DART recent advances in remote sensing modeling: chlorophyll fluorescence, urban radiative budget,...

Al Bitar A.[1], *KallelA.*[5], *BenHmida S.*[1], *Chavanon E.*[1],*Gastellu-Etchegorry J.P.*[1], *Gomez Duran N.*[1], *Guilleux J.*[1], *Landier L.*[1], *Malenovsky Z.*[4], *Meynier J* [1], *Nativel S.*[1], *Lauret N.*[1], *Qi J.*[1,3], *Yin T.*[6]

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Beijing Normal University, China

CRNS, ATMS (Sfax) Tunisia

Czech Globe, Czech republic

CENSAM, SMART (M.I.T.), Singapore

Cook B., Morton D. **NASA, GSFC,** USA

Outline

- DART model: objectives and history
- Theory and products: - TOA / BOA /In-situ spectro-radiometers
  - Sensors with finite FOV
  - Specular reflectance and polarization
  - LiDAR (waveform, photon counting)
  - Up-scaling chl fluorescence from leaf to canopy
- An application: EO satellite driven urban radiative budget maps
- On-going work

DART: objectives and history

Simulation of satellite, airborne and in-situ remote sensing systems

⇒ **Sensitivity of remote sensing acquisition**:

- Experimental point of view: vegetation phenology, atmosphere,…
- Instrumental point of view: date, spectral/spatial resolution,…

⇒ **Inversion** of remote sensing acquisition: biophysical parameters (LAI, albedo,…)

⇒ **Specification of new sensors**

Simulation of radiative budget

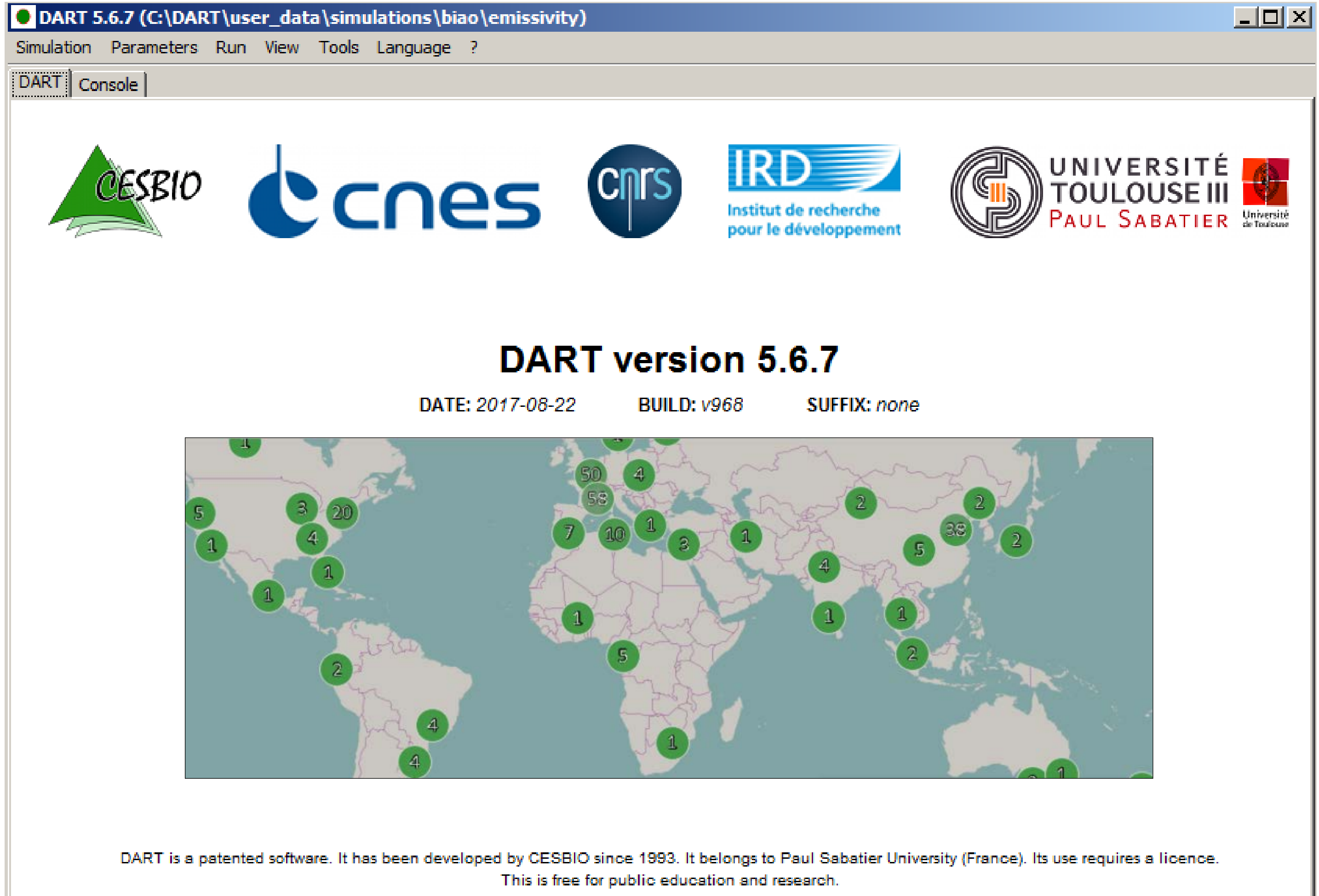
⇒ **Biosphere functioning** (incoming PAR, fluxes of gasses and energy, etc.)

⇒ **Urban meteorology**

Education in physics, remote sensing and radiative budget

The DART model: Objectives and history

History:
Developed since 1992 at CESBIO by 7-10 physicists / computer scientists.
Patented in 2003.



Users: 281 licenses
- NASA, USA: LiDAR, Fluo, RB
- ESA, EU: Fire, Hyperspectral
- CENSAM-MIT: RB
- KCL, GB: Fire,
- FORTH, Gr: Urban
- CNES, Fr: LiDAR
- ONERA, Fr: Hyperspectral
- Magellium, Fr: water
- IRSTEA, Fr: LiDAR, Hyper.
- …

License: free for research and education institutes (http://www.cesbio.ups-tlse.fr/dart/license/)

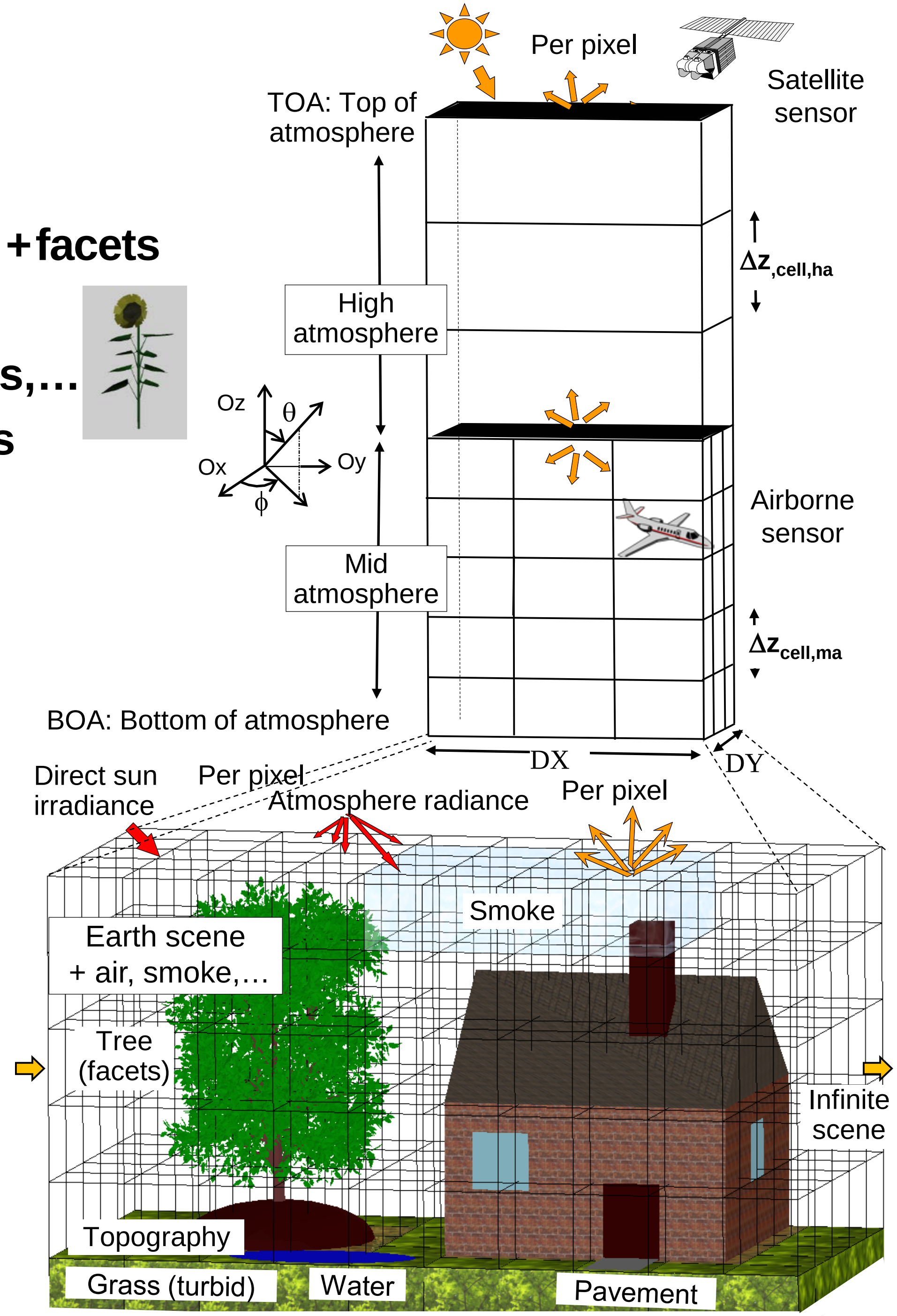
Yearly training courses: France (CNRS), China, Croatia, Lebanon, Tunisia, Cameroun,….

Theory and products

The DART model: ***Theory***

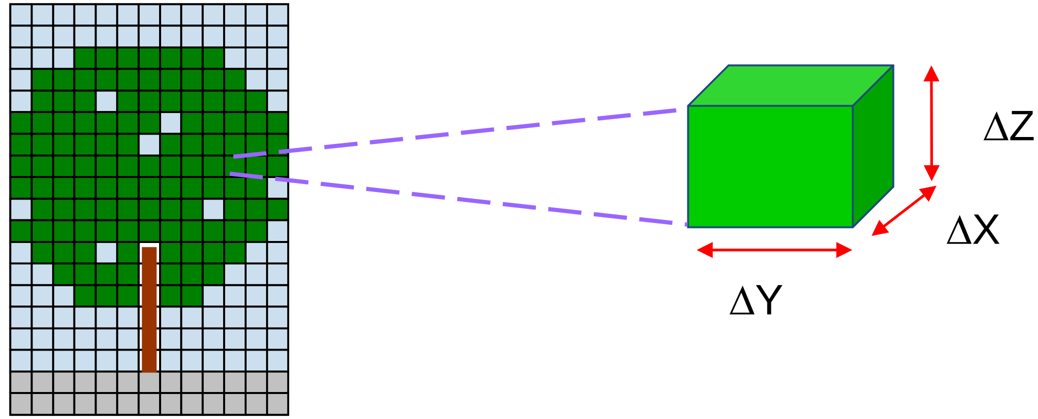
Principles

- **Discrete ordinates (space, directions)**
- **Landscape** (*vegetation, urban, atmosphere*)
  - **- Dual simulating approach: turbid + facets**
  - **- Repetitive or isolated**
  - **- Imported: BD_{atm}, L.C., 3D objects,…**
  - **- PROSPECT & Fluspect leaf models**

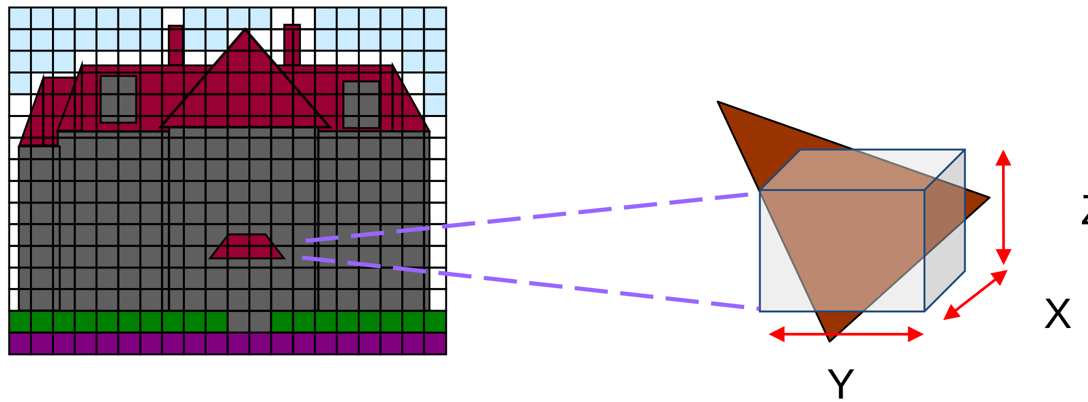


The DART model: ***Dual approach ("turbid" & "facets") for simulating Earth landscape elements***

Turbid cells
(volume)



Facets
(surfaces)



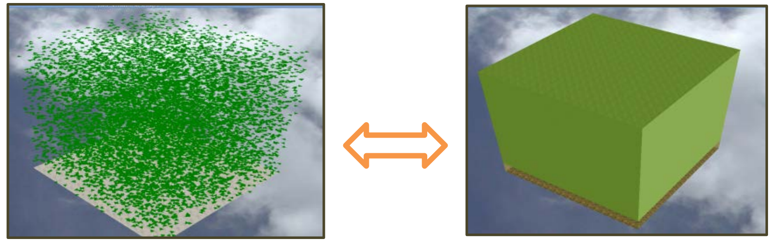
Turbid (Vegetation and/or Fluids) cells and triangles are totally independent

Turbid = medium made of small scatterers that are randomly distributed

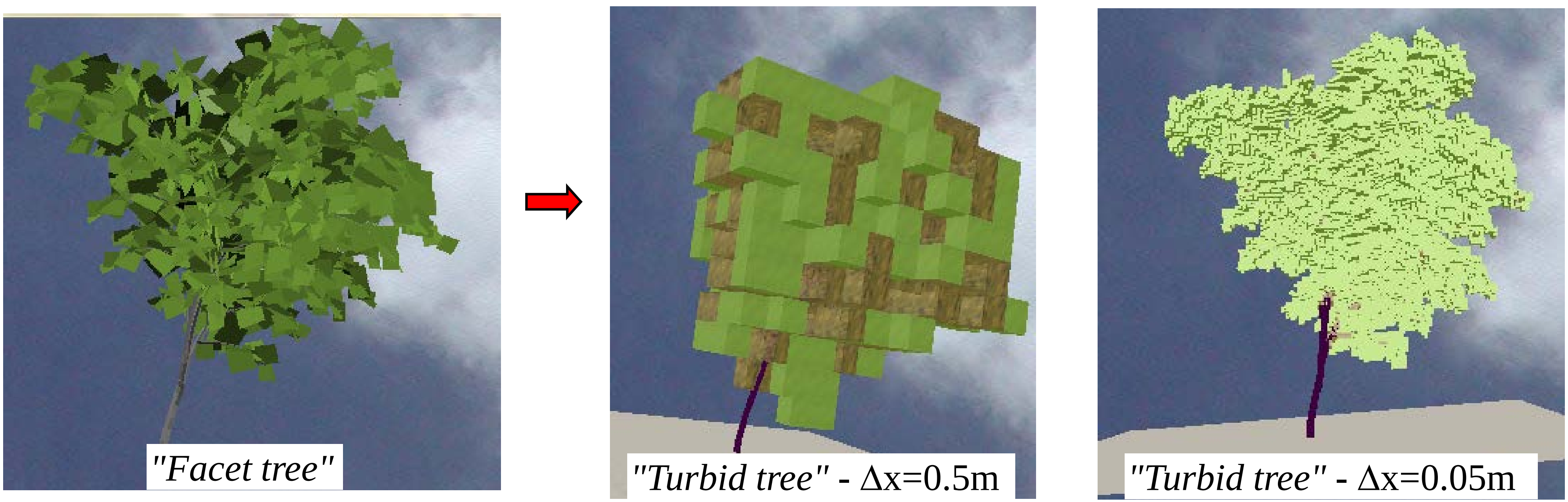
The DART model: Use of facets or turbid volumes for simulating landscapes?

No choice if 3D objects are simulated with too many facets: ⇒ Facets → Turbid 3D objects

Principle



"Facet" landscape *"Turbid" landscape*

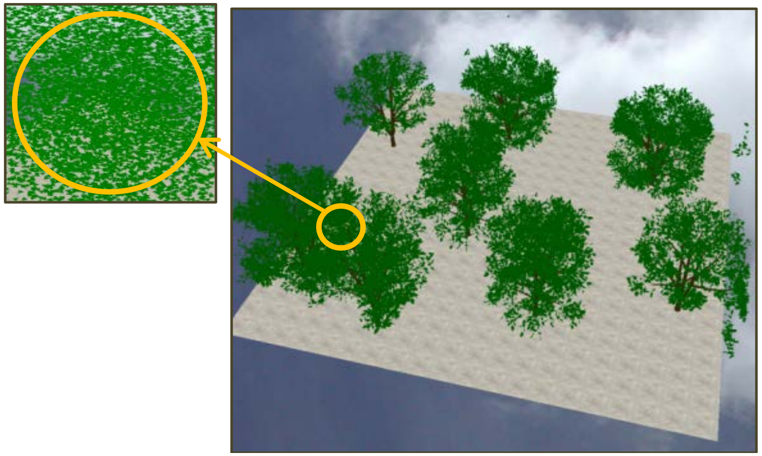


Example: *Transforming a "facet tree" (left) into a "turbid tree" with 2 spatial resolutions*

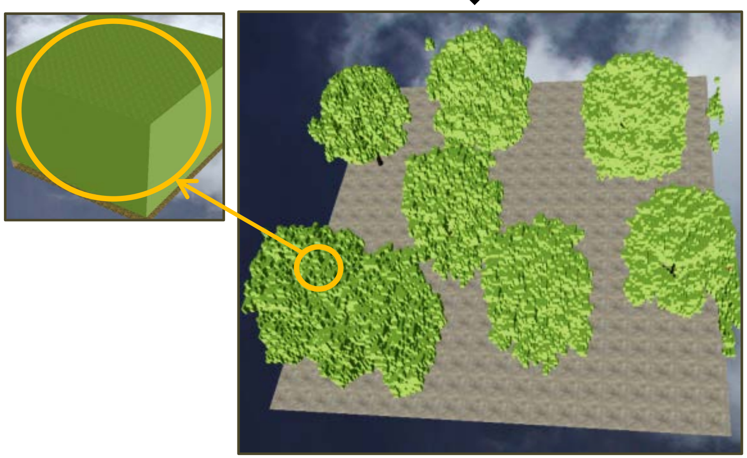
The DART model: Transformation of "facet" trees into "turbid" trees

Turbid trees derived from facet trees

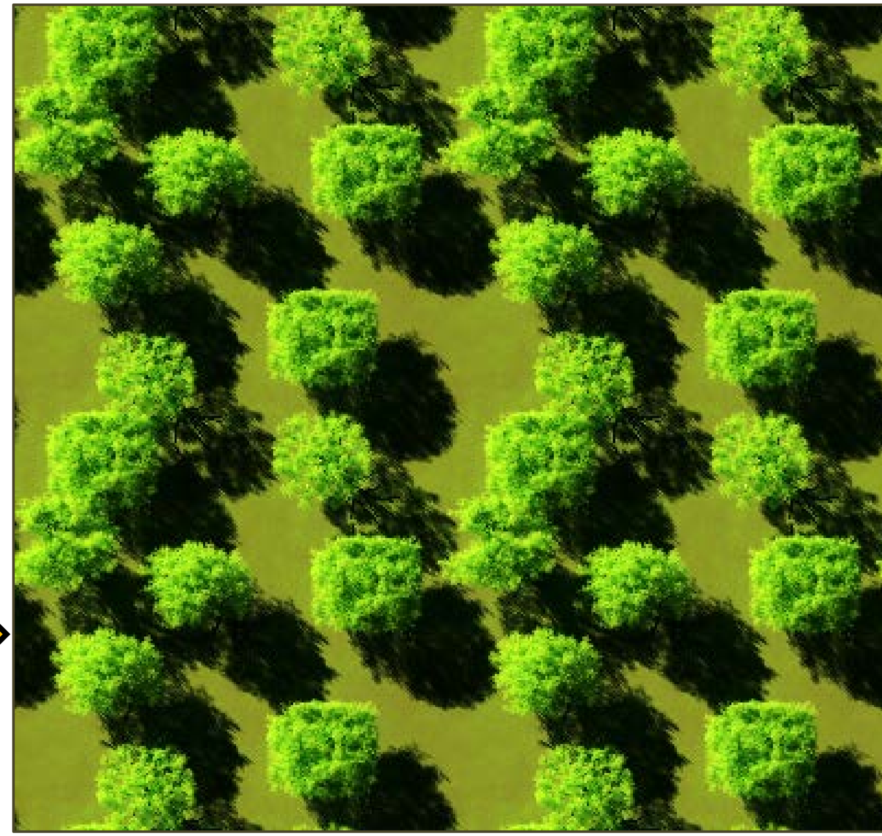
(relative to facet trees, $RMSE_{turbid}$ depends on Δr_{voxel}. $RMSE_{turbid}(\Delta r=0.0125m)=0.0023$)

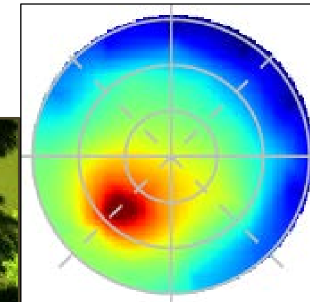


Facet trees



Turbid trees





DART RGB color composite

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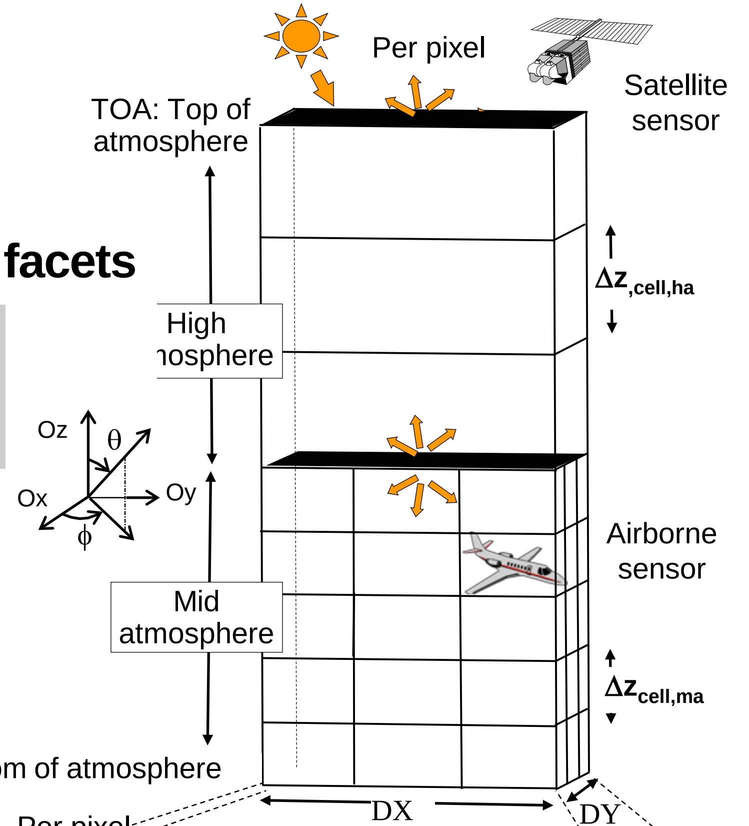
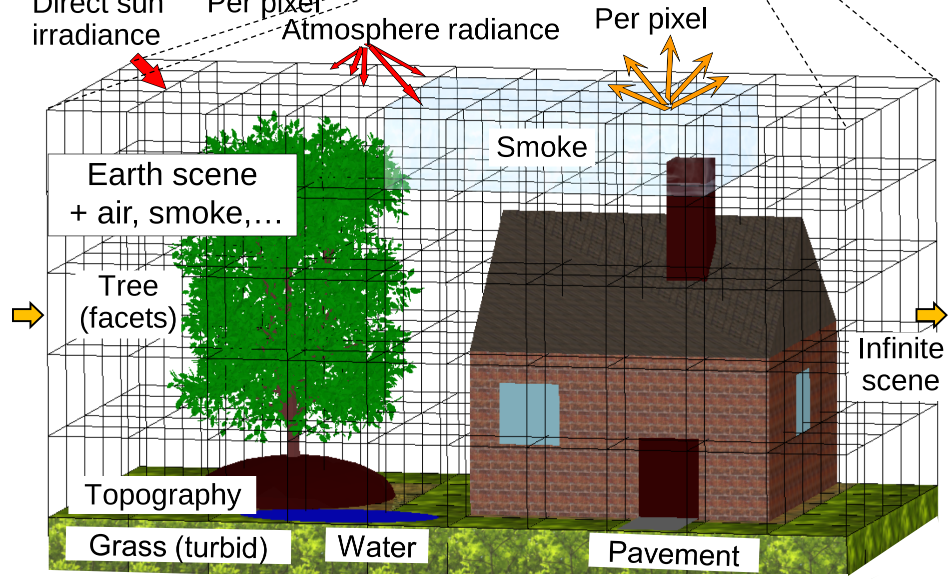
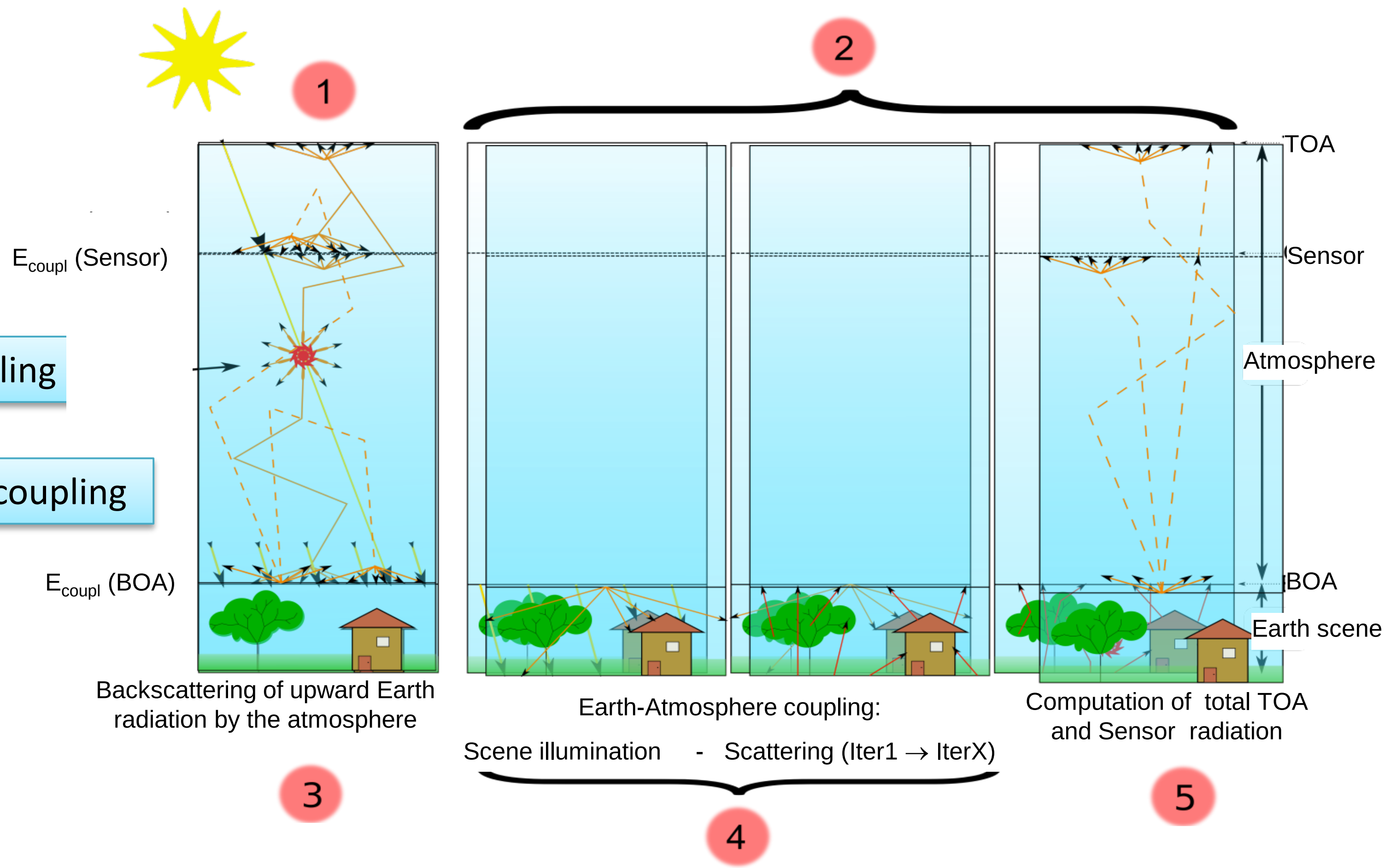




DART ***Ray-Tracking method*** in 5 steps:

1. Earth scene Irradiance
2. Earth scene R.T.
3. Earth-Atmosphere coupling
4. Earth scene R.T. due to coupling
5. TOA, Sensor



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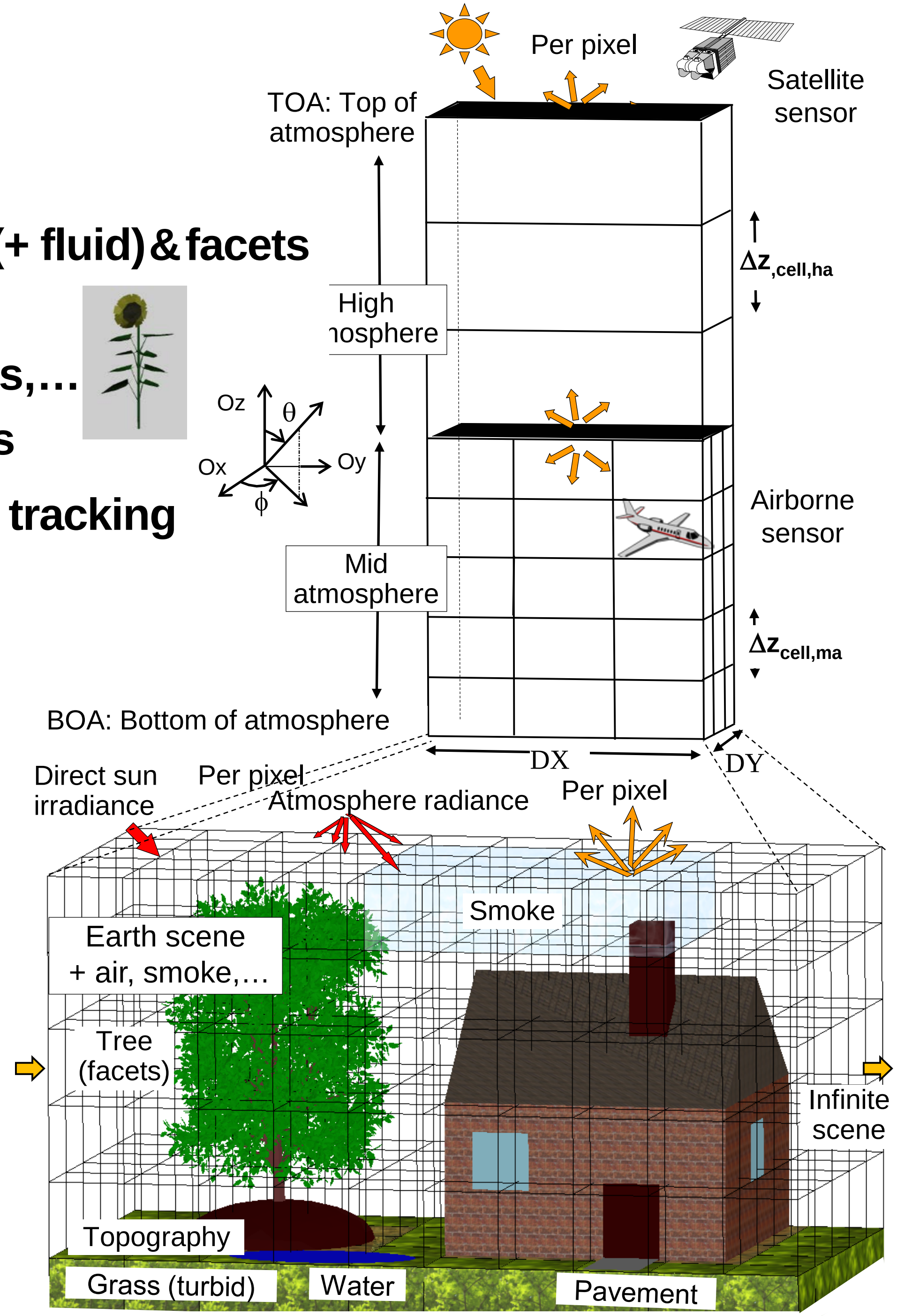
Operating modes (+ automatic sequences)

- **Reflectance (R), Thermal (T) and (R+T)**
- **LiDAR (RayCarlo: ray tracking + M. C.)**

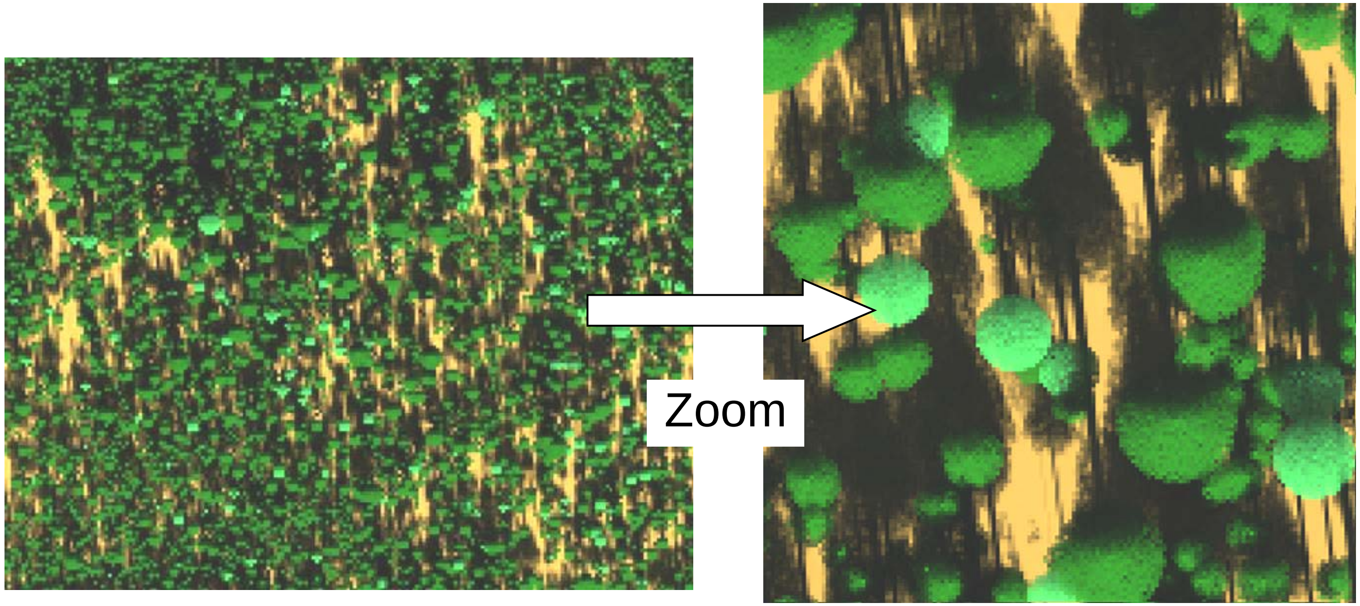
Products (TOA, BOA, in-situ)

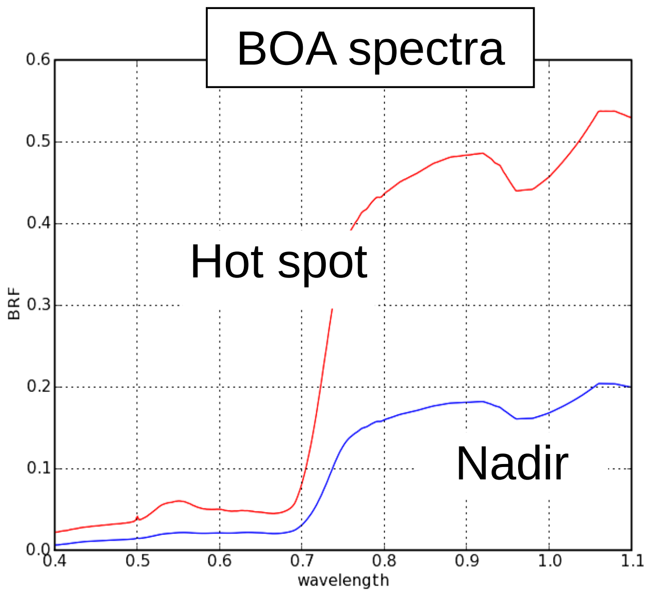
- **Spectro-images: $L_\lambda(\Omega_s,\Omega_v) \Rightarrow \rho_\lambda$, T_B $\forall \Omega_s,\Omega_v$**



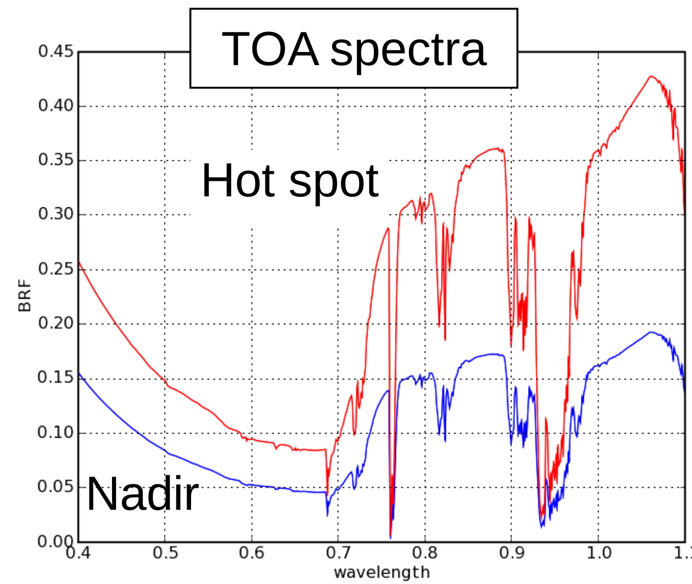
The DART model: ***BOA and TOA spectra (NASA project: DESDynl mission)***

DART Image
Howland forest
(USA)

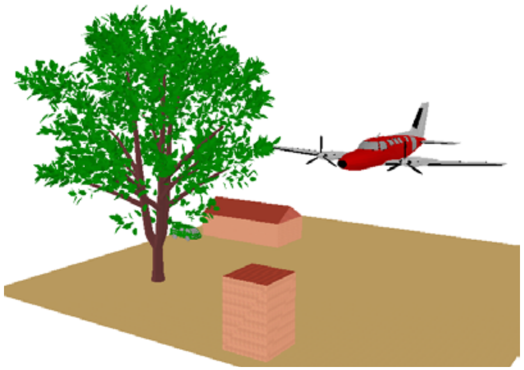




Very strong angular variability of TOA & BOA forest reflectance

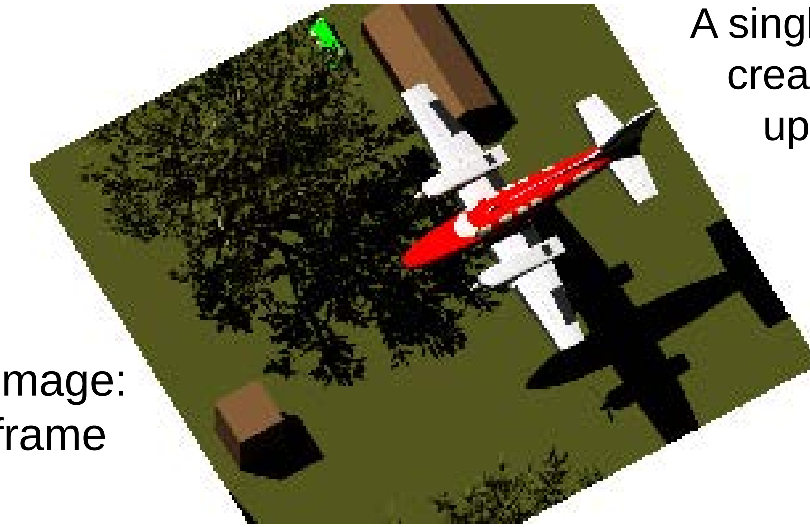


The DART model: ***Nadir, oblique and ortho-images***



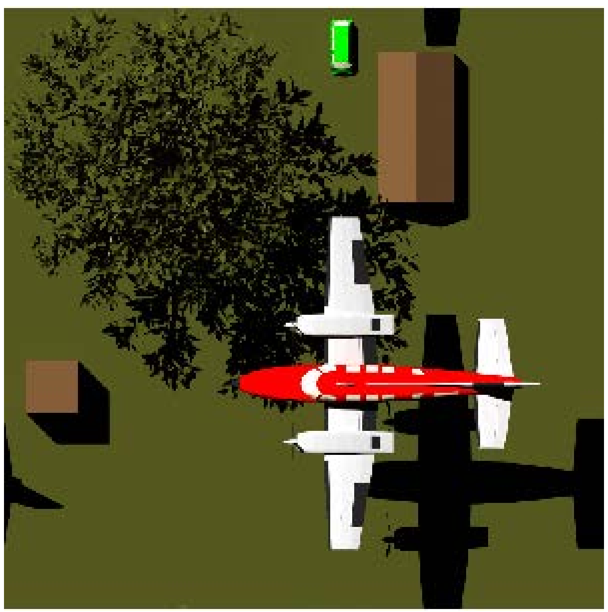
DART Earth scene:
tree, car, plane, house

Oblique image:
sensor frame



A single DART simulation creates images for all upward directions

Nadir image



Ortho-image

$L_{x,y,ortho}=0$: unseen for oblique direction

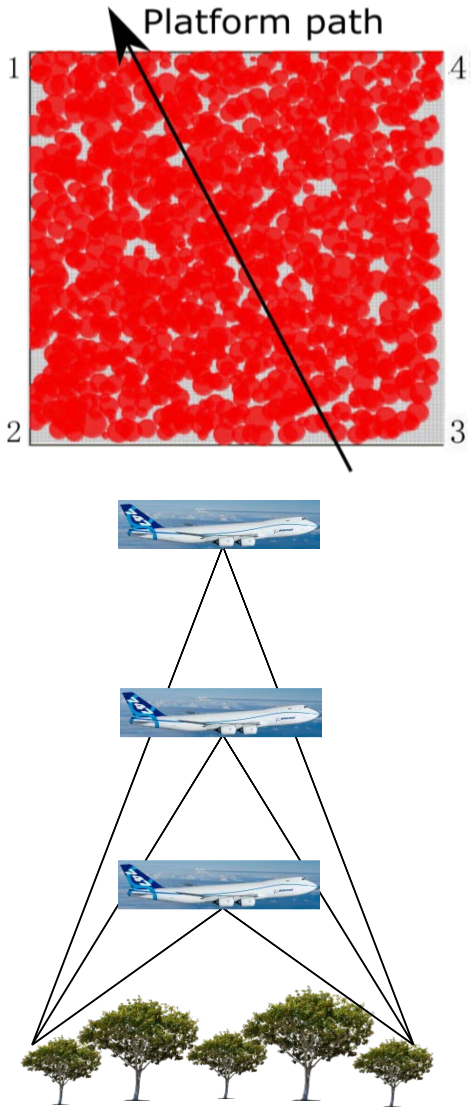
1 DART simulation ⇒ camera / scanner (satellite, plane, ground) images for all defined view directions

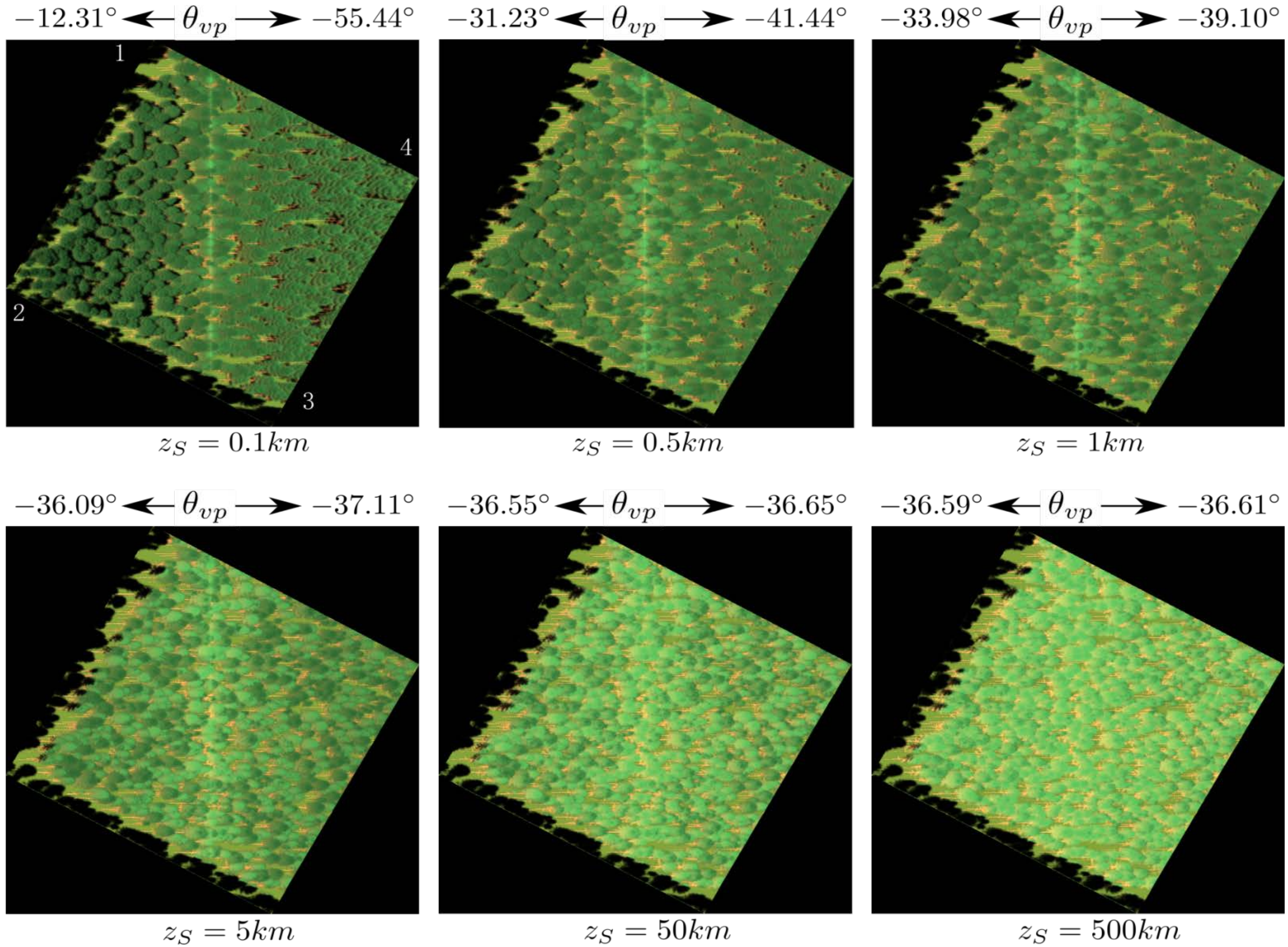
The DART model: **Airborne / Satellite sensor (pushbroom, camera) with FOV ≠ 0**

Järvselja pine stand, Estonia

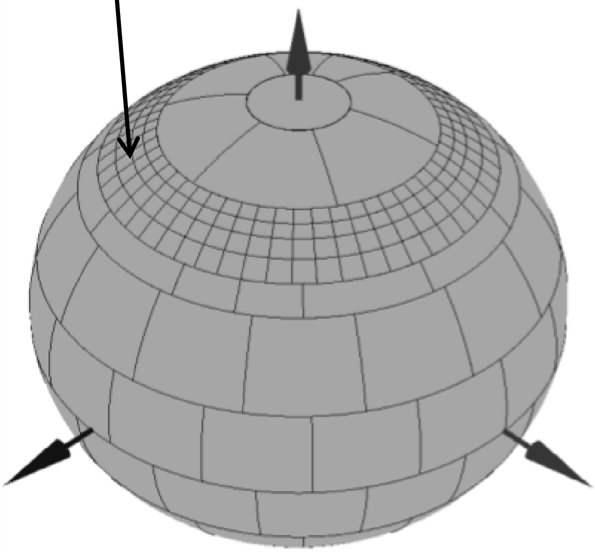
(Ω_{sun}: θ_s=36.6°, ϕ_s=299.06°)

Pushbroom: hot spot observed at 6 altitudes





The simulation is achieved with tracking directions that oversample the sensor FOV



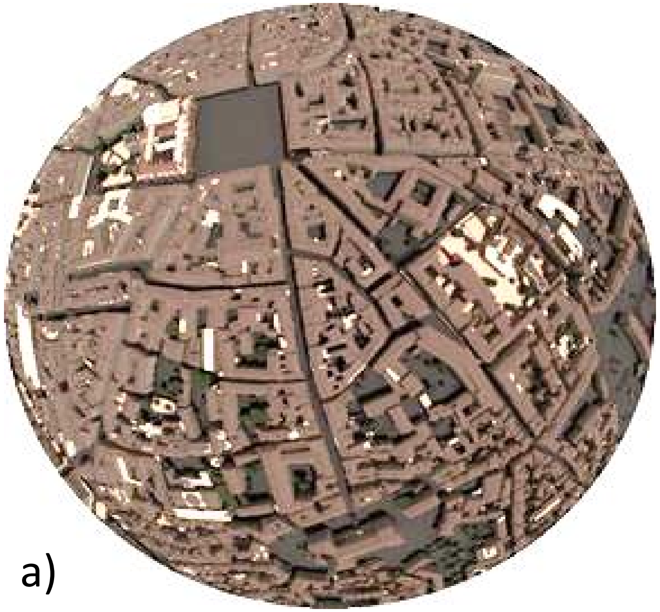
3D display of flux tracking directions in the 4π space.

Radiance values of identical objects (tree,…) differ due to sensor FOV (angular effects)

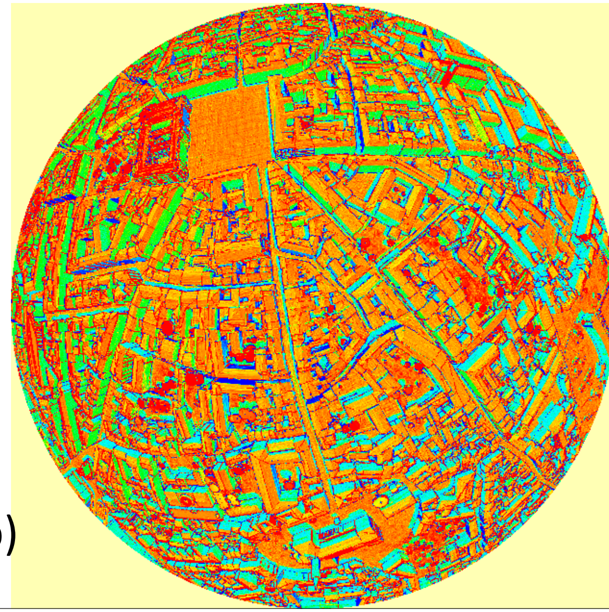
UAV camera - Järvselja pine stand, Estonia

$(\theta_v = 50°, z_{UAV} = 140m)$

The DART model: **In situ sensors**



a)



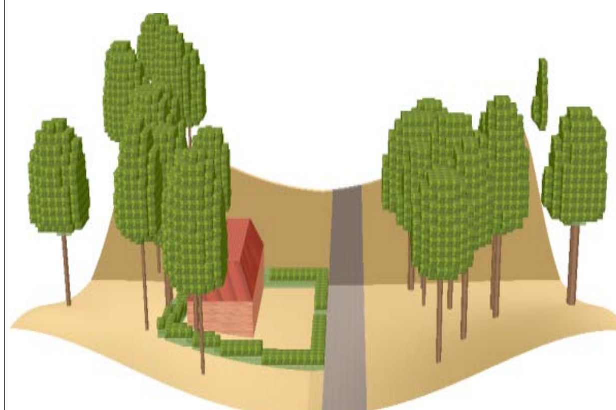
b)

DART: fish-eye camera over an urban canopy.

a) Short waves.

b) Thermal infrared.

Upward looking sensor



DART mock-up

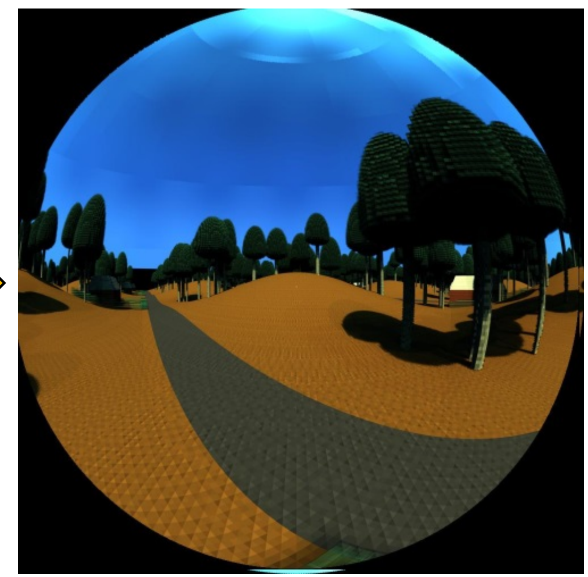
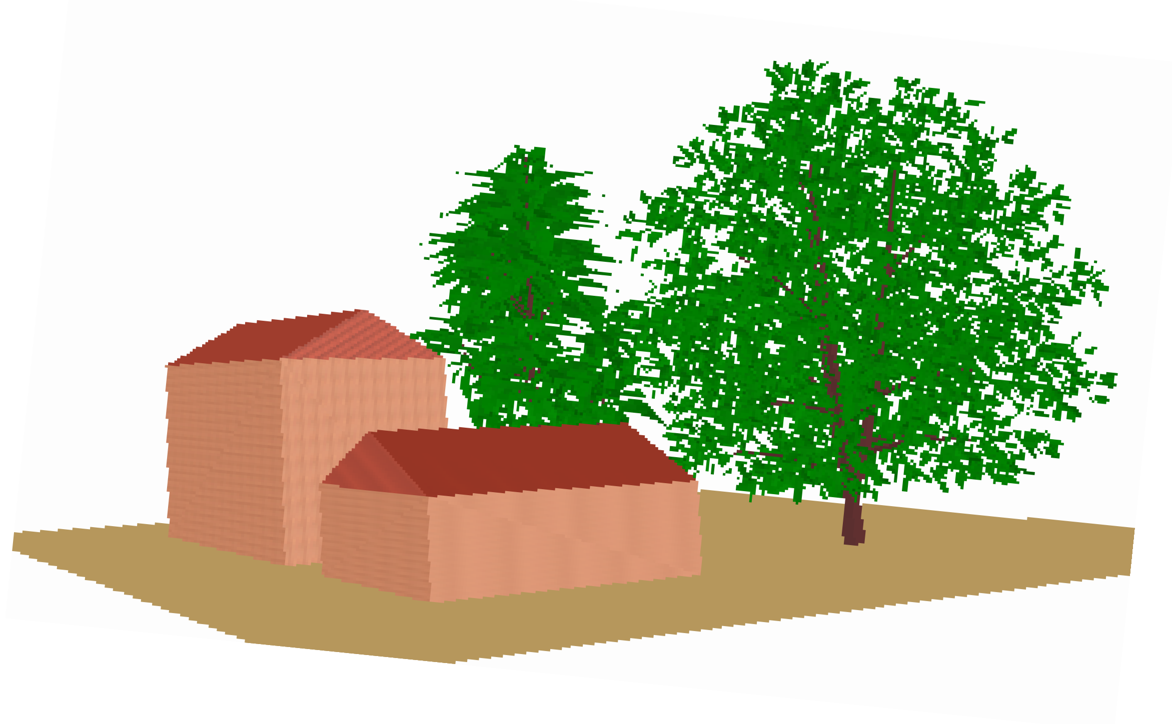


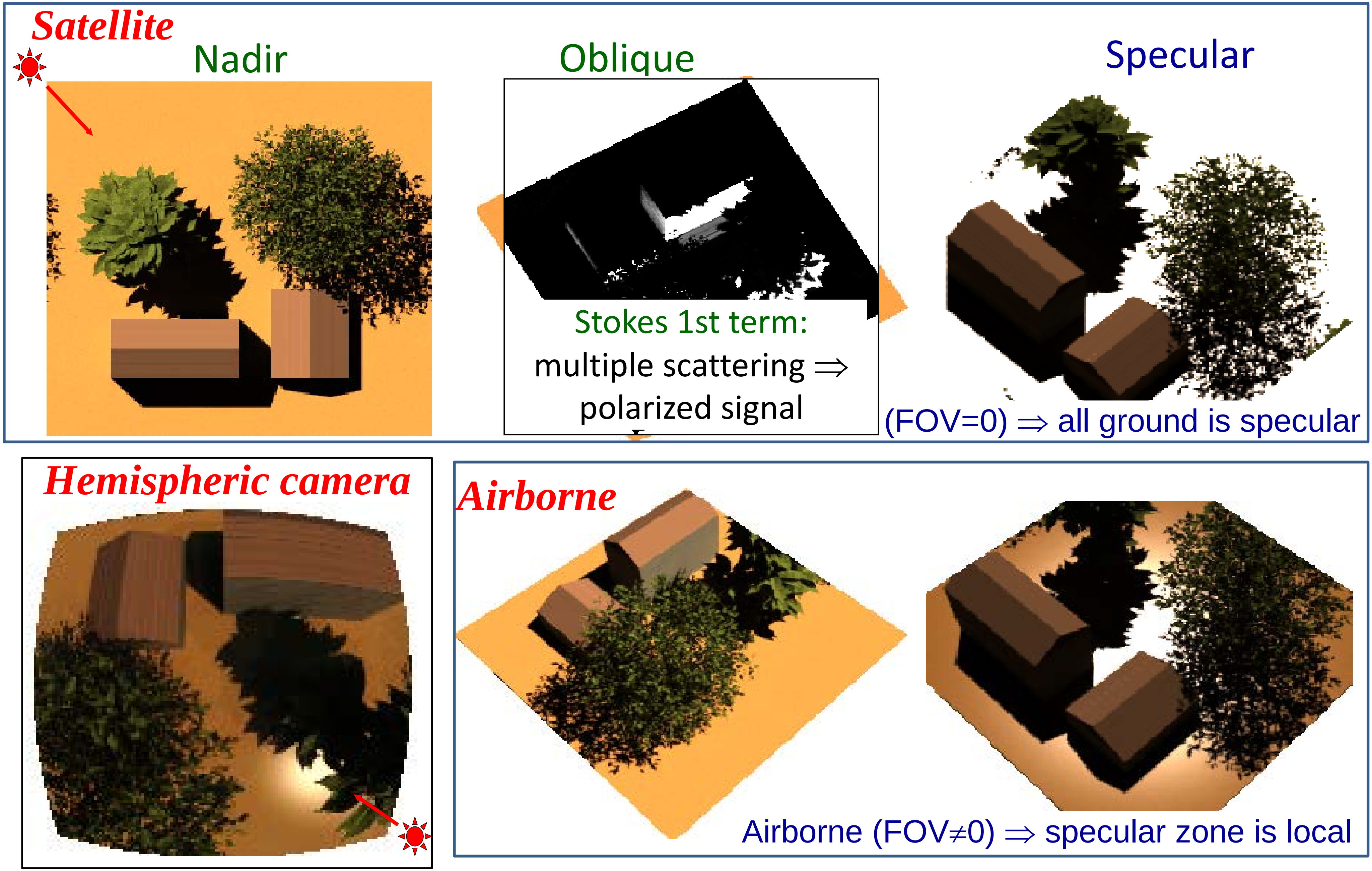
Illustration with DART simulated satellite, airborne and in-situ images for the case of a schematic flooded landscape



2 houses + 2 trees + flooded ground.

Only the flooded ground (water surface) has a specular behavior.

The DART model: **Specular reflectance and Polarization**



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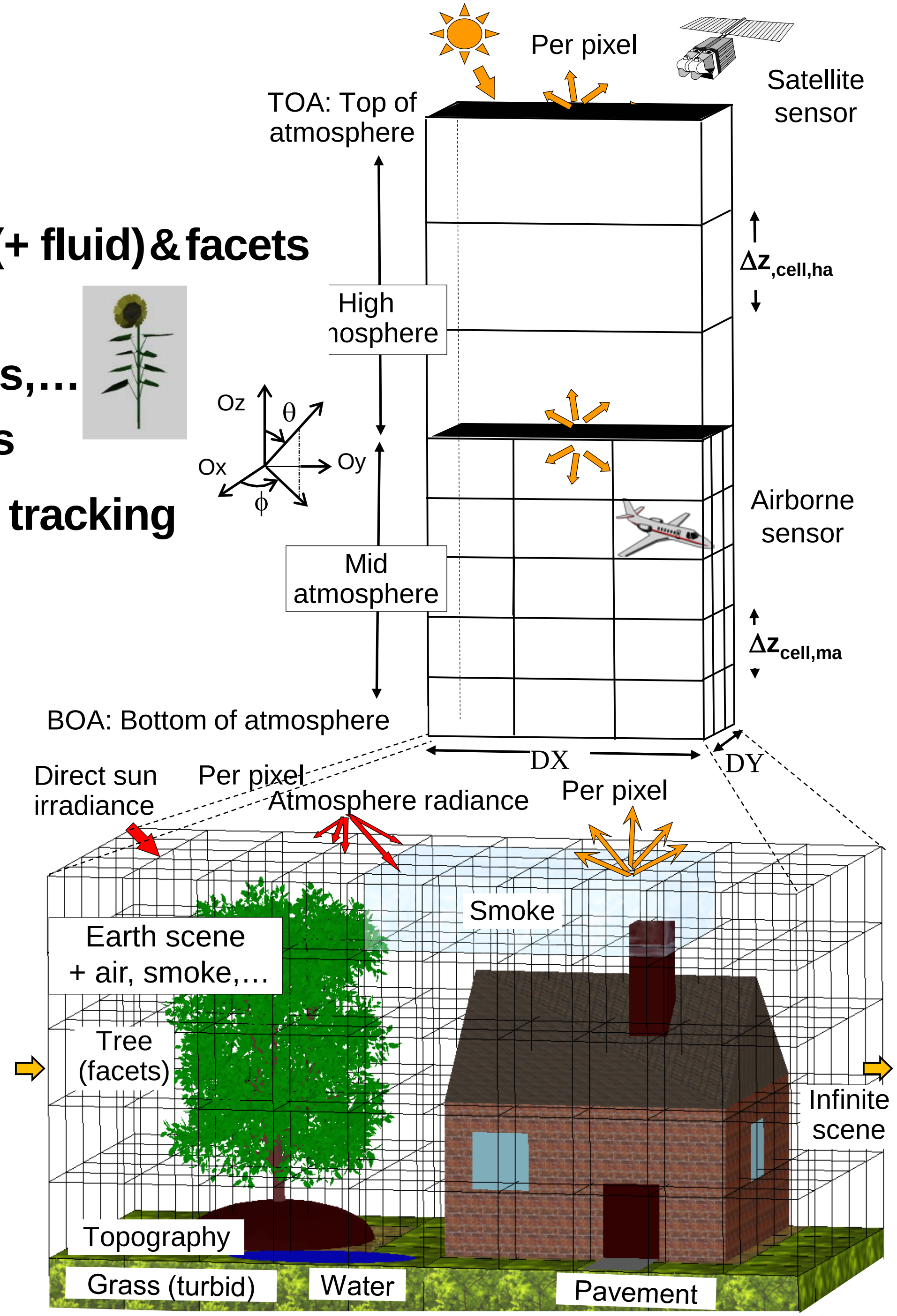
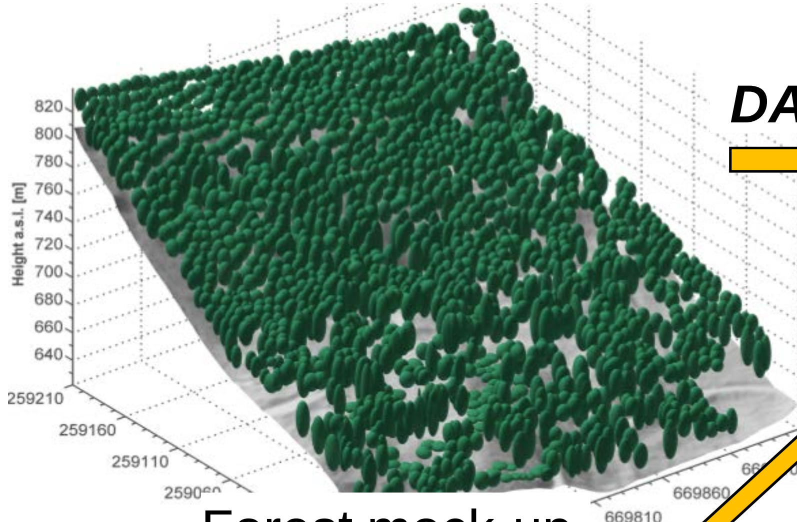
- **Spectro-images: $L_\lambda(\Omega_s,\Omega_v) \Rightarrow \rho_\lambda$, T_B $\forall\Omega_s,\Omega_v$**
- **LiDAR: waveform, photon counting, TLS**



The DART model: ***LiDAR (Laegeren forest, Switzerland – Collaboration RSL)***

- **Pulse**:
  - λ = 1550nm
  - 8µJ
- **Geometry**:
  - FOV = 25cm
  - Area: 0.04m^2
  - Altitude: 500m
- **Bin rate**: 1ns
- **Swath**:
  - 300m x 300m
  - 0.4m resolution

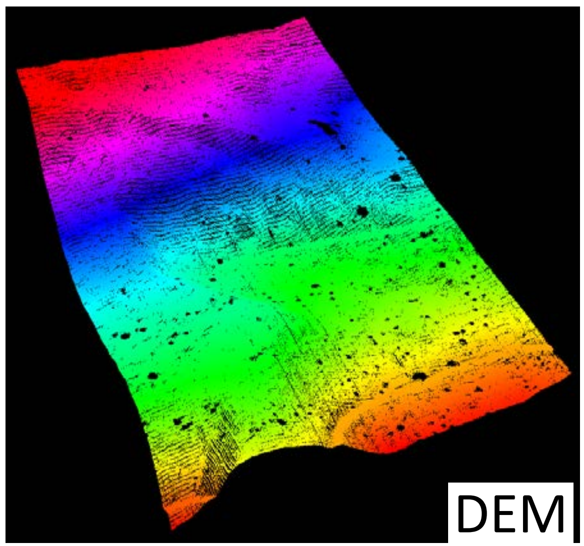


Forest mock-up

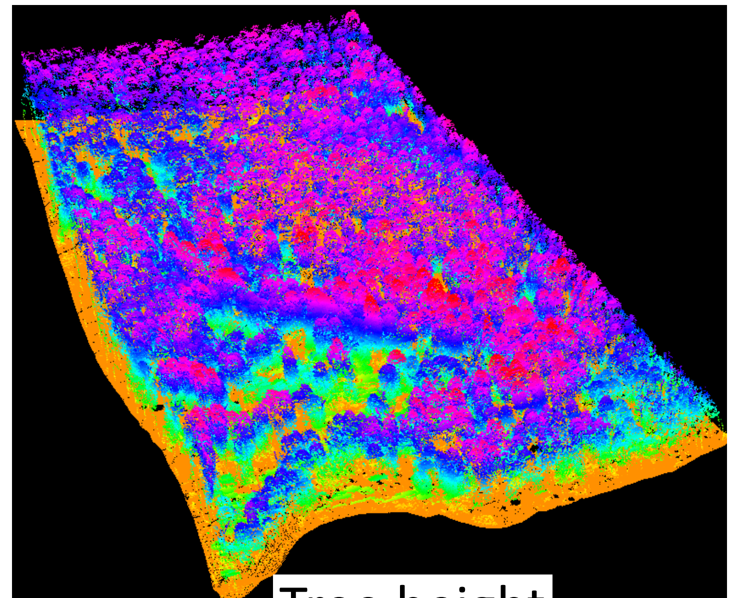
DART →

LiDAR 3D point cloud
0.5625 10^6 pulses,
6.25 points/m^2

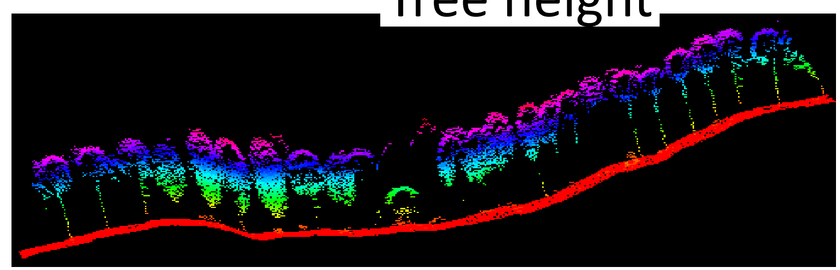
SPDLib: *LiDAR process & display*



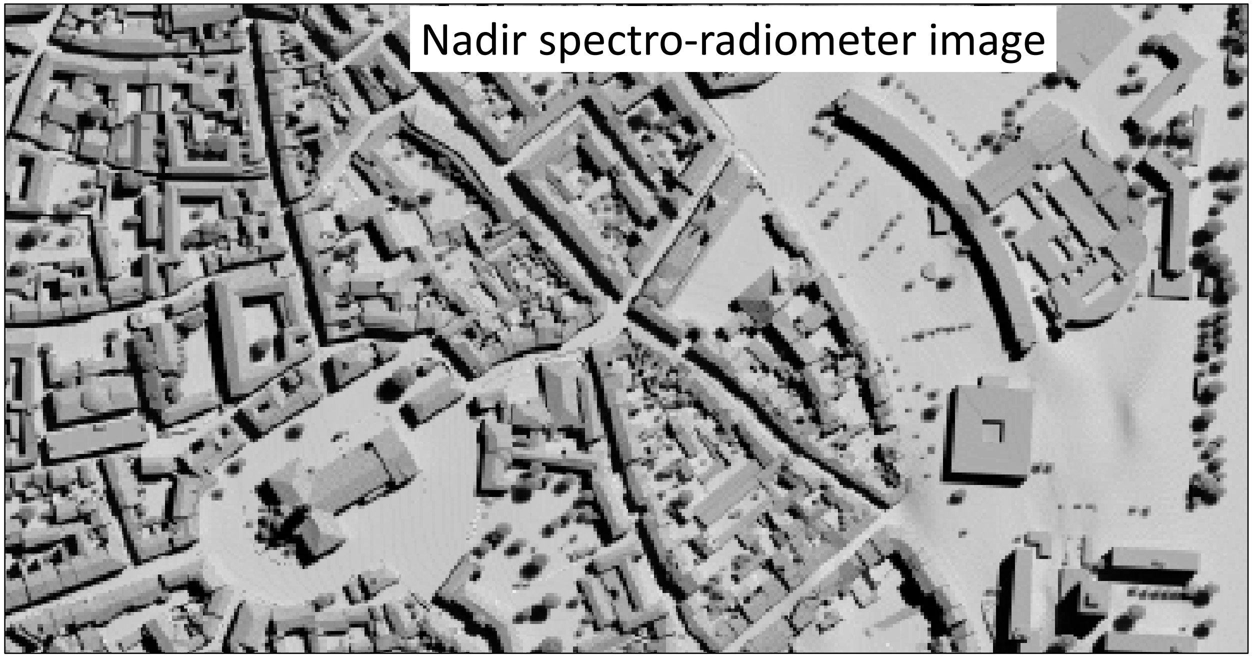
DEM

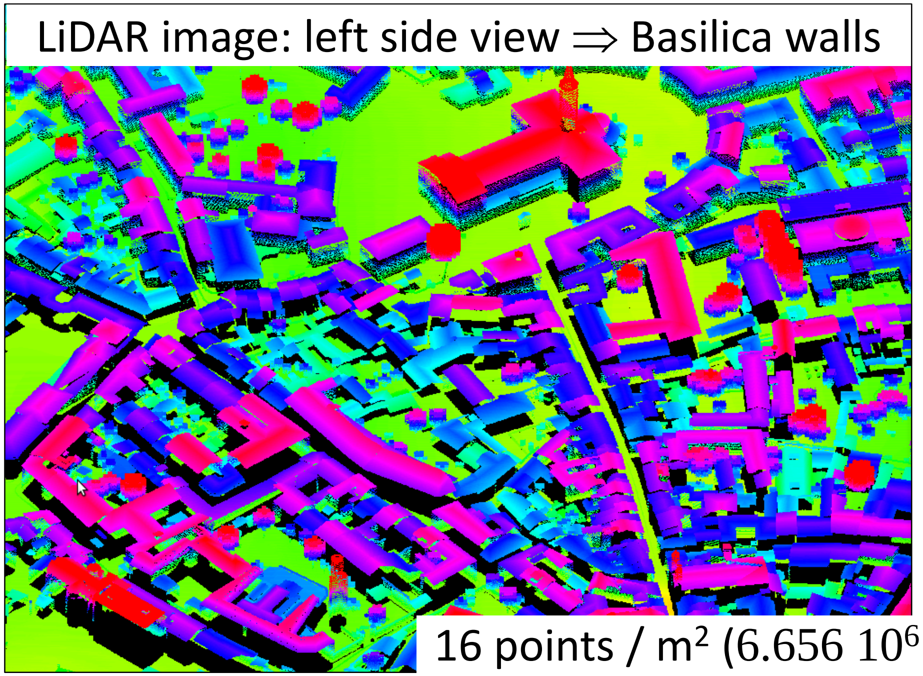


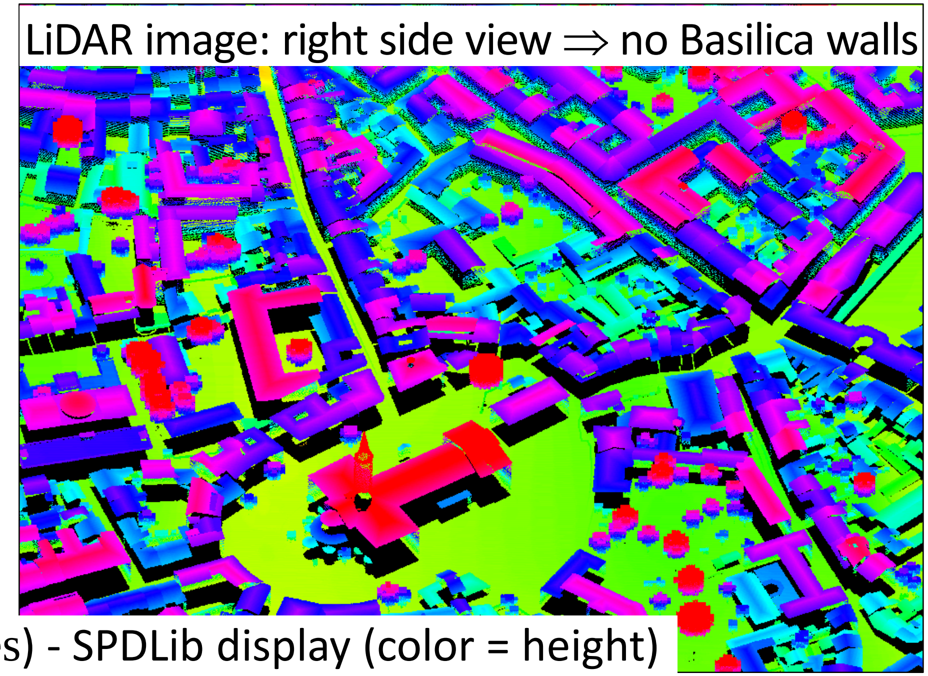
Tree height



The DART model: ***LiDAR (St Sernin Basilica, Toulouse)***







16 points / m^2 ($6.656\ 10^6$ pulses) - SPDLib display (color = height)

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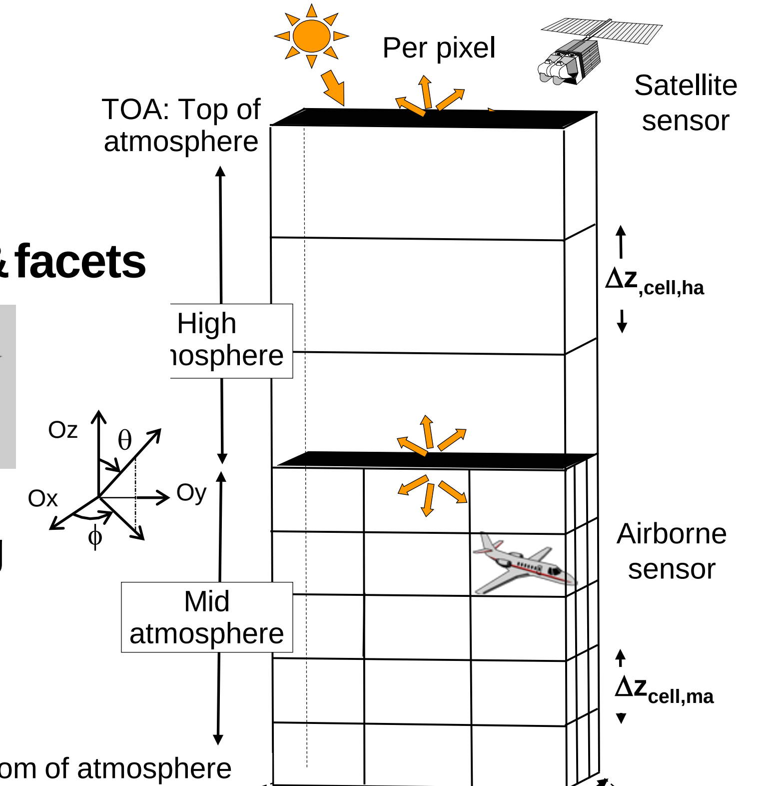

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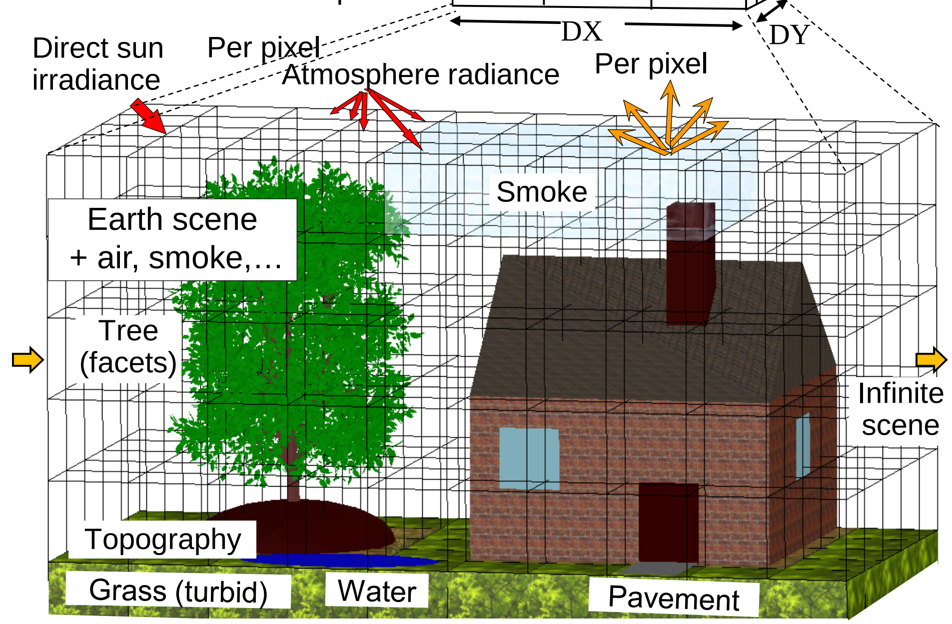

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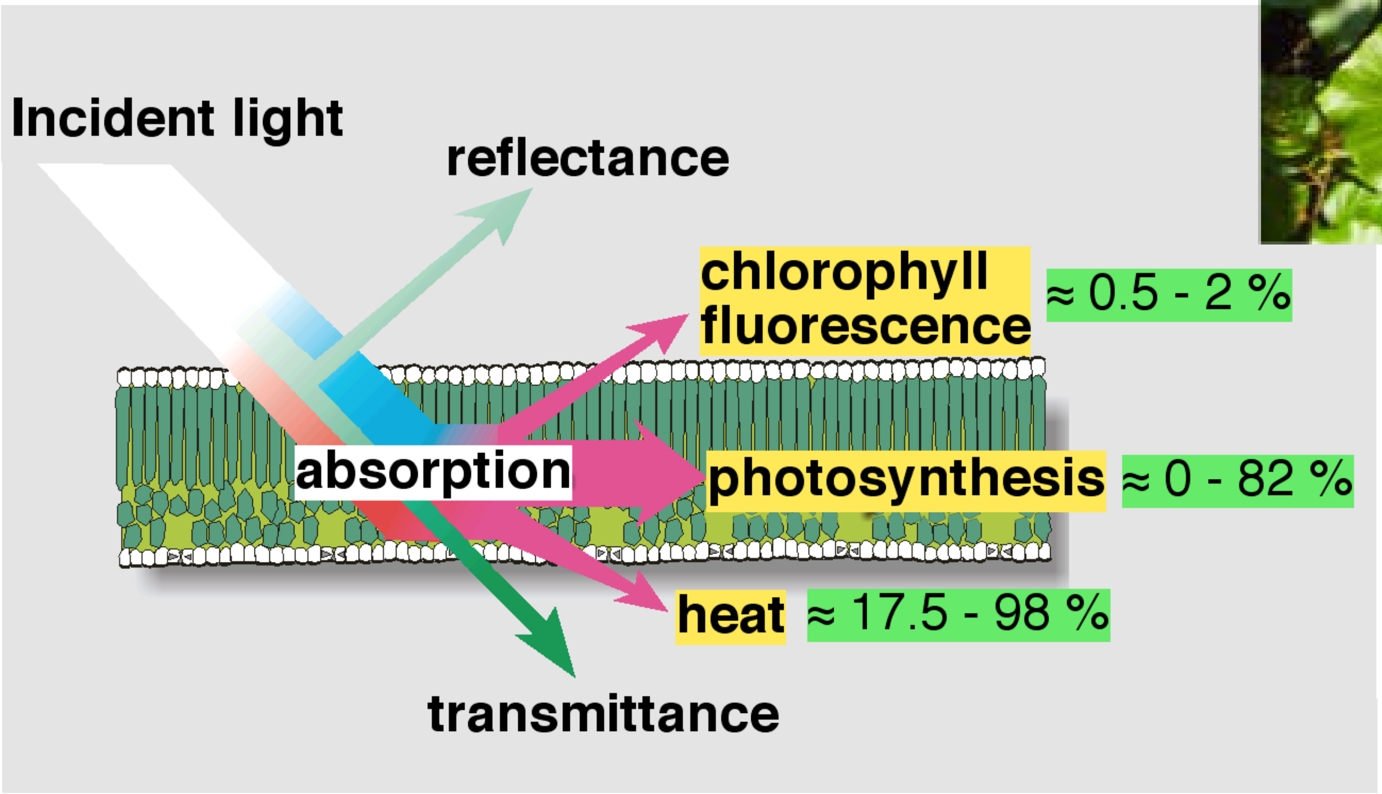
- **Spectro-images: $L_\lambda(\Omega_s,\Omega_v) \Rightarrow \rho_\lambda$, T_B $\forall \Omega_s,\Omega_v$**
- **LiDAR: waveform, photon counting, TLS**
- **3D Radiative budget**
- **Atmosphere terms $\rho_{atm,\lambda}$, $T_{B,atm,\lambda}$, $L_{atm,\lambda}$**
- **Fluorescence: on-going**

Sun induced fluorescence (SIF): info on leaf photosynthetic activity (PSI/PSII photosystems)



Future satellite mission (FLEX) to detect fluorescence from space.

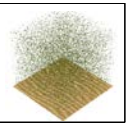
Questions: does canopy architecture affect fluorescence and its remote detection? etc.

Modeling objective: to up-scale chlorophyll SIF from leaf up to 3D complex canopies.

Homogeneous turbid landscape

DART (3D RT model)

Canopy: many small triangles



PS fluorescence quantum yield

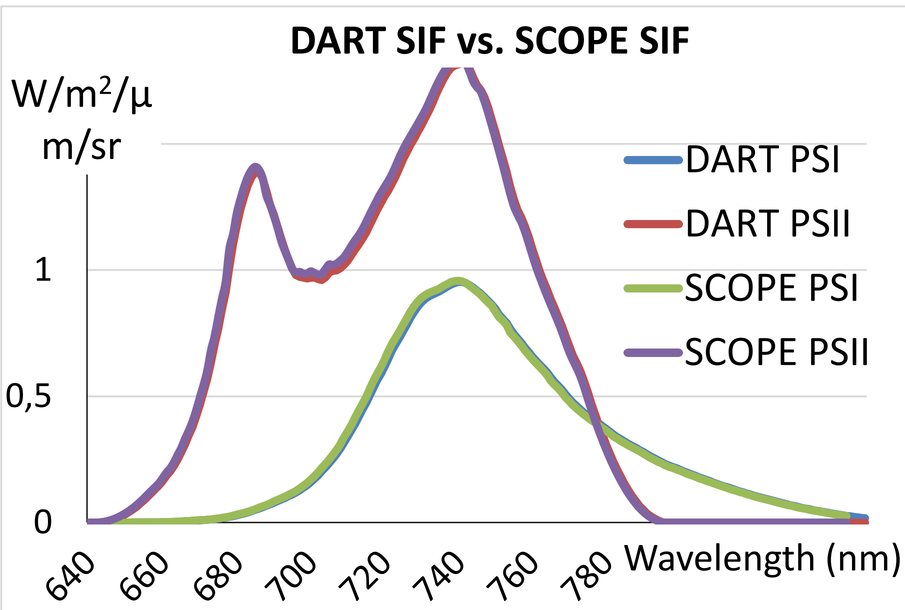
FLUSPECT: "dark" leaf

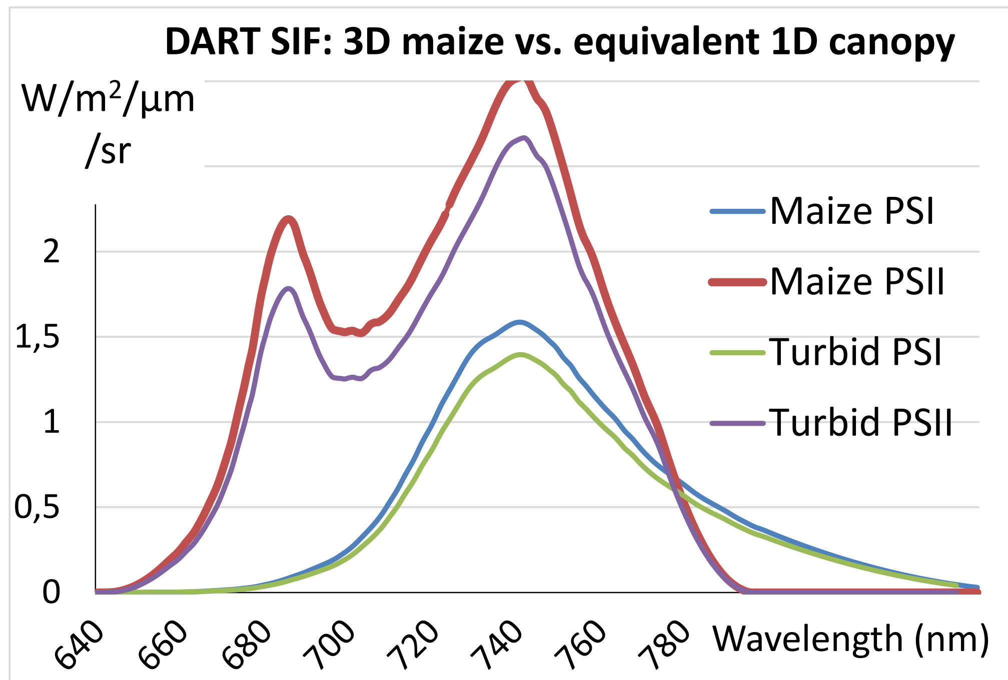
SCOPE (1D energy model ⇒ reference for 1D canopies)

Canopy climatology (T,…): $\xi_{sun}(z,\theta_f,\phi_f)$, $\xi_{shadow}(z)$

SCOPE canopy SIF

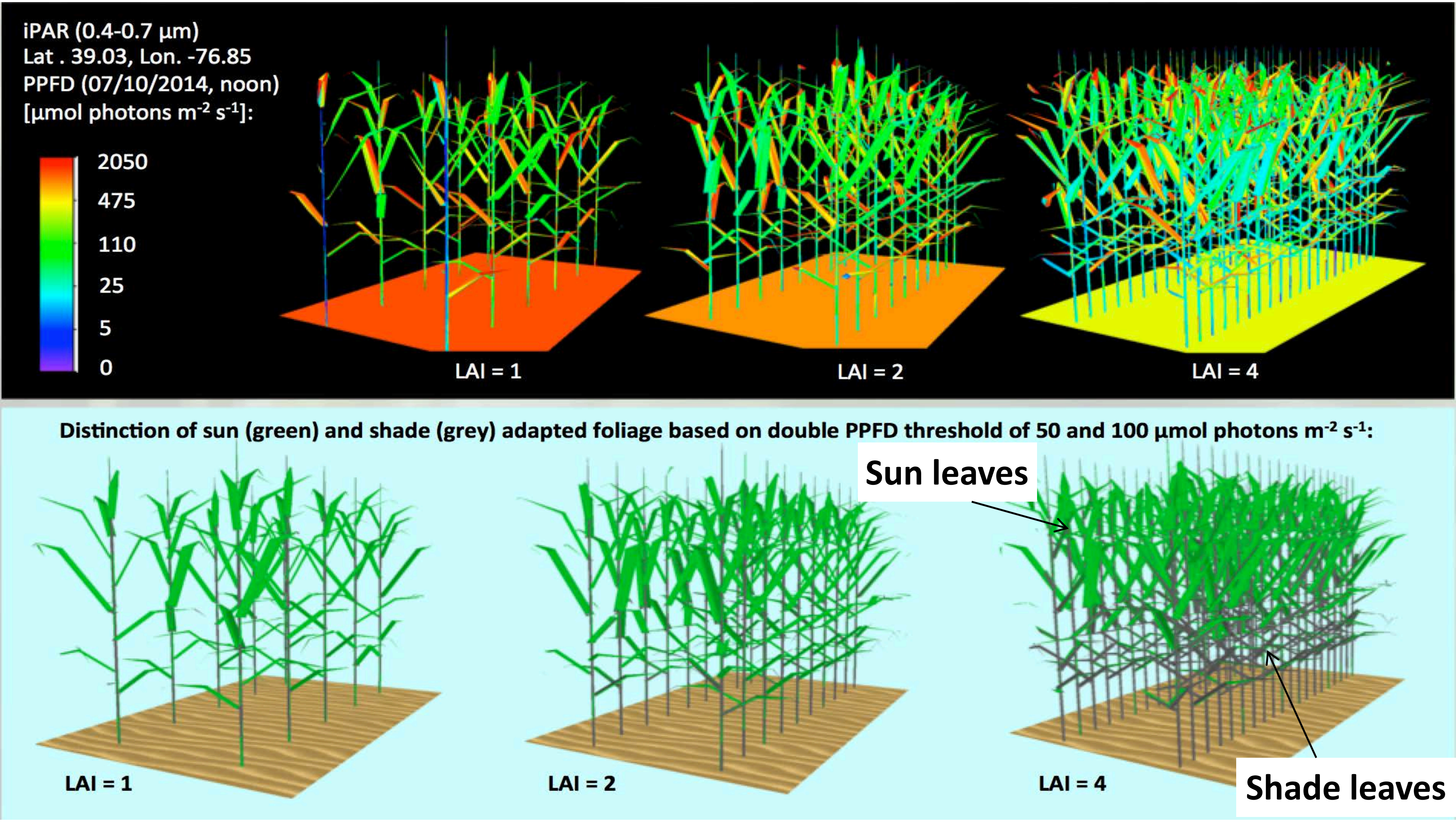
DART canopy SIF





Fluorescence: ***Differentiation between sun and shade leaves***

Leaf SIF depends on leaf radiative history ⇒ leaves are classified as "sun" & "shade" leaves, using DART time series of leaf radiative budget



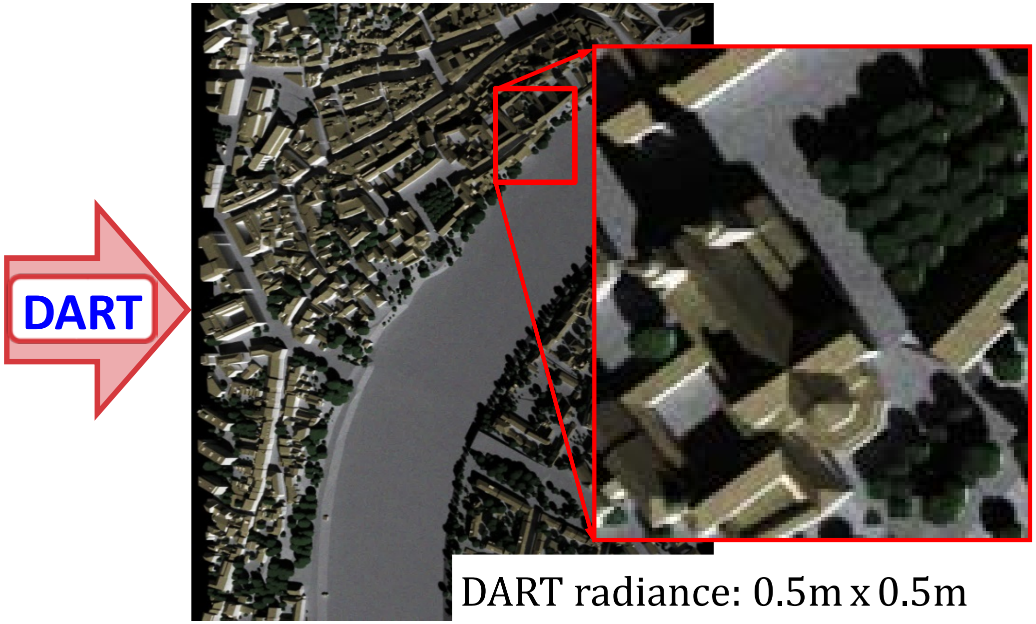
Satellite driven urban radiative budget (H2020 project)
(albedo, thermal exitance)

Satellite driven urban radiative budget: *H2020 UrbanFluxes* (http://urbanfluxes.eu/)

Objective: to improve our knowledge on anthropogenic heat fluxes in several European cities (London, Basel, Heraklion). (http://urbanfluxes.eu/)

Approach: **EO satellites + modeling.** 3D radiative budget is derived from "EO satellites + 3D radiative transfer model", and then combined with urban energy balance modeling.

3D model of Basel, with added trees and Digital Terrain Model (**DTM**)
+
Atmosphere



Satellite, airborne & in-situ camera / pushbroom images,…**3D radiative budget**

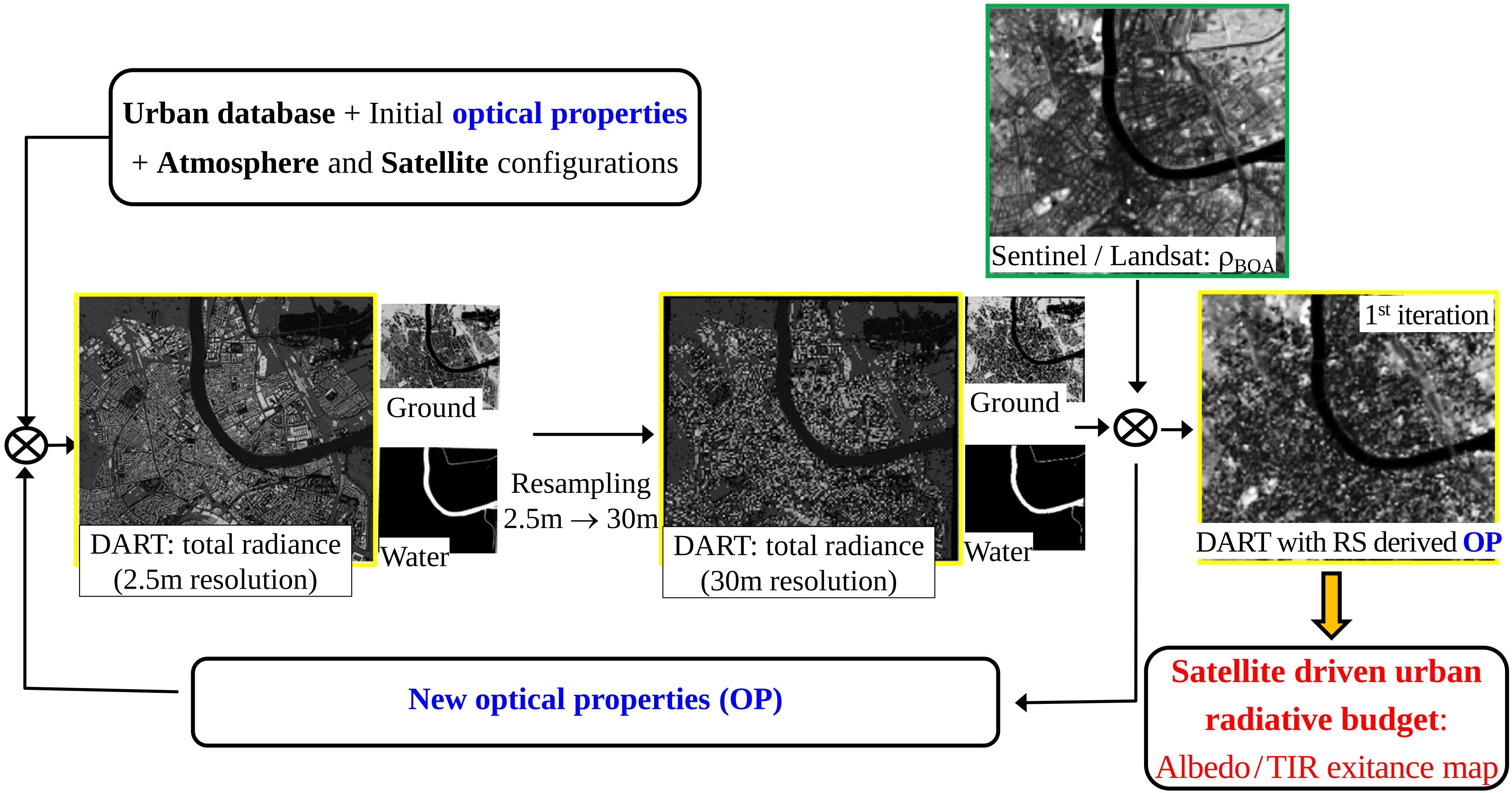
☠ **All roofs have the same optical property!!!**

Satellite driven urban radiative budget: H2020 UrbanFluxes (http://urbanfluxes.eu/)

Difficulty: **optical properties (OP) of the urban elements are highly spatially variable.**

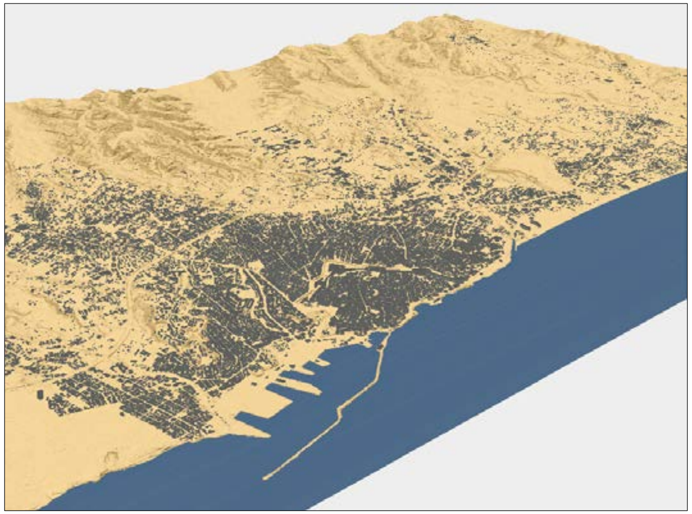
Solution: **to derive maps of urban elements OP from satellite at satellite spatial**

Iterative comparison of DART and satellite images per satellite pixel

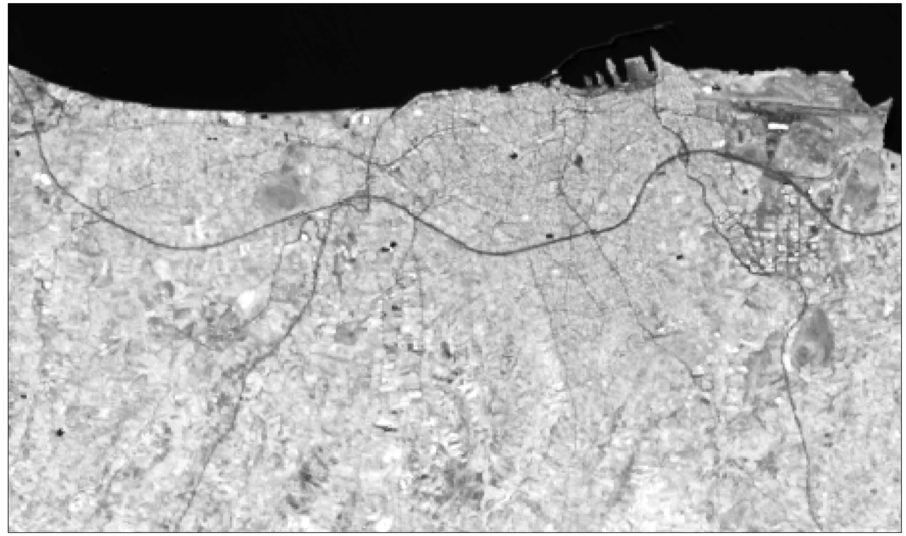


Satellite driven urban radiative budget: ***H2020 UrbanFluxes*** (http://urbanfluxes.eu/)

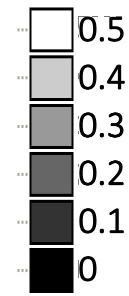
Heraklion

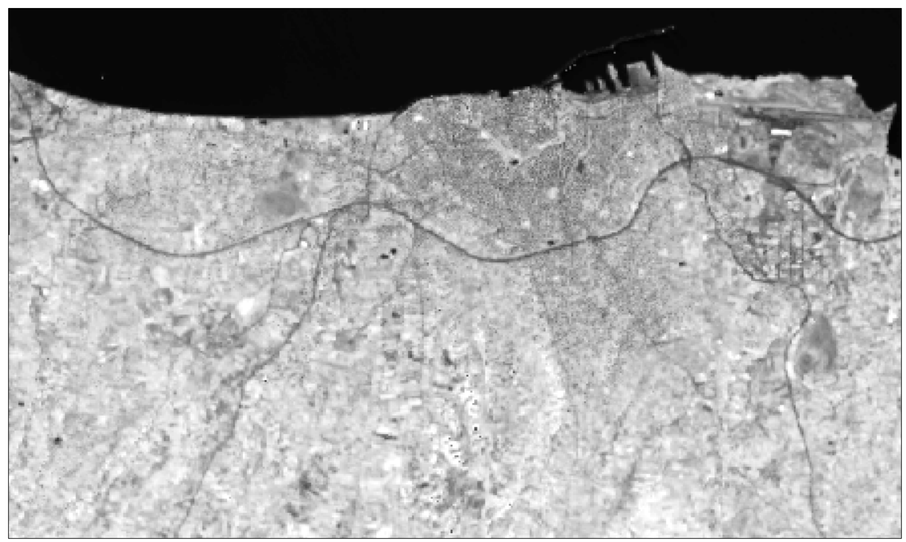


3D urban database



Landsat band 5: 13/07/2016. 30m resolution

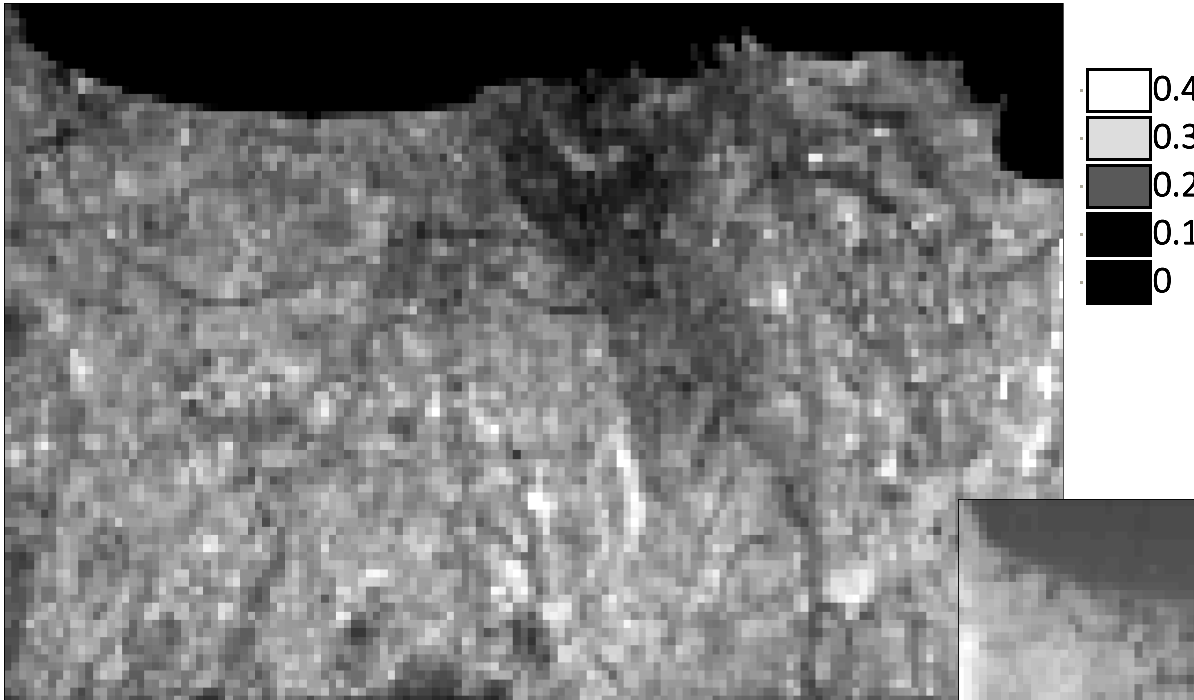




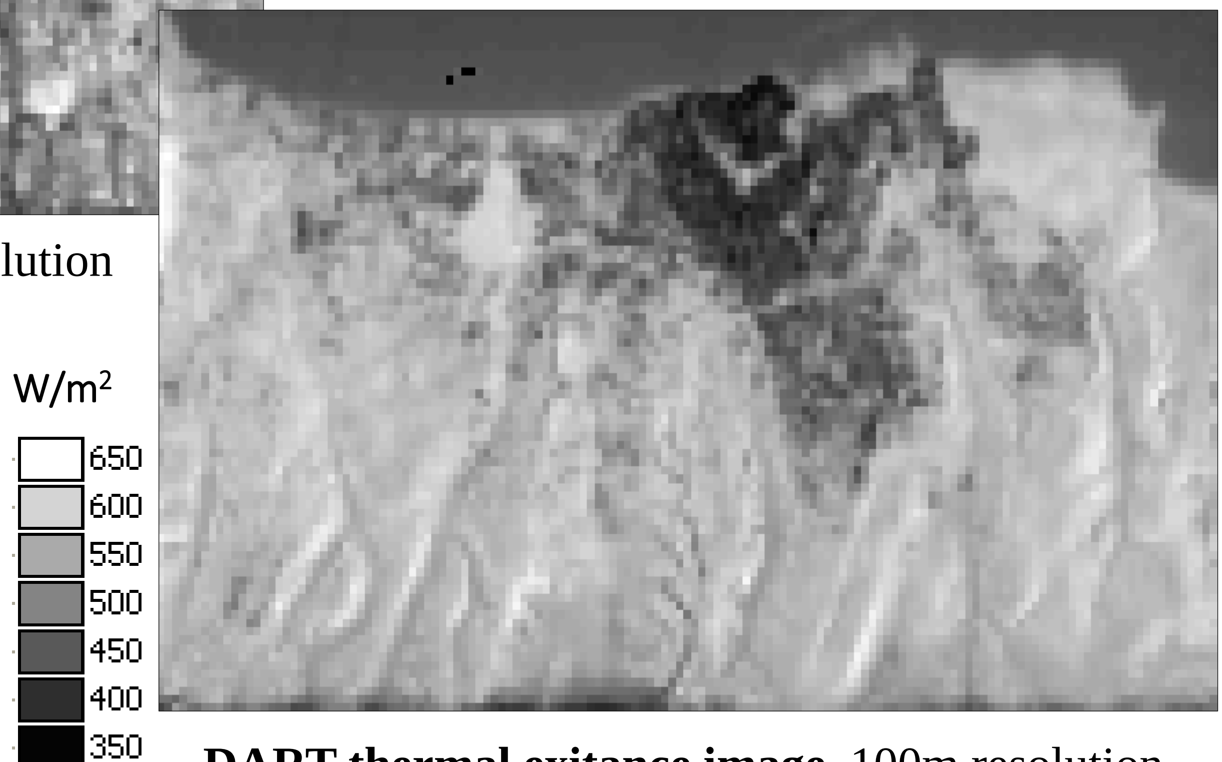
DART calibrated reflectance image

Heraklion

Landsat: 29/07/2016.
30m resolution



DART albedo image. 100m resolution

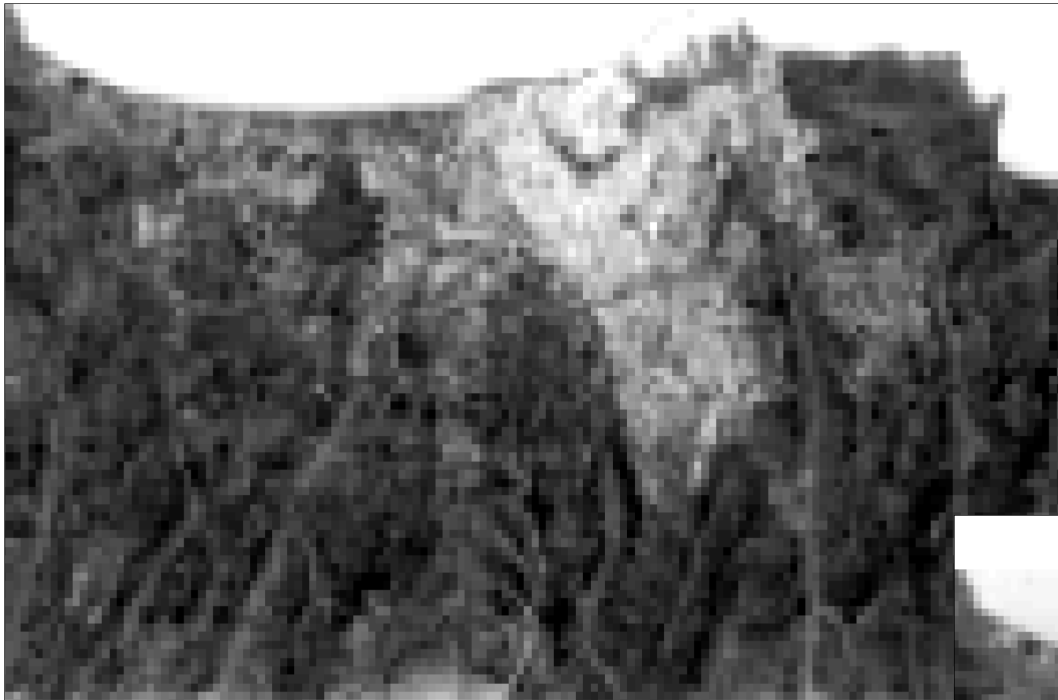


DART thermal exitance image. 100m resolution

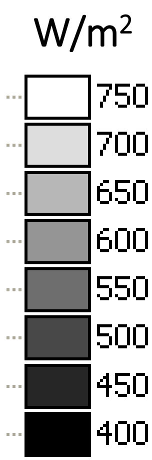
Satellite driven urban radiative budget: ***H2020 UrbanFluxes*** (http://urbanfluxes.eu/)

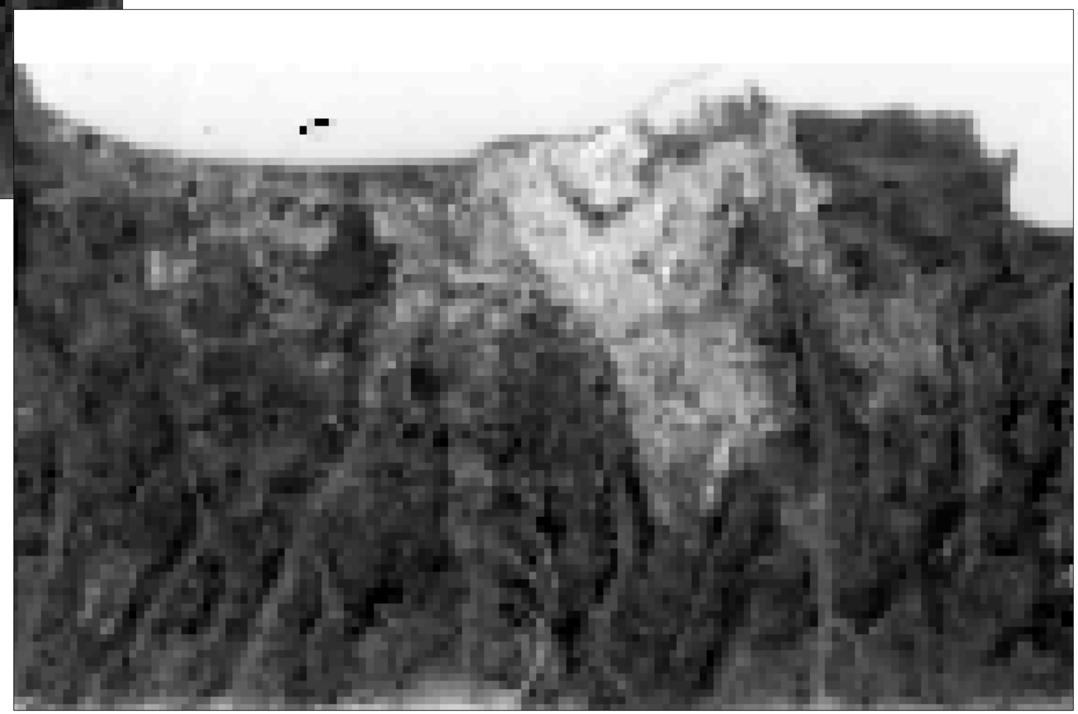
Heraklion

DART Q*
100m resolution

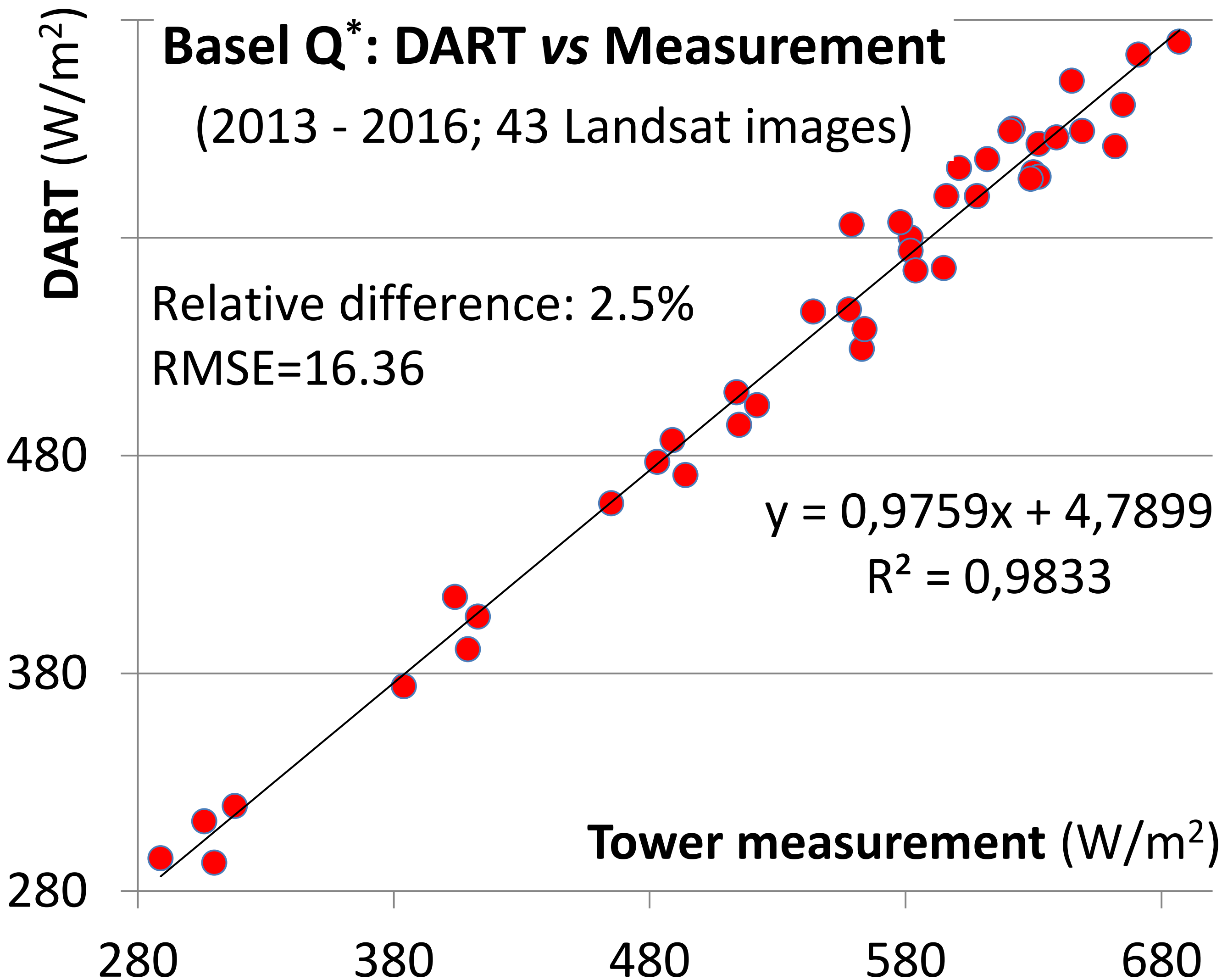


13/07/2016





29/07/2016



$LUT_{black\ sky}$ & $LUT_{white\ sky}$ for date with no satellite image $\Rightarrow$ Q*(t) with Δt=1h,…

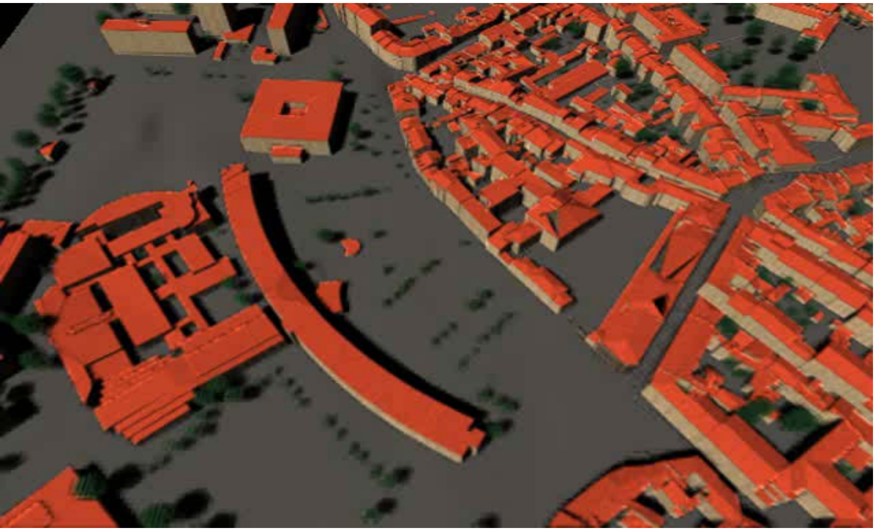
Conclusion and On-going work

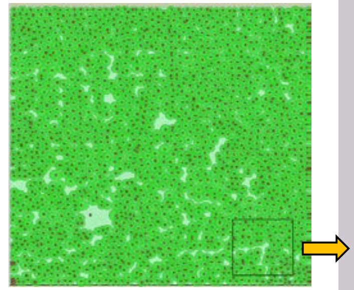
Conclusion: thanks to the "DART" team, collaborators and projects (RAMI,…) for making DART more and more accurate , robust , functional and open

On-going work:

- **Technical**: - New GUI, integration of INTEL embree library, etc.
  - New data format: to reduce computer time and volume,…
- **Water**: partly implemented. To be validated.
- **Polarization**: partly implemented. To be validated.
- **Satellite driven urban albedo**: partly validated. To be more operational.
- **Large landscapes**: voxel size adapted to local complexity, scene segm.,…
- **3D urban and vegetation energy budget**: still an exciting challenge.

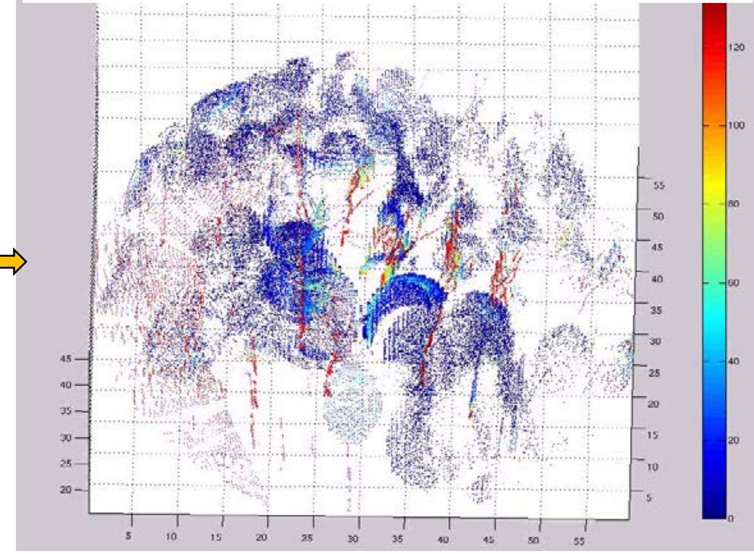
Airborne scanner: urban database (Toulouse, France)



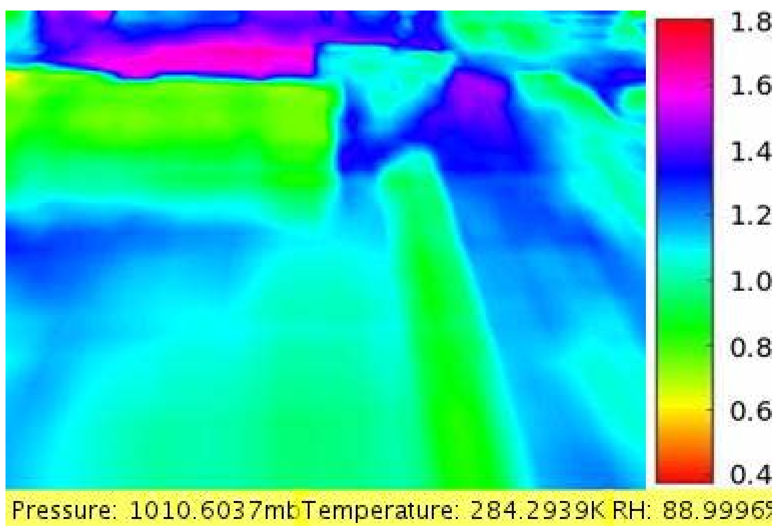


Lageren forest
(RSL, Switzerland)

Terrestrial LiDAR: 1st order echo amplitude



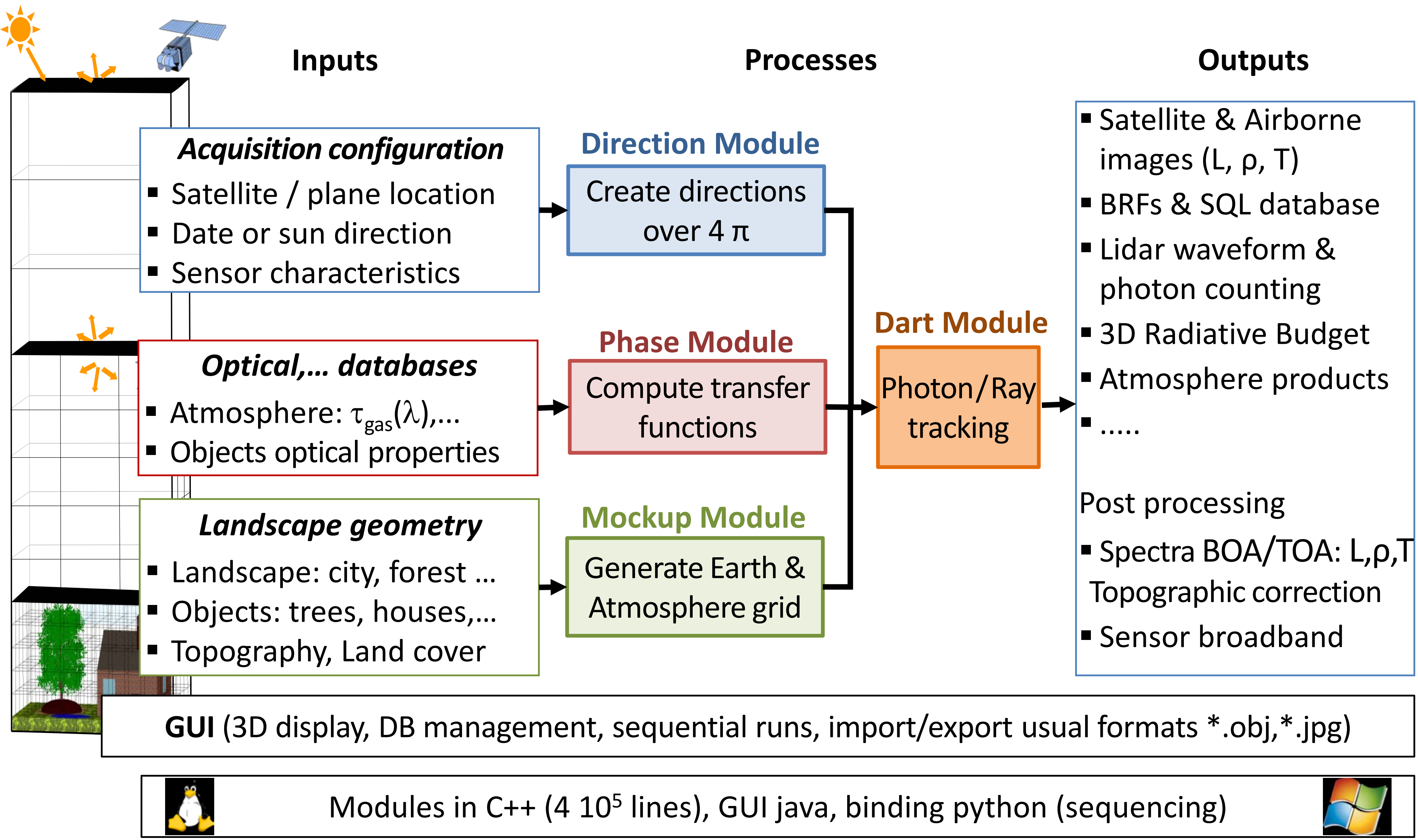
Thank you



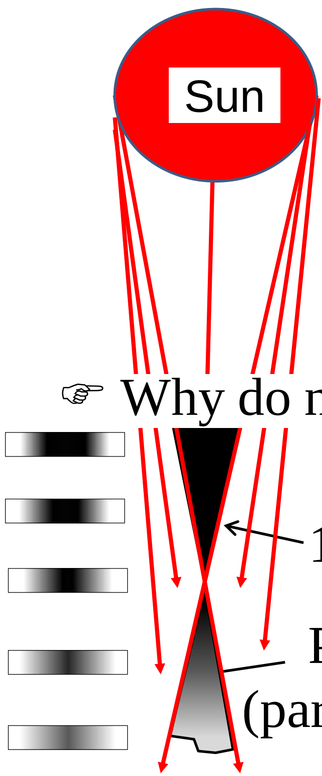
Simulation of TIR camera (London)

Thermal radiance varies with atmosphere pressure, relative humidity (RH) and temperature.

The DART model: Inputs, Processes and Products



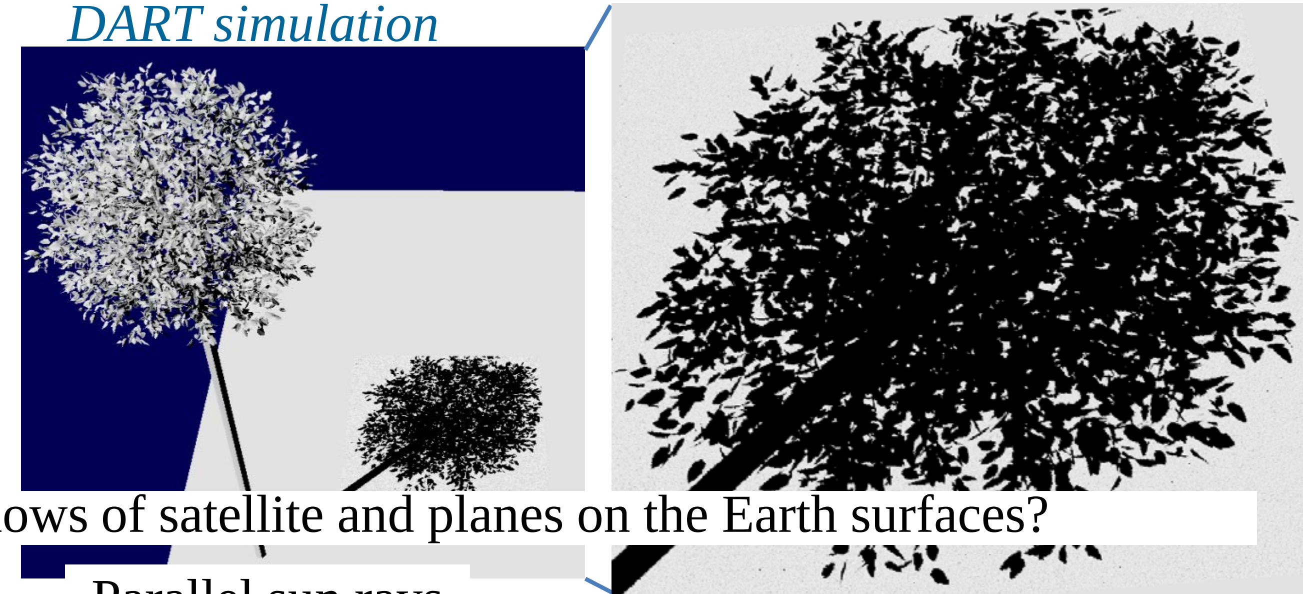
The sun with finite FOV: The penumbra effect



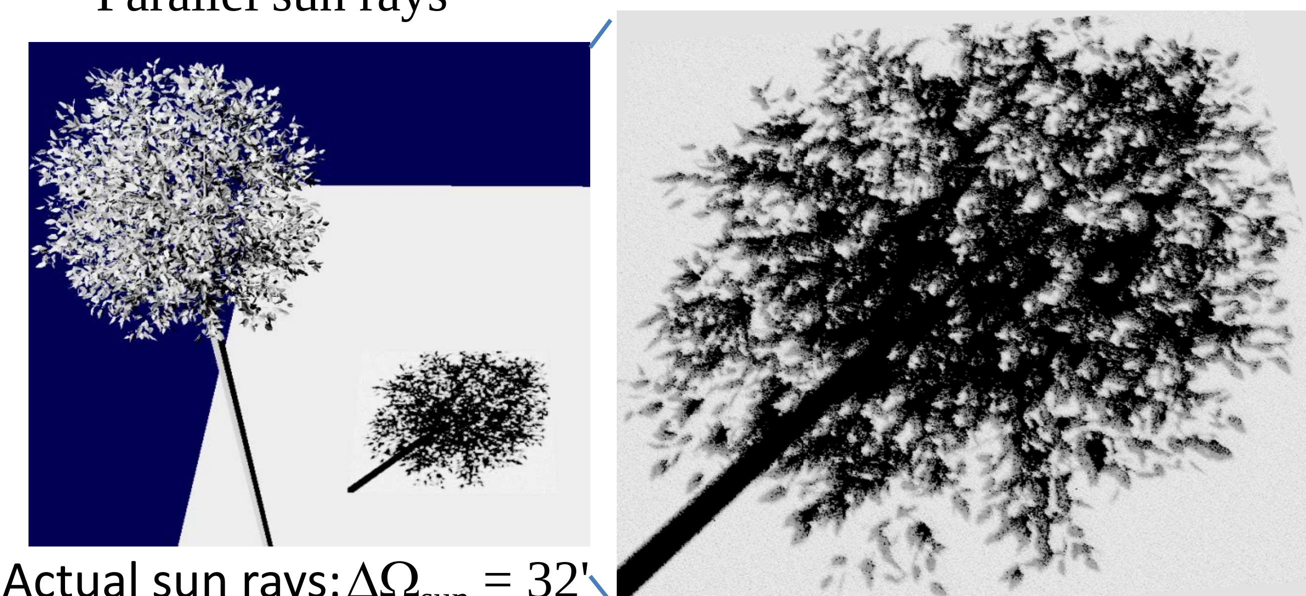
☞ Why do not we see the shadows of satellite and planes on the Earth surfaces?

Sun rays are not parallel
⇒ shadow is total at short distance and more and more partial as distance increases

DART simulation



Parallel sun rays



Actual sun rays: $\Delta\Omega_{sun}$ = 32'

Atmosphere

Gastellu-Etchegorry J.P., Lauret N., Yin T., Landier L., Al Bitar A., Aval J., Guilleux J., Jan C., Chavanon E., (2016) DART: Radiative transfer modeling for simulating Terrain, airborne and satellite spectroradiometer and LIDAR acquisitions and 3D radiative budget of natural and urban landscapes, **IGARSS 2016**.

- **Atmosphere**:- Voxel array with gas and aerosol spectral extinction coefficients, scattering albedo & scattering phase function

  - Account of non Beer law behavior

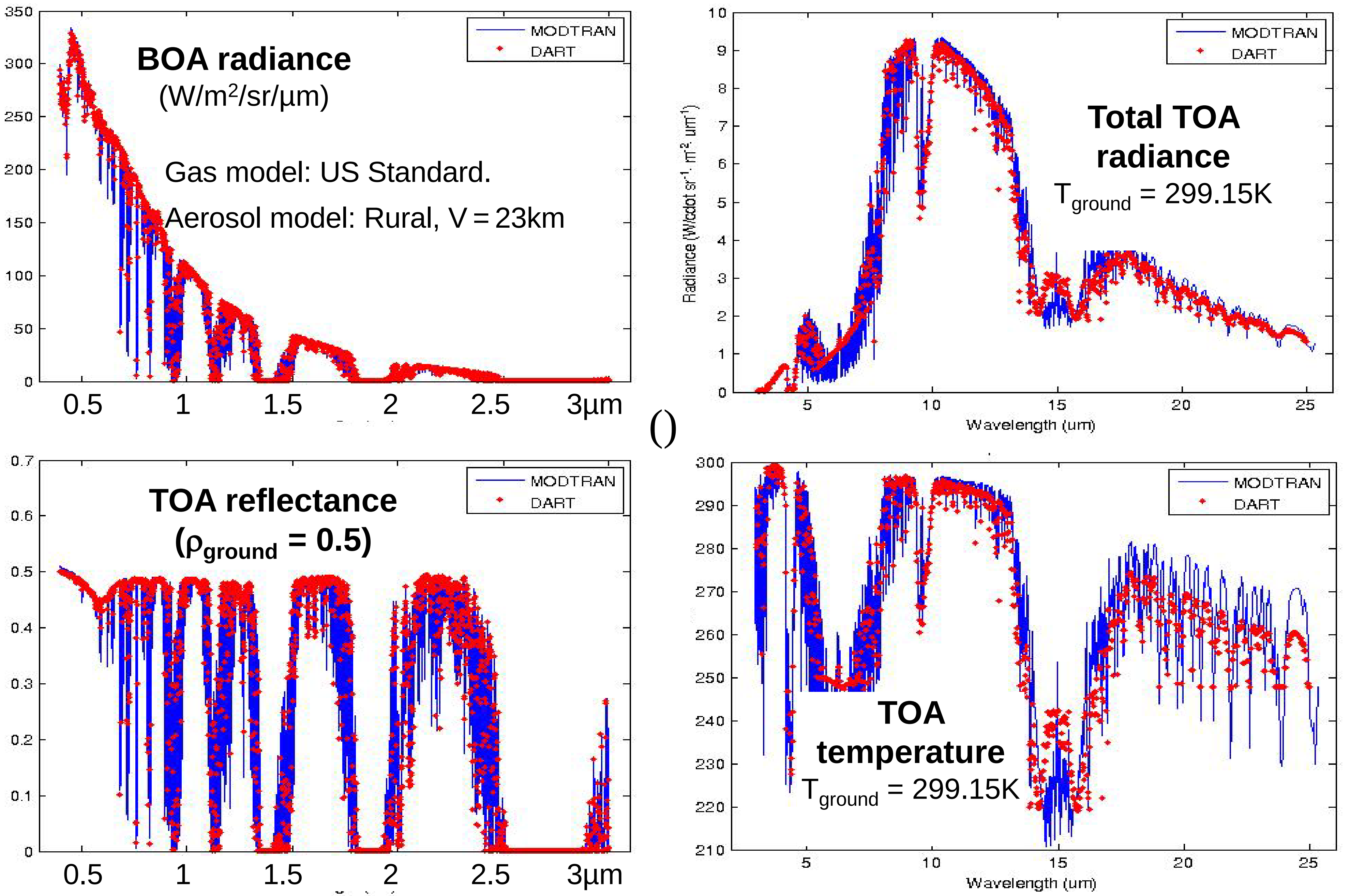
  - Account of Earth sphericity (geostationary satellite,…)

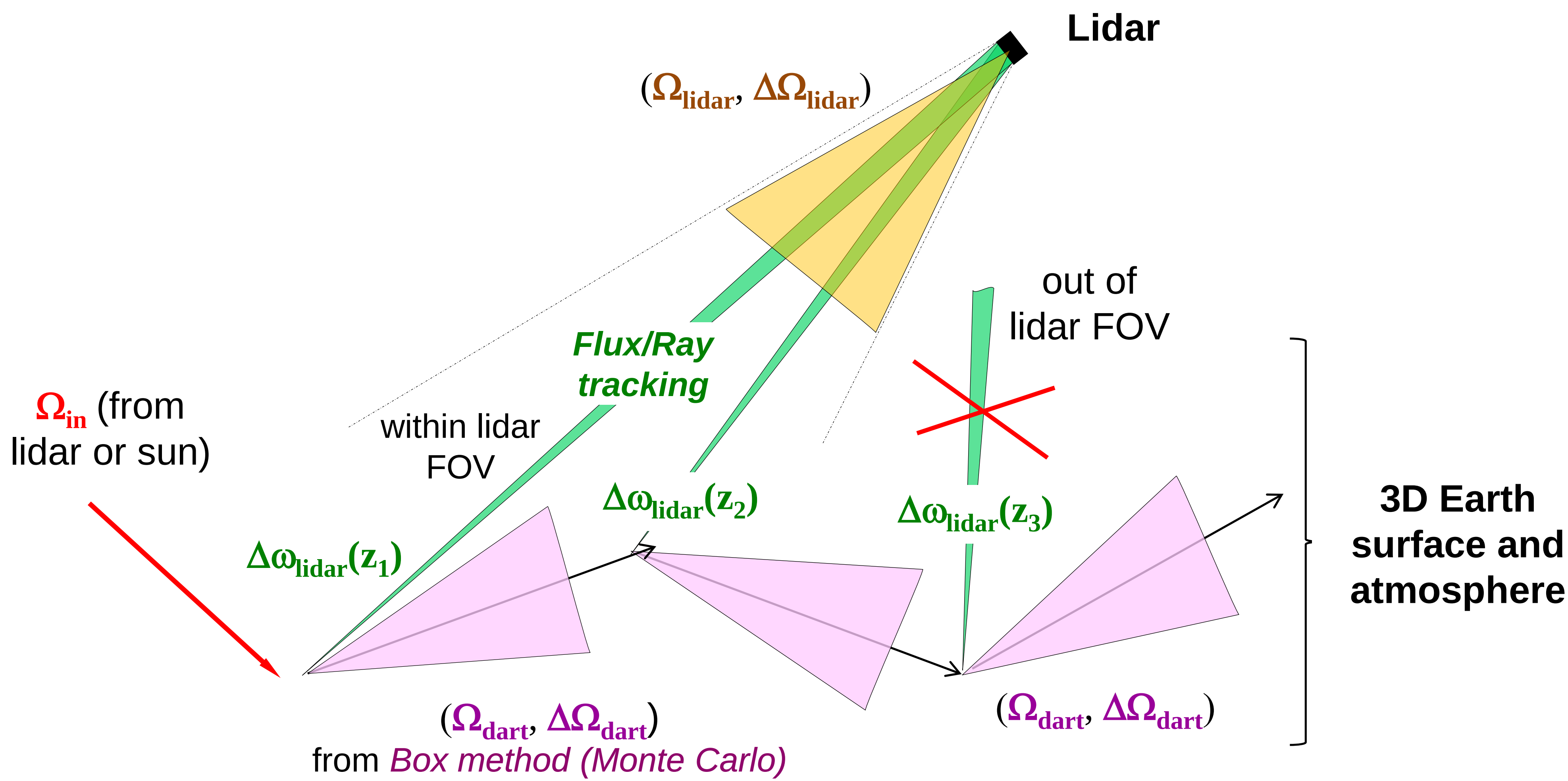
- **Database**: - Derived from Modtran 5 (US Standard,…) and Lowtran. Temperature and gas profiles can be directly managed

  - Possible input of data from Aeronet network, ECMWF,…

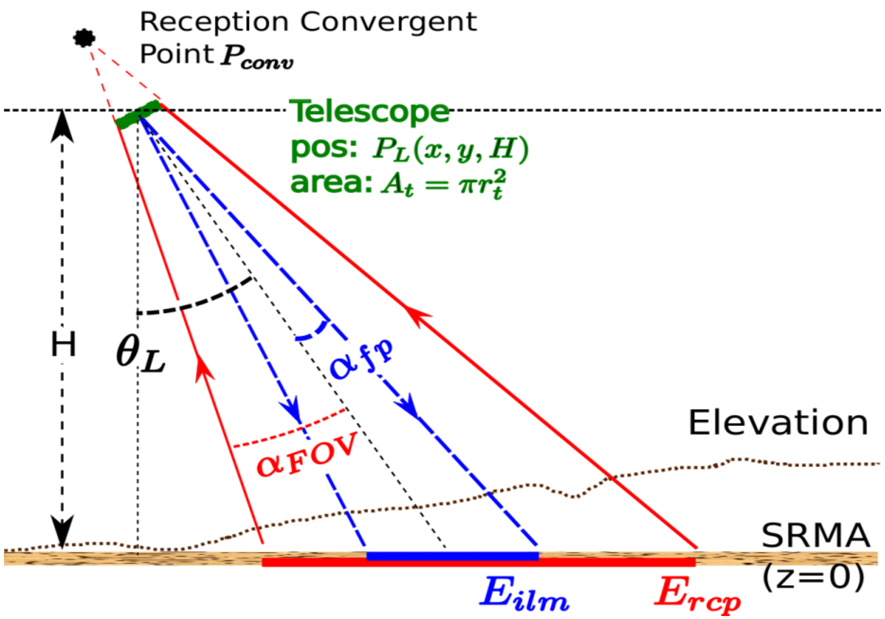
- **Air in the terrestrial landscape**: simulation of pollution by adding / removing aerosol & gases (CH_4, CO_2, H_2O, HNO_3, NO_2, N_2, NO, O_3, SO_2)

The Atmosphere : DART (red) vs. Modtran (blue)

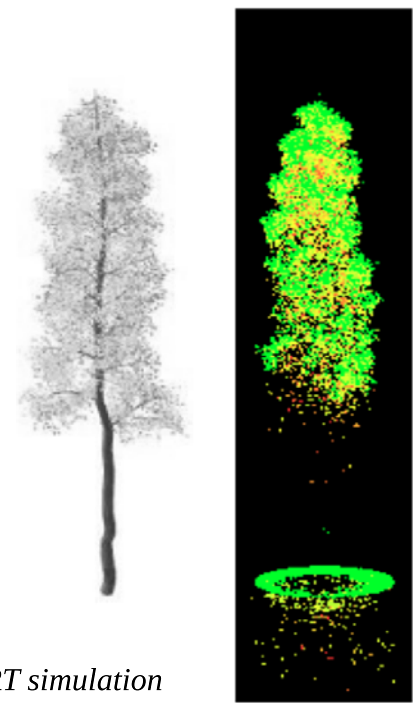



Lidar
(Ω_{lidar}, $\Delta\Omega_{lidar}$)
out of lidar FOV
Flux/Ray tracking
Ω_{in} (from lidar or sun)
within lidar FOV
$\Delta\omega_{lidar}(z_2)$
$\Delta\omega_{lidar}(z_3)$
$\Delta\omega_{lidar}(z_1)$
3D Earth surface and atmosphere
(Ω_{dart}, $\Delta\Omega_{dart}$)
from *Box method (Monte Carlo)*
(Ω_{dart}, $\Delta\Omega_{dart}$)

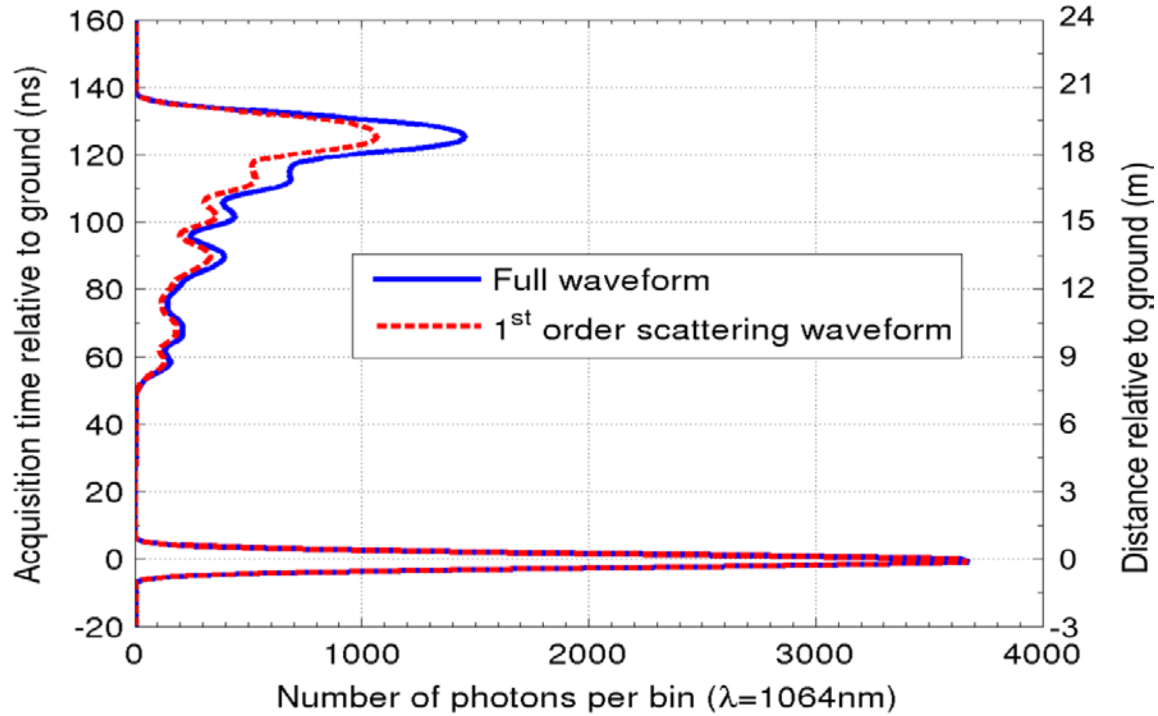
Small footprint waveform simulation: Linden tree from RAMI-4 (λ = 1064nm, H = 10km)



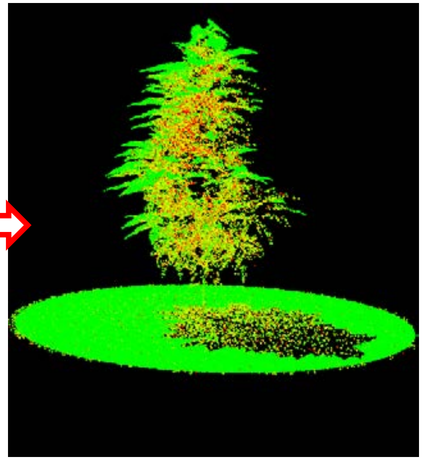
Parameters	Symbols	Values
Sensor area	A_t	$0.1m^2$
Time step per bin	δt_{bin}	1 ns
Footprint divergence half angle	β_{fp}	0.25 mrad
FOV divergence half angle	β_{FOV}	0.4 mrad

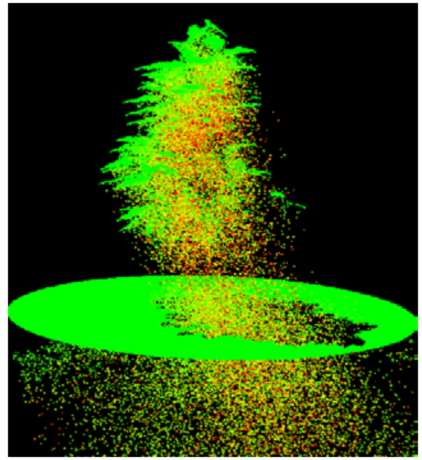


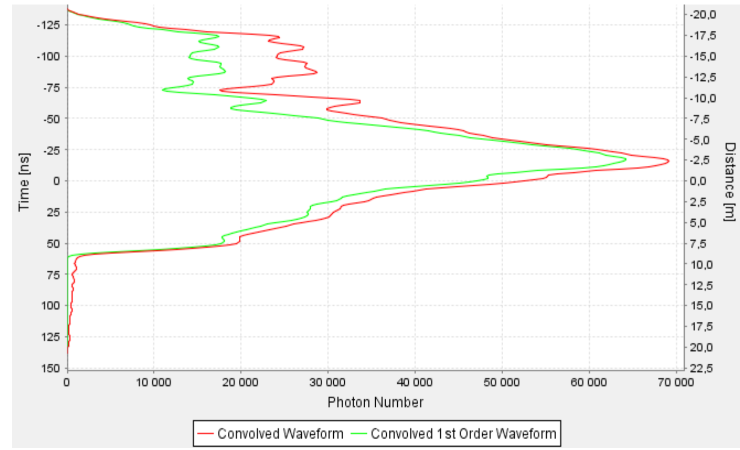
DART simulation



DART LiDAR: "Turbid tree" derived from "Triangle tree"





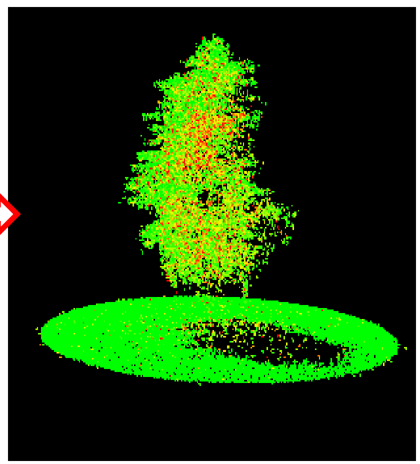


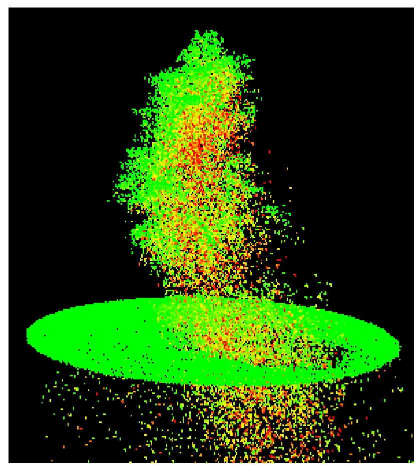
Triangle tree

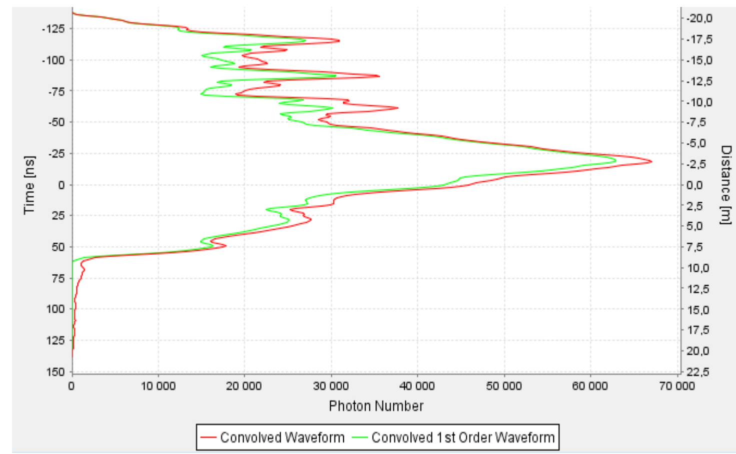
3D cloud of last returns (echoes)

3D waveform

1D waveform: 1st order (green) and total (red)

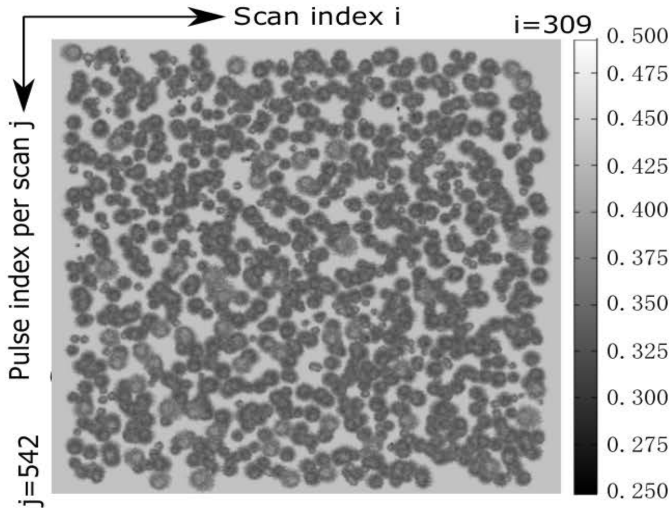


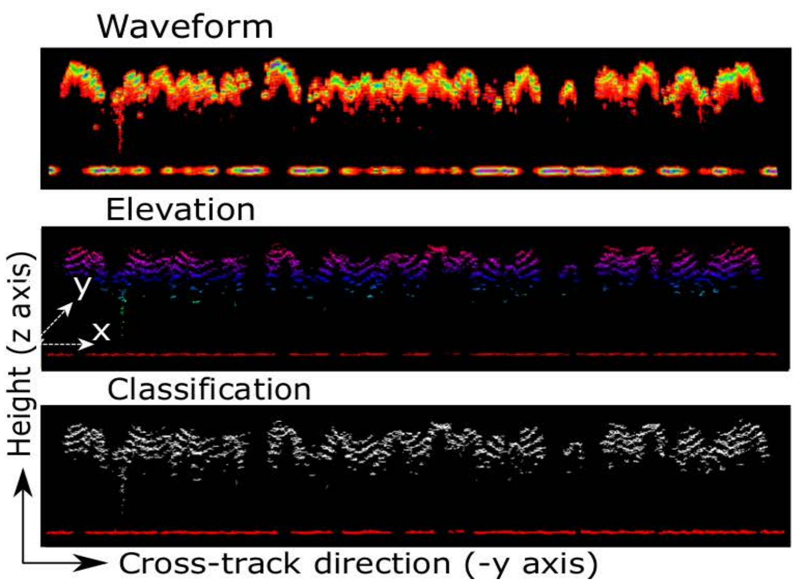




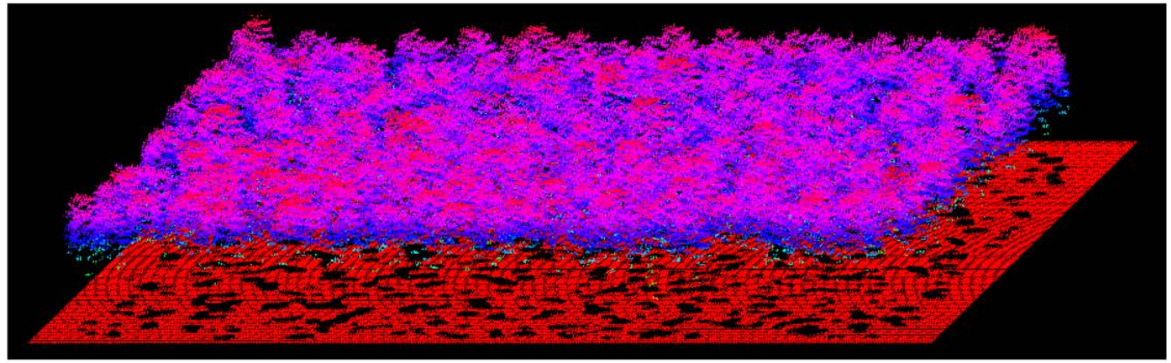
Turbid tree

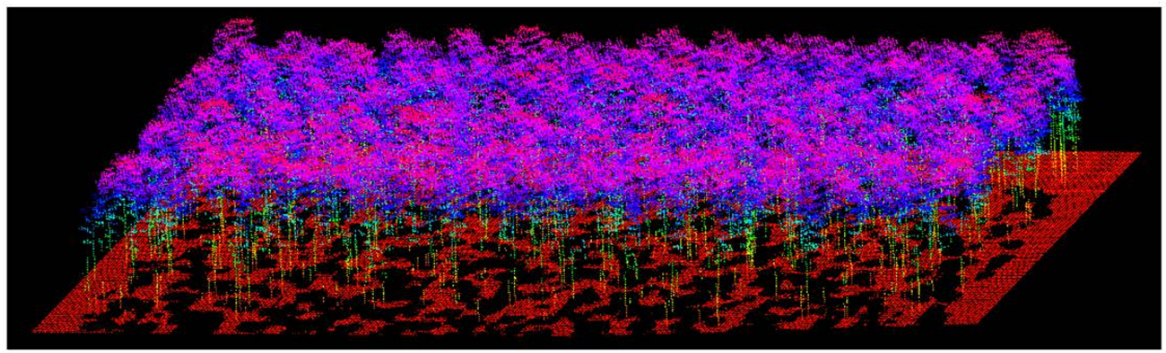
DART LiDAR: ALS simulation: LiDAR of CAO AtoMS system over Järvselja pine stand (RAMI-4)





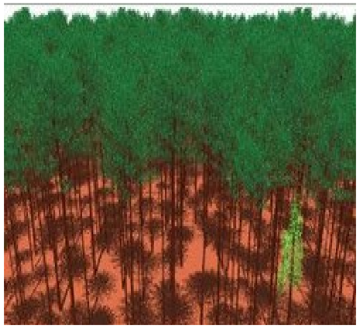
Display of DART simulations with SpDLib code (colour = height)



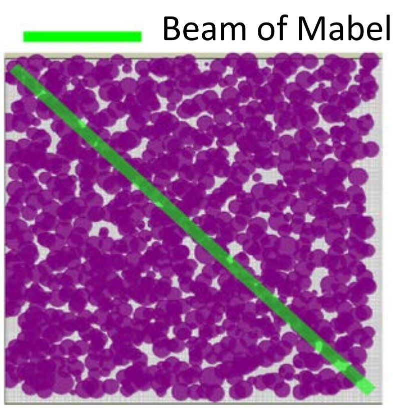


$\theta_L = 45°$ at the center of swath

DART LiDAR: Photon counting in the night (no solar noise)

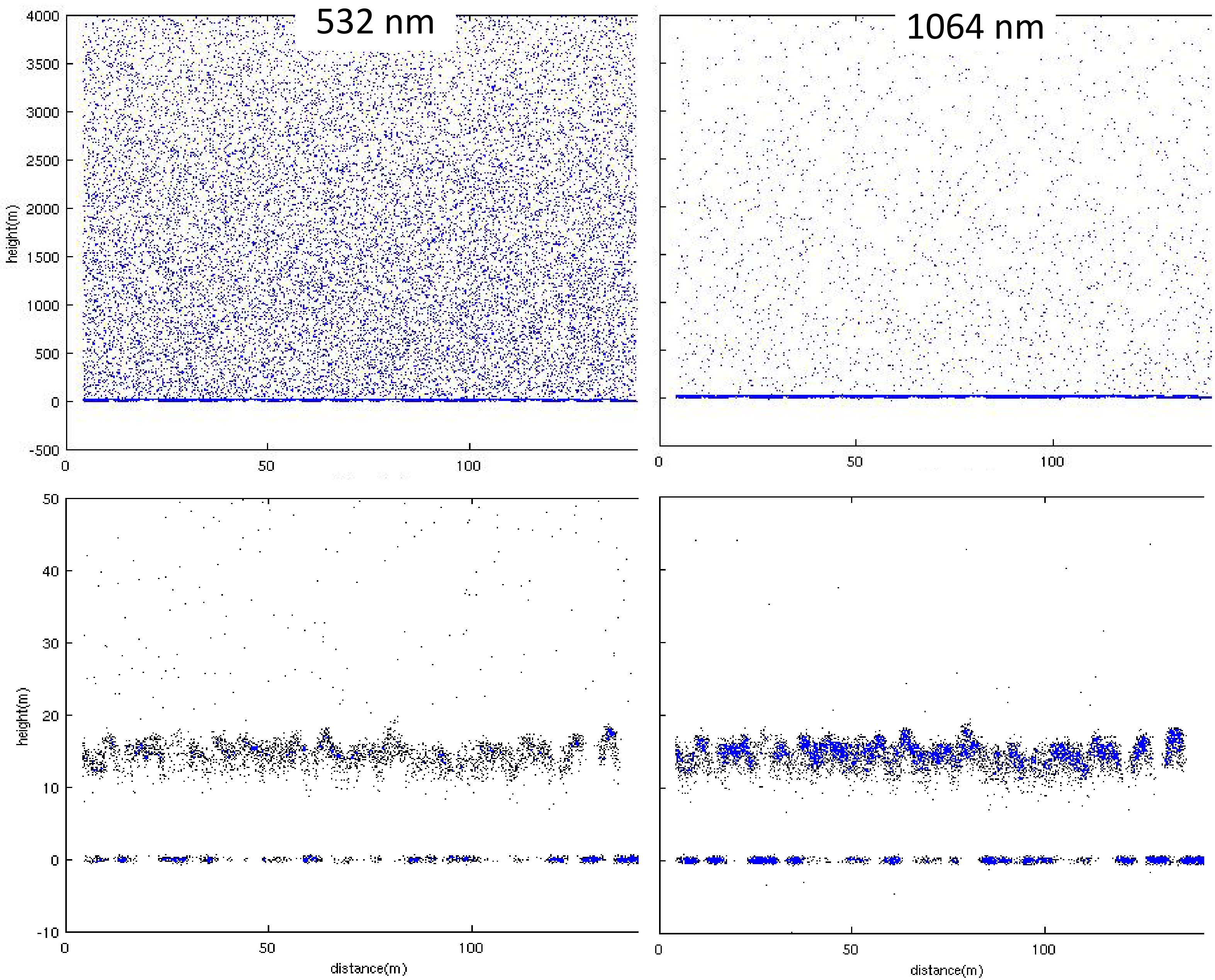


Jarselja pine stand
(Summer), Estonia

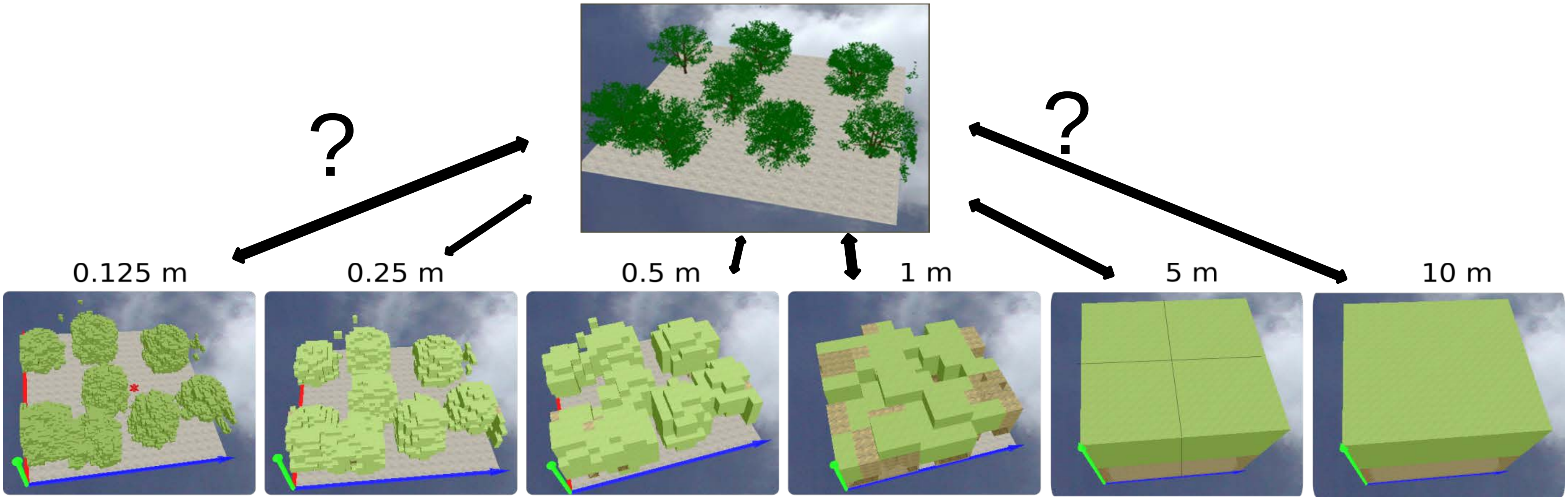


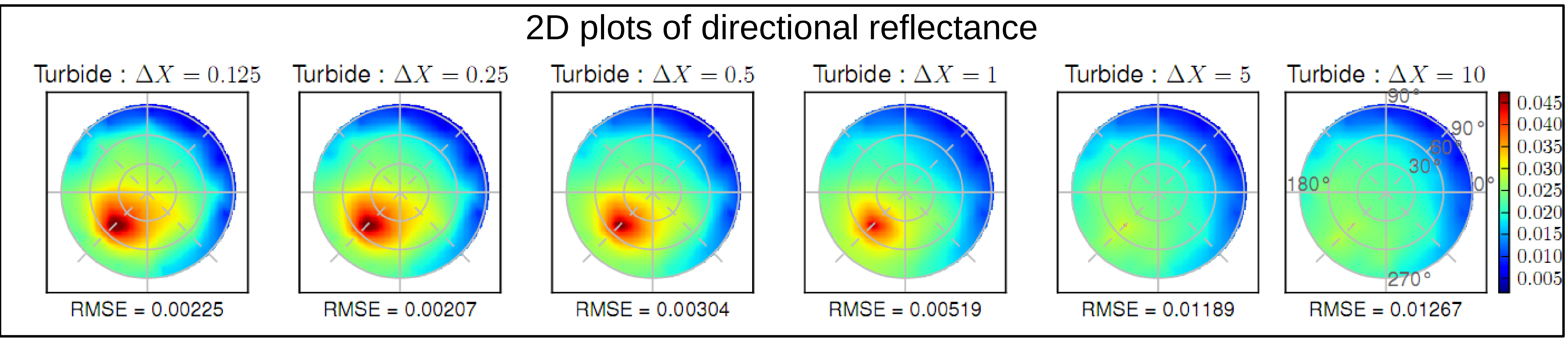
Atmosphere:
- Aerosol: rural, 23km
- Gas: US Std76

Stored range: [0 4km]
Beam distance: 137.2m
Pulse separation: 0.02m
Number of pulses: 6859
Look angle: nadir

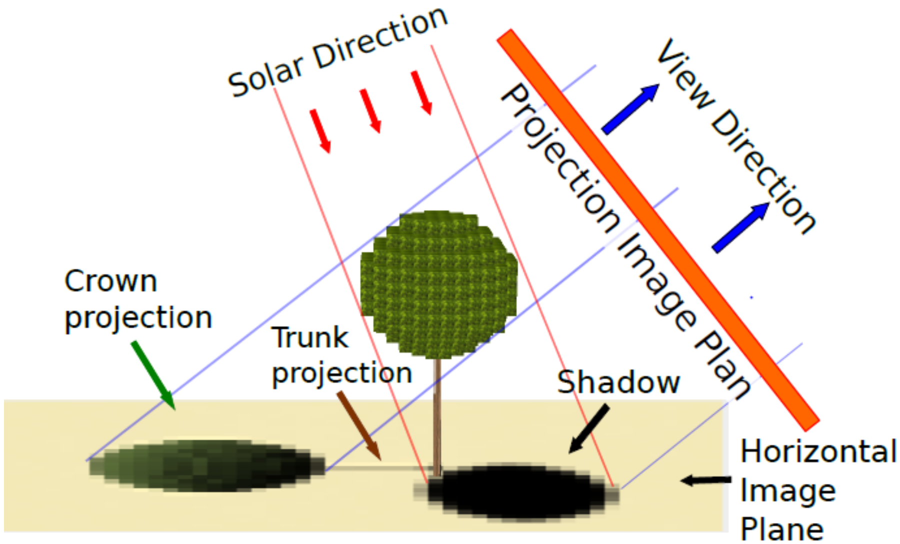


DART presentation: ***To simulate a landscape with which spatial resolution?***

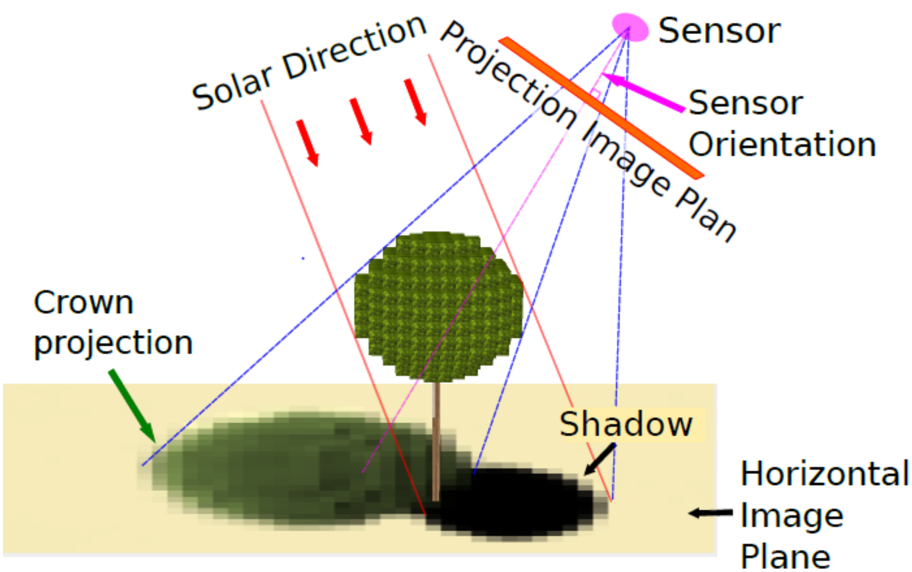




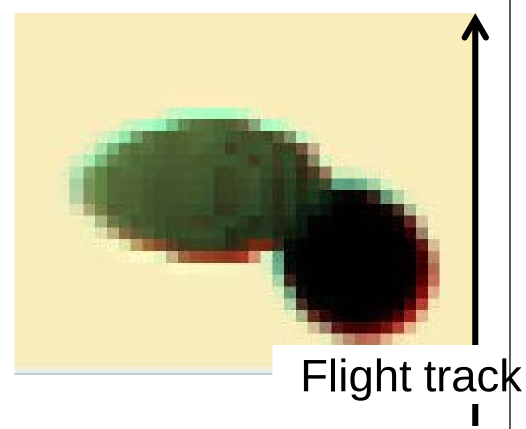
Spectro-radiometers with finite FOV: Perspective / Parallel projection



Sensor at infinite distance:
parallel projection $\Rightarrow \Phi_{crown} = \Phi_{shadow}$



Camera: perspective proj
$\Rightarrow \Phi_{crown} > \Phi_{shadow}$



Pushbroom/scanner:
parallel + perspective projection

Specular reflectance and polarization

- Modeling in DART -

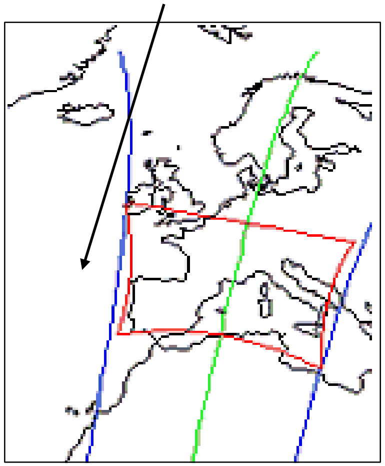
Atmospherically corrected POLDER acquisitions

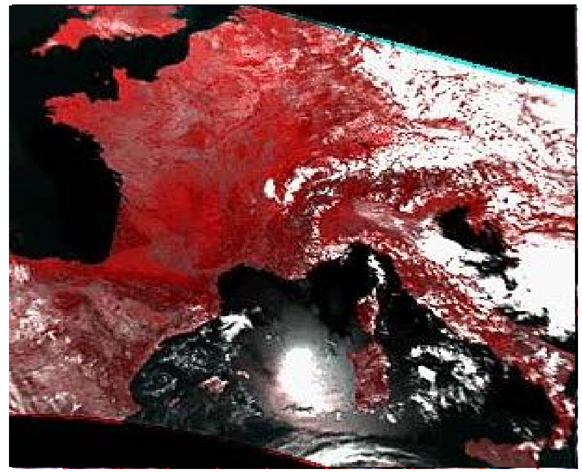
I: 1st term of Stokes vector

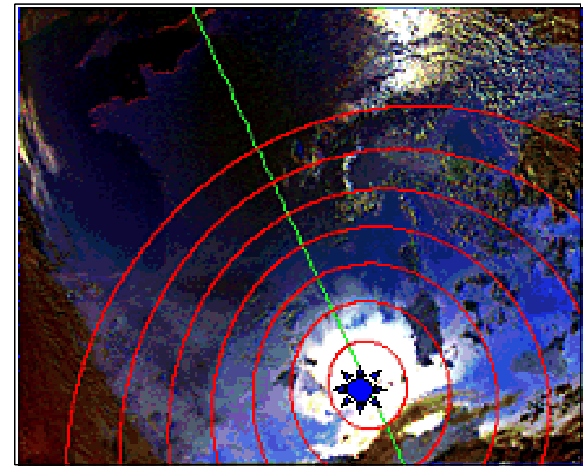
Q: 2nd term of Stokes vector

Sun glint

Mediterranean

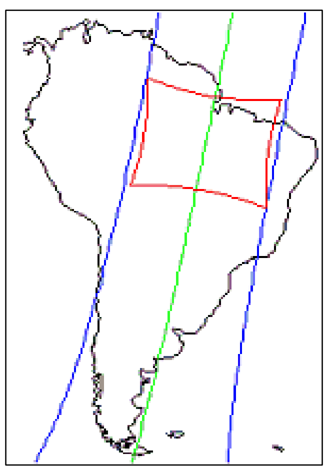


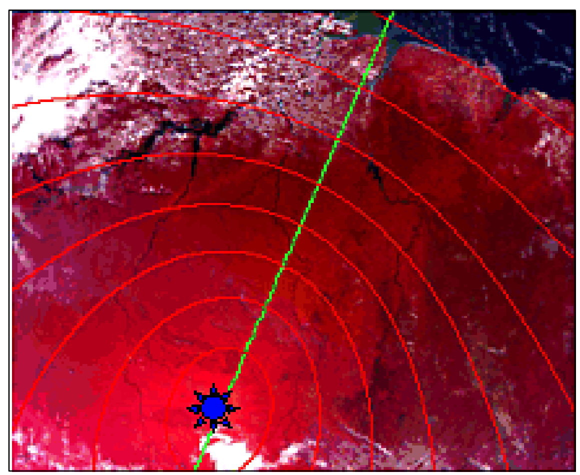


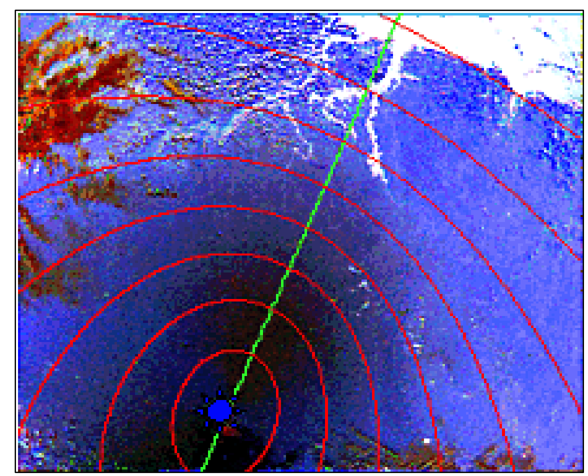


Hot spot

Amazonia







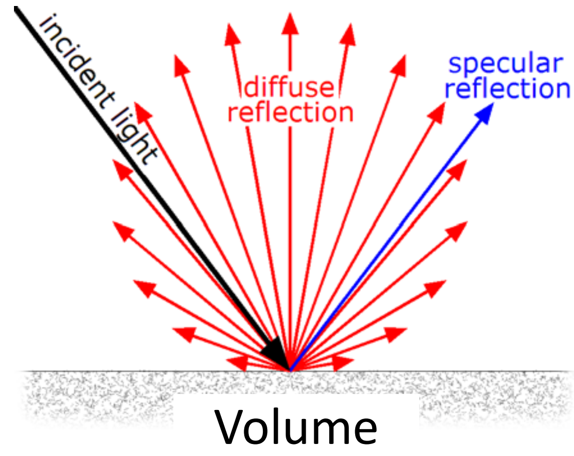
https://polder-mission.cnes.fr/fr/POLDER/Fr/gal_pola.htm

Specular reflectance and polarization: physical bases

Reflection = Diffuse + Specular reflection

Diffuse: mostly volume multiple scattering beneath the surface

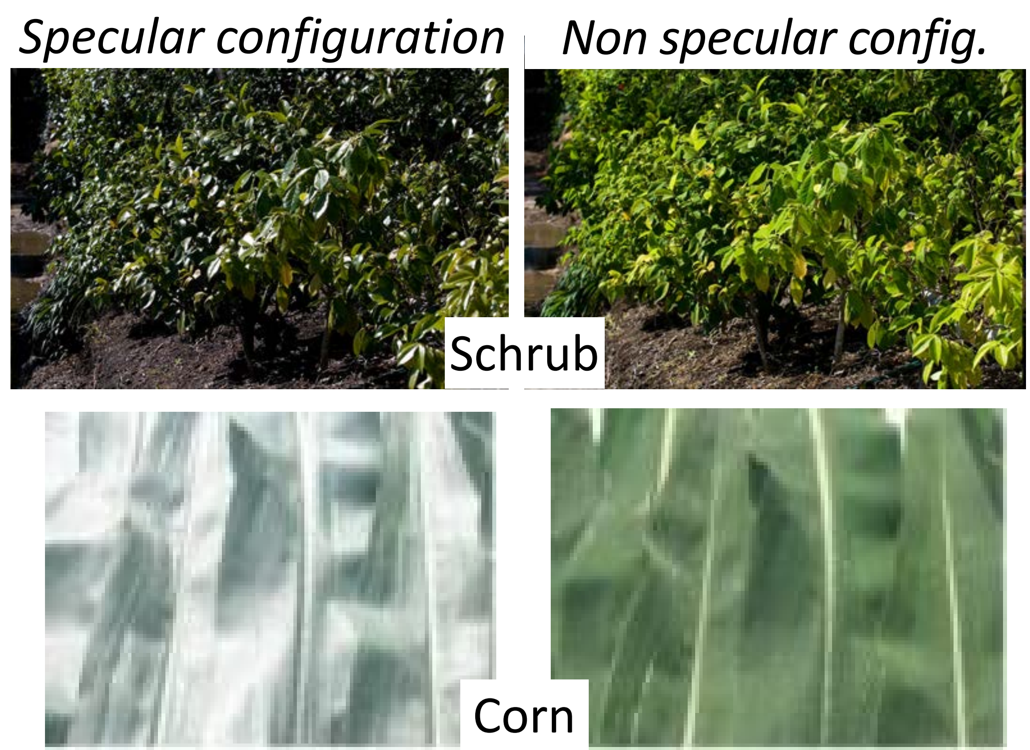
Specular: mirror-like reflection of light from smooth surface. Light from a single incoming direction is reflected into a single outgoing direction (specular). Its polarized component can be useful to discriminate volume (leaf biochemistry) and surface (leaf surface roughness, refractive index,…) information.



Specular reflectance

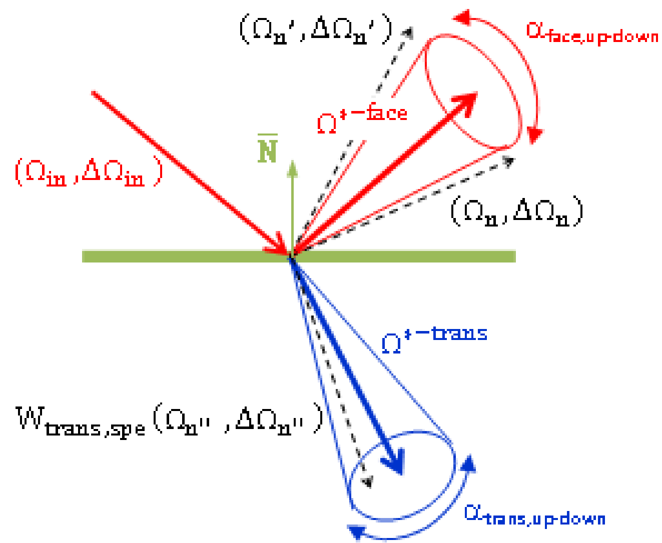
- Large increase of reflectance in specular configuration ⇒ white flecks on leaves

- Altered color perception, if large enough relative to diffuse reflection. It can be 35% of total light reflected by a wheat canopy with θ_{view} = 60° in blue region.



Notations: specular reflectance on horizontal surface.

incident direction zenith angle θ_{in} = Incidence angle $\theta_{in-local}$



Specular reflection modeling

- **Fresnel law** with weight A

  ⇒ **Mueller matrices** for considering polarization

- **Radiation propagation**

  - Specular signal distributed in an angular cone".

  - Account of the angular cone of incident radiation

- **Stokes vector** $S_P = \begin{pmatrix} I_P \\ Q_P \\ U_P \\ V_P \end{pmatrix}_{reference\ P}$: 4 terms that describe the wave polarization state

· Convenient alternative to the description of incoherent or partially polarized wave with total intensity I, degree of polarization p and shape parameters of the polarization ellipse.

The impact of any "wave - matter" interaction on wave polarization is determined as:

Output Stokes vector = Input Stokes vector x Mueller matrix M of interacting medium

In DART, it is a 3 steps procedure that transforms $S_{P,(\Omega_{in},\Delta\Omega_{in})}$:

$$\boldsymbol{S}_{\mathbf{P},(\Omega_{out},\Delta\Omega_{out})} = \boldsymbol{R}_{\mathbf{P},(\Omega_{out},\Delta\Omega_{out})-\mathbf{scat}\rightarrow\mathbf{P},(\Omega_{out},\Delta\Omega_{out})}.\mathbf{M}.\boldsymbol{R}_{\mathbf{P},(\Omega_{in},\Delta\Omega_{in})\rightarrow\mathbf{P},(\Omega_{in},\Delta\Omega_{in})-scat}.\boldsymbol{S}_{\mathbf{P},(\Omega_{in},\Delta\Omega_{in})}$$

Step 1: $S_{P,(\Omega_{in},\Delta\Omega_{in})-scat}$ = Rotation matrix $R_{P,(\Omega_{in},\Delta\Omega_{in})\rightarrow P,(\Omega_{in},\Delta\Omega_{in})-scat}$ x $S_{P,(\Omega_{in},\Delta\Omega_{in})}$

Step 2: $S_{P,(\Omega_{out},\Delta\Omega_{out})-scat} = M.S_{P,(\Omega_{in},\Delta\Omega_{in})-scat}$

Step 3: $S_{P,(\Omega_{out},\Delta\Omega_{out})}$ = Rotation matrix $R_{P,(\Omega_{out},\Delta\Omega_{out})\rightarrow P,(\Omega_{out},\Delta\Omega_{out})-scat}$ x $S_{P,(\Omega_{out},\Delta\Omega_{out})-scat}$

General expressions of Mueller matrices

- **Volumes**: gasses, aerosols, turbid vegetation, and fluids (water, soot,…)

$$M_r = \begin{pmatrix} 1 & \frac{1-\cos^2\Psi}{1+\cos^2\Psi} & 0 & 0 \\ \frac{1-\cos^2\Psi}{1+\cos^2\Psi} & 1 & 0 & 0 \\ 0 & 0 & \frac{2\cos\Psi}{1+\cos^2\Psi} & 0 \\ 0 & 0 & 0 & \frac{2\cos\Psi}{1+\cos^2\Psi} \end{pmatrix}_{\text{Rayleigh scattering}}$$

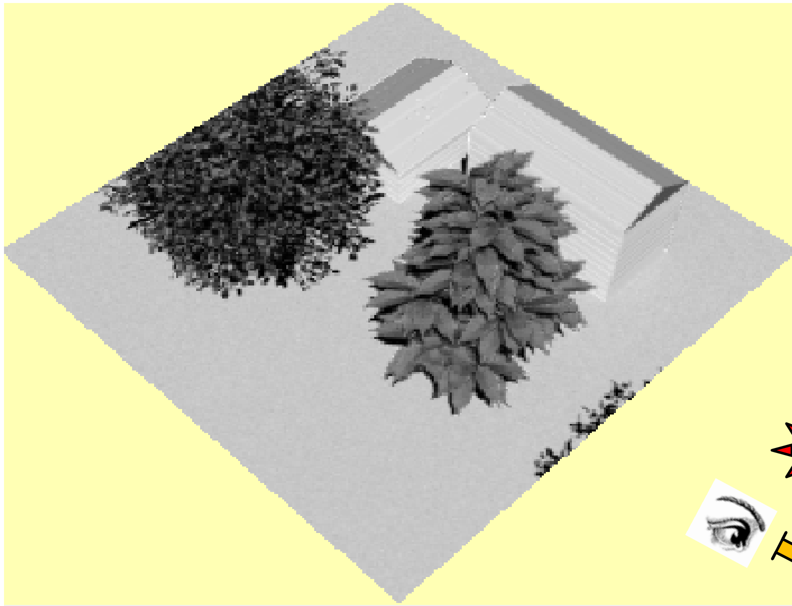
$$M_r = \begin{pmatrix} 1 & M_{12}(\Psi) & 0 & 0 \\ M_{12}(\Psi) & 1 & 0 & 0 \\ 0 & 0 & M_{33}(\Psi) & 0 \\ 0 & 0 & 0 & M_{33}(\Psi) \end{pmatrix}_{\text{Mie scattering}}$$

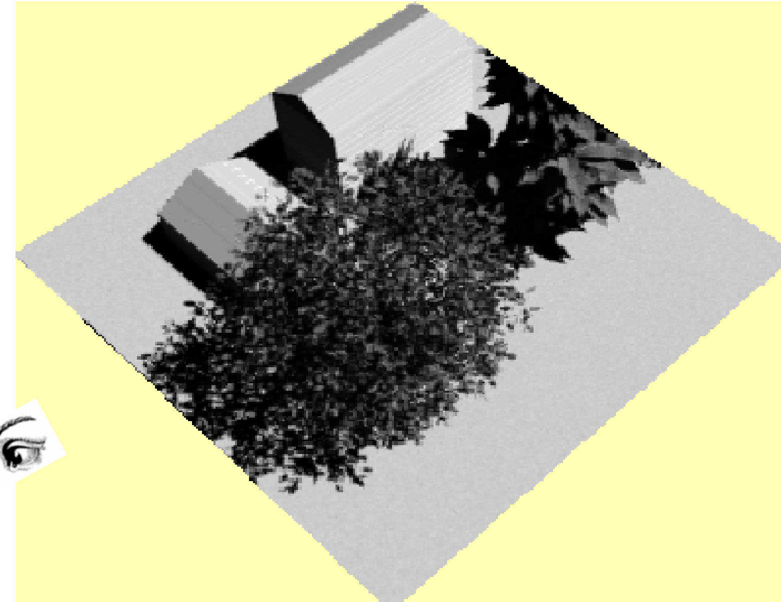
- **Surfaces** with any isotropic and anisotropic reflectance property (special case for water)

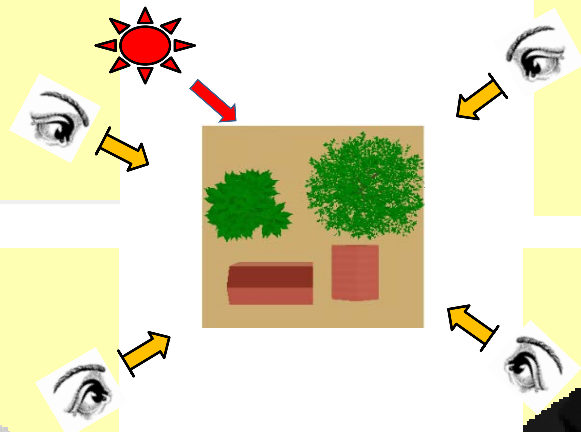
$$M_r = \begin{pmatrix} 1 & \frac{r^2_{x_{P,(\Omega_{in},\Delta\Omega_{in})-scat}} - r^2_{y_{P,(\Omega_{in},\Delta\Omega_{in})-scat}}}{r^2_{x_{P,(\Omega_{in},\Delta\Omega_{in})-scat}} + r^2_{y_{P,(\Omega_{in},\Delta\Omega_{in})-scat}}} & 0 & 0 \\ \frac{r^2_{x_{P,(\Omega_{in},\Delta\Omega_{in})-scat}} - r^2_{y_{P,(\Omega_{in},\Delta\Omega_{in})-scat}}}{r^2_{x_{P,(\Omega_{in},\Delta\Omega_{in})-scat}} + r^2_{y_{P,(\Omega_{in},\Delta\Omega_{in})-scat}}} & 1 & 0 & 0 \\ 0 & 0 & \frac{2.\, r^2_{x_{P,(\Omega_{in},\Delta\Omega_{in})-scat}} .\, r^2_{y_{P,(\Omega_{in},\Delta\Omega_{in})-scat}}}{r^2_{x_{P,(\Omega_{in},\Delta\Omega_{in})-scat}} + r^2_{y_{P,(\Omega_{in},\Delta\Omega_{in})-scat}}} & 0 \\ 0 & 0 & 0 & \frac{2.\, r^2_{x} .\, r^2_{y_{P,(\Omega_{in},\Delta\Omega_{in})-scat}}}{r^2_{x_{P,(\Omega_{in},\Delta\Omega_{in})-scat}} + r^2_{y_{P,(\Omega_{in},\Delta\Omega_{in})-scat}}} \end{pmatrix}$$

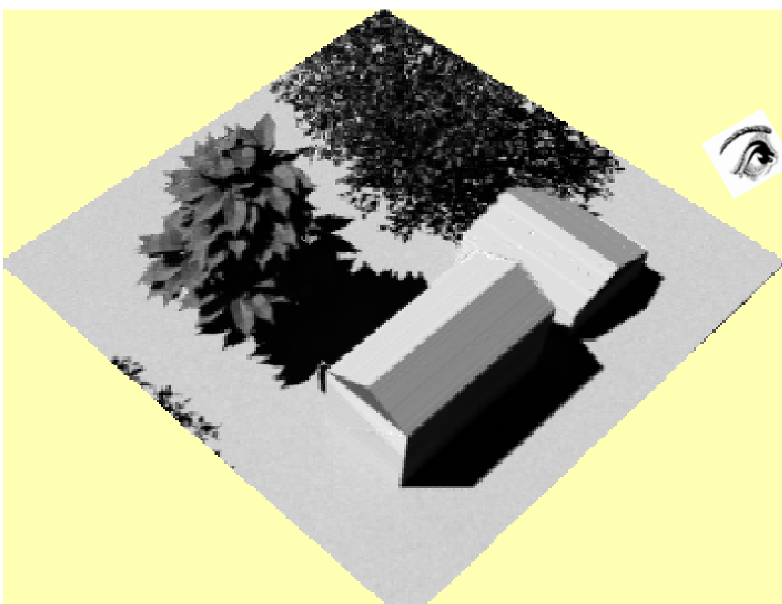
Specular reflection and Polarization: Airborne configuration, no atmosphere, 400nm

Total radiance



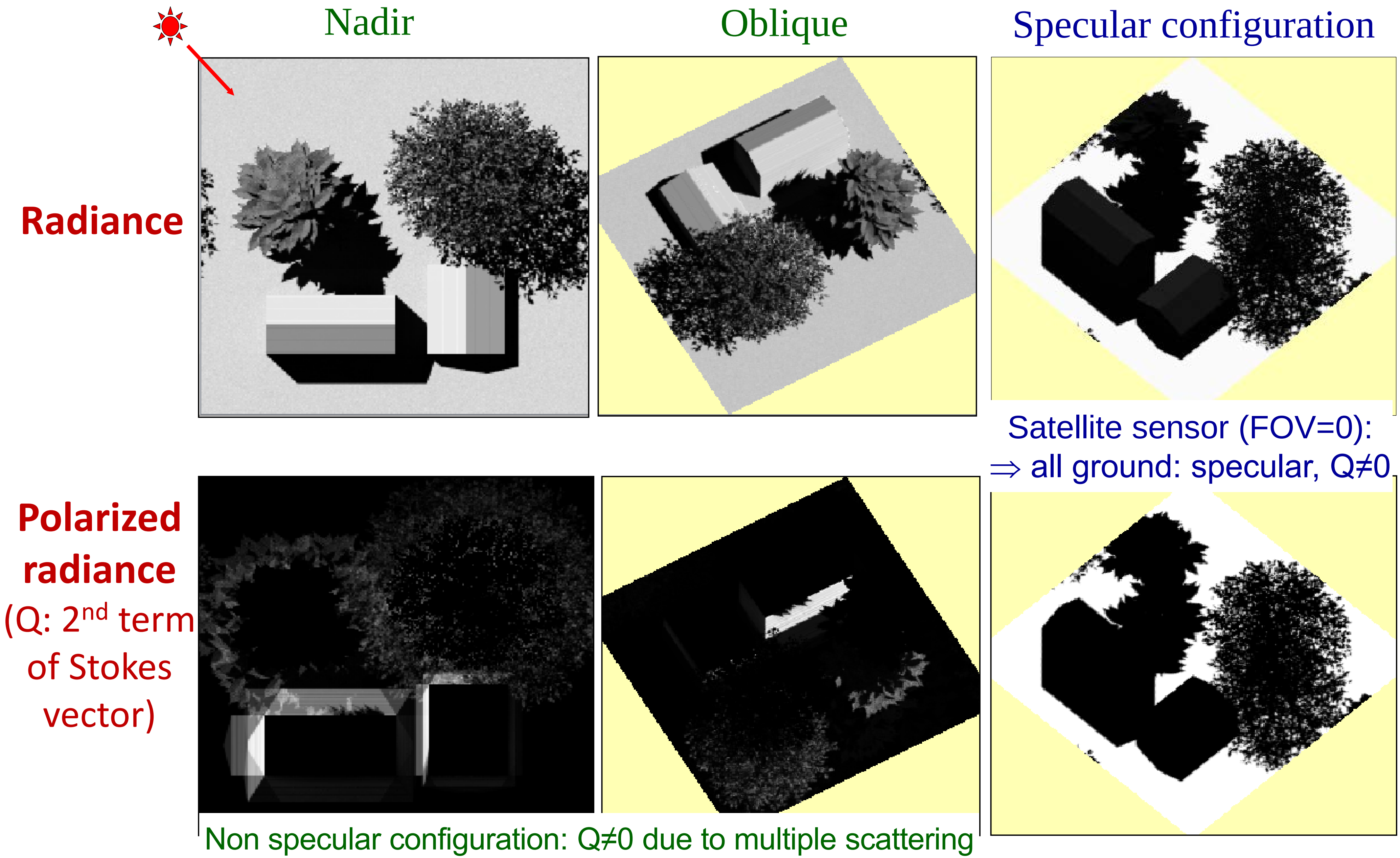






Airborne specular configuration:
$\Rightarrow$ specular zone is local

Specular reflection and polarization: Satellite sensor (FOV=0), no atmosphere, 400nm



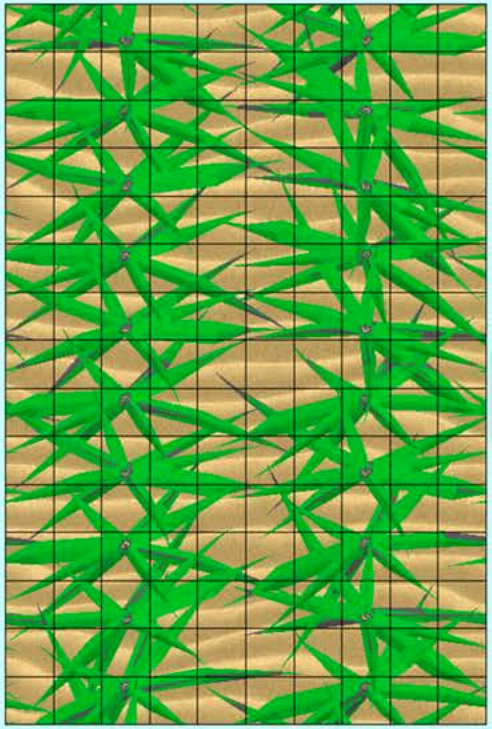
DART chlorophyll fluorescence: maize canopy

FLUSPECT inputs:

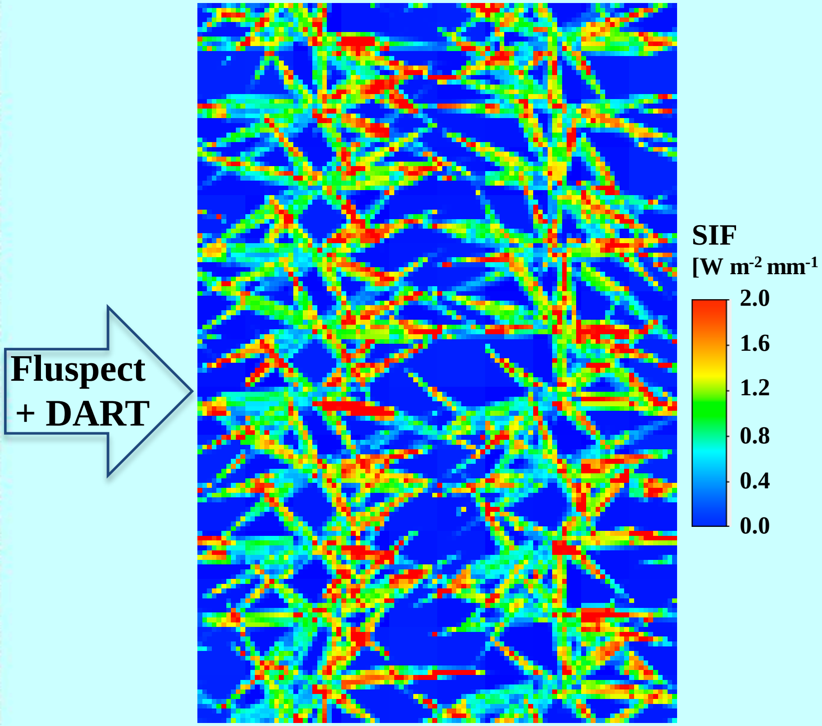
Fluspect inputs	Cab	Car	Cw	Cdm	N	PSI fqe	PSII fqe
Sun adapted leaves	50	15	0.009	0.0021	1.5	0.002	0.016
Shade adapted leaves	75	20	0.012	0.0028	2.0	0.002	0.022

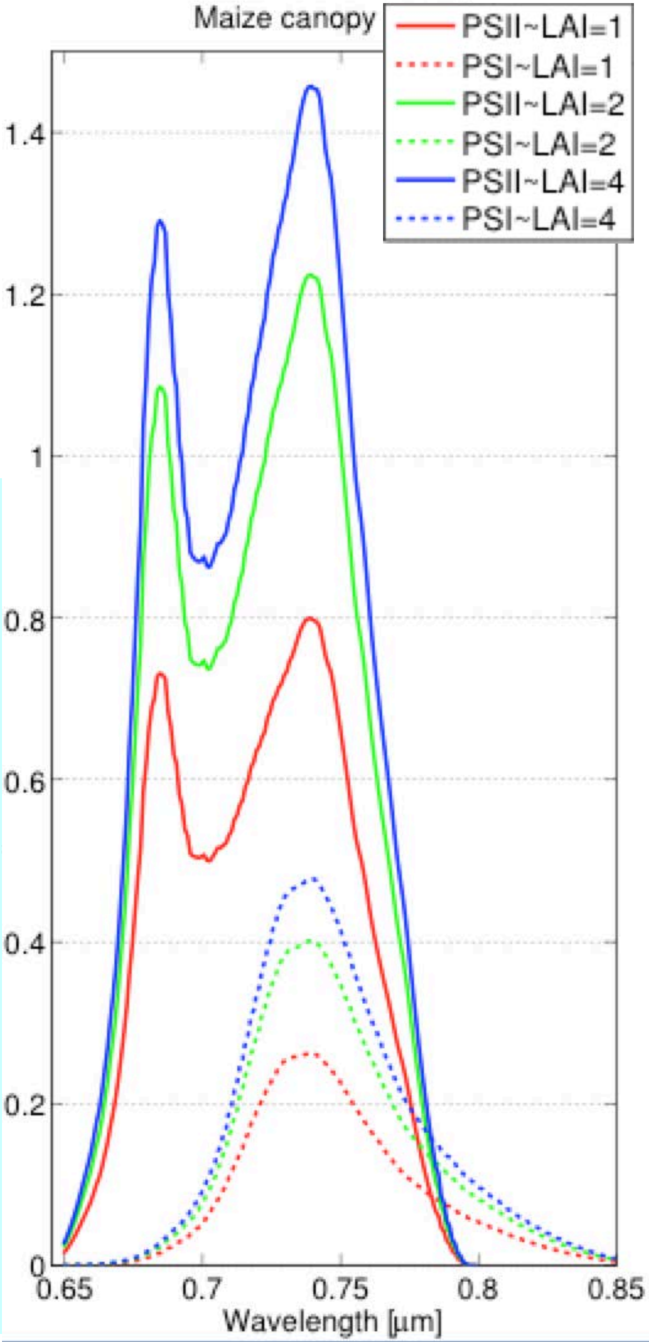
DART upscaling:

Maize canopy mock-up (nadir view)



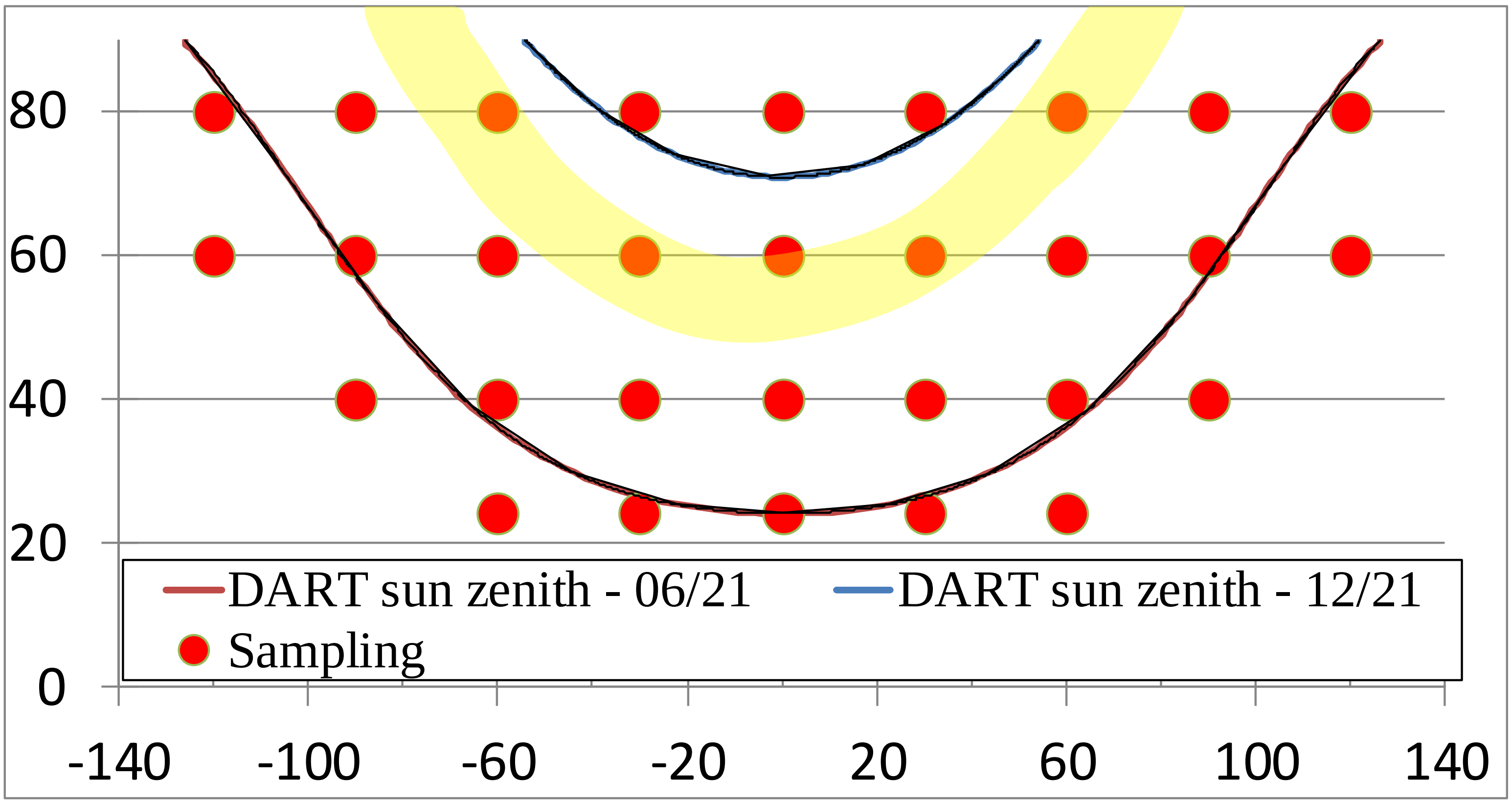
Top-of-canopy SIF of PSII (@ 740 nm, FWHM = 1 nm)





Objective: ***Time series of Q^{*}_{short} maps*** ⇒ Computation of $LUT_{A_{\Delta\lambda}}$

Sampling the space of sun directions for the period of interest (*e.g.*, 1 year). DART simulations will be run for these directions for creating the $LUT_{A_{\Delta\lambda}}$.



Basel