KOLMEMÕÕTMELINE KIIRGUSLEVI VÕRRAND TAIMKATTE KAUGSEIRE TEOREETLISE ALUSENA

3D RADIATIVE TRANSFER EQUATION AS THEORETICAL BASIS FOR VEGETATION REMOTE SENSING

Juri Knjazihhin
(*Yuri Knyazikhin*)
Boston Ülikool, Boston, Ameerika Ühendriigid
Boston University, Boston, USA

JUHAN ROSSI PÄRANDI SÜMPOOSION
TARTU OBSERVATOORIUM , TÕRAVERE, EESTIMAA
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3D RADIATIVE TRANSFER IN VEGETATION CANOPY

$$\Omega\nabla I_\lambda + \sigma(r,\Omega)I_\lambda(r,\Omega) = \int_{4\pi} \sigma_{s,\lambda}(r,\Omega' \to \Omega)I_\lambda(r,\Omega')d\Omega'$$

$$\sigma(r,\Omega) = u_L(r)G(r,\Omega)$$

$$\frac{1}{2\pi}\int_{2\pi^+} g_L(r,\Omega_L)|\Omega\cdot\Omega_L|d\Omega_L = G(r,\Omega)$$

$$\sigma_s(r,\Omega' \to \Omega) = u_L(r)\frac{1}{\pi}\Gamma_\lambda(r,\Omega' \to \Omega)$$

$$\frac{1}{2\pi}\int_{2\pi^+} g_L(r,\Omega_L)|\Omega\cdot\Omega_L||\Omega'\cdot\Omega_L|\gamma_{L,\lambda}(r,\Omega_L)d\Omega_L = \frac{1}{\pi}\Gamma_\lambda$$

Ross' team revolutionary results

- **validity of RTE to describe photon-canopy interaction had been clearly demonstrated**
- **parameterization of its coefficients in terms of foliage area density, $u_L(r)$, leaf normal distribution function, $g_L(r,\Omega_L)$, and leaf scattering phase function, $\gamma_L(r,\Omega_L)$**

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Forward Problem: ***given coefficients, find solution***

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Inverse Problem: *given solution, find coefficients*

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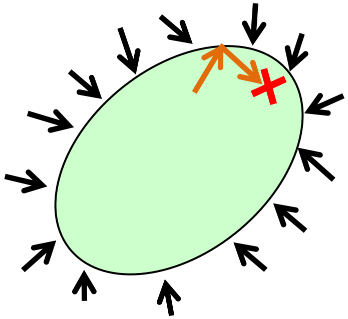
Discuss methodologies and techniques developed in other scientific areas, motivated by other sciences and applications that can be applied in optical remote sensing of vegetation

3D RADIATIVE TRANSFER PROBLEM: BASIC



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  - ➢ **Standard problem:** ***RT problem with nonreflecting boundary***
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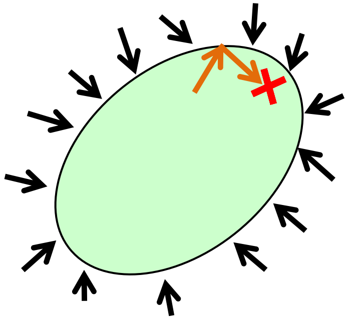

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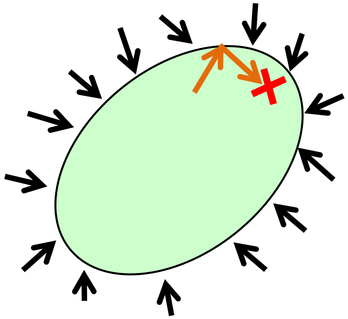

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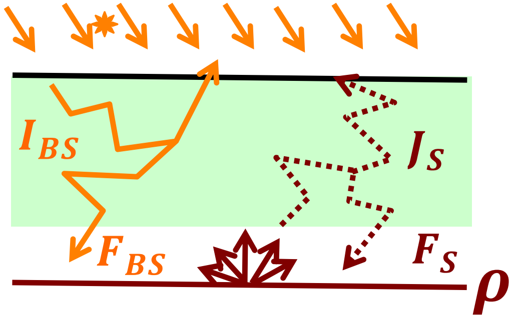

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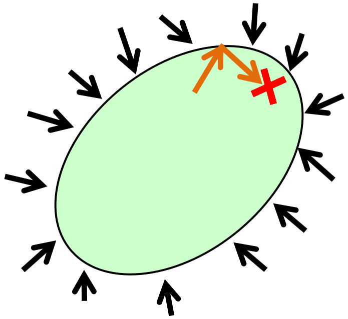

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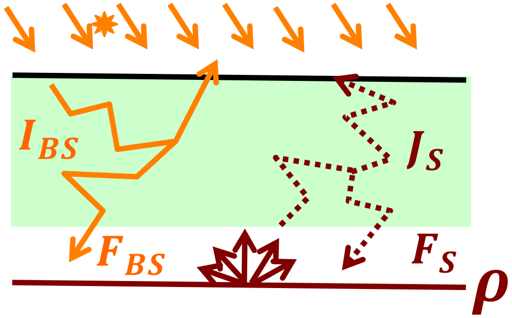

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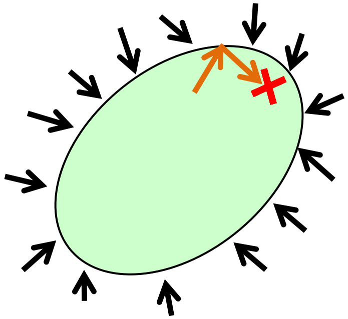

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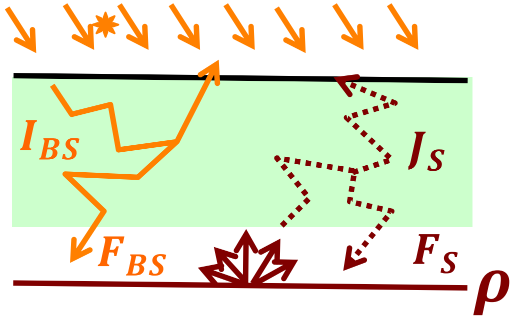

- **Less important for the forward problem**
- **Critical for the inverse problem**

In developing inverse techniques, special emphasis should be given to the standard problem

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3D EFFECTS IN REMOTE SENSING DATA

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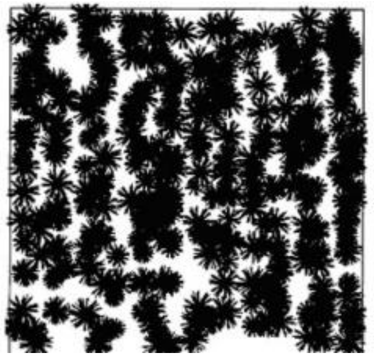

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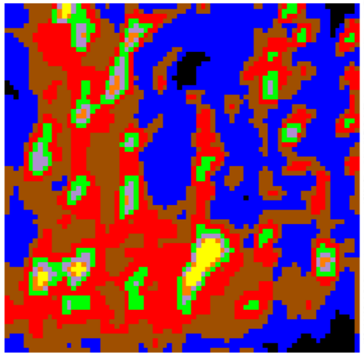

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$$\boldsymbol{I_\lambda(\cancel{r_{\mathrm{top}}}, \Omega)}$$

Mean Intensity

mean intensity emanating from heterogeneous vegetation pixels

$$\boldsymbol{\bar{I}_\lambda(\Omega) = \frac{1}{S}\int_S I_\lambda(r_{\mathrm{top}}, \Omega) dr_{\mathrm{top}}}$$

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Stochastic RTE

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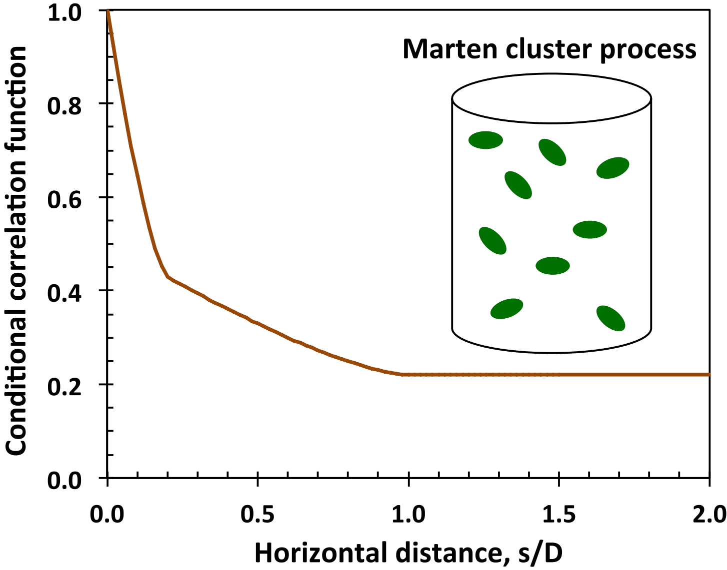
Stochastic RTE

Parameterization of 3D clumped canopy structure: Conitional Pair Correlation Function

$$K(z,\xi,\Omega)$$



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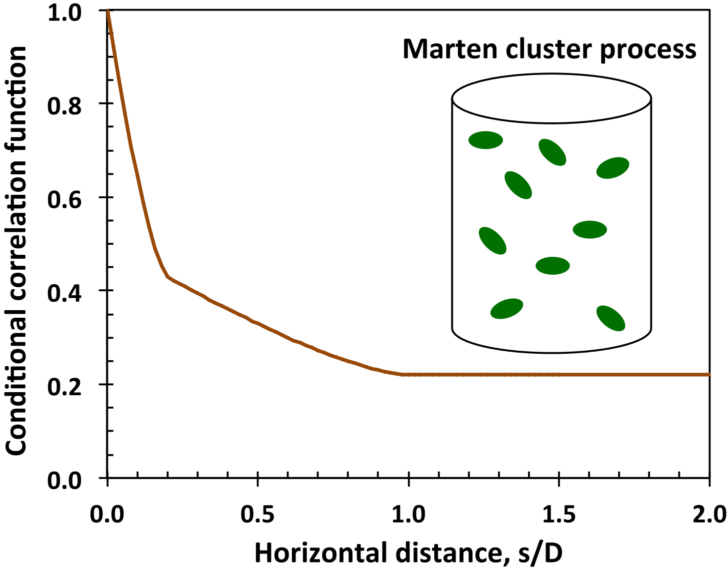
SRTE can reproduce all 3D effects reported in literature



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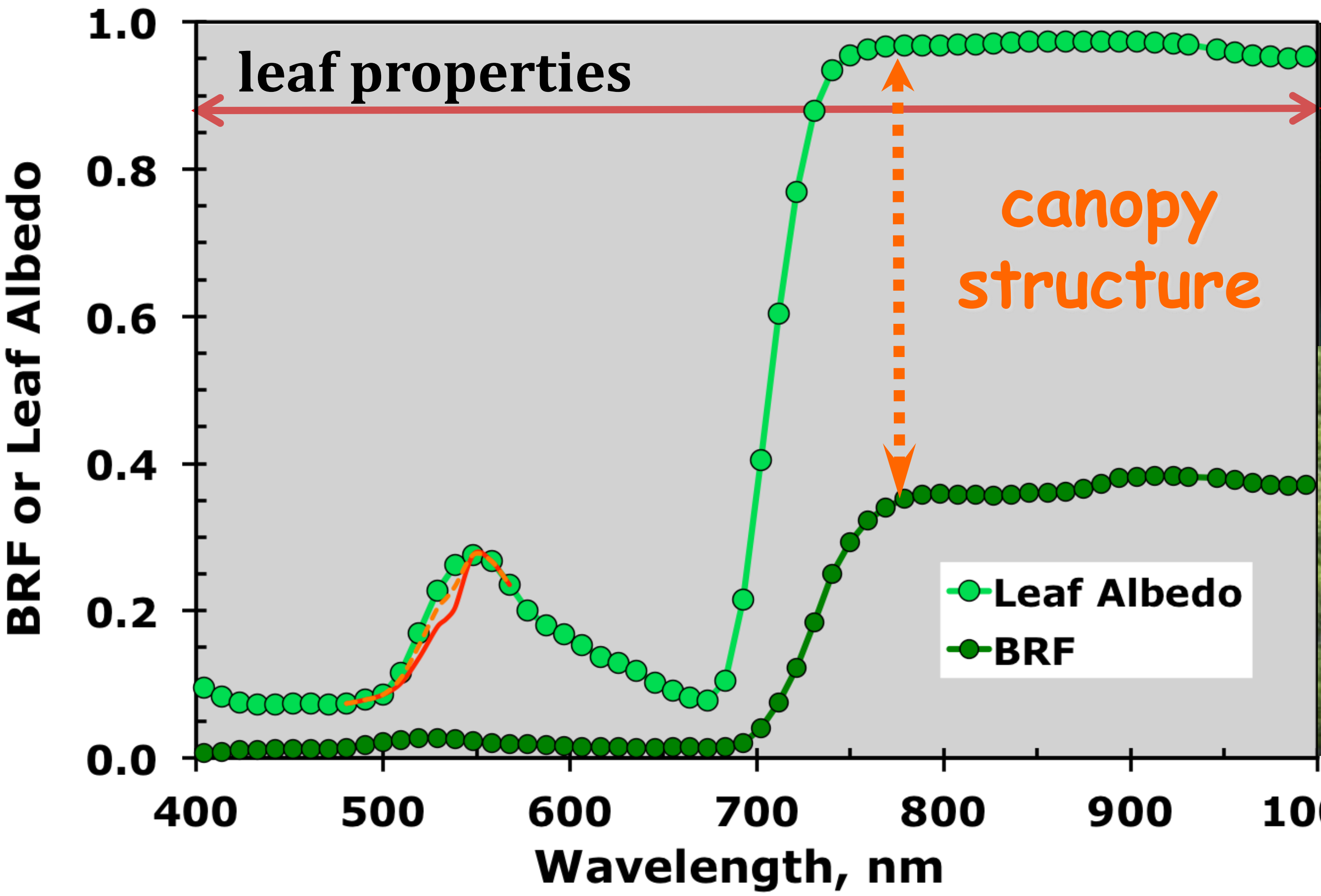
LEAF AND CANOPY SPECTRAL REFLECTANCE



Leaf scattering and canopy reflectance are similar in shape, differ in magnitude

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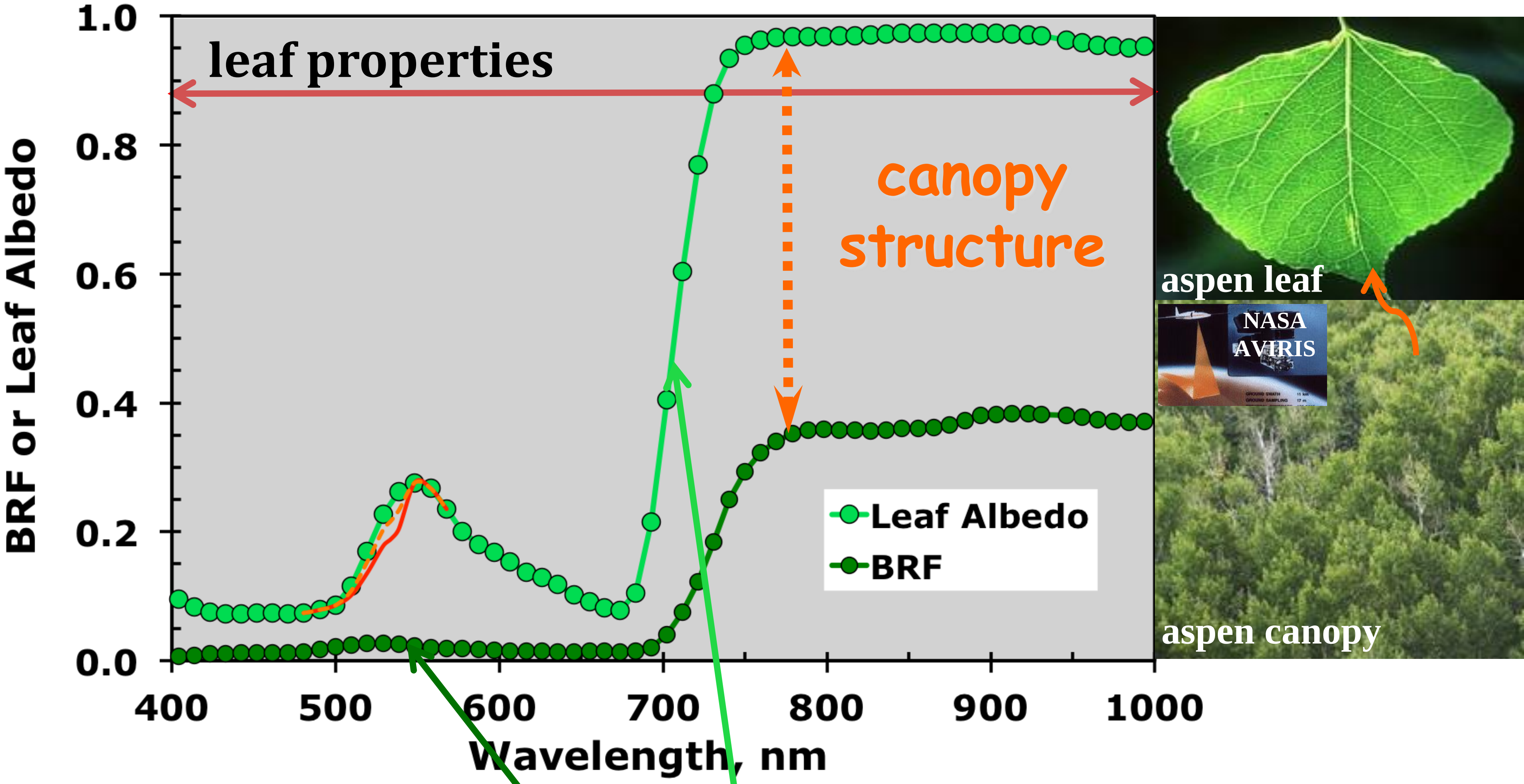

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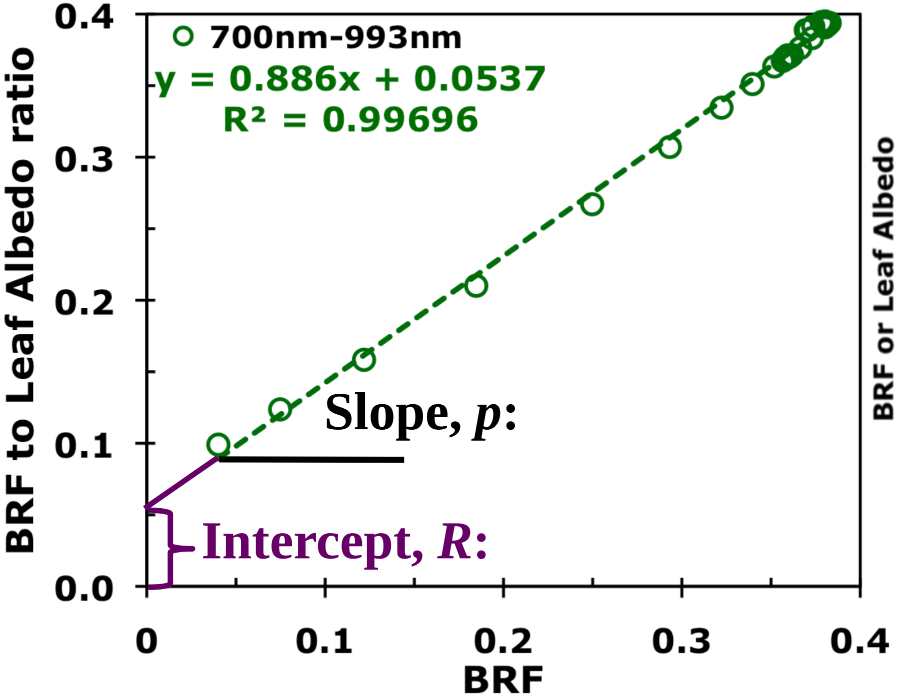
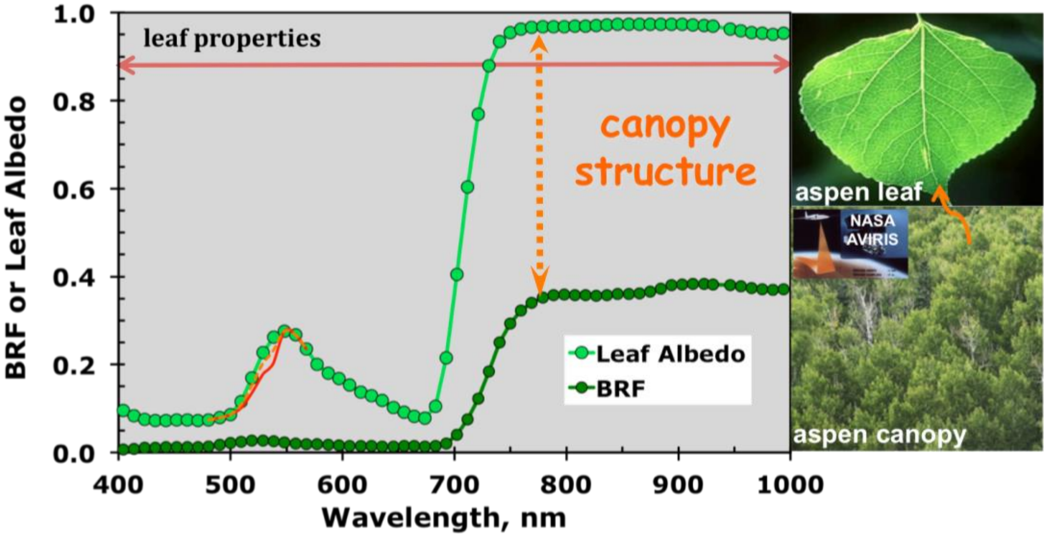
SPECTRAL INVARIANTS IN VEGETATION CANOPIES



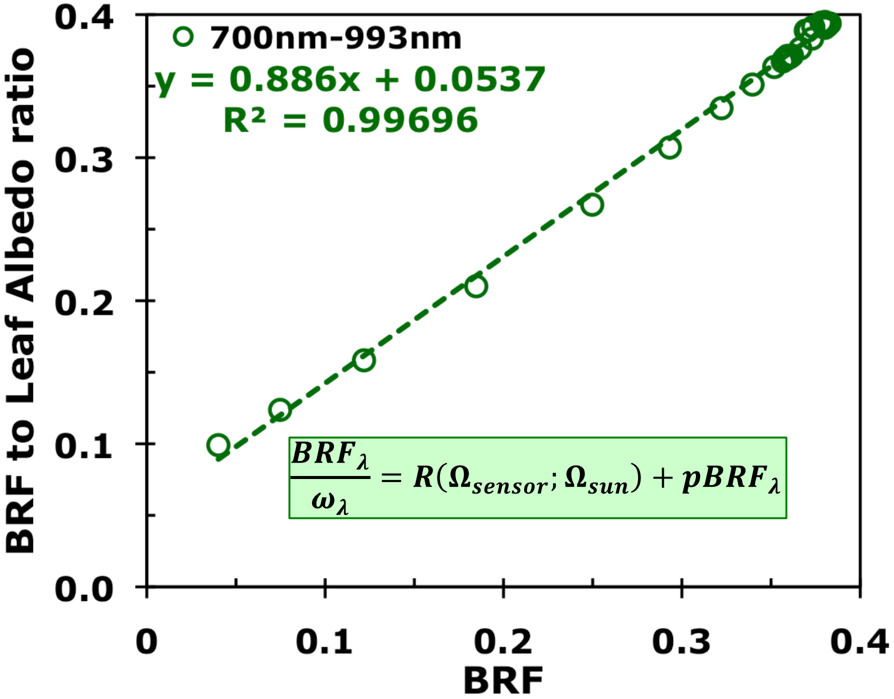


- **BRF to Leaf Albedo Ratio is linearly related to BRF**

$$\frac{BRF_\lambda}{\omega_\lambda} = R(\Omega_{sensor};\Omega_{sun}) + pBRF_\lambda$$

Determined by distribution of photon free path

DECOMPOSITION OF THE STANDARD PROBLEM



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Solution of the *standard RTE*

$$BRF_\lambda = DASF(\Omega_{sensor};\Omega_{sun})W_\lambda$$

Directional Area Scattering Factor: canopy BRF if no absorption

$$DASF = \frac{\rho(\Omega_{sensor};\Omega_{sun})i_0(\Omega_{sun})}{1-p}$$

Canopy scattering coefficient

$$W_\lambda = \omega_\lambda \frac{1-p}{1-p\omega_\lambda}$$

- DASF determines BRF angular shape while the scattering coefficient its magnitude
- Solution of the standard RTE is expressed in terms measurable variables

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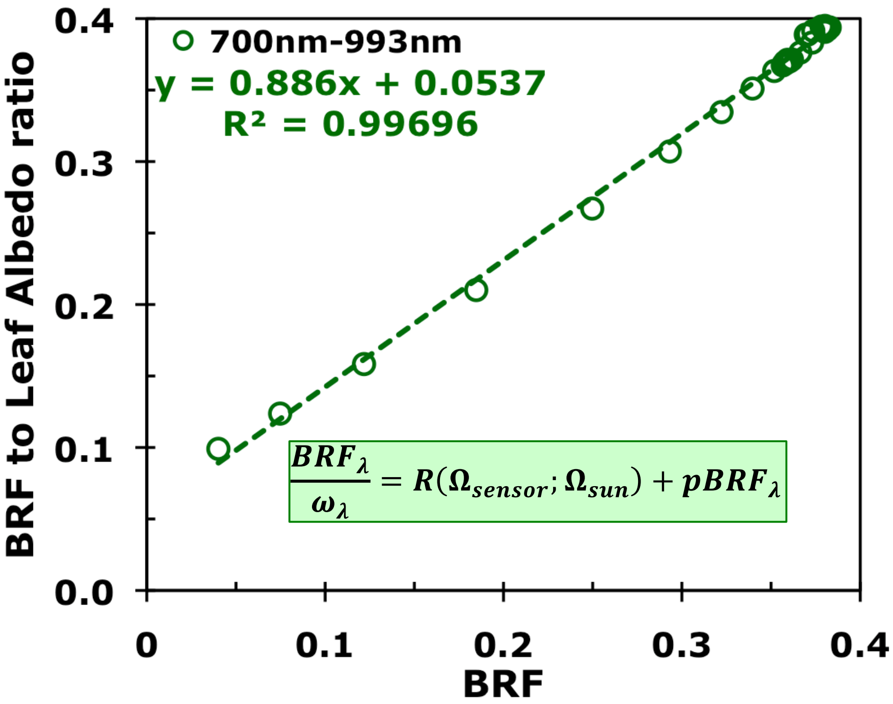

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TRUE AND EFFECTIVE LEAF AREA

$$\boldsymbol{\sigma(\Omega) = G(\Omega)\, u_L\, f}$$

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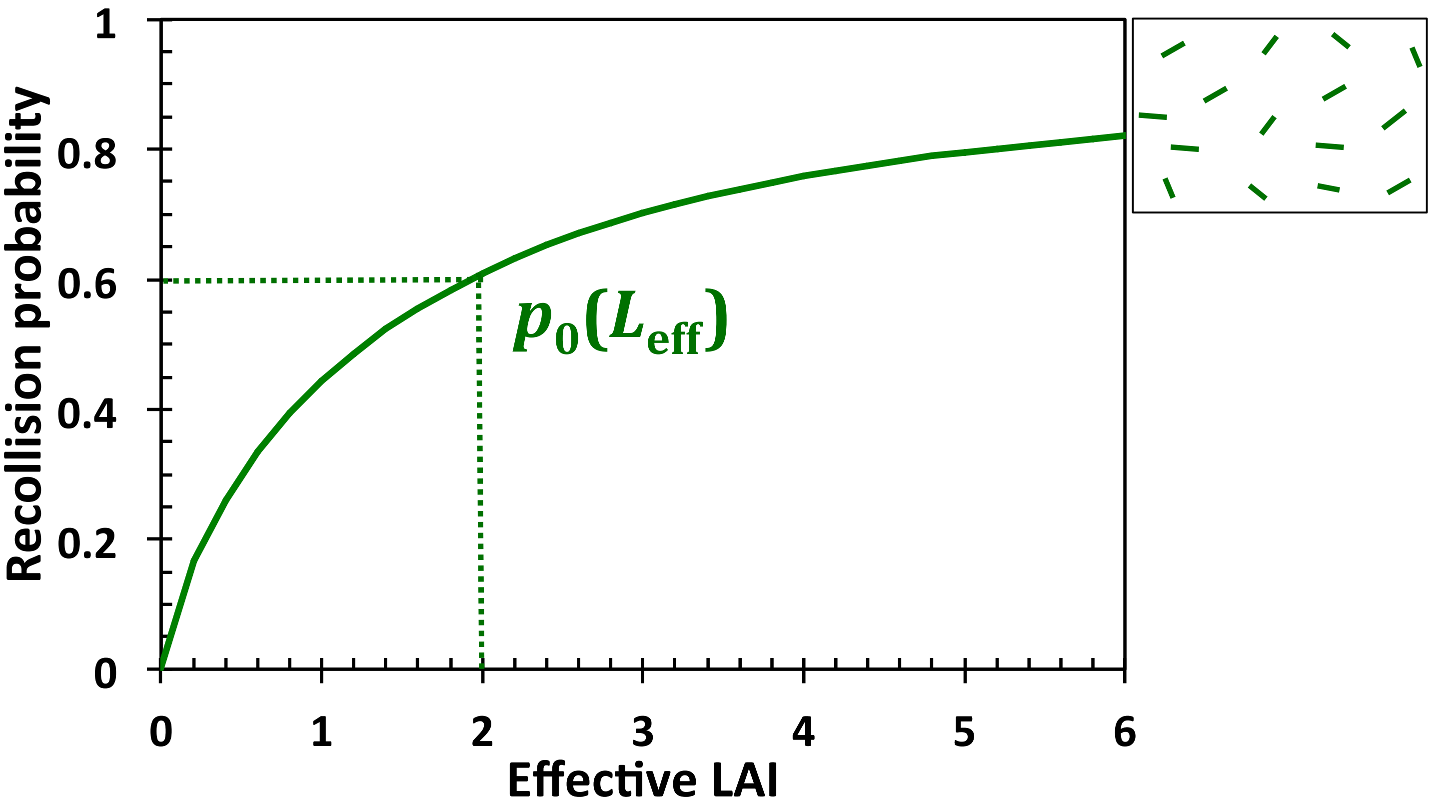

clumping: no

$L_{\text{eff}} = L_{\text{true}}$

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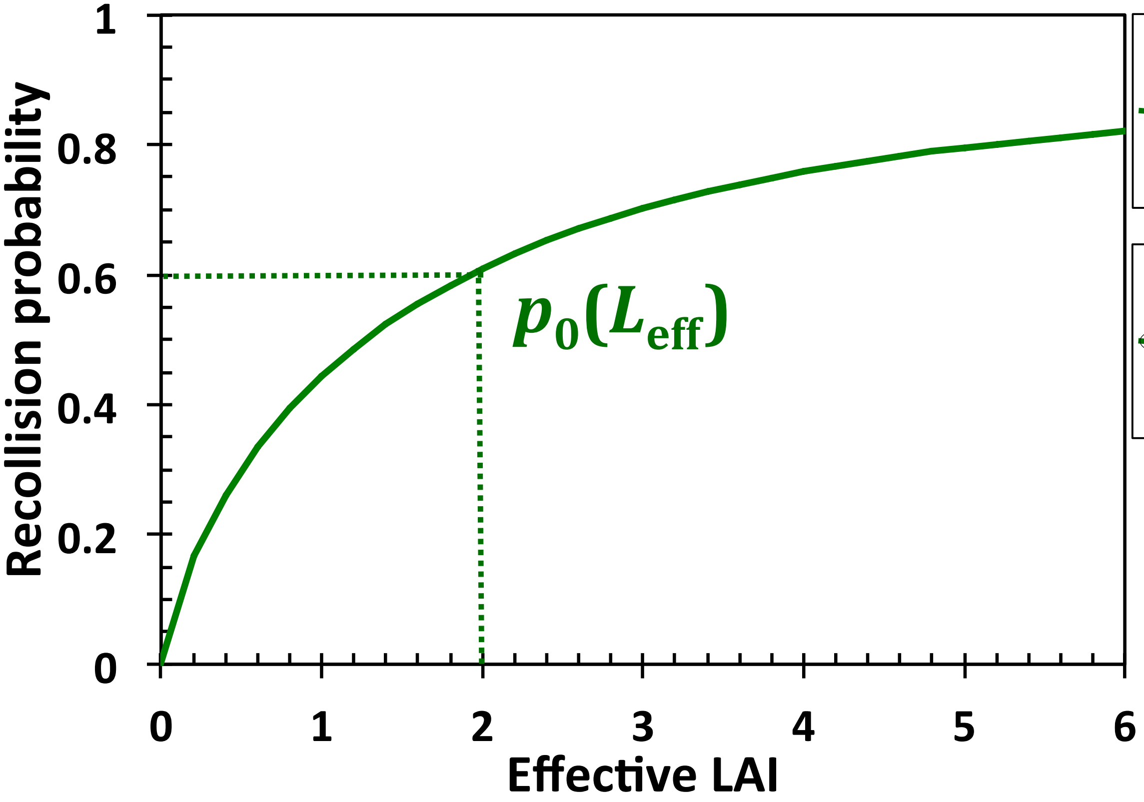

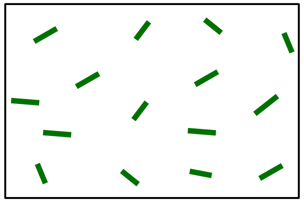

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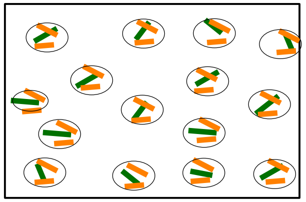

$L_{\text{eff}} < L_{\text{true}}$ increase

DASF same

Rec prob increase

W_λ decrease

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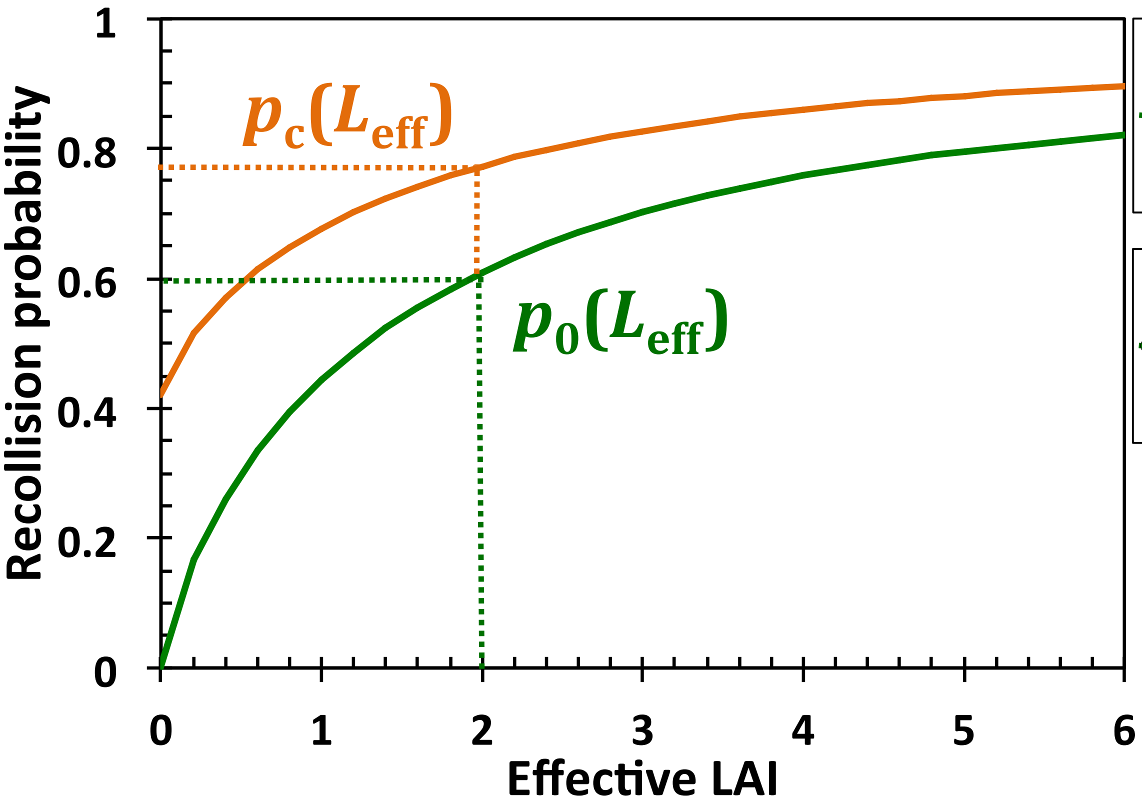
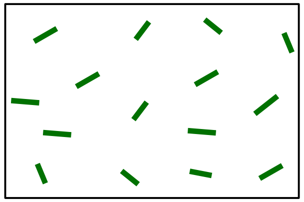
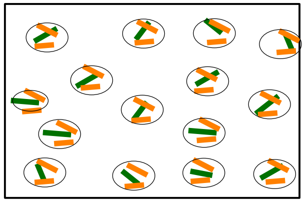
$$BRF_\lambda = DASF \cdot W_\lambda$$





clumping: *no*

$L_{eff}=L_{true}$

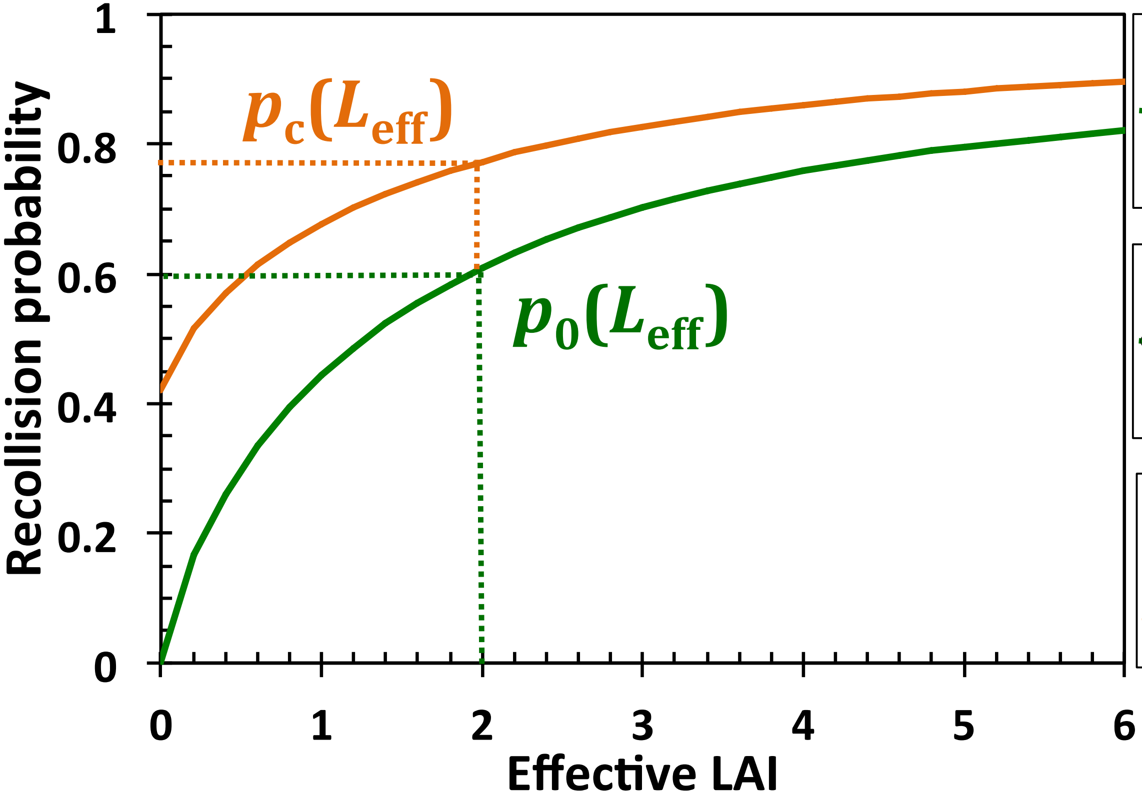


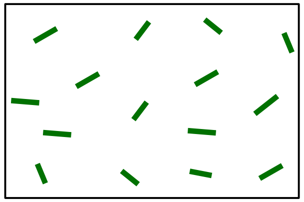
$L_{eff}<L_{true}$	increase
DASF	same
Rec prob	increase
W_λ	decrease

TRUE AND EFFECTIVE LEAF AREA

$$\sigma(\Omega) = G(\Omega)\,\underbrace{\overbrace{u_L}^{\text{true leaf area}}\,f}_{\text{effective leaf area}}$$

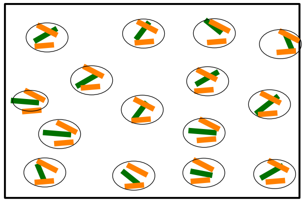
$$BRF_\lambda = DASF \cdot W_\lambda$$





clumping: *no*

$L_{eff}=L_{true}$



$L_{eff}<L_{true}$	increase
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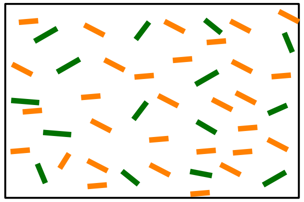


clumping: *no*

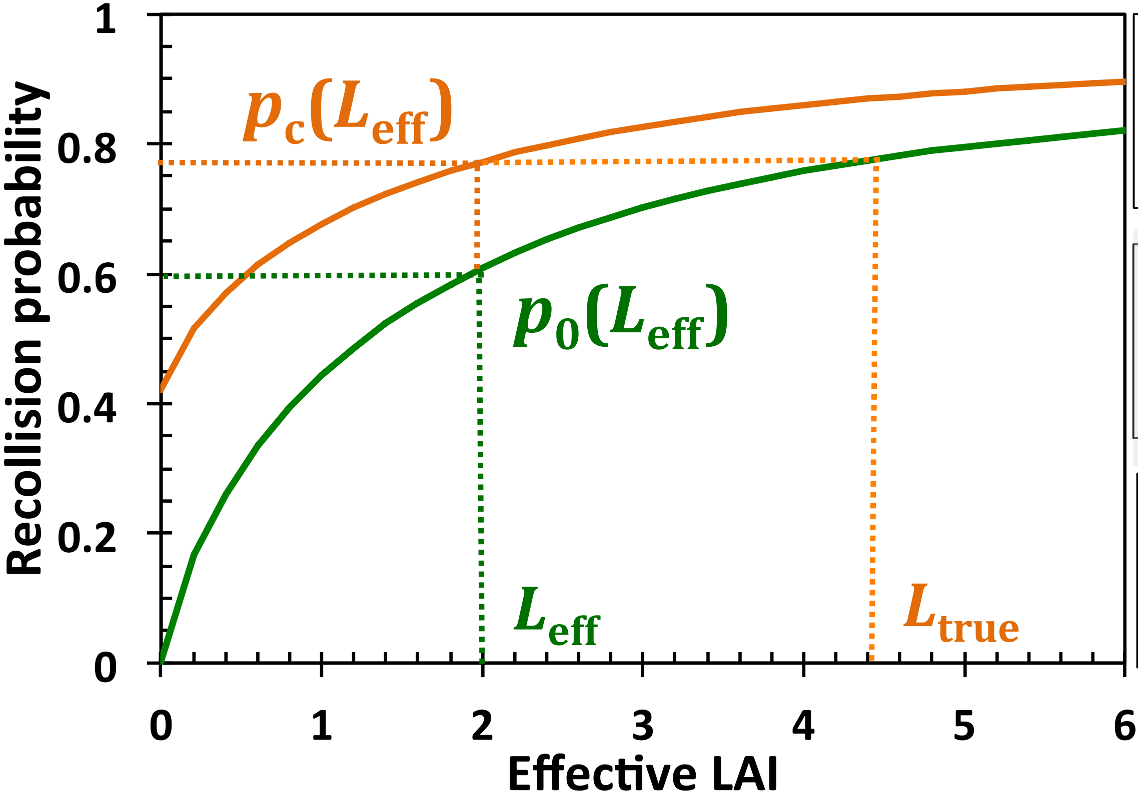
$L_{eff}=L_{true}$

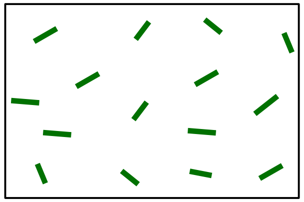
W_λ same if $p_0=p_c$

TRUE AND EFFECTIVE LEAF AREA

$$\sigma(\Omega) = G(\Omega)\, \overbrace{\underbrace{u_L\, f}_{\text{effective leaf area}}}^{\text{true leaf area}}$$

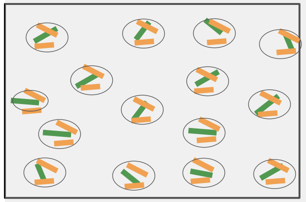
$$BRF_\lambda = DASF \cdot W_\lambda$$





clumping: *no*

$L_{eff}=L_{true}$



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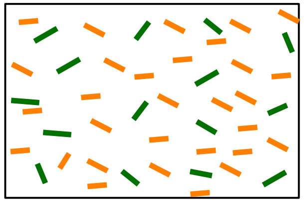


clumping: *no*

$L_{eff}=L_{true}$

W_λ same if $p_0=p_c$

$$p_0(L_{true}) = p_{sh} + (1 - p_{sh})p_0(L_{eff})$$

p_c: Smolander&Stenberg, 2005

interpretation

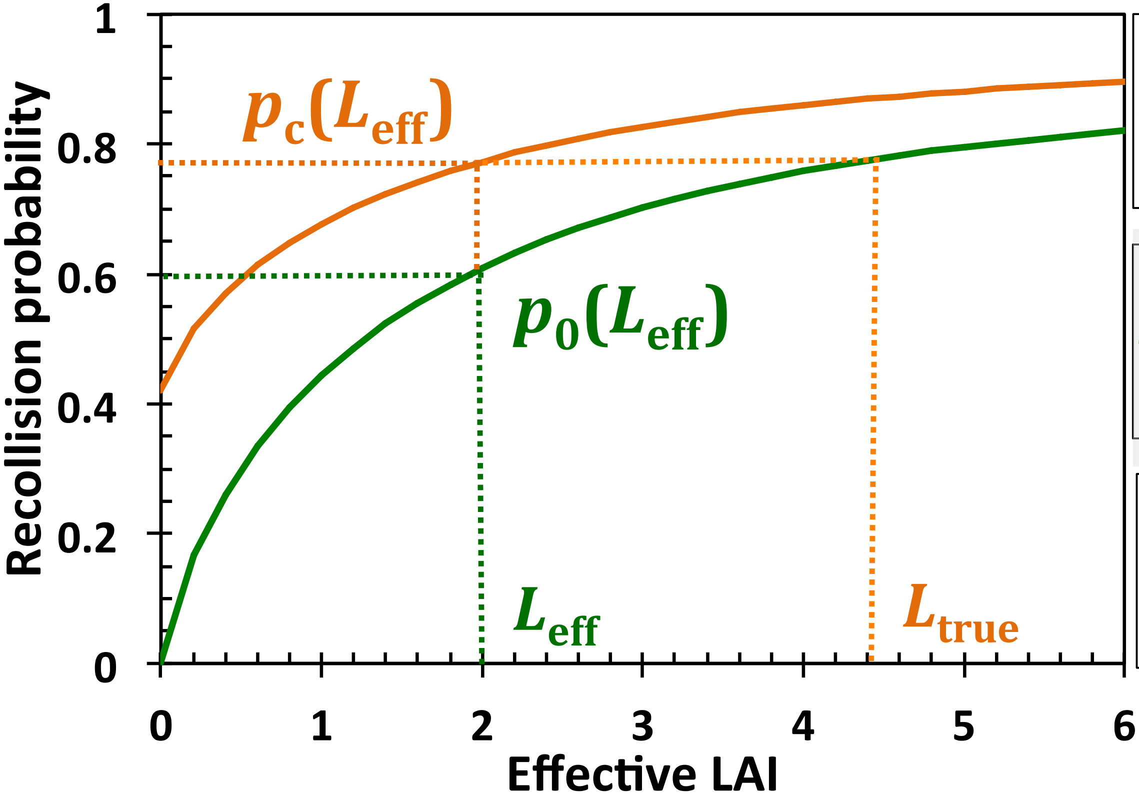
$$A_\lambda = 1 - W_\lambda = (1 - \omega_\lambda)\frac{1}{1 - p_c\omega_\lambda}$$

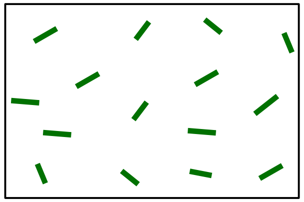
Smolander, S., & Stenberg, P. (2005). Simple parameterizations of the radiation budget of uniform broadleaved and coniferous canopies. *RSE 94*, 355-363.
Huang et al. (2007). Canopy spectral invariants for remote sensing and model applications. *Remote Sens. Environ. 106, 106-122*
Knyazikhin et al. (2011) Canopy spectral invariants. Part 1: A new concept in remote sensing of vegetation. *J. Quant. Spectrosc. Radiat Transf. 112, 727-735*

TRUE AND EFFECTIVE LEAF AREA

$$\sigma(\Omega) = G(\Omega)\,\underbrace{\overbrace{u_L\, f}^{\text{true leaf area}}}_{\text{effective leaf area}}$$

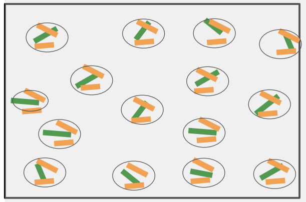
$$BRF_\lambda = DASF \cdot W_\lambda$$





clumping: *no*

L_{eff}=L_{true}



L_{eff}<L_{true}	increase
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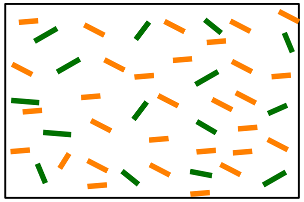


clumping: *no*

L_{eff}=L_{true}

W_λ **same if** p_0=p_c

$$p_0(L_{true}) = p_{sh} + (1-p_{sh})p_0\left(L_{eff}\right)$$

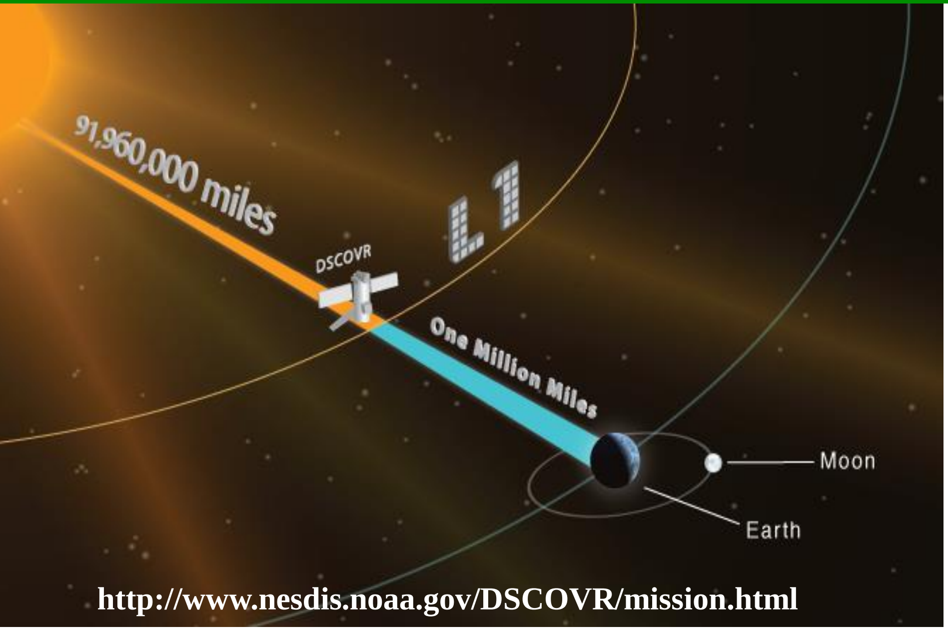
p_c: **Smolander&Stenberg, 2005**

$$W_\lambda = \omega_\lambda \frac{1-p_c}{1-p_c\omega_\lambda} = \omega_{c,\lambda}\frac{1-p_0}{1-p_0\omega_{c,\lambda}}$$

Smolander, S., & Stenberg, P. (2005). Simple parameterizations of the radiation budget of uniform broadleaved and coniferous canopies. *RSE 94*, 355-363.

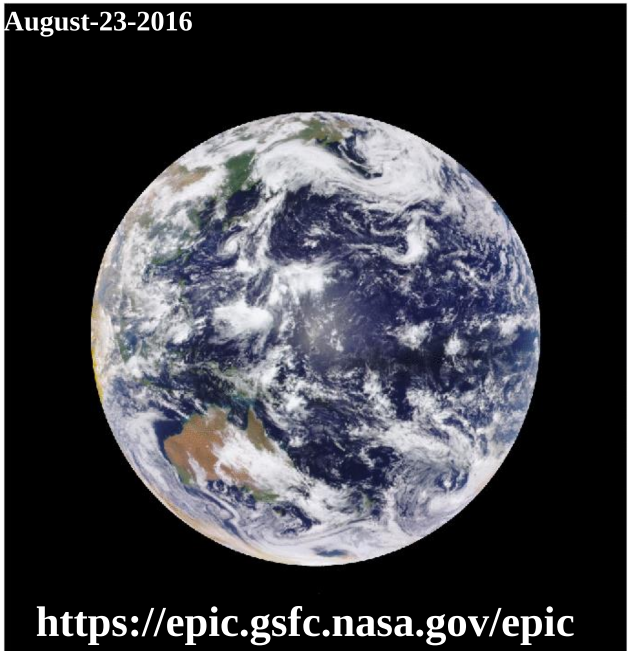
Lewis, P., & Disney, M. (2007). Spectral invariants and scattering across multiple scales from within-leaf to canopy. *Remote Sens. Environ. 109*, 196-206.

DEEP SPACE CLIMATE OBSERVATORY (DSCOVR)



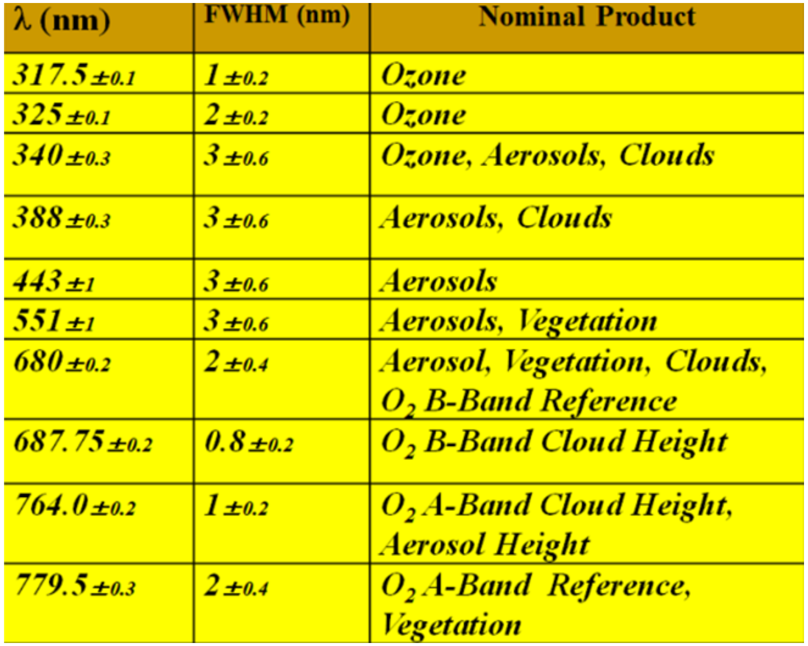
http://www.nesdis.noaa.gov/DSCOVR/mission.html

- DSCOVR mission was launched on February 11, 2015 to the Sun-Earth Lagrangian L1 point
  - to monitor solar weather to provide early warning of solar storms affecting the Earth
  - hosts NASA Earth-Observing Instrument: the Earth Polychromatic Imaging Camera (EPIC)
- EPIC measures Earth's reflected radiation at 10 UV to NIR spectral bands
- Temporal resolution: 65 to 110 min
- Pixel size near center: 10x10 km
- L1B EPIC reflectance data (πI/F) are available from Langley ASDC



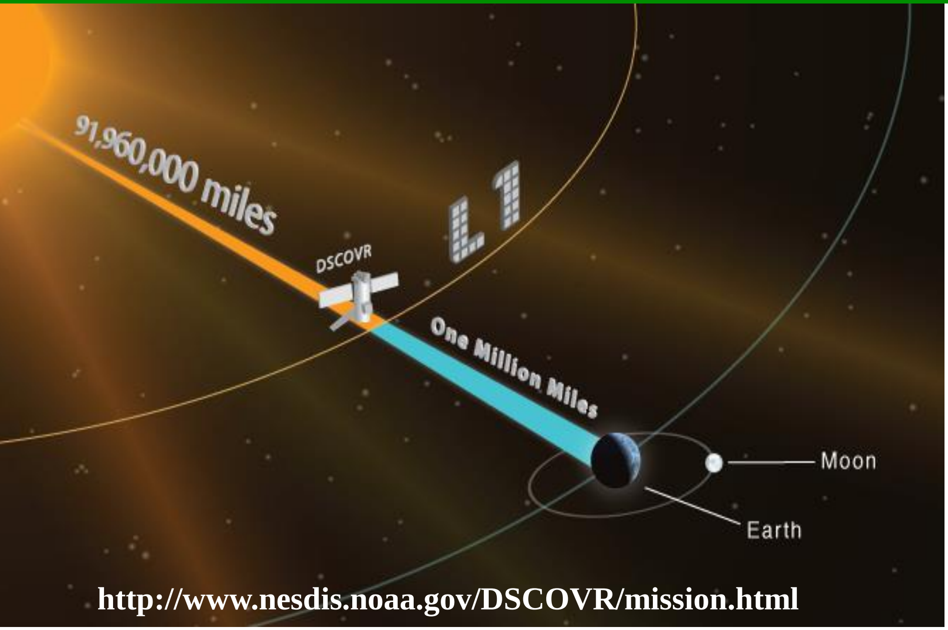
August-23-2016

https://epic.gsfc.nasa.gov/epic



λ (nm)	FWHM (nm)	Nominal Product
317.5±0.1	*1±0.2*	*Ozone*
325±0.1	*2±0.2*	*Ozone*
340±0.3	*3±0.6*	*Ozone, Aerosols, Clouds*
388±0.3	*3±0.6*	*Aerosols, Clouds*
443±1	*3±0.6*	*Aerosols*
551±1	*3±0.6*	*Aerosols, Vegetation*
680±0.2	*2±0.4*	*Aerosol, Vegetation, Clouds, O_2 B-Band Reference*
687.75±0.2	*0.8±0.2*	*O_2 B-Band Cloud Height*
764.0±0.2	*1±0.2*	*O_2 A-Band Cloud Height, Aerosol Height*
779.5±0.3	*2±0.4*	*O_2 A-Band Reference, Vegetation*

DEEP SPACE CLIMATE OBSERVATORY (DSCOVR)



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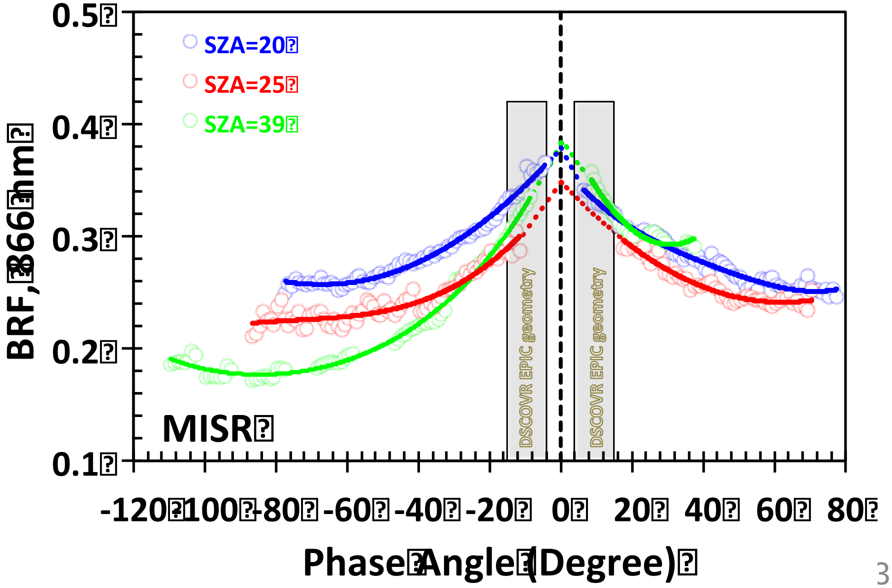
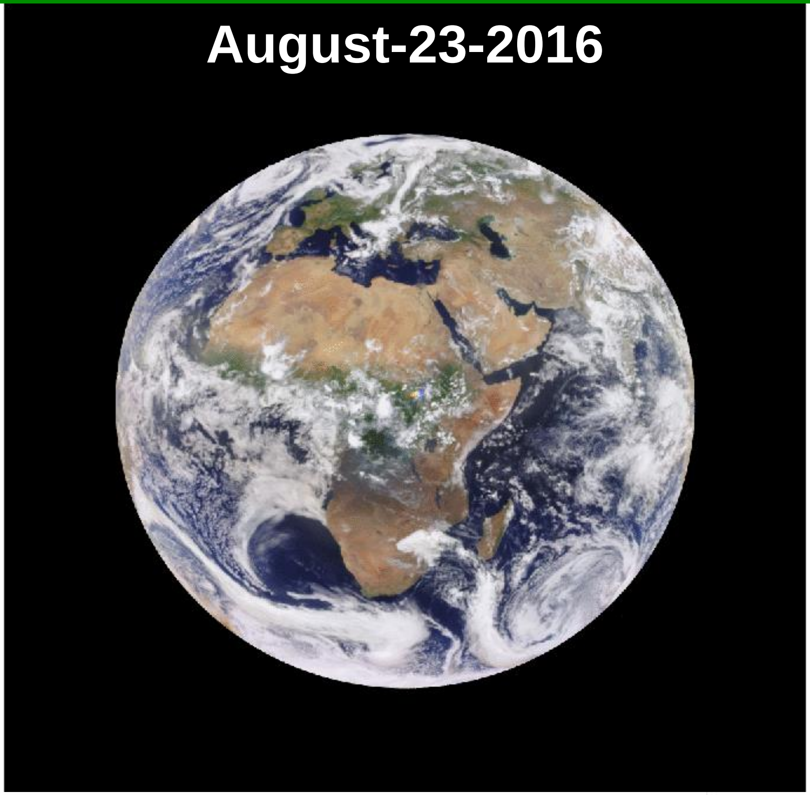
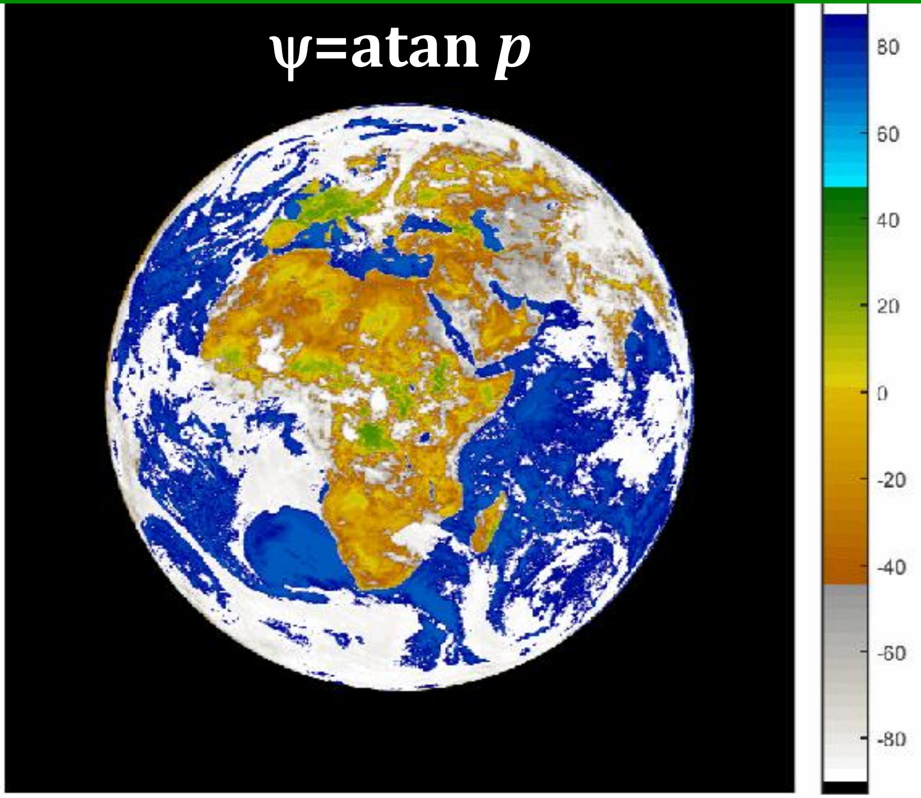
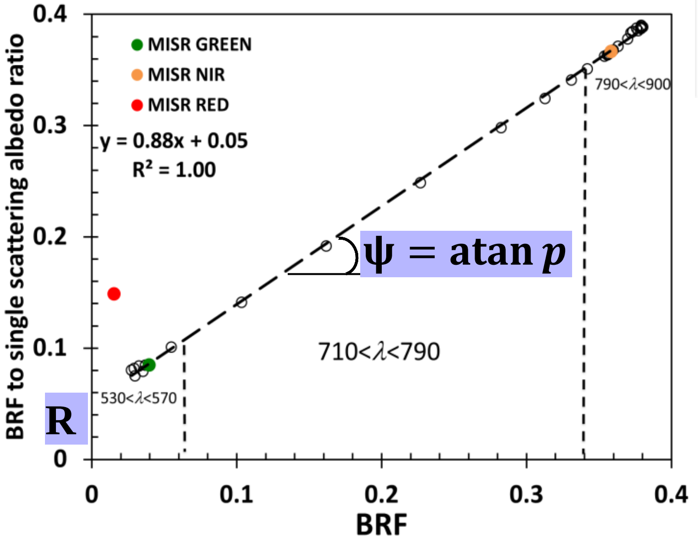


RECOLLISION PROBABILITY OF CLOUD AND VEGETATION



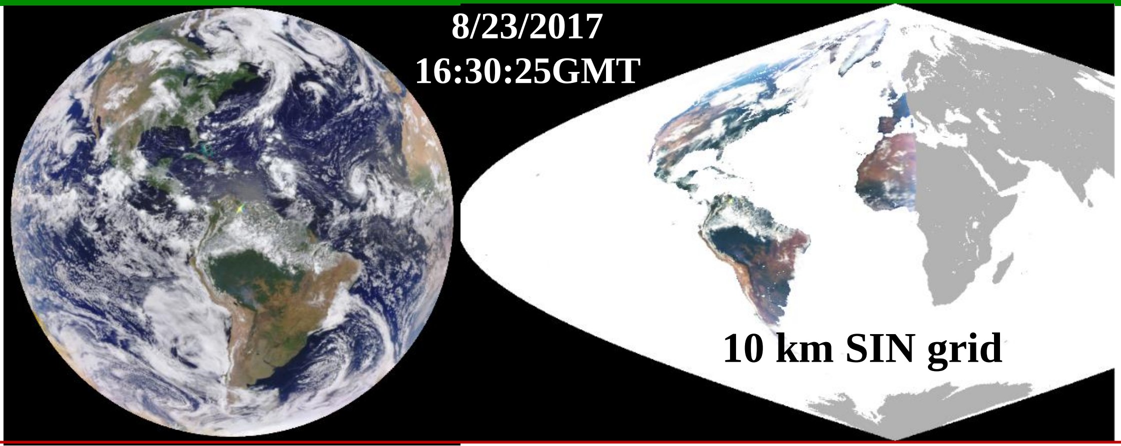


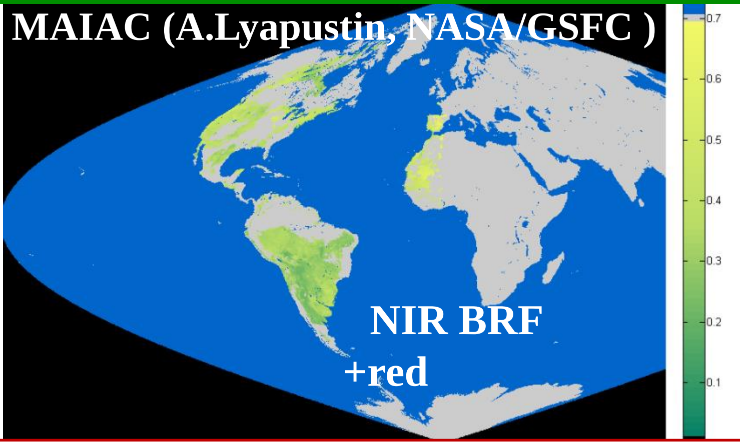


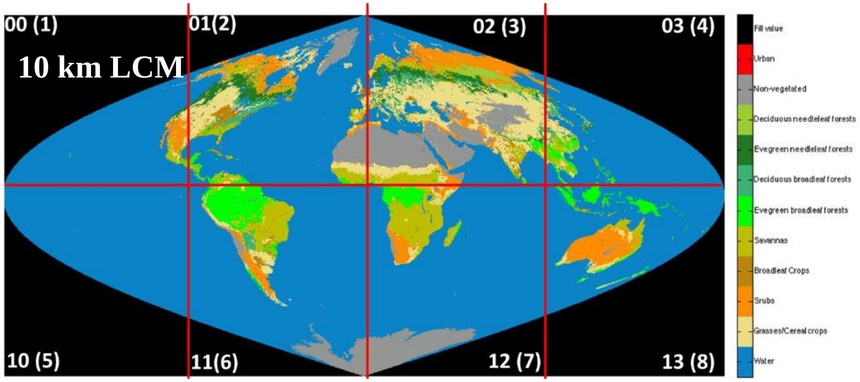
$$\frac{BRF_\lambda}{\omega_\lambda} = R + pBRF_\lambda$$

$$\psi = \operatorname{atan} p\ , DEG$$

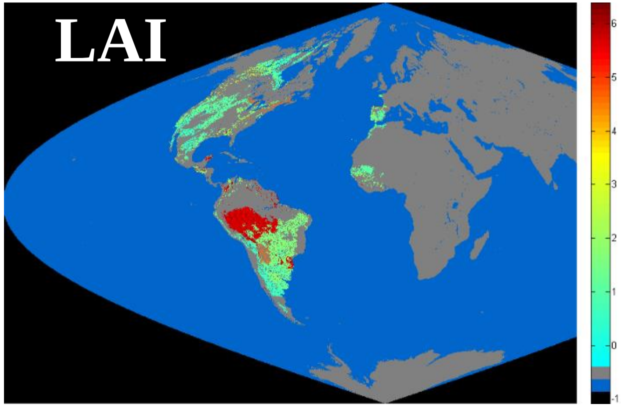
VEGETATION EARTH SYSTEM DATA RECORD (VESDR)

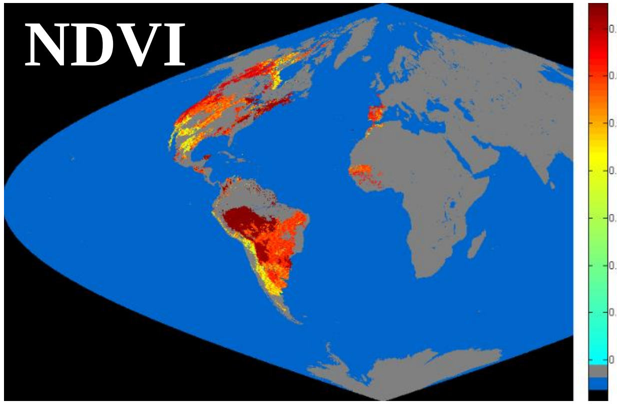


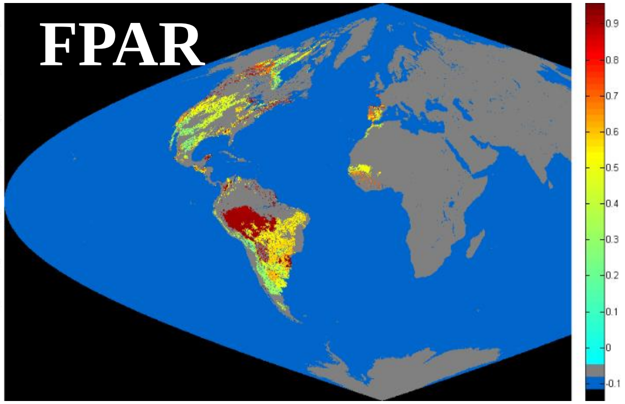


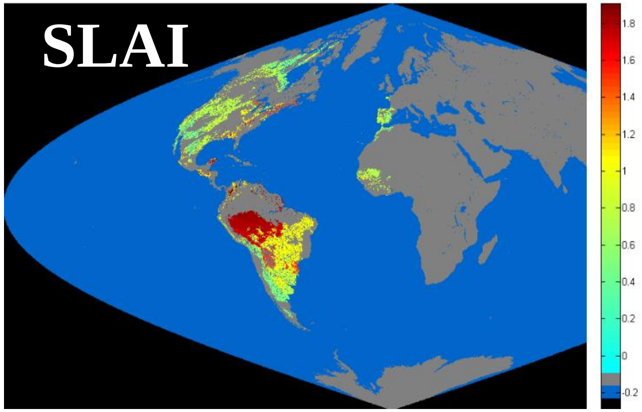


VESDR









VESDR ALGORITHM

- Uses decomposition of the boundary value problem for RTE
- Based on the stochastic RTE equation
  - accounts for 3D effects in surface reflectance data
- Incorporates recent advances in the theory of canopy spectral invariants
  - Special attention to the relationship between “true” and “effective” LAI
  - Kuusk’s theory is incorporated into spectral invariants
  - Energy conservation law is not violated
- Parametrized in terms of measurable parameters
  - allows for direct validation of the algorithm, facilitates identification of its deficiencies and development of refinements

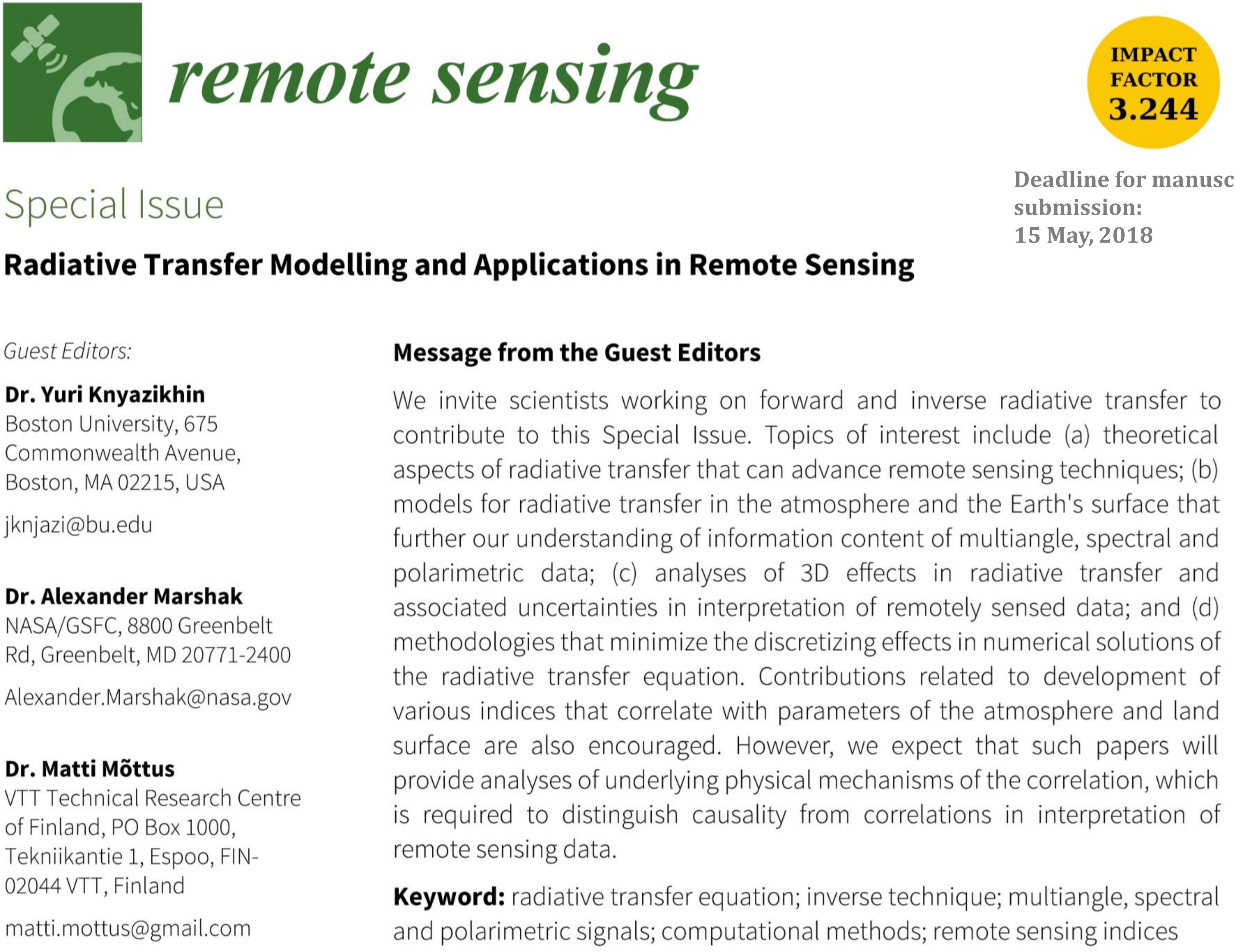
Yang et al. (2017). Estimation of leaf area index and its sunlit portion from DSCOVR EPIC data: Theoretical basis. *Remote Sensing of Environment, 198, 69-84*

SUMMARY

Methodologies and techniques developed in other scientific areas, motivated by other sciences and applications:

- Decomposition of the boundary value problem for RTE
  - ☐ Reactor physics, atmospheric physics, astrophysics
- Stochastic radiative transfer equation
  - ☐ Cloud physics, mathematics
- Spectral invariants
  - ☐ Reactor physics (criticality condition), mathematics
- Hot spot phenomenon
  - ☐ Vegetation, amplified by reactor/cloud physics, mathematics

http://www.mdpi.com/journal/remotesensing/special_issues/rt_rs



remote sensing

IMPACT FACTOR 3.244

Deadline for manuscript submission:
15 May, 2018

Special Issue

Radiative Transfer Modelling and Applications in Remote Sensing

Guest Editors:

Dr. Yuri Knyazikhin
Boston University, 675
Commonwealth Avenue,
Boston, MA 02215, USA

jknjazi@bu.edu

Dr. Alexander Marshak
NASA/GSFC, 8800 Greenbelt
Rd, Greenbelt, MD 20771-2400

Alexander.Marshak@nasa.gov

Dr. Matti Mõttus
VTT Technical Research Centre
of Finland, PO Box 1000,
Tekniikantie 1, Espoo, FIN-
02044 VTT, Finland

matti.mottus@gmail.com

Message from the Guest Editors

We invite scientists working on forward and inverse radiative transfer to contribute to this Special Issue. Topics of interest include (a) theoretical aspects of radiative transfer that can advance remote sensing techniques; (b) models for radiative transfer in the atmosphere and the Earth's surface that further our understanding of information content of multiangle, spectral and polarimetric data; (c) analyses of 3D effects in radiative transfer and associated uncertainties in interpretation of remotely sensed data; and (d) methodologies that minimize the discretizing effects in numerical solutions of the radiative transfer equation. Contributions related to development of various indices that correlate with parameters of the atmosphere and land surface are also encouraged. However, we expect that such papers will provide analyses of underlying physical mechanisms of the correlation, which is required to distinguish causality from correlations in interpretation of remote sensing data.

Keyword: radiative transfer equation; inverse technique; multiangle, spectral and polarimetric signals; computational methods; remote sensing indices