SPARTACUS-Surface: Representing the 3D Interaction of Radiation with Vegetation and Urban Areas for Weather and Climate Applications

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Overview

Speedy Algorithm for Radiative Transfer through Cloud Sides

- “SPARTACUS” is a fast method to treat radiative transfer in the presence of permeable objects that are randomly distributed horizontally (initially clouds)
- “SPARTACUS-Surface” is an open-source software package (Fortran 2003) for computing flux profiles and absorption rates in forests and urban areas:
  - Fortran implementation for offline use or incorporation into larger-scale models: https://github.com/ecmwf/spartacus-surface (including RAMI5 scenarios)
  - Now available in TEB and SUEWS urban energy exchange scenes
- Evaluation of SPARTACUS-Surface:
  - **Realistic cities:** evaluated against DART (Stretton et al, 2022, 2023)
  - **Idealized forests:** evaluated against solar Monte Carlo from RAMI4PILPS (Hogan, Quaife & Braghiere, GMD 2018)
  - ***Realistic forests:*** *need evaluation data from RAMI5!*

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Two-stream equations for vegetation (Sellers 1985), used in many vegetation models e.g. JULES

Gradient of flux with height

Extinction coefficient

Loss of flux by scattering or absorption

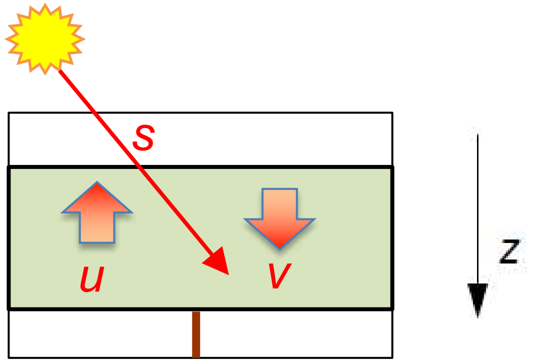
Gain in flux by scattering from other direction

Gain from scattering of the direct solar beam

Upwelling diffuse flux: $$-\frac{du}{dz} = \sigma\left(-\gamma_1 u + \gamma_2 v + \gamma_3 s\right)$$

Downwelling diffuse flux: $$\frac{dv}{dz} = \sigma\left(-\gamma_1 v + \gamma_2 u + \gamma_4 s\right)$$

Downwelling *direct* flux: $$\frac{ds}{dz} = -\sigma / \mu_0$$



Coefficients γ_1 to γ_4 are functions of the leaf scattering properties (assuming random orientation)

Write as vectors and matrices: $$\frac{d}{dz}\begin{pmatrix} u \\ v \\ s \end{pmatrix} = \sigma \begin{pmatrix} \gamma_1 & -\gamma_2 & -\gamma_3 \\ \gamma_2 & -\gamma_1 & \gamma_4 \\ & & -1/\mu_0 \end{pmatrix} \begin{pmatrix} u \\ v \\ s \end{pmatrix}$$

- Solution provided by Meador & Weaver (1980), also used in all atmospheric radiation schemes
- *But trees are not horizontally homogeneous!*

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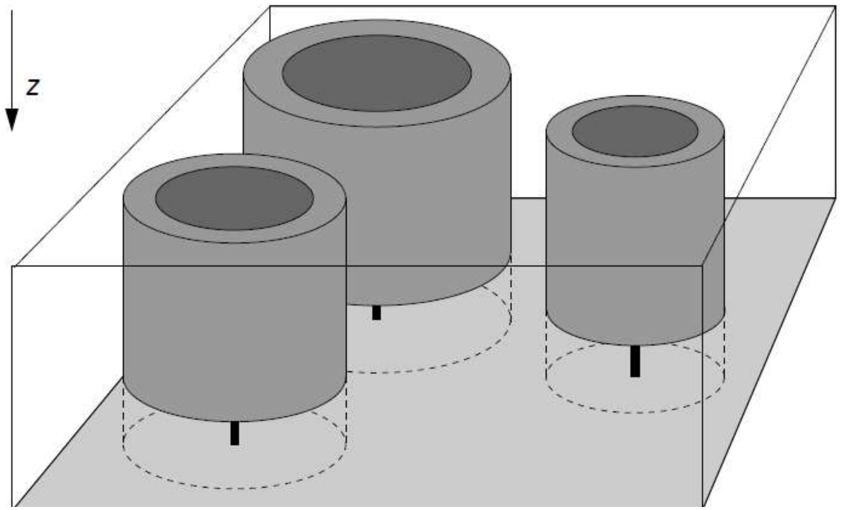
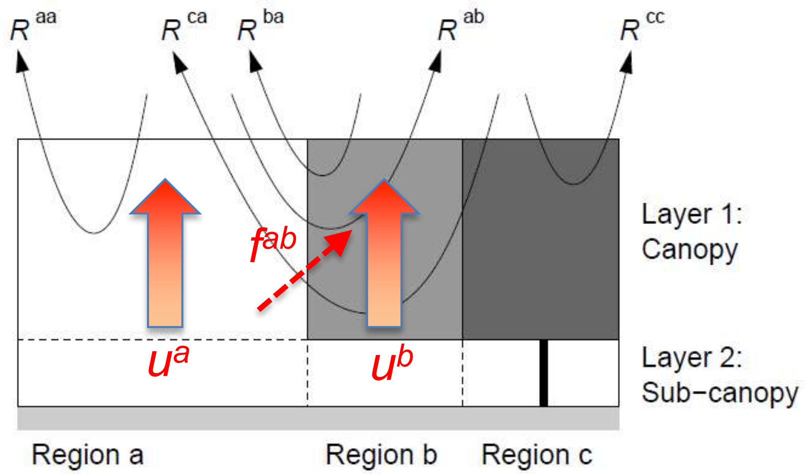
The SPARTACUS method applied to forests… … and cities

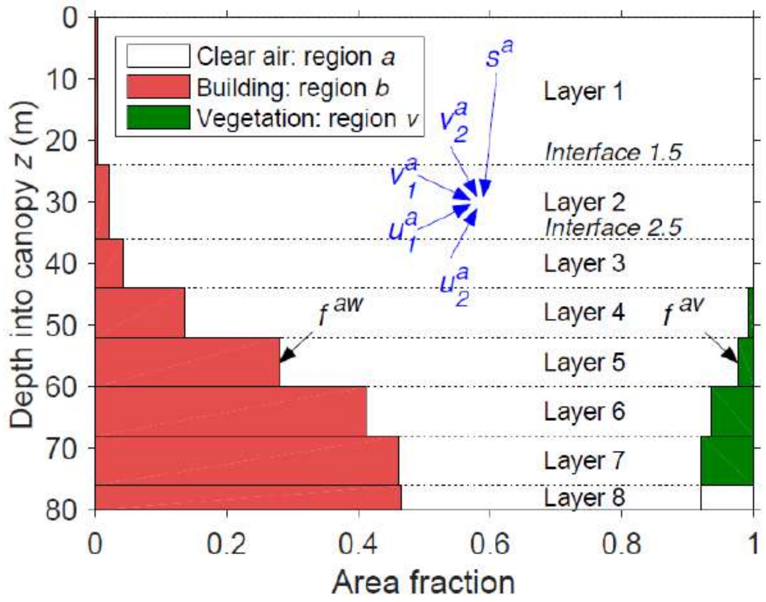
- Idea: apply the two-stream equations in each of two or three regions *a*–*c*
- New terms represent horizontal exchange of radiation between regions





- Define each flux component as a vector and solve system of nine ODEs

$$\mathbf{u} = \begin{pmatrix} u^a \\ u^b \\ \vdots \end{pmatrix} \longrightarrow \frac{d}{dz}\begin{pmatrix} \mathbf{u} \\ \mathbf{v} \\ \mathbf{s} \end{pmatrix} = \Gamma \begin{pmatrix} \mathbf{u} \\ \mathbf{v} \\ \mathbf{s} \end{pmatrix}$$



- Add an impermeable region in each layer to represent buildings (or tree trunks!)
- Street trees represented with one or two permeable regions in each layer

How do we relate exchange matrix Γ to vegetation properties?

- Write as:

$$\boldsymbol{\Gamma} = \begin{pmatrix} -\boldsymbol{\Gamma}_1 & -\boldsymbol{\Gamma}_2 & -\boldsymbol{\Gamma}_3 \\ \boldsymbol{\Gamma}_2 & \boldsymbol{\Gamma}_1 & \boldsymbol{\Gamma}_4 \\ & & \boldsymbol{\Gamma}_0 \end{pmatrix}$$

- Rate of change of diffuse radiation along its path is sum of 1D and 3D terms:

$$\boldsymbol{\Gamma}_1 = \begin{pmatrix} -\sigma^a\gamma_1^a & & \\ & -\sigma^b\gamma_1^b & \\ & & -\sigma^c\gamma_1^c \end{pmatrix} + \begin{pmatrix} -f_{\mathrm{diff}}^{ab} & +f_{\mathrm{diff}}^{ba} & \\ +f_{\mathrm{diff}}^{ab} & -f_{\mathrm{diff}}^{ba} - f_{\mathrm{diff}}^{bc} & +f_{\mathrm{diff}}^{cb} \\ & +f_{\mathrm{diff}}^{bc} & -f_{\mathrm{diff}}^{cb} \end{pmatrix}$$

- Assume that the rate of exchange (per unit height) is proportional to the length of the interface, L^{ab}, between regions *a* and *b*, valid if trees are randomly separated:

$$f_{\mathrm{diff}}^{ab} = \frac{L^{ab}\tan\theta}{\pi c_a} = \frac{2c_v}{Dc_a}$$

Vegetation cover fraction

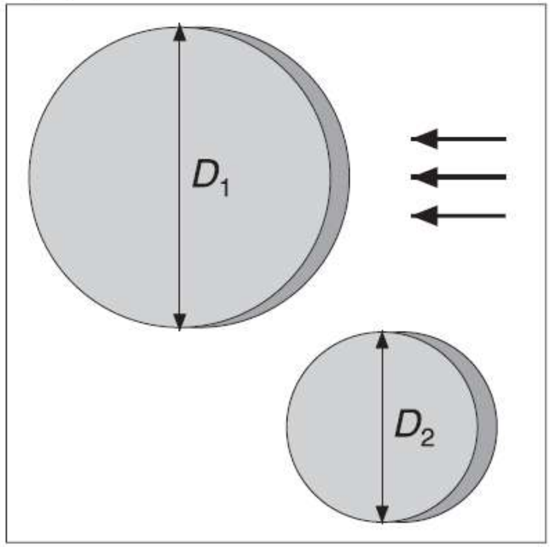
Clear-air fraction

Effective crown diameter

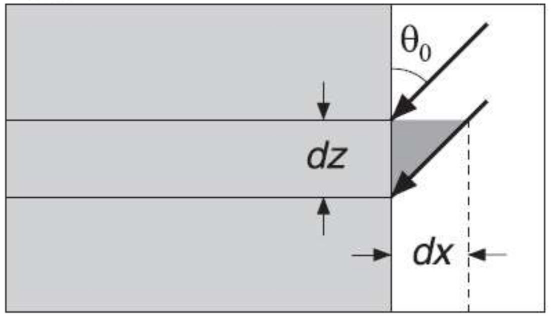
- Equations solved using eigenvalue decomposition, like in DISORT

trees

(b) Circular clouds

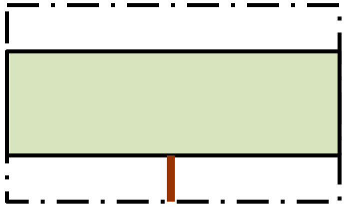


(e) Detail: side view

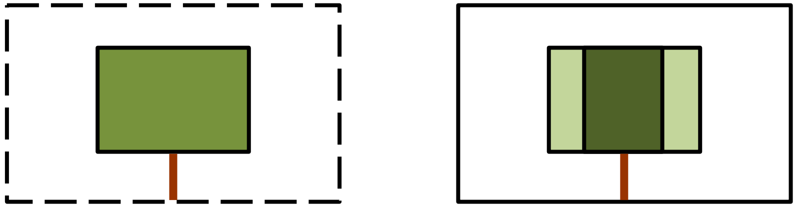


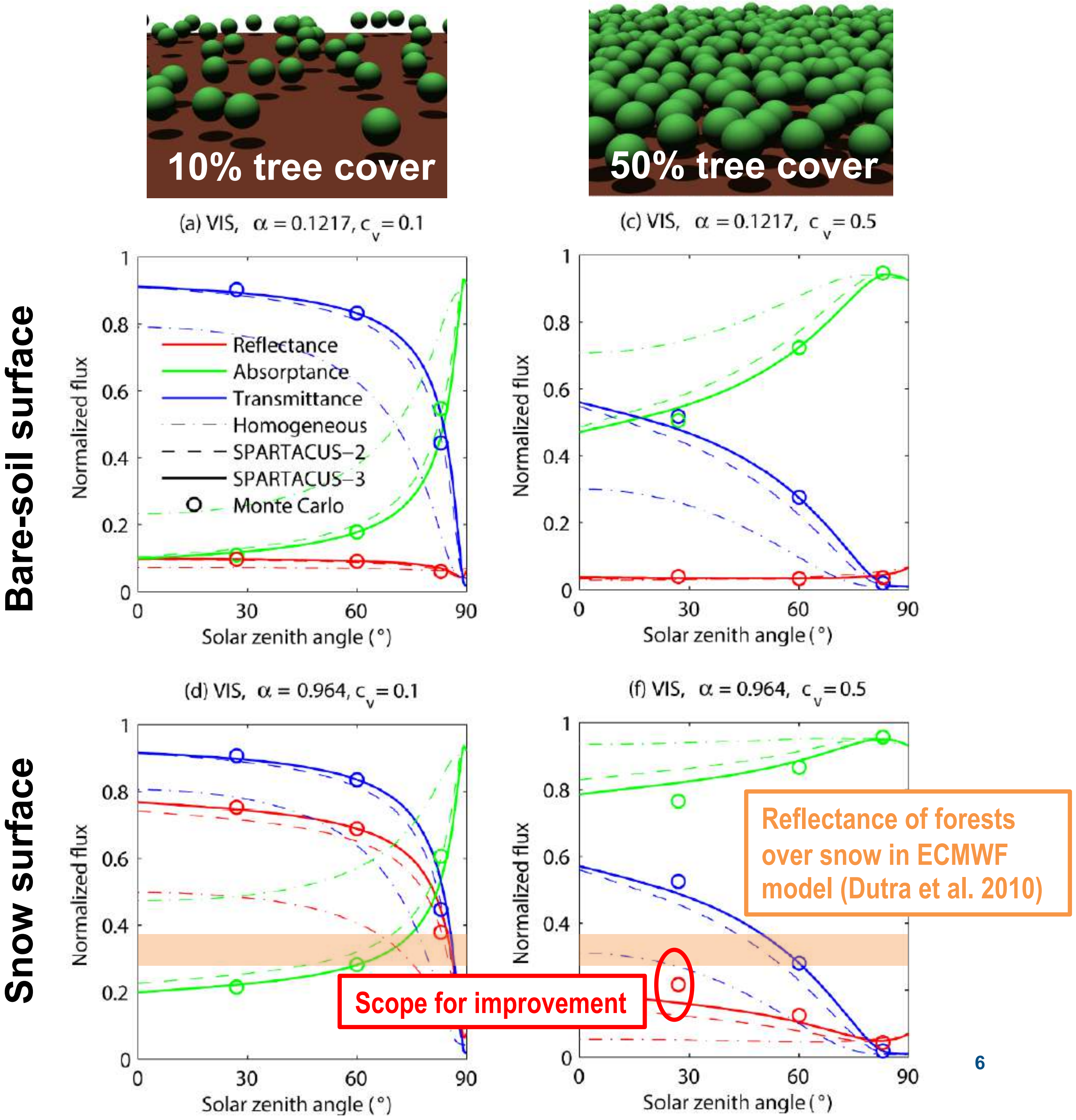
RAMI4PILPS evaluation

- Compare to Monte Carlo calculations for idealized representations of forests (thanks to Jean-Luc Widlowski)
- Most vegetation models assume homogeneous canopies (Sellers 1985): *photosynthesis rates overestimated*



- SPARTACUS with 2 or 3 regions: *agrees much better with Monte Carlo*





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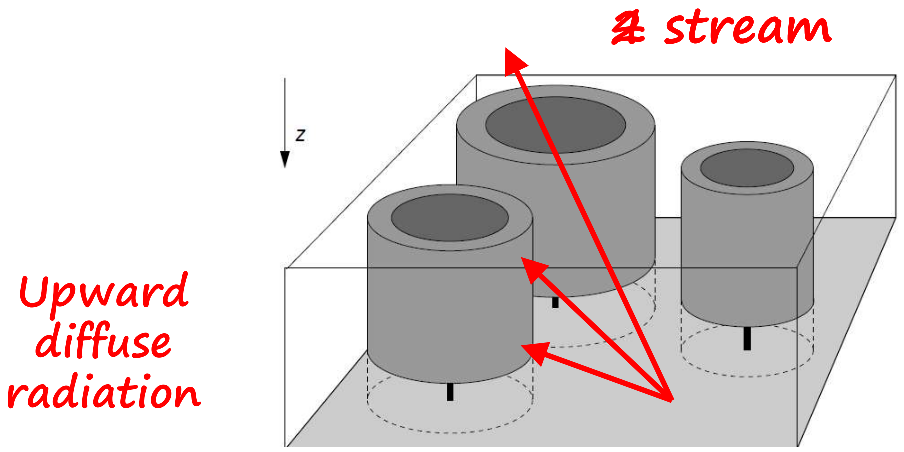
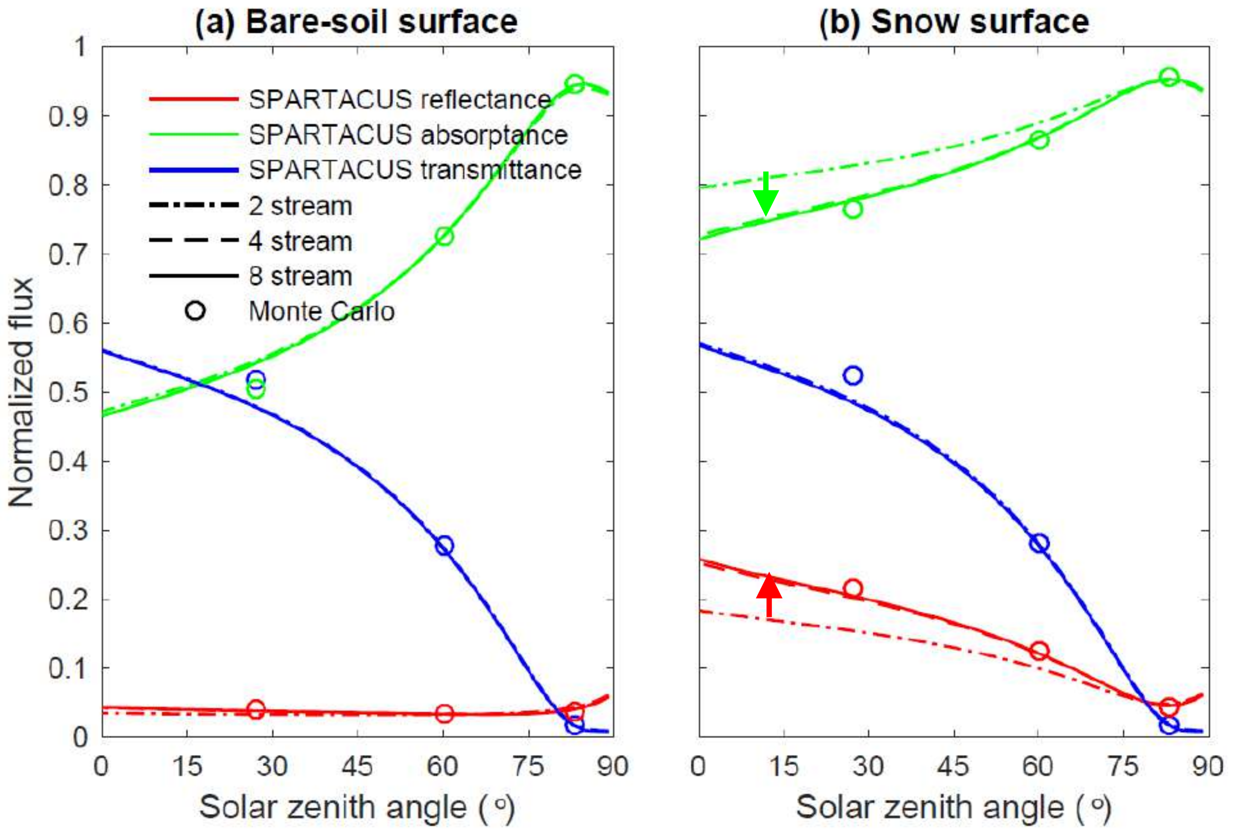
Hogan et al. (GMD 2018)

Beyond two streams

- Two-stream approximation limited by assumption that diffuse radiation all travels at same zenith angle (typically 60° or μ_1=0.5)
- **Discrete Ordinate** method generalizes to 2*N* streams and underpins DISORT (Stamnes et al. 1988) and many other accurate radiative transfer solvers
- Solve using eigenvalue decomposition method (like DISORT), which I have found is more stable than matrix exponential
- SPARTACUS is more accurate for reflectance and absorptance of trees over snow with 4 or more streams
- *Would be useful to have more solar zenith angles in reference dataset!*

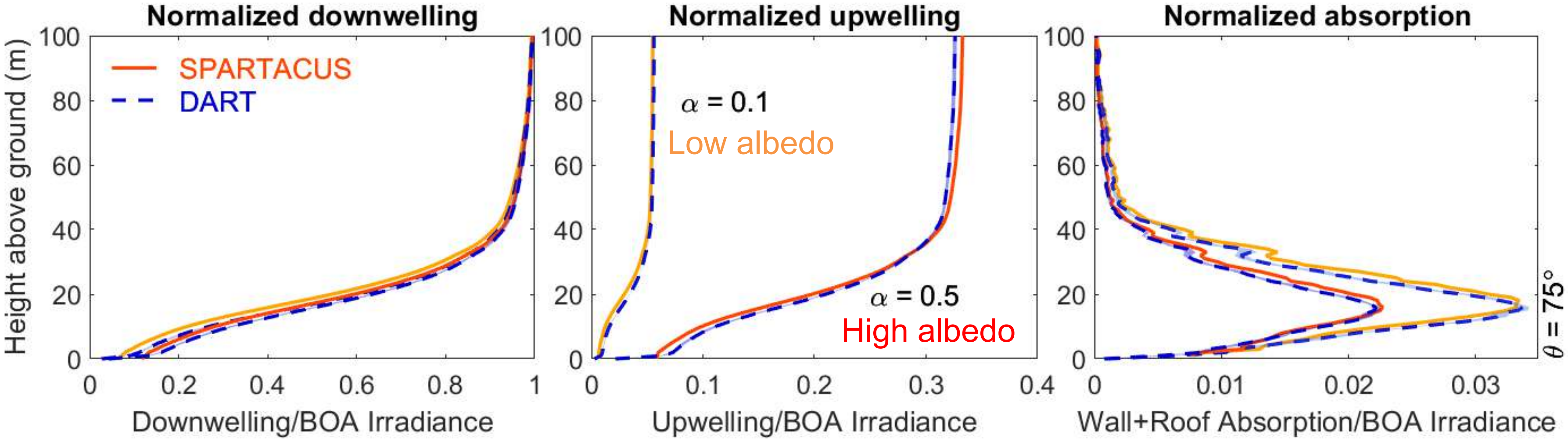




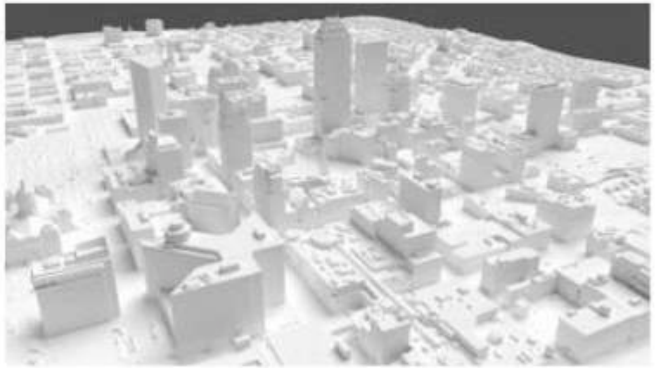
Solar evaluation in 2x2 km city scenes (Stretton et al. BLM 2022)

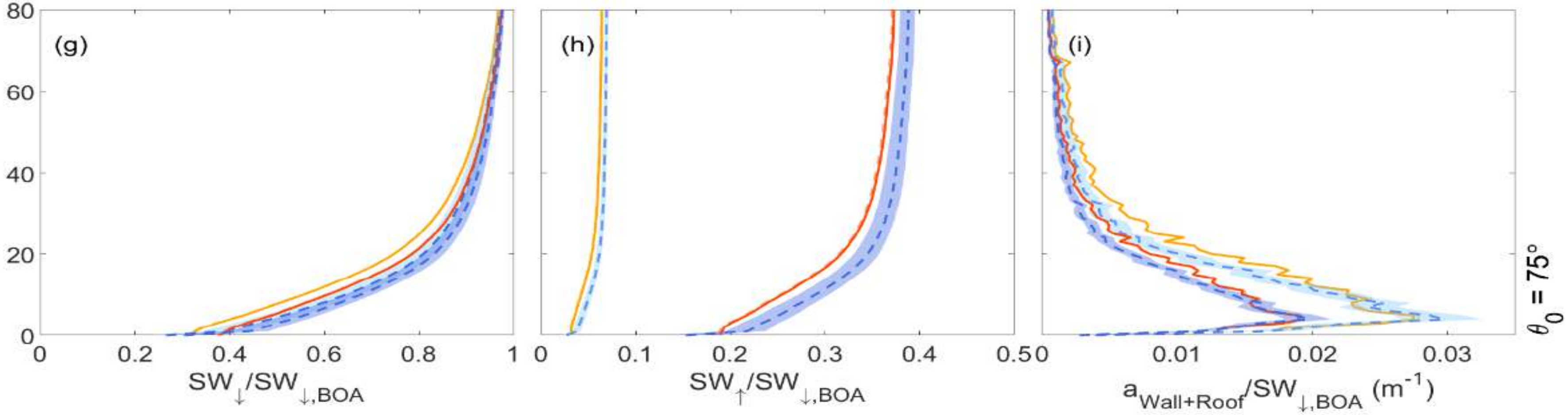
- Good agreement with reference calculations by DART that represent every building
- Similar thermal-infrared results reported by Stretton et al. (EGUsphere, in review)

London



Indianapolis





SPARTACUS is between 8 and 9 orders of magnitude faster than DART!

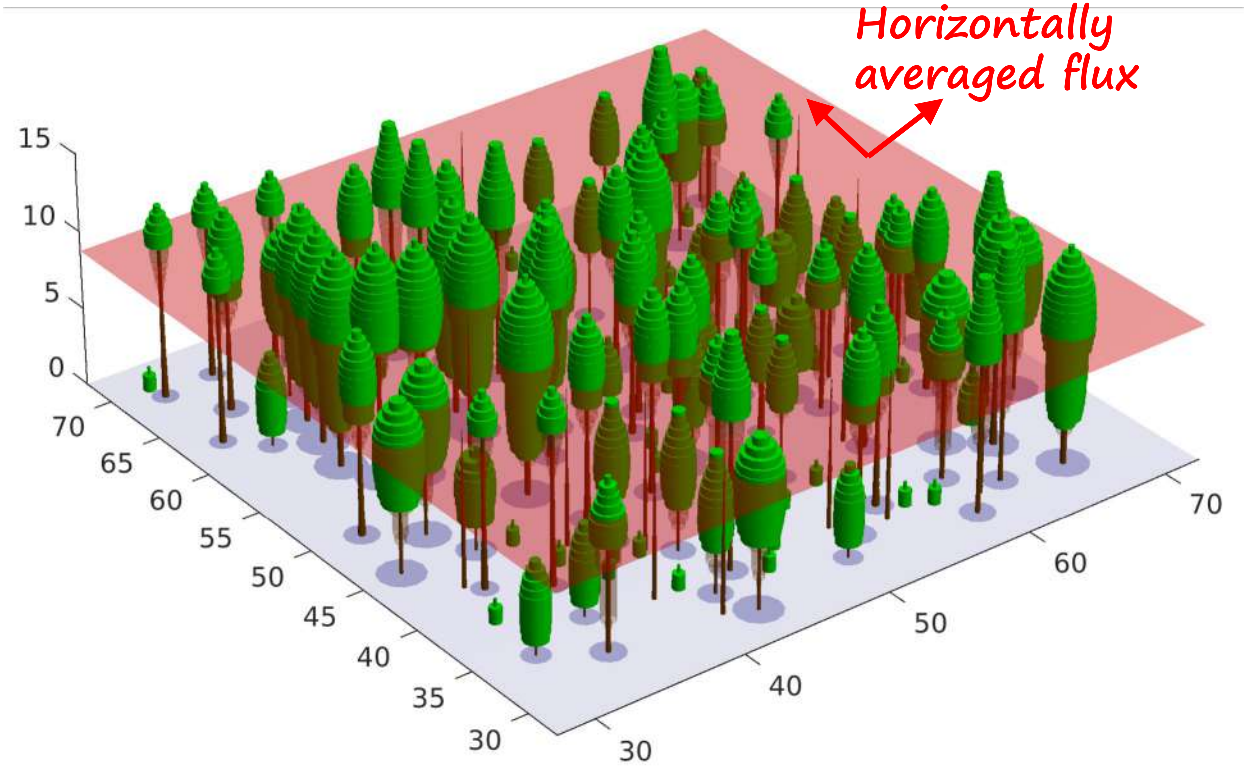
Model	Layers	Time (s)
SPARTACUS (2 streams)	1	0.000 012
SPARTACUS (2 streams)	6	0.000 050
SPARTACUS (2 streams)	151	0.001 1
SPARTACUS (8 streams)	151	0.003 0
DART (explicit)	151	250 000

Timings for a single urban scene reported by Stretton et al. (BLM 2022)

- Intercomparison exercises need to distinguish between:
  - **Fast parametric models** that make approximations to treat the distributions of buildings and/or trees statistically in order that they are fast enough to be used in weather and climate models
  - **Explicit reference models** that resolve every building or tree (sometimes every leaf)

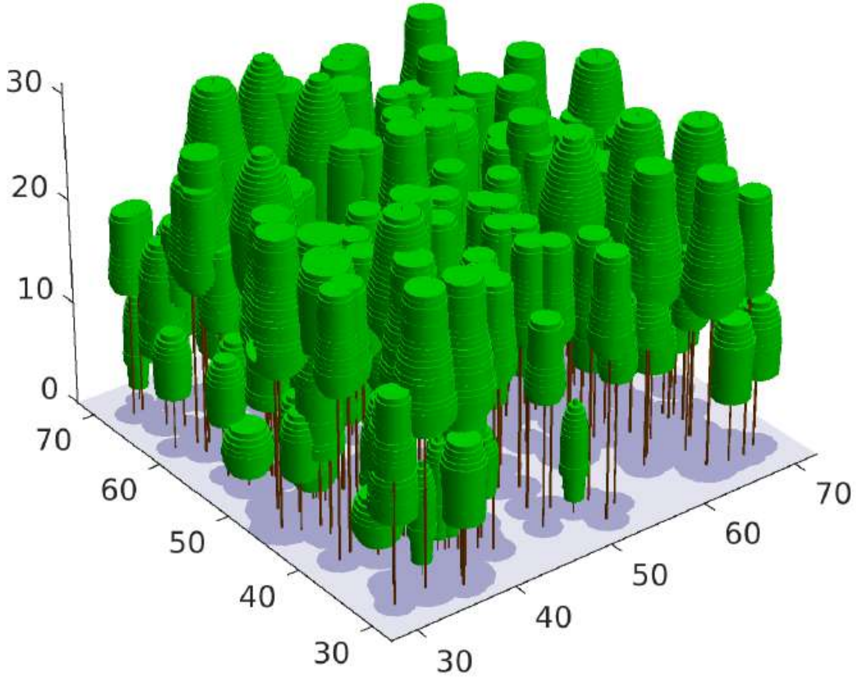
Why does the SPARTACUS method work?

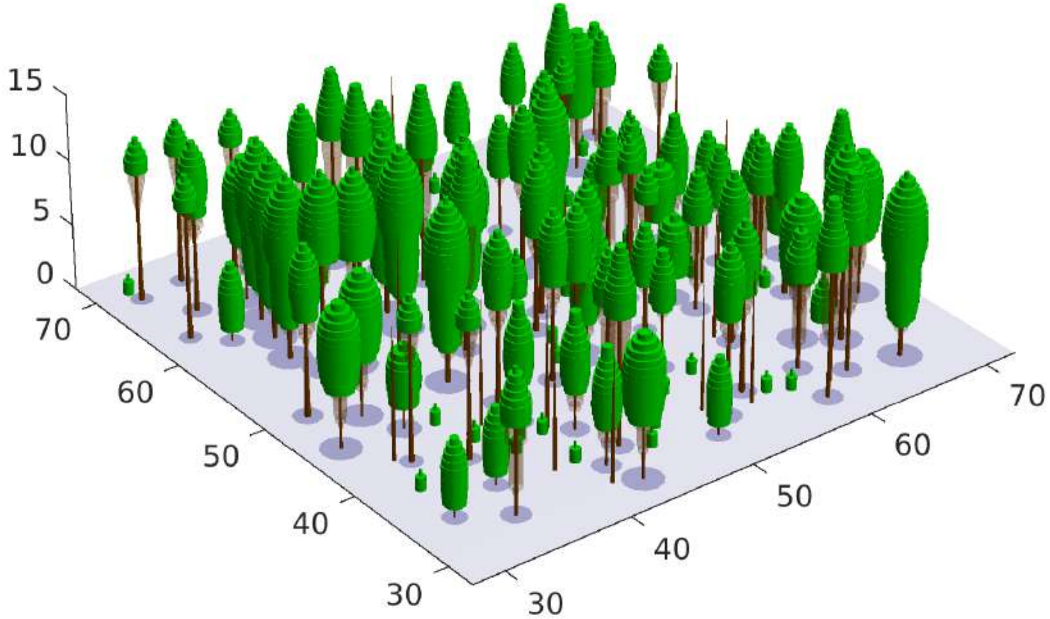
- All clear-sky radiation in a layer travelling with one zenith angle is represented by *only one number* representing the average
- Assume the rate of exchange between clear-sky & vegetated regions is proportional to *crown perimeter length*
- This is valid if buildings and trees are *randomly distributed in the horizontal plane*, resulting in the probability distribution of wall-to-wall or tree-to-tree distances following an *exponential distribution*
- This is a good approximation for cities (Hogan, BLM 2019); what about forests?

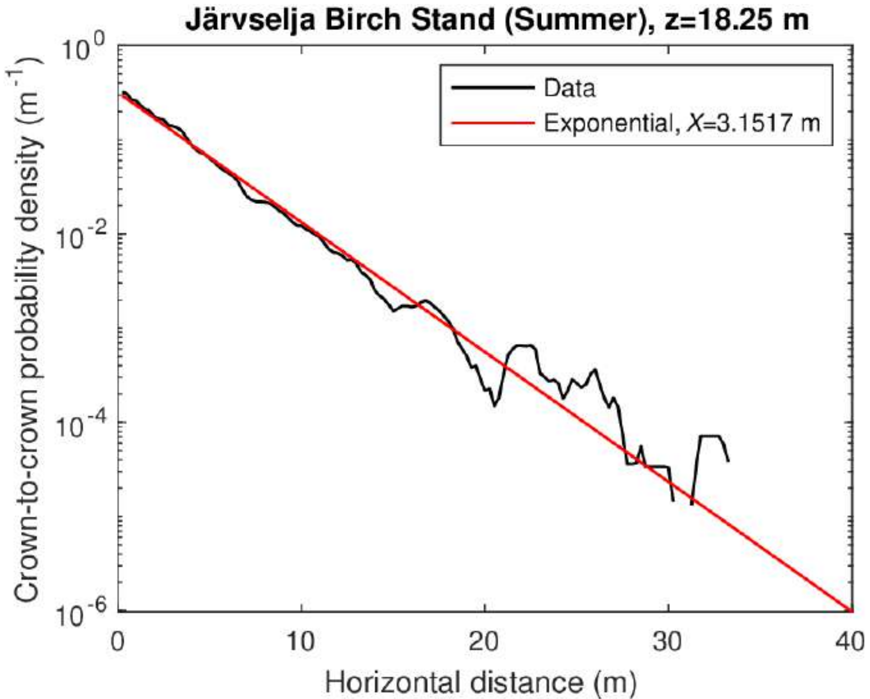


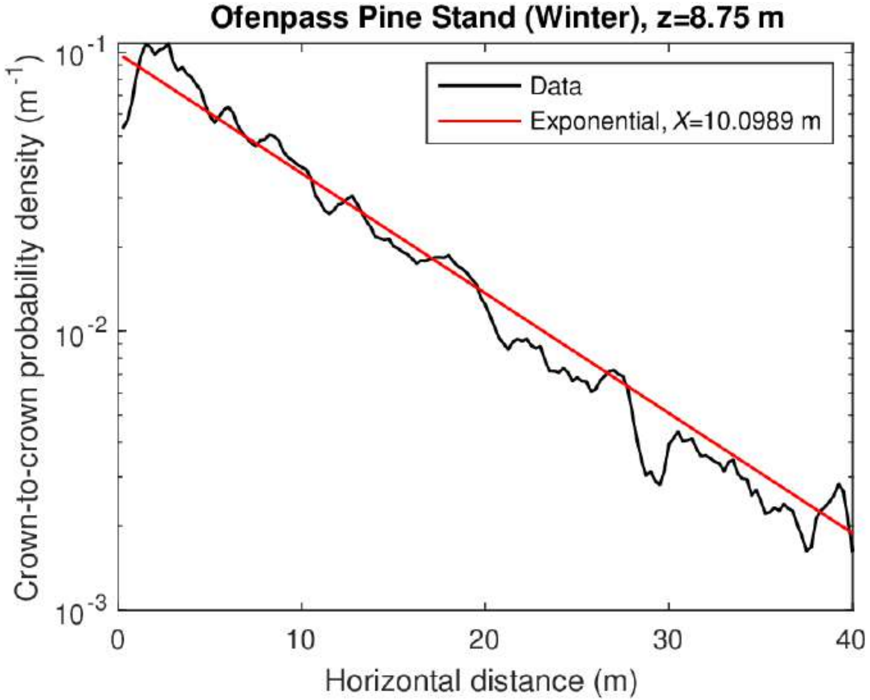
RAMI-V scenes (1)

- Analyze each layer of the scene to extract properties for input into SPARTACUS
- Probability density of crown-to-crown distances well fitted by an exponential, confirming random distribution!
- Characterized by the horizontal mean-free-path X or equivalently the normalized edge length $L^{ab} = \pi\, c_a / X$









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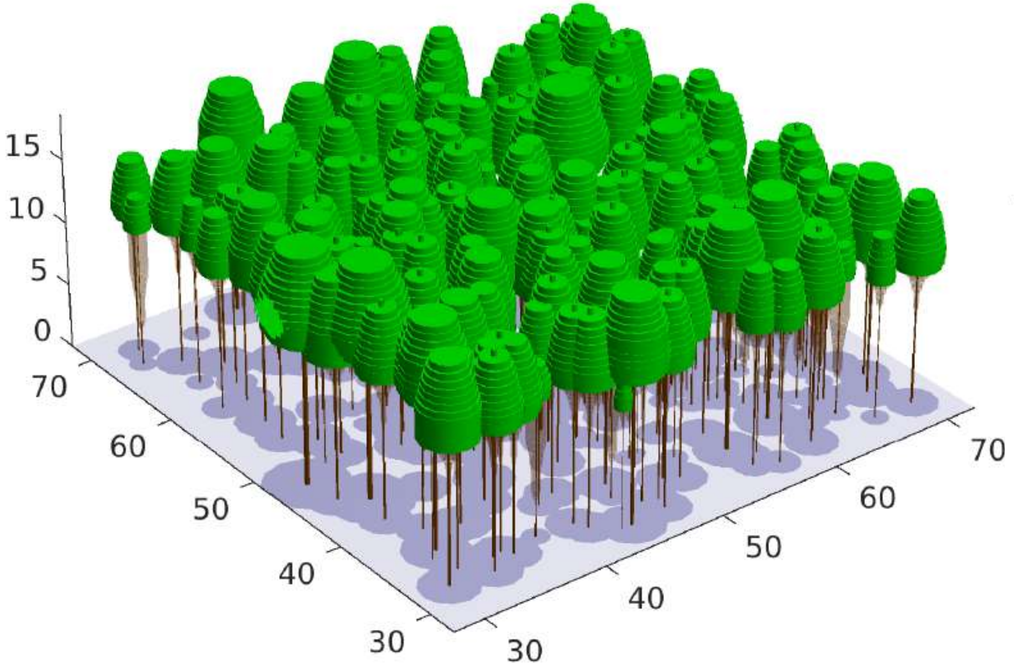
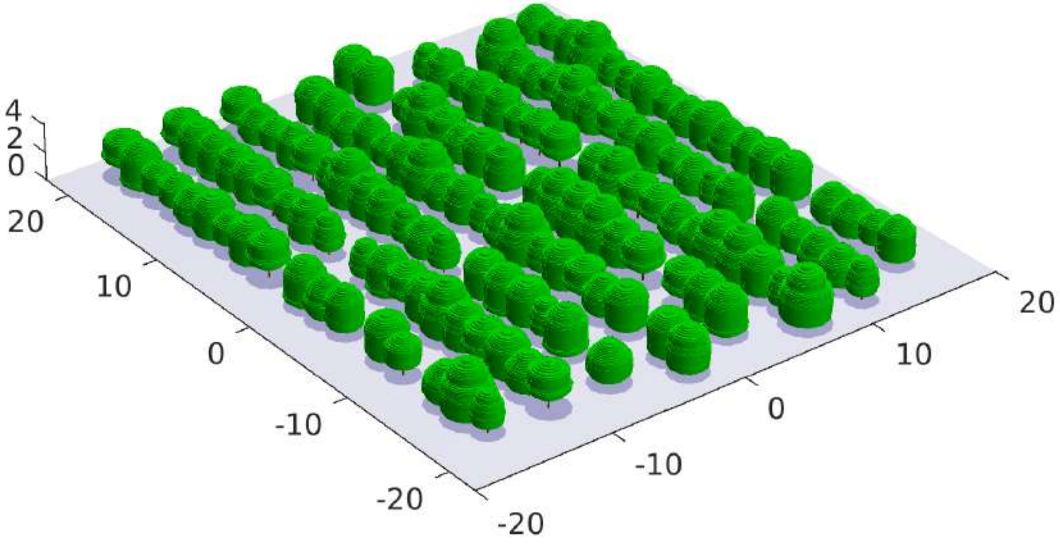
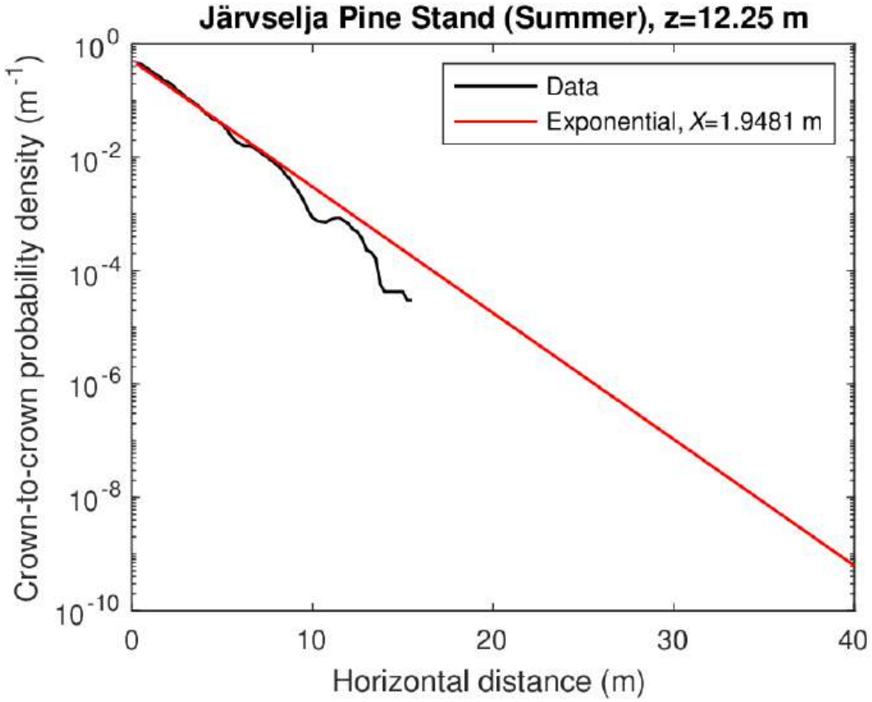
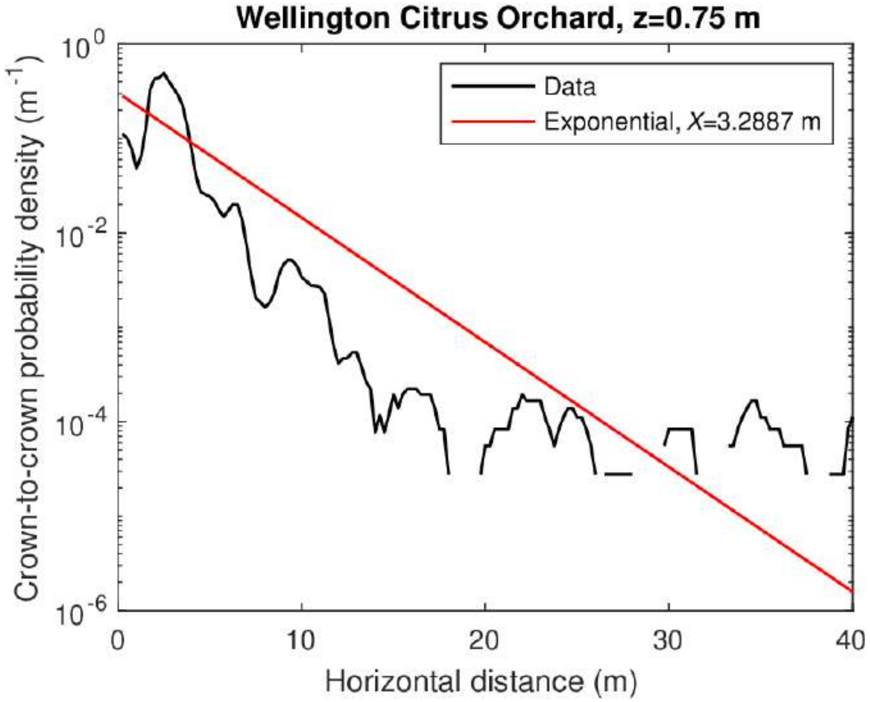
RAMI-V scenes (2)





- JPS is a denser canopy but still follows an exponential
- WCO is in rows: not well fitted by an exponential (but how much does this matter?)





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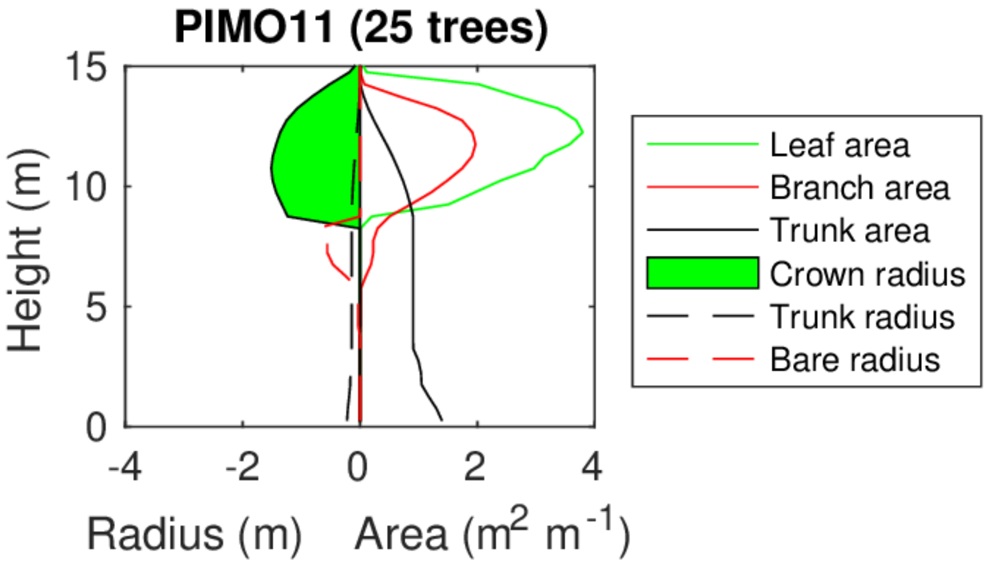
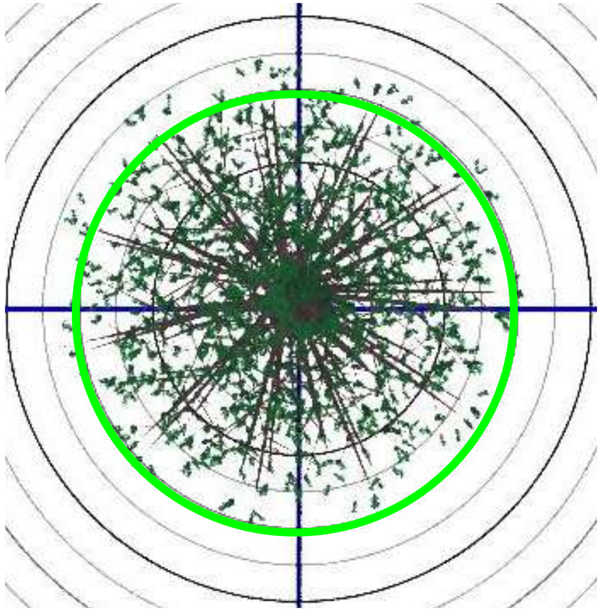
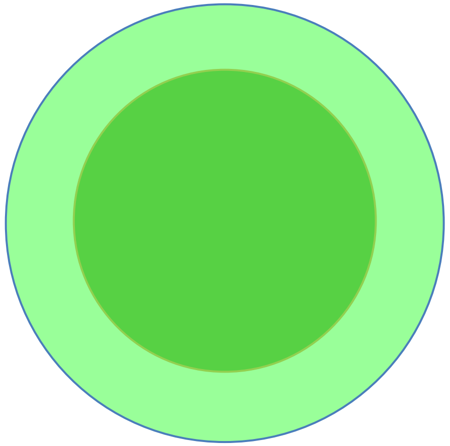
Analysis of Mountain Pine (PIMO11) from Ofenpass Pine Stand

- Radii of **trunks** & **crowns** to determine fraction of each region
- **Trunks** treated as impermeable
- Use **bare region** for unfoliated branches



- **Leaf** and **branch** area used to compute extinction assuming random orientation
- **Trunk** assumed to be vertical (like building walls)





- Crown in each layer defined as 90% of enclosing circle
- Characterize heterogeneity by fractional standard deviation (FSD) of leaf/branch density: FSD(leaf)=0.7, FSD(branch)=1.4
- Use FSD to specify extinction of inner and outer regions (equal area)

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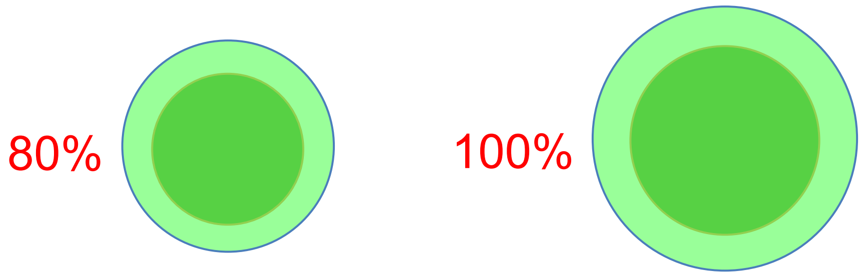
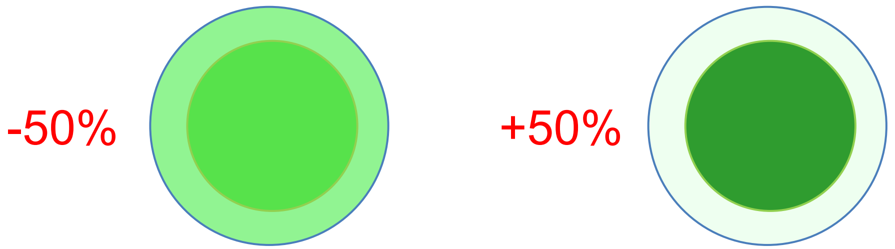
Uncertain parameters in SPARTACUS

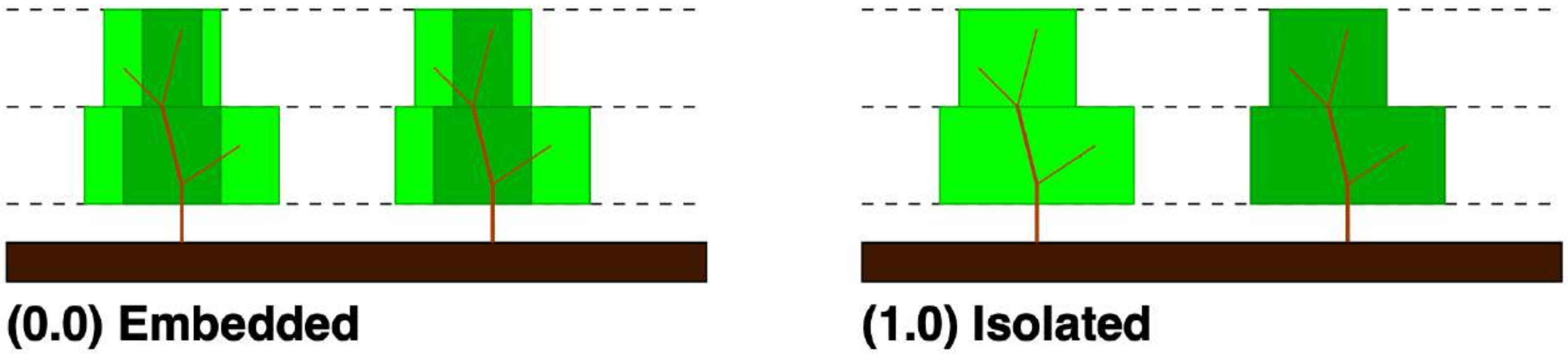
1. Where is the effective edge of the crown? Default is 90% of enclosing circle: try also 80% and 100%.



2. What is the appropriate FSD? Try reducing and increasing by 50%.



3. Is the centre of a crown always the most optically thick? SPARTACUS allows the “isolation factor” to be defined: default=0 but we also try 1



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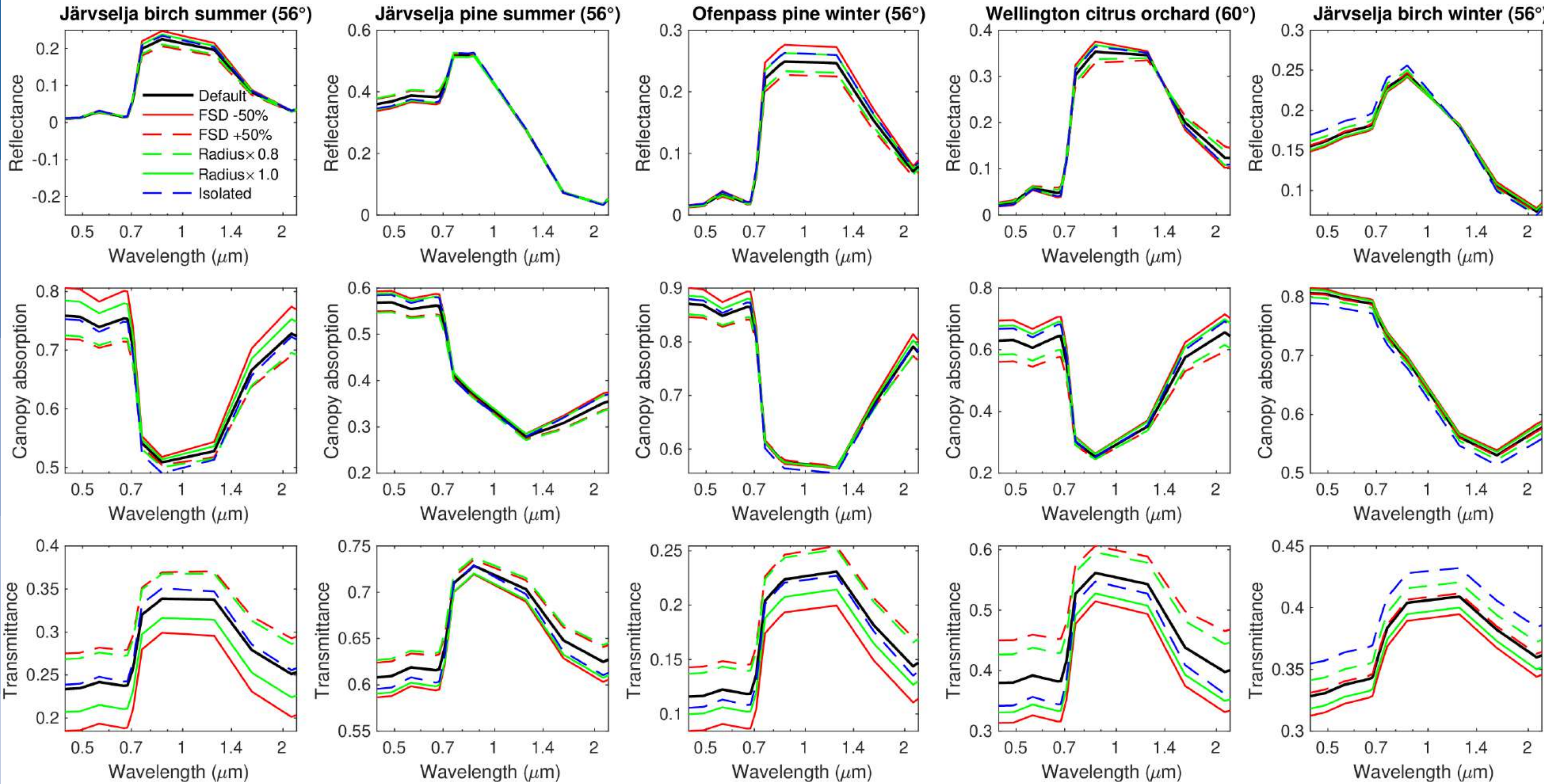

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How does this compare with a reference model (e.g. DART?)

Summary

- SPARTACUS is a very promising fast method for calculating 3D interaction of radiation with forests & urban areas, suitable for weather & climate models if fed with good physiographic data
- Conceivably the 3-region idea could be extended to radiance & SIF modelling for remote sensing
- Links to published SPARTACUS papers: http://www.met.reading.ac.uk/clouds/spartacus/
- *Evaluation needed against a RAMI-V reference model to refine uncertain parameters*

Suggestions for future RAMIs

- Distinguish between explicit reference models and fast parametric models: the latter can be 8-9 orders of magnitude faster than the former!
- Scenes should be tested for all solar zenith angles from 0 to 90º, a key test of vegetation radiation schemes for weather and climate models
- Consider an intercomparison of radiation schemes for urban areas
- Plan for public data release (although participants may opt out): *lasting value of an intercomparison is open datasets to validate new fast models, and is a crucial way to engage with a wider range of participants including weather/climate modellers (and consistent with EU's open data policy)*