KOLMEMÕÕTMELINE KIIRGUSLEVI VÕRRAND TAIMKATTE KAUGSEIRE TEOREETLISE ALUSENA

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

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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, $\gamma_L(r, \Omega_L)$
3D RADIATIVE TRANSFER IN VEGETATION CANOPY

\[ \Omega \nabla I_\lambda + \sigma(r, \Omega)I_\lambda(r, \Omega) = \int 4\pi \sigma_s(r, \Omega' \to \Omega)I_\lambda(r, \Omega')d\Omega' \]

\[ \frac{1}{2\pi} \int_{2\pi^+} \sigma(r, \Omega) = u_L(r)g(r, \Omega) \]

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

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Forward Problem: *given coefficients, find solution*
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\[ \sigma_s(r, \Omega' \to \Omega) = u_L(r) \frac{1}{\pi} \Gamma_{\lambda}(r, \Omega' \to \Omega) \]

\[ \frac{1}{2\pi} \int_{2\pi^+} g_L(r, \Omega_L)|\Omega \cdot \Omega_L| d\Omega_L = \frac{1}{\pi} \Gamma_{\lambda} \]

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

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

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.
Classification of RTE (Germogenova, 1986)

- Standard problem: *RT problem with nonreflecting boundary*
- *Boundary value problem for RTE*

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- *Relationships between forward and adjoint RTE*
- *Green’s function approach (George Green, 7/14/1793-5/31/1841)*
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\[
I(z, \Omega) = I_{BS}(z, \Omega) + \frac{\rho F_{BS}}{1 - \rho F_S} J_S(z, \Omega)
\]

3D RADIATIVE TRANSFER PROBLEM: BASIC

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- Critical for the inverse problem

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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

3D EFFECTS IN REMOTE SENSING DATA

\[ \Omega \nabla I_\lambda + \sigma(r, \Omega) I_\lambda(r, \Omega) = \int_{4\pi} \sigma_{s,\lambda}(r, \Omega' \to \Omega) I_\lambda(r, \Omega') d\Omega' \]
\[ \nabla \cdot I_\lambda + \sigma(r, \Omega) I_\lambda(r, \Omega) = \int_{4\pi}^{\sigma_{s,\lambda}(r, \Omega' \to \Omega) I_\lambda(r, \Omega') d\Omega' \quad I_\lambda(r_{\text{top}}, \Omega) \]
\[ \Omega \nabla I_\lambda + \sigma(r, \Omega)I_\lambda(r, \Omega) = \int_{4\pi} \sigma_{s,\lambda}(r, \Omega' \rightarrow \Omega)I_\lambda(r, \Omega')d\Omega' \]

Mean Intensity

\[ \bar{I}_\lambda(\Omega) = \frac{1}{S} \int_S I_\lambda(r_{\text{top}}, \Omega)dr_{\text{top}} \]

mean intensity emanating from heterogeneous vegetation pixels
Can we derive equation for $\bar{I}_\lambda$?
Mean Intensity

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

\[
I_\lambda(r_{\text{top}}, \Omega) \quad \text{Mean Intensity}
\]

Vainikko (1973): Mean intensity satisfies a simple system of equations

Titov (1990): Physical processes in clouds as stochastic process

Can we derive equation for \(I_\lambda\)?

\[
|\mu|I(z, \Omega) + \int_a^b \sigma p(\xi) U(\xi, \Omega) d\xi \\
= \int_a^b p(\xi) S(\xi, \Omega) d\xi + |\mu|I(0, \Omega)
\]

\[
|\mu|U(z, \Omega) + \int_a^b \sigma K(z, \xi, \Omega) U(\xi, \Omega) d\xi \\
= \int_a^b K(z, \xi, \Omega) S(\xi, \Omega) d\xi + |\mu|U(0, \Omega)
\]

Stochastic RTE
3D EFFECTS IN REMOTE SENSING DATA

\[ \Omega \nabla I_\lambda + \sigma(r, \Omega)I_\lambda(r, \Omega) = \int_4^{\infty} \sigma_{s,\lambda}(r, \Omega') \rightarrow \Omega)I_\lambda(r, \Omega')d\Omega' \]

Mean Intensity

\[ \bar{I}_\lambda(\Omega) = \frac{1}{S} \int S_\lambda(r_{top}, \Omega)dr_{top} \]

Can we derive equation for \( \bar{I}_\lambda \)?

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Stochastic RTE

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


3D EFFECTS IN REMOTE SENSING DATA

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

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**Vainikko (1973):** Mean intensity satisfies a simple system of equations

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

\[ |\mu| \bar{I}(z, \Omega) + \int_a^b \sigma p(\xi) U(\xi, \Omega) d\xi \]

\[ = \int_a^b p(\xi) S(\xi, \Omega) d\xi + |\mu| \bar{I}(0, \Omega) \]

\[ |\mu| U(z, \Omega) + \int_a^b \sigma K(z, \xi, \Omega) U(\xi, \Omega) d\xi \]

\[ = \int_a^b K(z, \xi, \Omega) S(\xi, \Omega) d\xi + |\mu| U(0, \Omega) \]

SRTE can reproduce all 3D effects reported in literature

Stochastic RTE


Leaf scattering and canopy reflectance are similar in shape, differ in magnitude.
LEAF AND CANOPY SPECTRAL REFLECTANCE

\[
\Omega \nabla I_\lambda + \sigma(r, \Omega) I_\lambda(r, \Omega) = \omega_\lambda \int g(r, \Omega' \rightarrow \Omega) I_\lambda(r, \Omega') d\Omega'
\]

canopy structure

leaf properties

canopy structure
SPECTRAL INVARIANTS IN VEGETATION CANOPIES

\[ y = 0.886x + 0.0537 \]
\[ R^2 = 0.99696 \]

Slope, \( p \):
Intercept, \( R \):

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

- BRF to Leaf Albedo Ratio is linearly related to BRF

escape probability
resollision probability

Determined by distribution of photon free path
**Solution of the standard RTE**

\[ BRF_\lambda = DASF(\Omega_{\text{sensor}}; \Omega_{\text{sun}})W_\lambda \]

**Directional Area Scattering Factor:**
- canopy BRF if no absorption

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

**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.

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

**Graph:**
- 700nm-993nm
- \[ y = 0.886x + 0.0537 \]
- \( R^2 = 0.99696 \)
DECOMPOSITION OF THE STANDARD PROBLEM

Solution of the **standard RTE**

\[ BRF_\lambda = DASF(\Omega_{\text{sensor}}; \Omega_{\text{sun}})W_\lambda \]

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\[ I(z, \Omega) = I_{BS}(z, \Omega) + \frac{\rho F_{BS}}{1 - \rho F_S} J_S(z, \Omega) \]
\[ \sigma(\Omega) = G(\Omega) \, u_L \, f \]

\[ BRF_\lambda = DASF \cdot W_\lambda \]
TRUE AND EFFECTIVE LEAF AREA

\[ \sigma(\Omega) = G(\Omega) u_L f \text{ true leaf area} \]

\[ BRF_\lambda = DASF \cdot W_\lambda \text{ effective leaf area} \]
TRUE AND EFFECTIVE LEAF AREA

\[ \sigma(\Omega) = G(\Omega) \mu_L \mathcal{f} \] true leaf area

effective leaf area

\[ BRF_\lambda = DASF \cdot W_\lambda \] clumping: no

\[ L_{eff} = L_{true} \]

\[ p_0(L_{eff}) \]
σ(Ω) = G(Ω) u_L f_{true leaf area} \quad BRF_\lambda = DASF \cdot W_\lambda

\begin{align*}
\text{clumping: } & \text{no} \\
L_{eff} &= L_{true} \\
\text{increase} & \quad \text{same} \quad \text{increase} \quad \text{decrease}
\end{align*}

\begin{align*}
\text{Recollision probability} & = p_0(L_{eff}) \\
\text{Effective LAI} & = 0, 1, 2, 3, 4, 5, 6
\end{align*}
TRUE AND EFFECTIVE LEAF AREA

\[ \sigma(\Omega) = G(\Omega) u_L f \]

true leaf area

effective leaf area

\[ BRF_\lambda = DASF \cdot W_\lambda \]

Rec prob: increase

W: decrease

clumping: no

[diagram showing the relationship between effective LAI and recollision probability]

\[ p_c(L_{\text{eff}}) \]

\[ p_0(L_{\text{eff}}) \]

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

DASF: increase

same

W: increase
decrease
TRUE AND EFFECTIVE LEAF AREA

\[ \sigma(\Omega) = G(\Omega) u_L f \]
\[ BRF_\lambda = DASF \cdot W_\lambda \]

- **True leaf area**
- **Effective leaf area**

**Recollision probability**

- \[ p_c(L_{\text{eff}}) \]
- \[ p_0(L_{\text{eff}}) \]

**Effective LAI**

- \[ L_{\text{eff}} \]
- \[ L_{\text{true}} \]

**Interpretation**

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


TRUE AND EFFECTIVE LEAF AREA

\[ \sigma(\Omega) = G(\Omega) \, u_L \, f \]

true leaf area

\[ BRF_\lambda = DASF \cdot W_\lambda \]

effective leaf area

\[ p_c(L_{eff}) \]

Recollision probability

\[ p_0(L_{eff}) \]

Effective LAI

\[ p_0(L_{true}) = p_{sh} + (1 - p_{sh})p_0(L_{eff}) \]

\[ p_c : \text{Smolander}&Stenberg, 2005 \]


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 (\(\pi I/F\)) are available from Langley ASDC

<table>
<thead>
<tr>
<th>(\lambda) (nm)</th>
<th>FWHM (nm)</th>
<th>Nominal Product</th>
</tr>
</thead>
<tbody>
<tr>
<td>317.5 ±0.1</td>
<td>1 ±0.2</td>
<td>Ozone</td>
</tr>
<tr>
<td>325 ±0.1</td>
<td>2 ±0.2</td>
<td>Ozone</td>
</tr>
<tr>
<td>340 ±0.3</td>
<td>3 ±0.6</td>
<td>Ozone, Aerosols, Clouds</td>
</tr>
<tr>
<td>388 ±0.3</td>
<td>3 ±0.6</td>
<td>Aerosols, Clouds</td>
</tr>
<tr>
<td>443 ±1</td>
<td>3 ±0.6</td>
<td>Aerosols</td>
</tr>
<tr>
<td>551 ±1</td>
<td>3 ±0.6</td>
<td>Aerosols, Vegetation</td>
</tr>
<tr>
<td>680 ±0.2</td>
<td>2 ±0.4</td>
<td>Aerosol, Vegetation, Clouds, O(_2) B-Band Reference</td>
</tr>
<tr>
<td>687.75 ±0.2</td>
<td>0.8 ±0.2</td>
<td>O(_2) B-Band Cloud Height</td>
</tr>
<tr>
<td>764.0 ±0.2</td>
<td>1 ±0.2</td>
<td>O(_2) A-Band Cloud Height, Aerosol Height</td>
</tr>
<tr>
<td>779.5 ±0.3</td>
<td>2 ±0.4</td>
<td>O(_2) A-Band Reference, Vegetation</td>
</tr>
</tbody>
</table>
DEEP SPACE CLIMATE OBSERVATORY (DSCOVR)

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August-23-2016

https://epic.gsfc.nasa.gov/epic
\[ \Psi = \tan \rho \]

\[ \frac{B_{RF_\lambda}}{\omega_\lambda} = R + pB_{RF_\lambda} \]

\[ \Psi = \tan \rho , DEG \]
VEGETATION EARTH SYSTEM DATA RECORD (VESDR)

MAIAC (A. Lyapustin, NASA/GSFC)

LAI

SLAI

FPAR

NDVI

NIR BRF + red

10 km SIN grid

10 km LCM

8/23/2017 16:30:25 GMT

VESDR

8 (5)

10 (6)

11 (7)

12 (8)

00 (1)

01 (2)

02 (3)

03 (4)

0

+ red
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

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
Special Issue

Radiative Transfer Modelling and Applications in Remote Sensing

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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