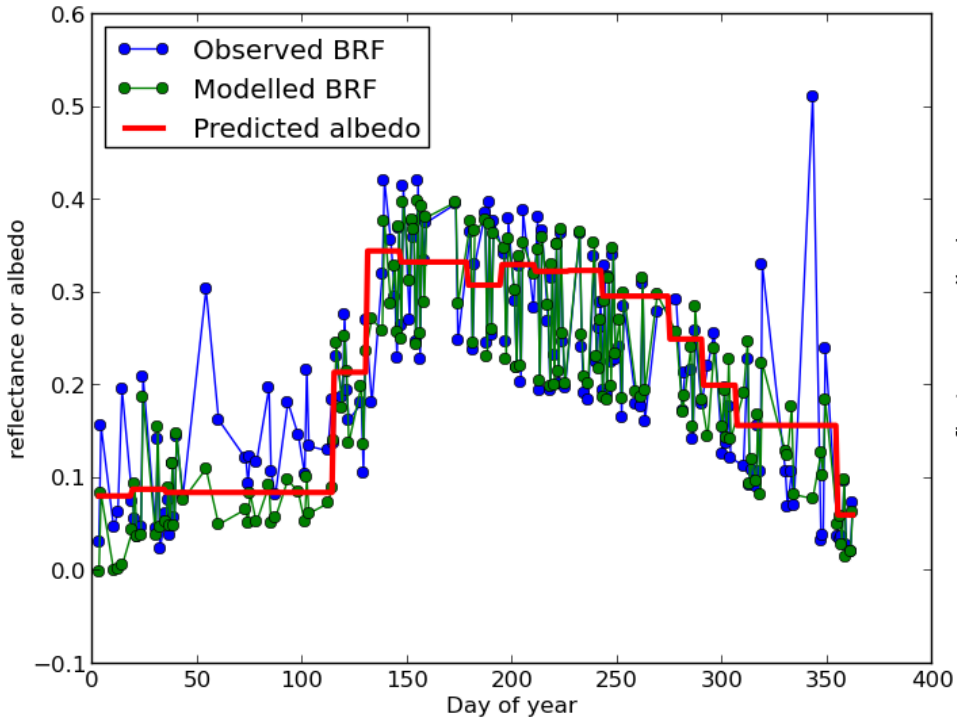

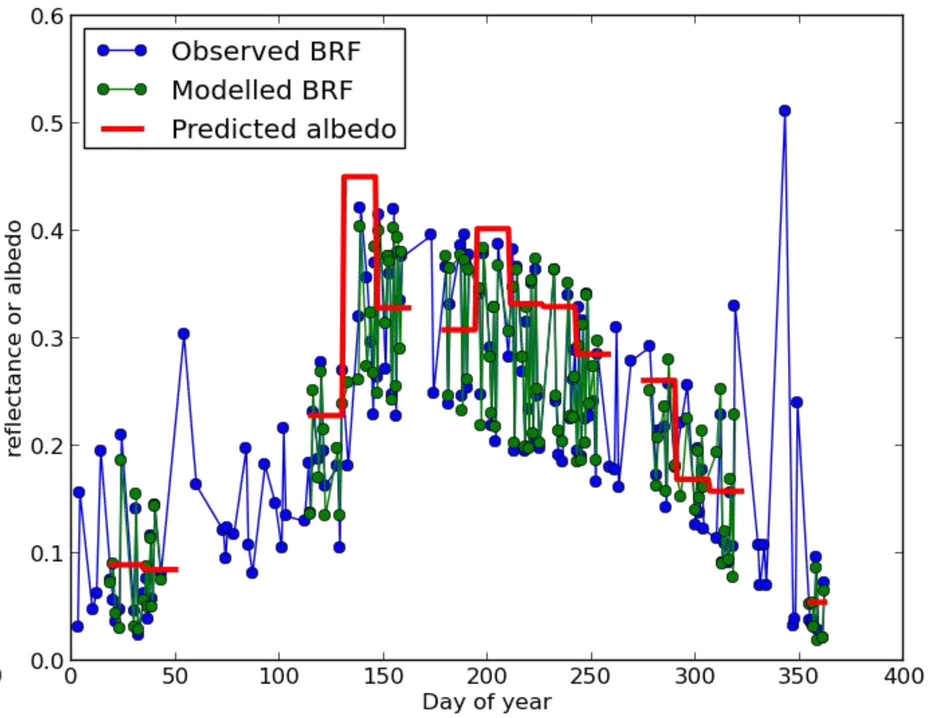

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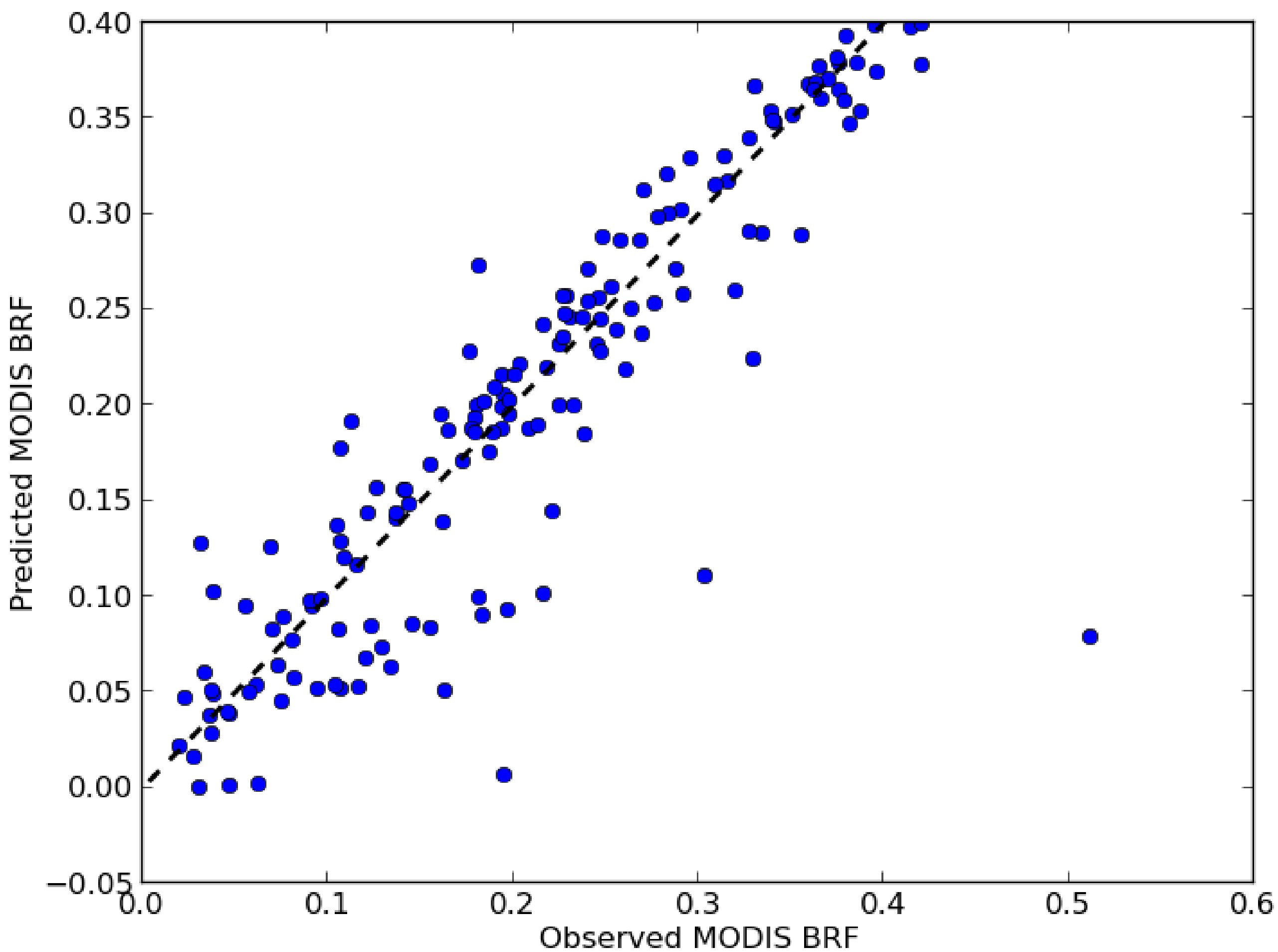
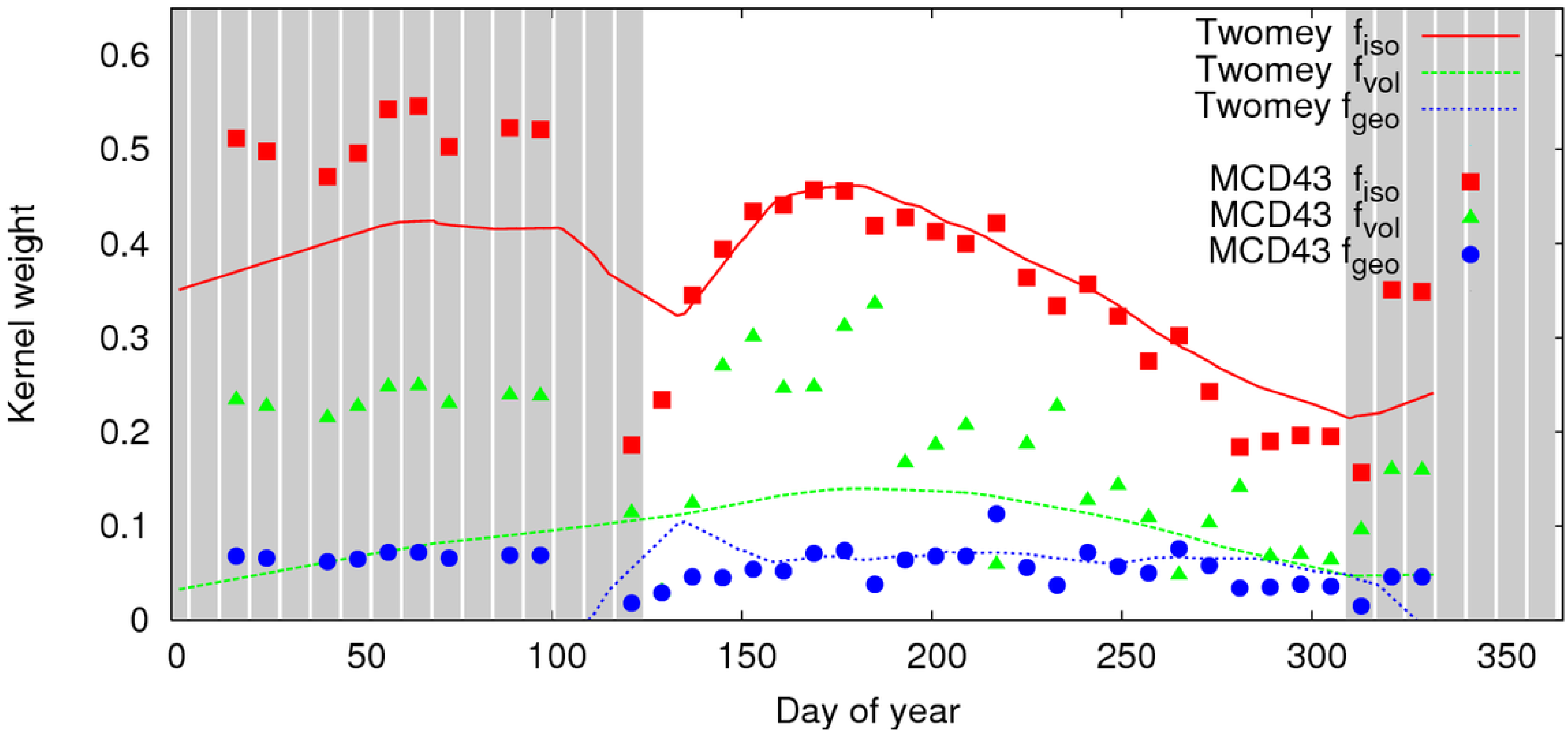
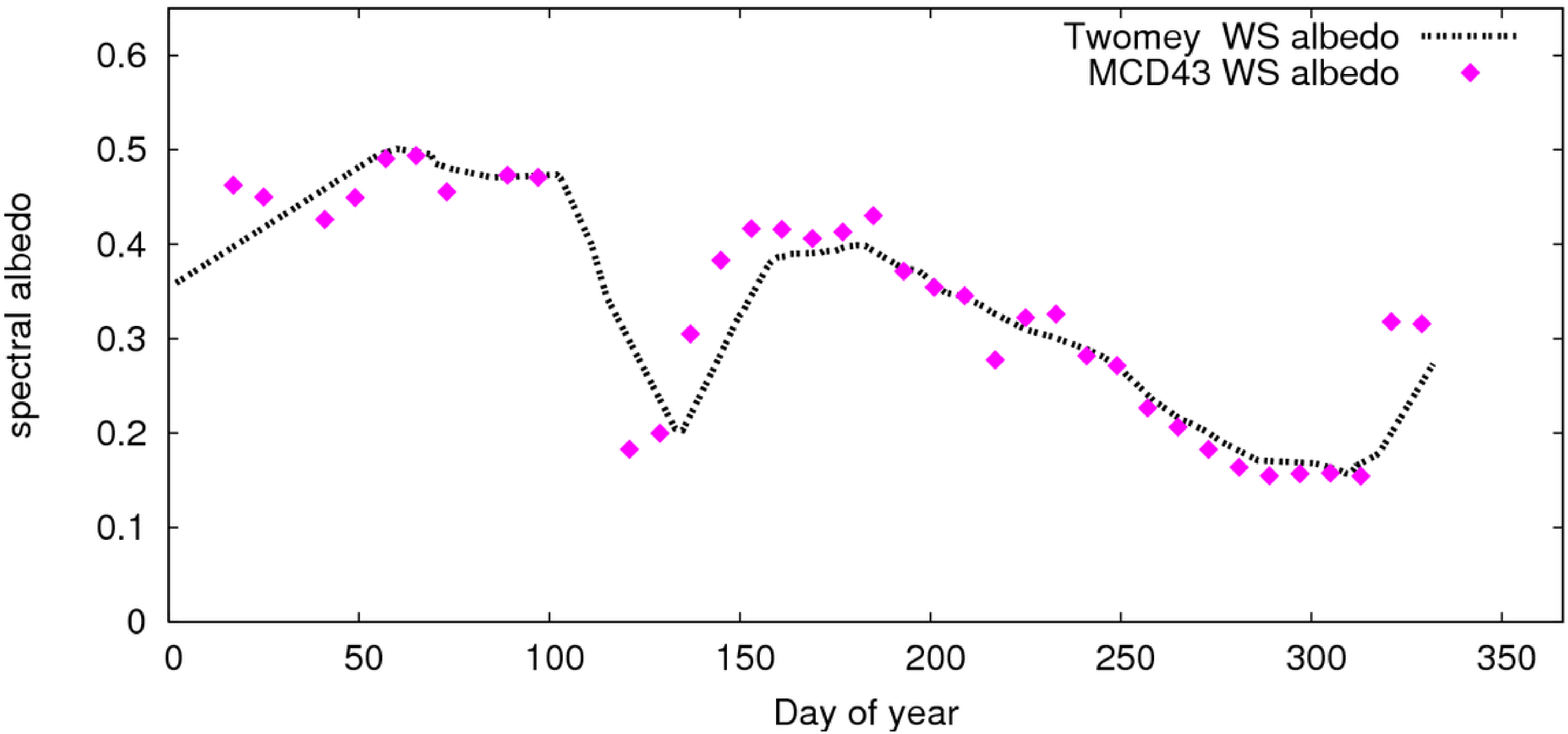


In the practical you will…

- Experiment with changing:
  - P, Q, R
  - The size of the analysis window
  - The spectral channel & sensor
- Also there are data from two regions:
  - Spain (nice, cloud free data)
  - Siberia (sparse, cloudy data)



Quaife and Lewis (2010) Temporal constraints on
linear BRDF model parameters. IEEE TGRS



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EOLDAS

- European Space Agency Project to improve data retrievals and inter-sensor calibration
- Weak constraint variational DA scheme using the following cost function:

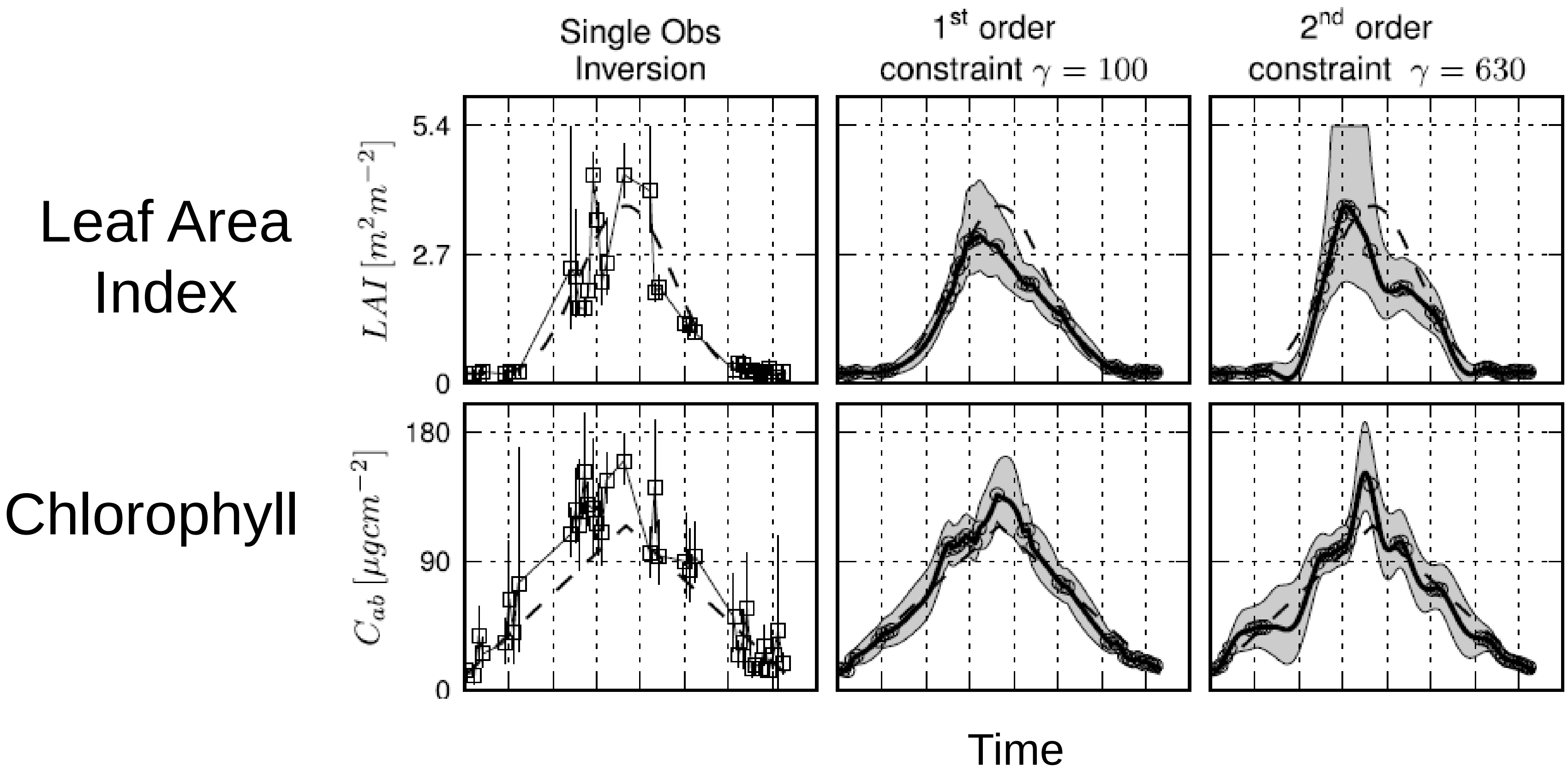
$$J = J_{obs} + J_{smooth}$$

$$J_{obs} = (1/2)(\mathbf{y}_{\mathrm{obs}} - H(\mathbf{x}))^T(\mathbf{C}_{\mathrm{obs}}{}^{-1} + \mathbf{C}_{\mathbf{H}}{}^{-1})(\mathbf{y}_{\mathrm{obs}} - H(\mathbf{x}))$$

$$J_{smooth} = (1/2)\gamma^2(\mathbf{\Delta x})^T\mathbf{C}_{\mathrm{smooth}}{}^{-1}(\mathbf{\Delta x})$$

http://www.eoldas.info/

EOLDAS examples



Lewis P, Gomez-Dans J, Kaminski T, Settle J, Quaife T, Gobron N, Styles J & Berger M (2012), An Earth Observation Land Data Assimilation System (EOLDAS), *Remote Sensing of Environment*.