DART: a 3D radiative transfer model for studying natural and urban surfaces

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DART Discrete Anisotropic Radiative Transfer
since 1992

CESBIO

Outline

1. Introduction to DART model

2. DART applications

3. Conclusion

CESBIO

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DART model: an overview

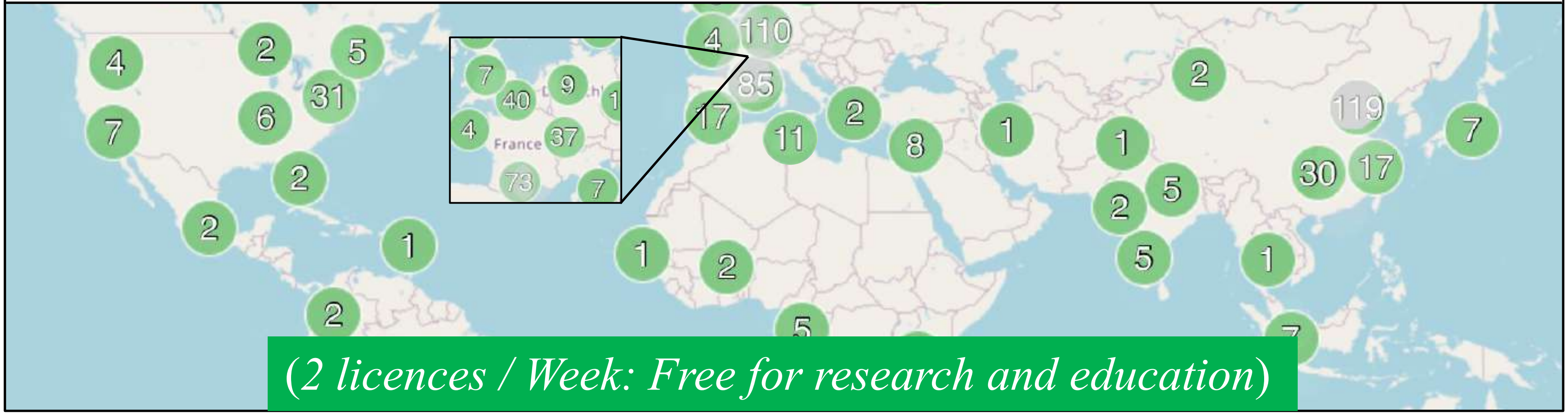
History: developed in CESBIO since 1992 by 10 scientists. Patented in 2003

Code: 500,000 lines C++ (RT), 100,000 lines Java (GUI) + Python (Tools)

Accuracy (relative difference ε, RMSE) assessed with:

- Monte Carlo models (RAMI-III experiment): $\varepsilon_\rho \leq 1\%$ (*Widlowski et al., 2007*)
- Measurements: $\varepsilon_\rho \leq 2.5\%$ (*Landier et al.,2018*), $RMSE_{T_B} < 2K$ (*Sobrino et al., 2011*)

589 DART licences: Universities, Research centres (CNES, ESA, …)



(2 licences / Week: Free for research and education)

DART Team (CESBIO)

Jean-Philippe Gastellu-Etchegorry
Professor (UT3)
Scientific leader

Nicolas Lauret
Dr, Engineer (CNRS)
Lead Developer

Science

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ATER (UT3)
Atm., polarization

Zhijun Zhen
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Inversion

Paul Boitard
PhD (UT3)
Biosphere processes

Romain Demoulin
PhD (UT3)
Vegetation

Ameni Mkaouar
Post-Doc (NASA)
LiDAR

Huaan Jin
Assoc. Prof (CAS)
Vegetation

Computer science

Jordan Guilleux
Engineer (CNRS)
Interfaces, databases, ….

Eric Chavanon
Engineer (UT3)
Compilation, Scientific tools, …

Outside CESBIO:

Z. Malenovsky, O. Regaieg, T. Nguyen *(Univ. Bonn, Germany): SIF, TIR, RB.*

A. Kallel *(CRNS, Tunisia): Monte Carlo*

T. Yin *(HPU, China): Photogrammetry, LiDAR*

R. Paugam *(UCP, Spain): Fire*

TETIS (Montpellier): F. De Boissieu, J.-B. Feret, S. Durrieu

Pytools4dart: https://gitlab.com/pytools4dart

Development of DART model

More than 30 years
constantly improvement
for land surface studies

DART-FT Since 1992 Radiative transfer: Adaptation of **DOM**

(Optical and thermal radiometer images and radiative budget, with SIF)

DART-RC Since 2010 Radiative transfer: forward **MC**

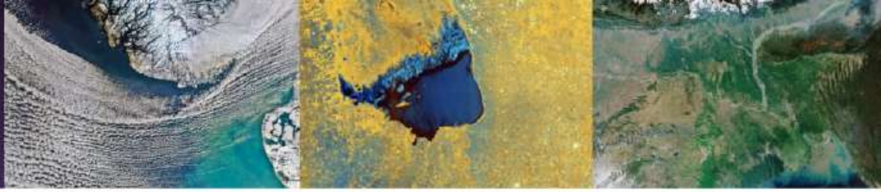
(LiDAR: waveform, point cloud, photon counting)

DART-Lux Since 2018 Radiative transfer: bidirectional **MC**

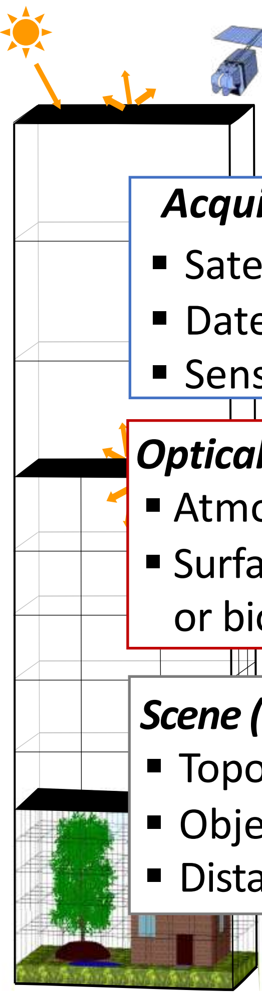
(Optical and thermal radiometer images, LiDAR and radiative budget, with SIF and polarization)

DART-EB Since 2020 Energy balance

(Heat flux, temperature, evapotranspiration)



DART: an overview



Inputs

Acquisition configuration
- Satellite / plane location
- Date or sun direction
- Sensor characteristics

Optical/Structure databases
- Atmosphere: $\tau_{gas}(\lambda)$,...
- Surface: optical properties or biochemistry

Scene (city, forest...) geometry
- Topography, land cover,...
- Objects: trees, houses,...
- Distance between plants,...

3D LAI,...

Modules

Direction
Sun & viewing directions

Phase
Values per spectral band

Mock-up
Atmosphere & Earth mock-up

DAO: mock-up direct creation

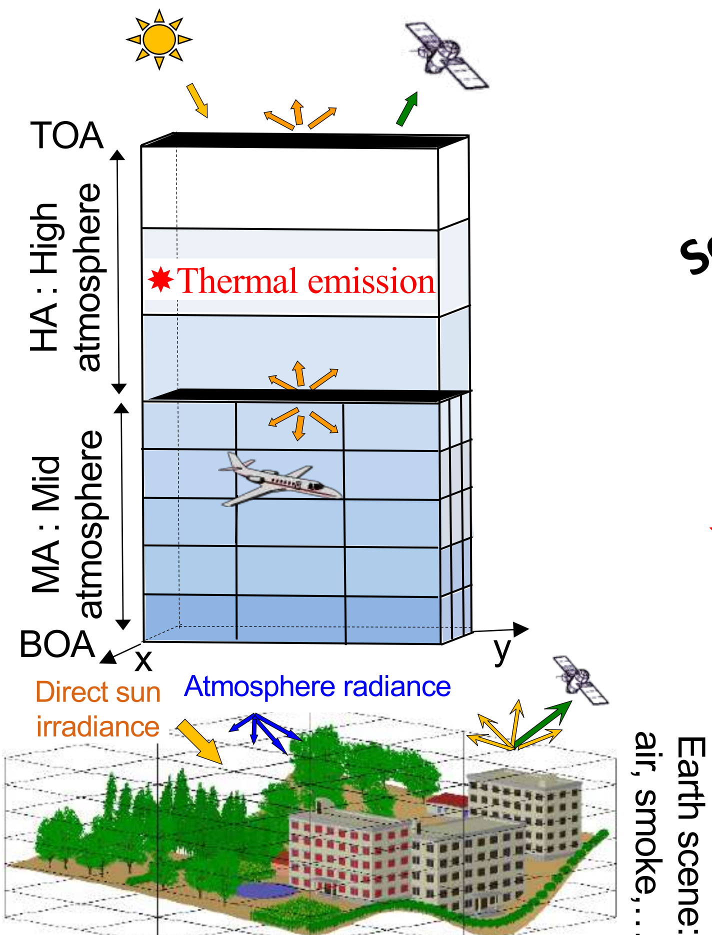
Dart
Photon / Ray tracking

Outputs

- ***Remote sensing***:
  - Radiometer images (VIS-TIR): satellite, airborne, in-situ (sensor, orthorectified, per element/source).
  - LiDAR: waveform, point cloud, photon counting (Sat./ALS/TLS)
  - SIF (fluorescence)
  - Polarization
- ***3D radiative budget***

Post processing (Python tools)
- Inversion: maps of OP
- Sensor broadband,...

DART-FT (since 1992)

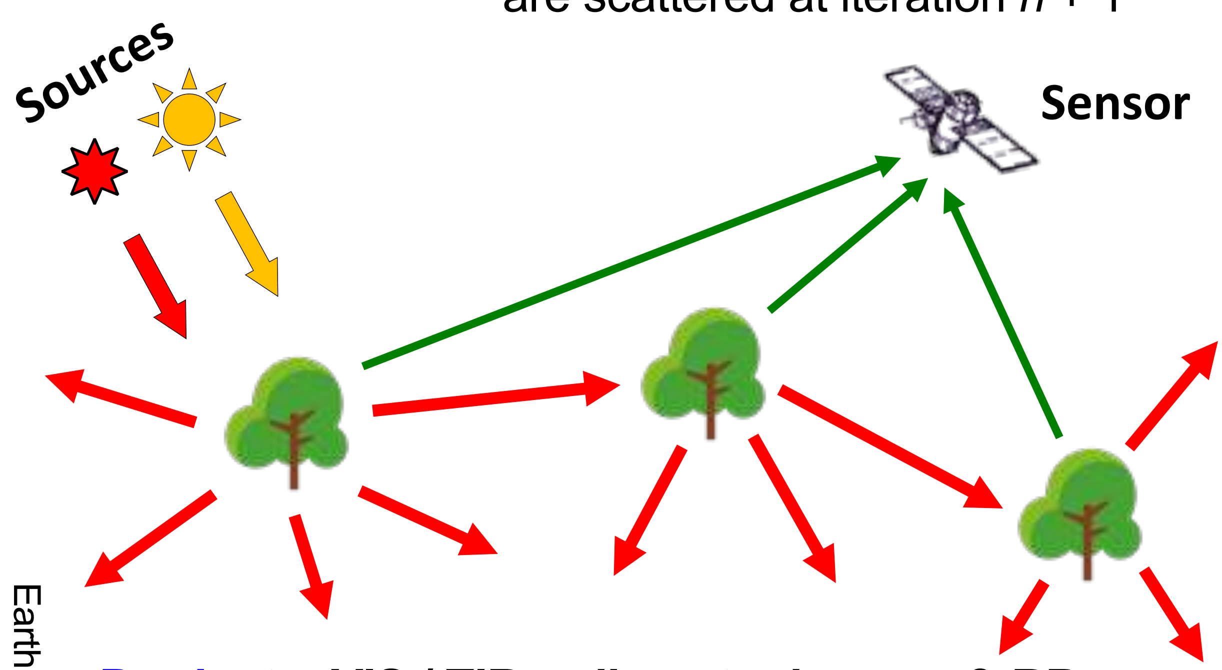


[(Gastellu-Etchegorry et al., 1996)]

Scene: Array of turbid / fluid voxels + facets

RT modelling: - Discrete Ordinate Method (DOM)

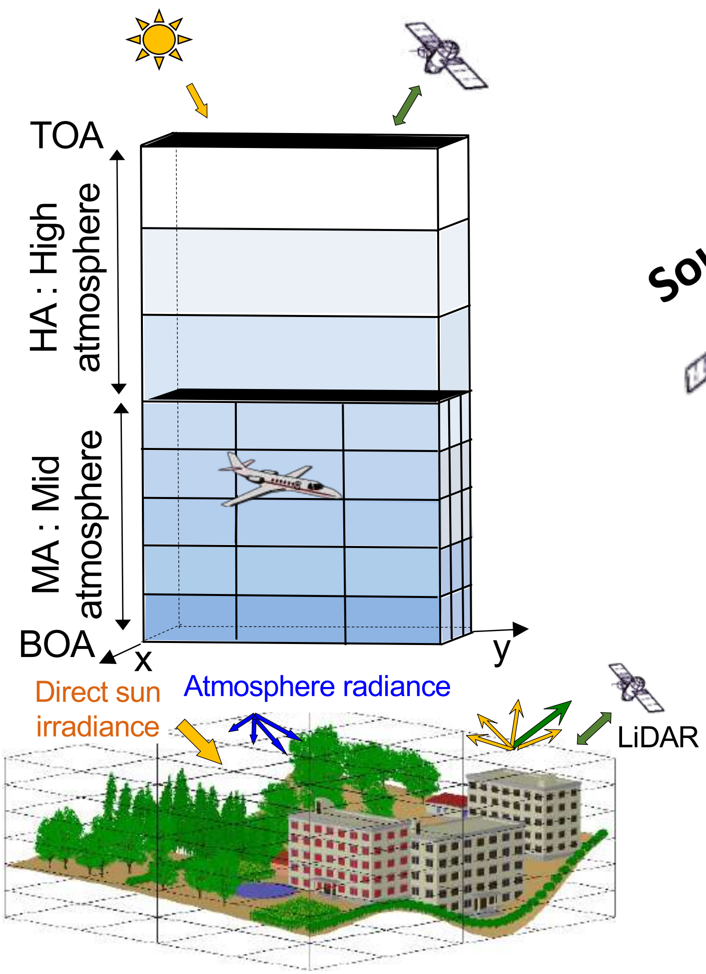
- Iterative: rays intercepted at iteration *n* are scattered at iteration *n* + 1



Products: VIS / TIR radiometer images & RB

RB (radiative budget) ⇒ simulation of photosynthesis, evapotranspiration, …

DART-RC (since 2010)

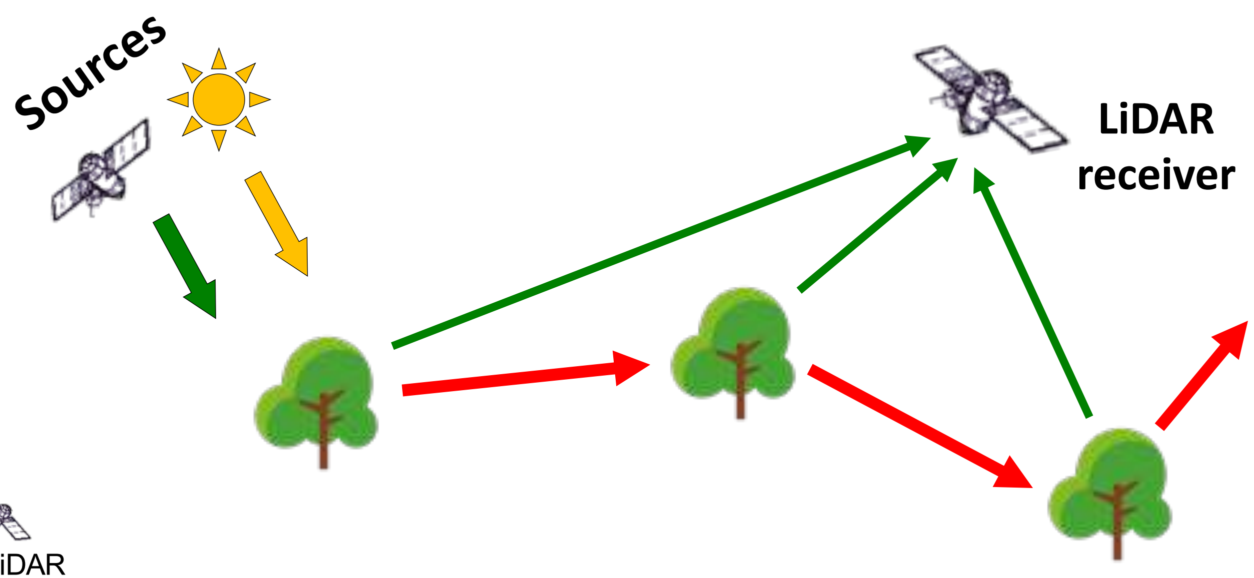


[(Yin et al., 2015)](#)

Scene: **Array of turbid / fluid voxels + facets**

RT modelling: **- Forward Monte Carlo**

- Secondary ray: a ray is sent to sensor after each interaction.



Products: **Satellite, ALS and TLS LiDAR**

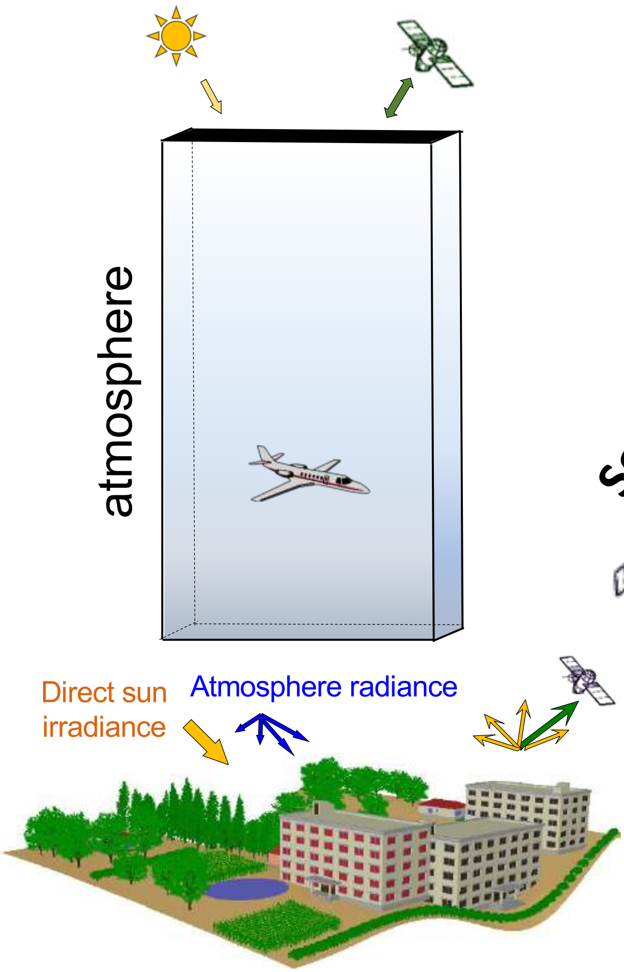
DART-Lux (since 2018)

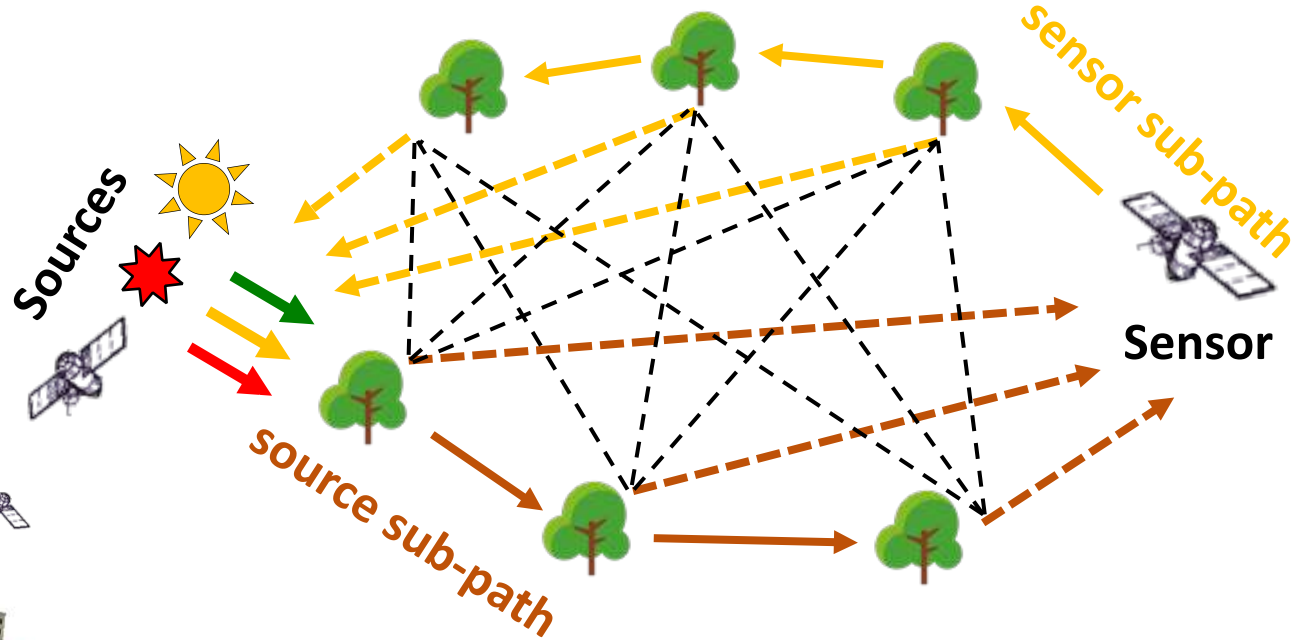
Scene: Turbid / fluid volumes, facets; no voxel

RT modelling: - Bi-directional Monte Carlo

⇒ Computer time & RAM reduced by > 100 !

Rays run over **most probable "Source - Sensor" paths**





Products: VIS / TIR radiometer images, RB and LiDAR

(*Wang and Gastellu-Etchegorry, 2021; Yang et al., 2022; Regaieg et al., 2023*)

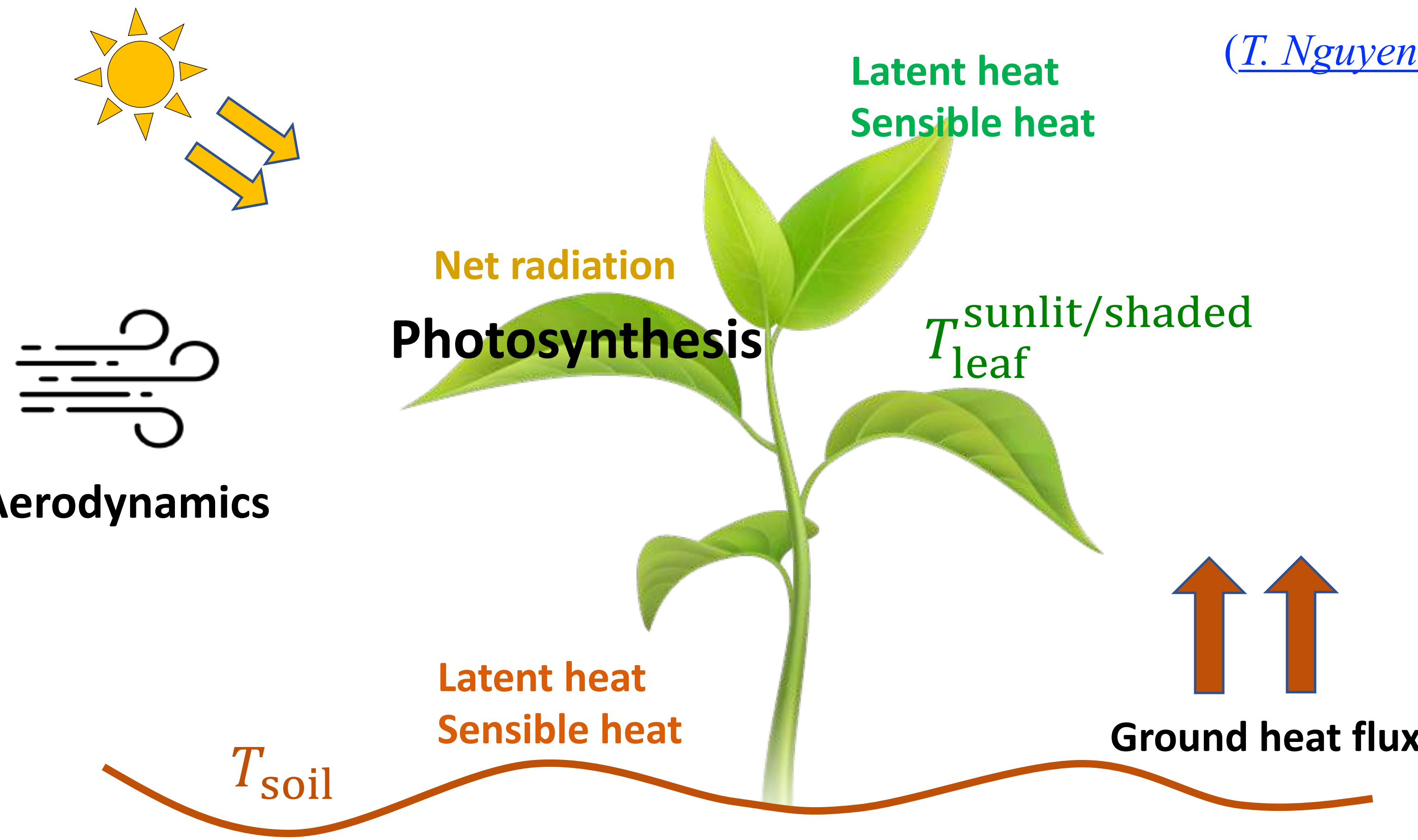
DART-EB (since 2020)

Scene: **1D (3D scene modelling is on-going)**

EB modelling: Photosynthesis, heat flux, turbulence, fluorescence, evapotranspiration, *etc*. + RT (DART)

Products: Vertical heat flux, temperature profile, …

(*T. Nguyen, 2022*)



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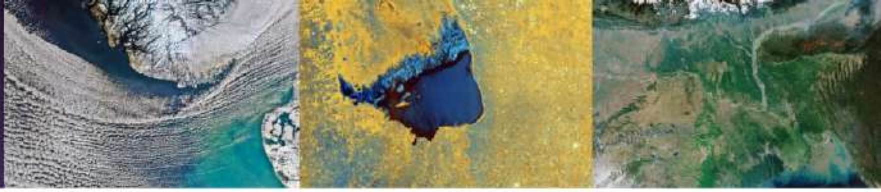


DART applications

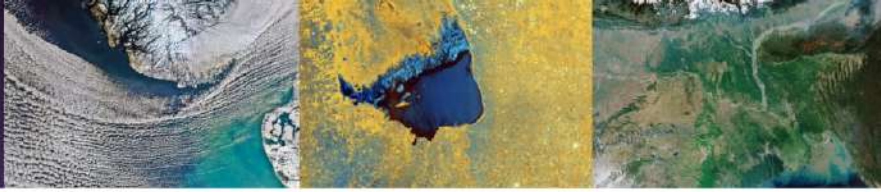
Research works with indication of projects:

- Vegetation functioning (hyperspectral): RedEdge, HyPOS (ESA)
- Urban radiative budget: H2020 UrbanFluxes, ERC Urbisphere (EU)
- AI algorithms: DIAPOS (CNES)
- Normalization of satellite images: COPA (ESA)

Preparing satellite missions:

- Sentinel-2 NG (ESA): trade-off "Several satellites *vs.* Large FOV"
- TRISHNA (CNES-ISRO), LSTM (ESA): optimal TIR bands, DART scenes used as references, correction of directional effects in TIR images
- Surface Topography and Vegetation (STV: NASA): LiDAR, stereo, …

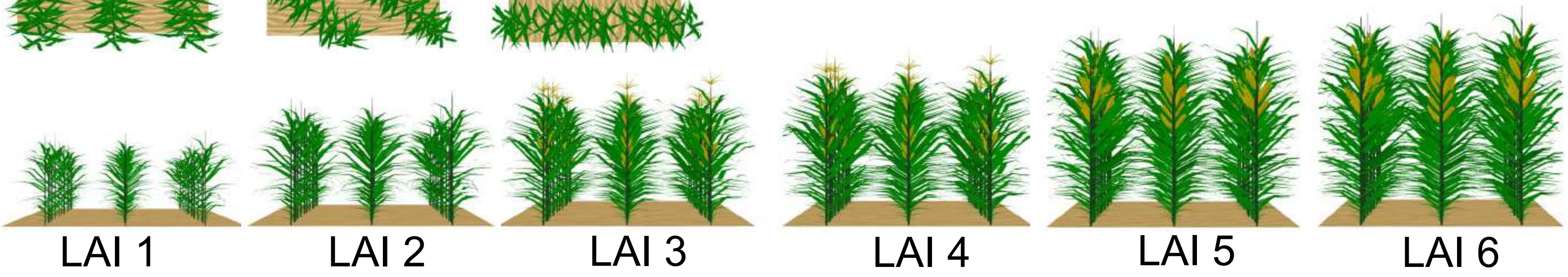
Community code certification (French National Research Centre, **CNRS**): to facilitate scientific collaboration on research domains using DART (Submitted)



Remote sensing images

Impact of vegetation growth stage and field orientations on satellite signal and radiative budget. Projects LSTM & S2 NG (ESA)

Maize at 6 growth stages (LAI, height…)
3 orientations, 3 ground reflectances, ...

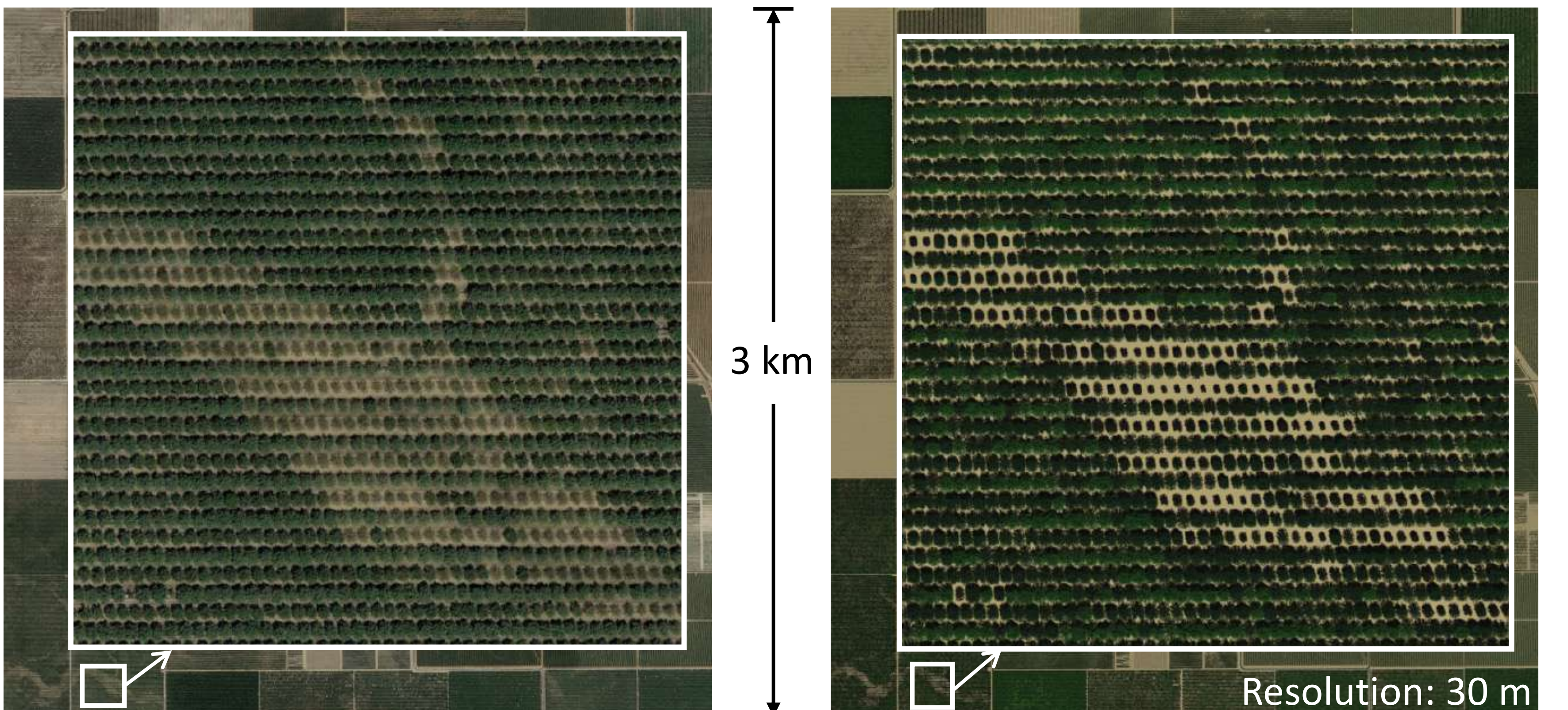


	Maize stage (BBCH scale)					
Plant height	0.92	1.28	1.55	1.79	2.04	2.24
Number of leaves	14	14	19	19	22	22
LAI	1	2	3	4	5	6
Leaf max. area	0.105	0.21	0.315	0.42	0.525	0.63

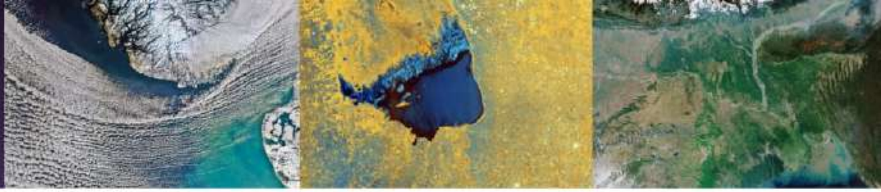
Remote sensing images

DART scenes used as ref. ⇐ High resolution images. Project S2 NG (ESA)

(Gastellu-Etchegorry et al., 2022)

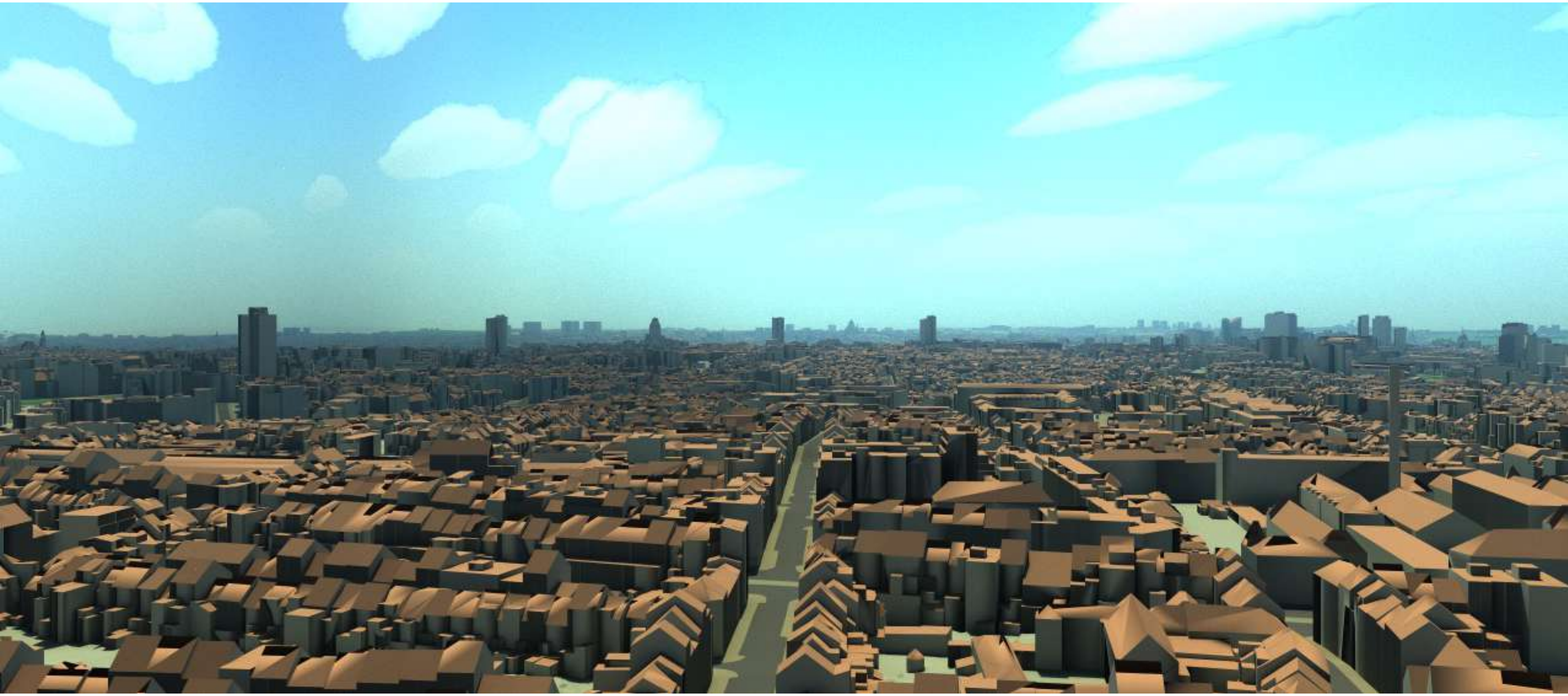


Google map (Sept. 2018) DART Simulation

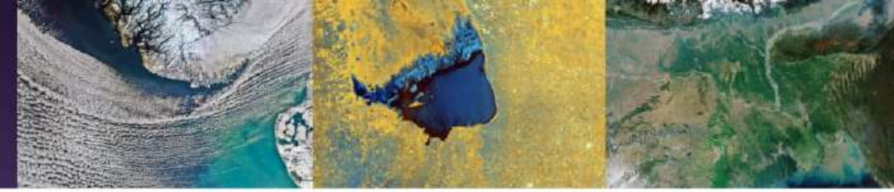


Remote sensing images

Urban short wave and long wave radiative budget. Project Suabe (Belgium)

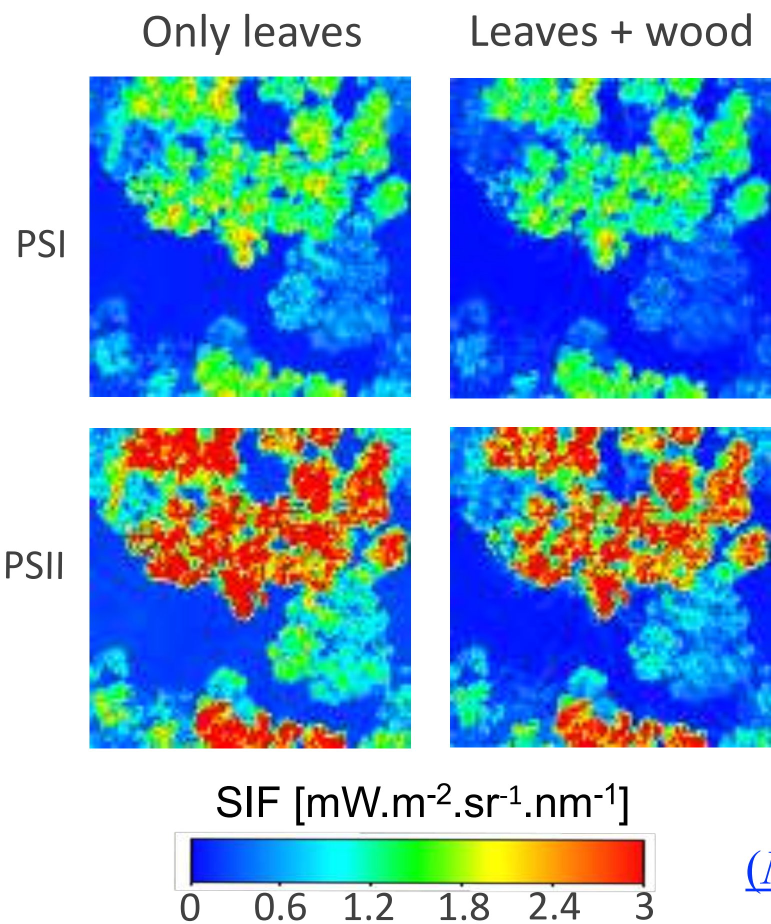


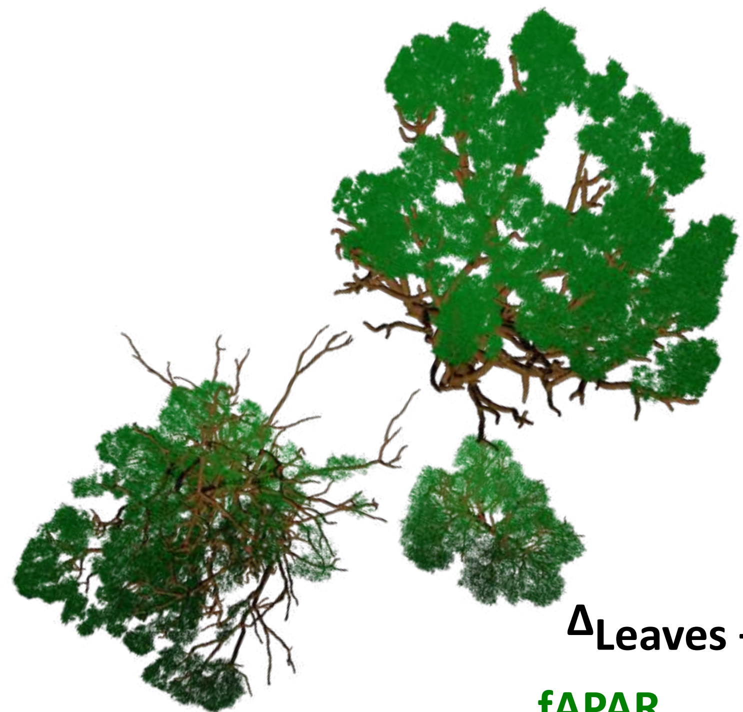
DART image: Brussels city (17 km x 17 km, no trees) + Atmosphere + Clouds



Chlorophyll fluorescence

Impact of wood on SIF emission and observation at 740nm: Eucalyptus forest





Eucalyptus trees (DART simulation)

$\Delta_{\text{Leaves - Leaves+Wood}}$ %	
fAPAR$_{green}$	**17% ↓**
SIF emitted	**17% ↓**
SIF exitance	**24% ↓**

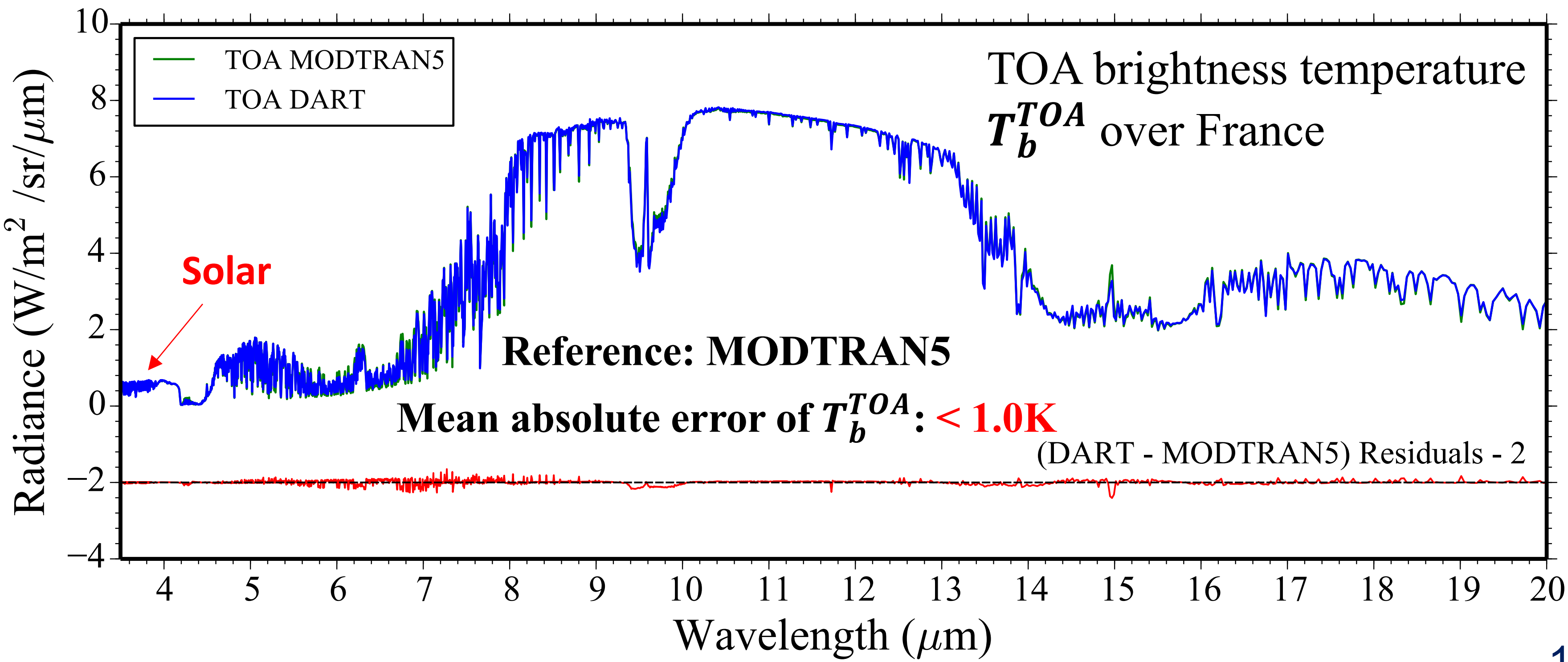
(Malenovský et al., 2021)

Atmosphere

ECMWF: vertical profile of gases and temperature. **DART:** atmospheric RT

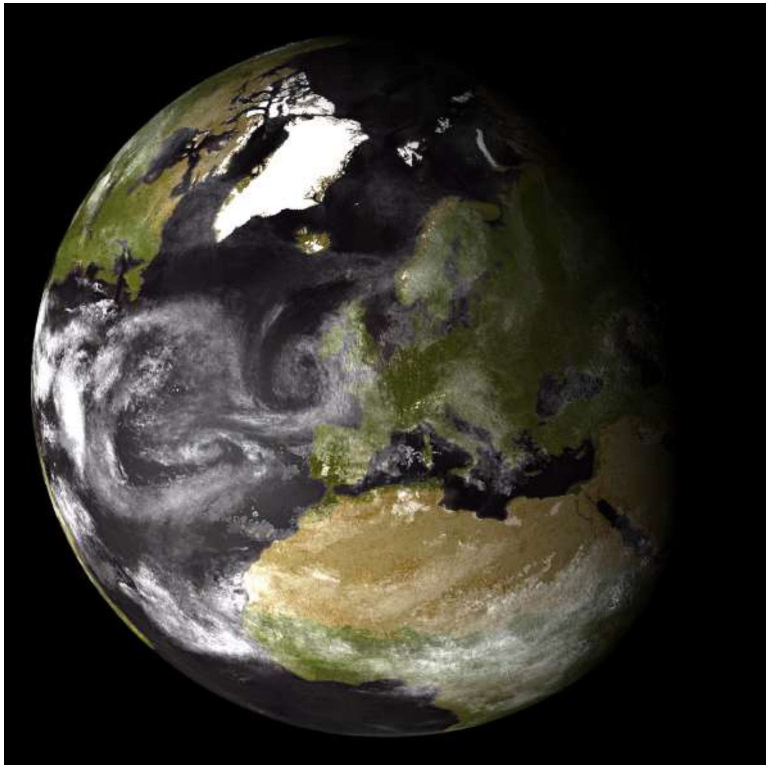
ECMWF + DART

(Wang et al., 2020)

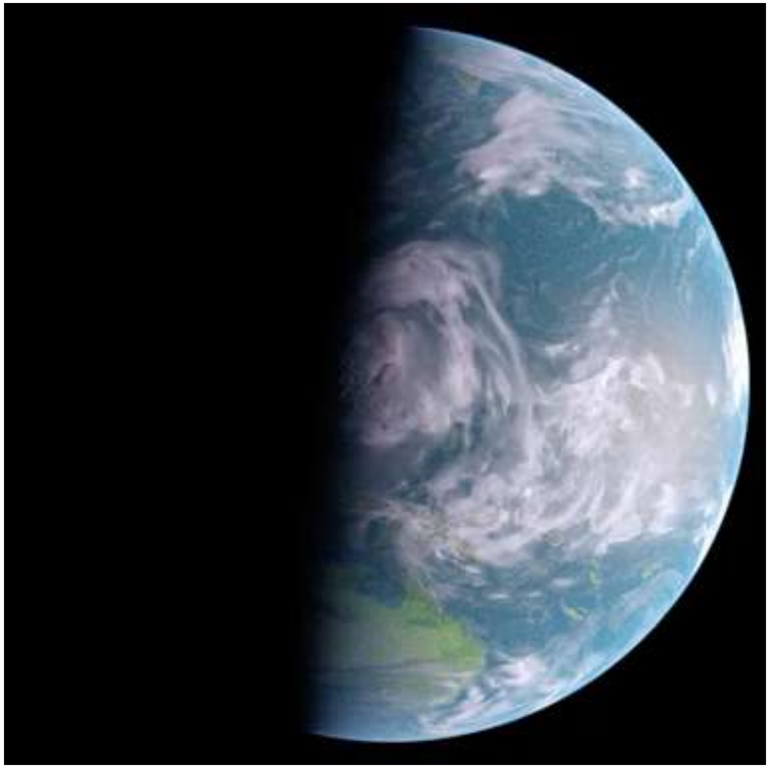


Atmosphere

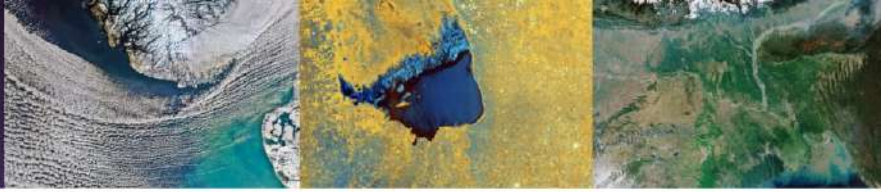
Data sources: Earth DEM (GEBCO 2022), Land cover (EarthEnv), Clouds cover (Copernicus EUMETSAT), Atmosphere profile (AFGL: USSTD76)



No Atmosphere



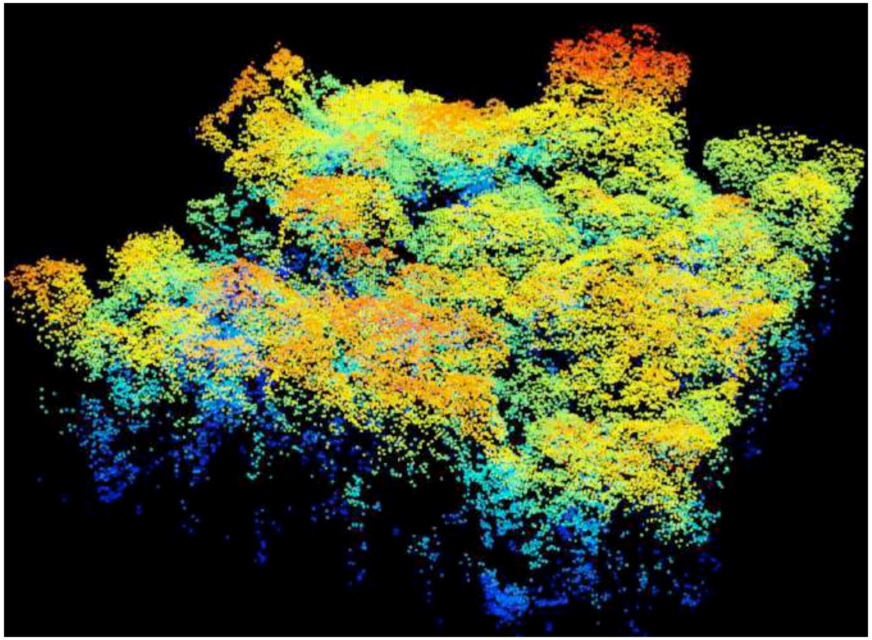
Spherical Atmosphere (E. Chavanon)



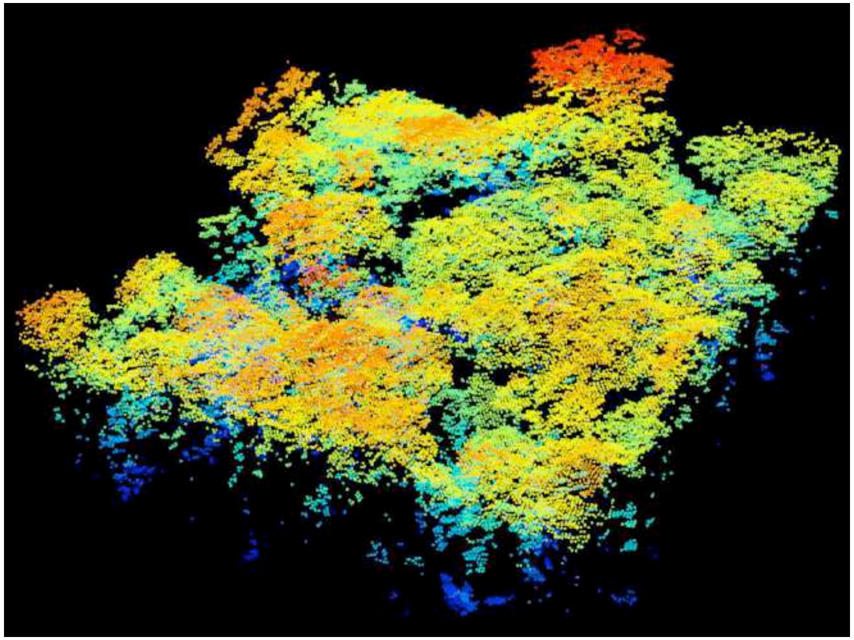
LiDAR

Simulation of airborne and satellite LiDAR signals of tropical forest (Paracou, Guyana) in order to prepare the satellite mission LEAF (LiDAR)

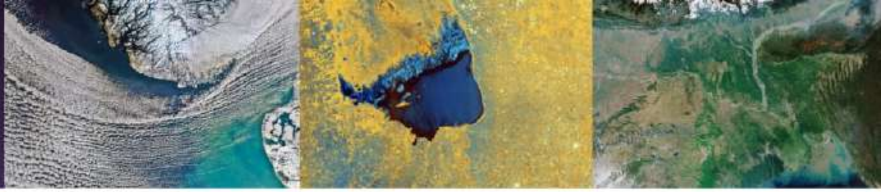
(Durrieu et al., 2019)



Airborne **Riegl LMS-Q780**

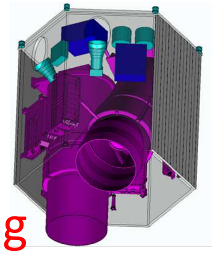


DART: Measurements ⇒ optical properties
TLS ⇒ 3D architecture



LiDAR

Design next generation instrument ⇒ HR global topography. Project STV (NASA)

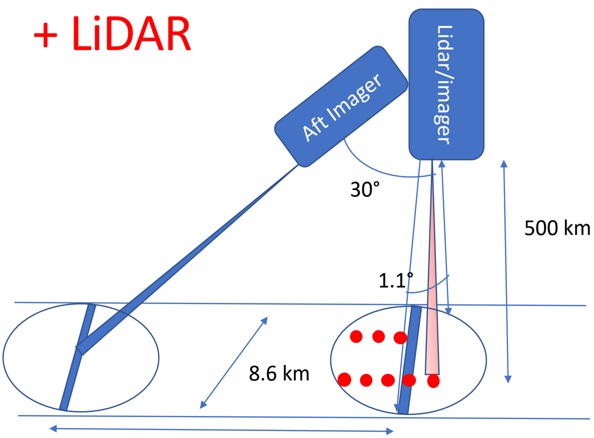


DART gives images and (x, y, z) coordinates of scene elements

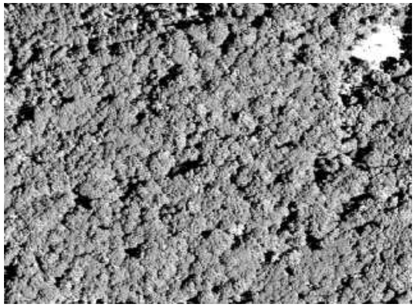
⇒ NASA uses DART to define the optimal satellite configuration

Stereo imaging

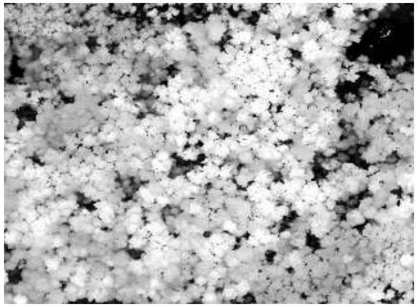
+ LiDAR



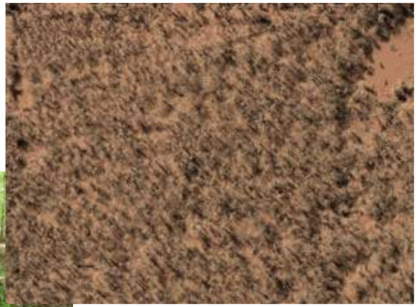
DART: 400x400m SERC forest



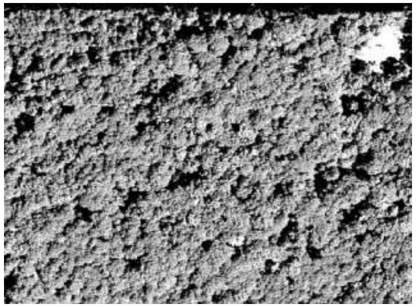
DART: nadir (15/06/2012, 9am)



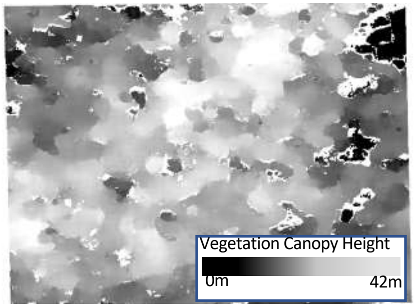
NASA G-LiHT Lidar Reference



DART: scene-leaf off

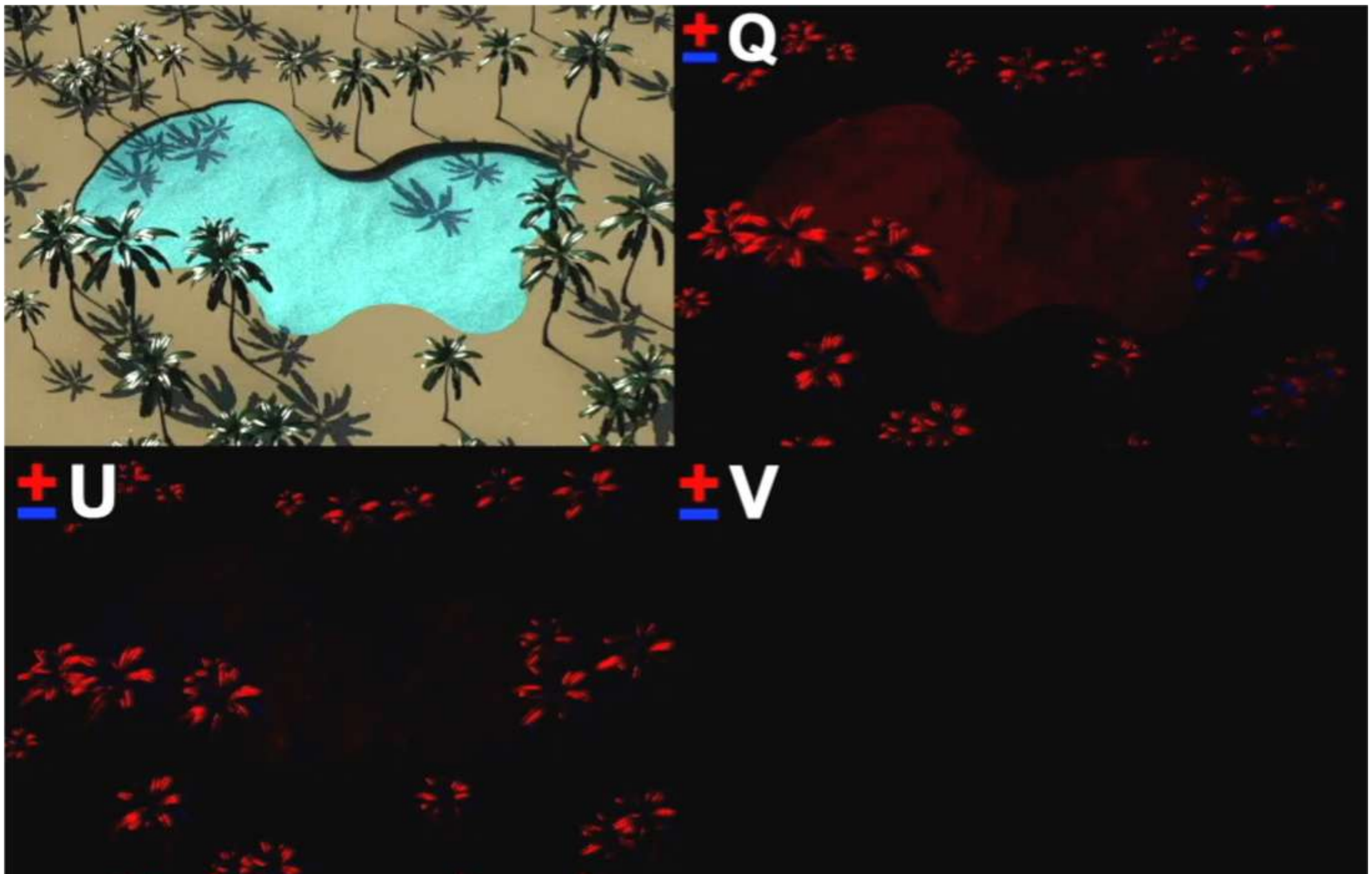


DART -20° (15/06/2012, 9am)



Canopy height from DART stereo pair

Polarization



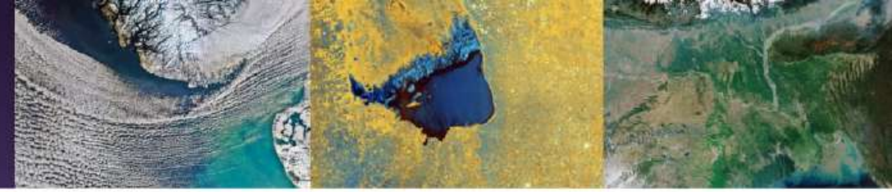
Specular reflection & Polarization

Stokes vector: [I, Q, U, V]

Future polarimetric satellite missions:

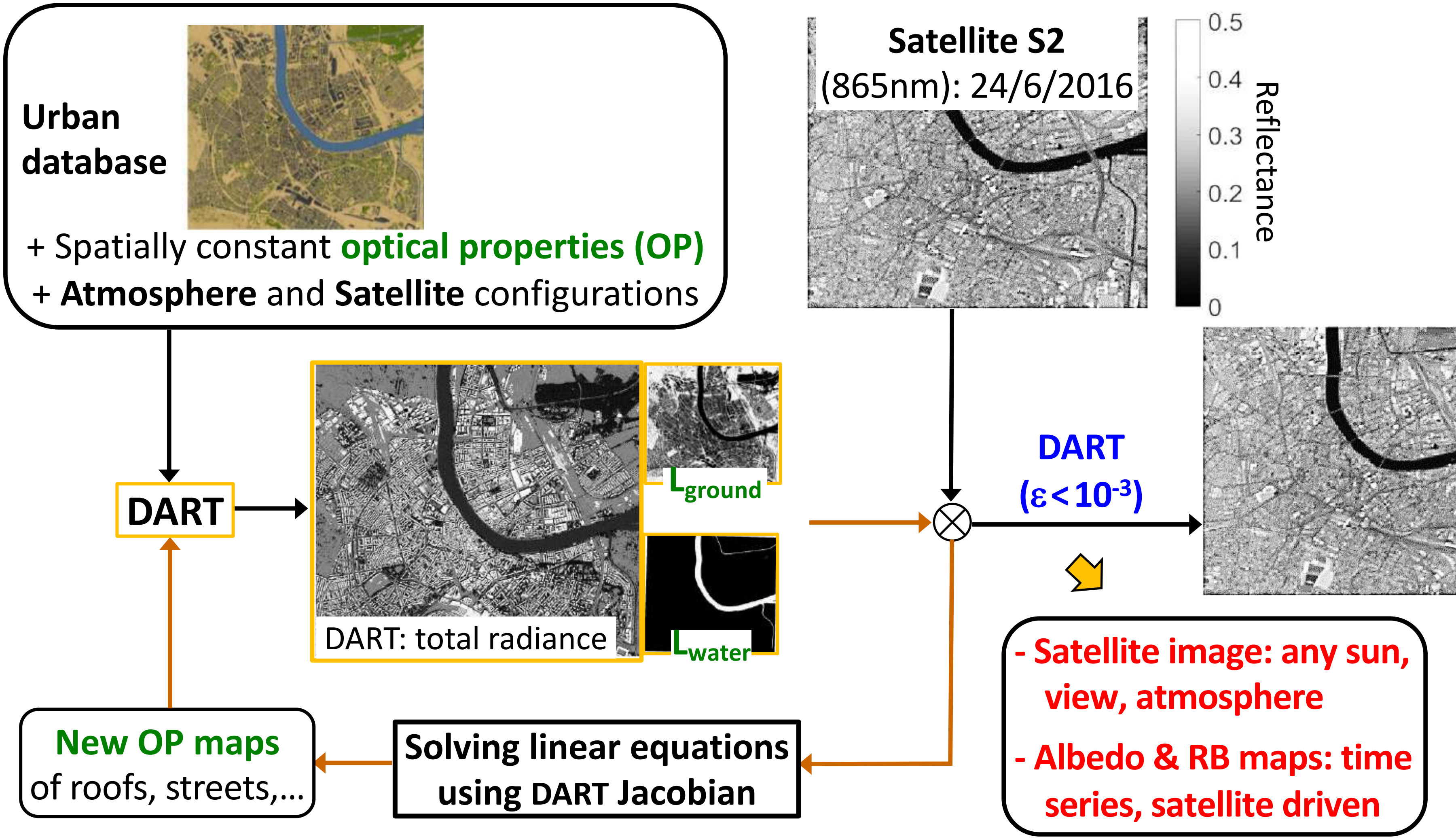
METOP-SG-A (ESA)
OTB-2 (NASA)

(Wang Yingjie, 2022)



Inversion

(Zhen et al., 2021)



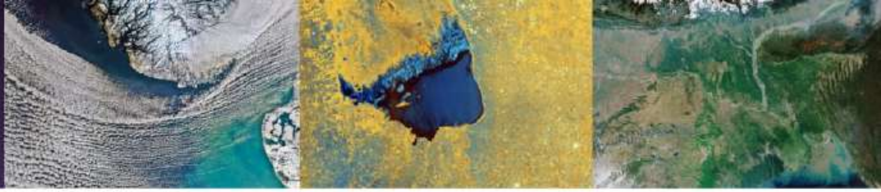
Inversion

(Zhen et al., 2021)

Sentinel 2 (B2, B3, B4)

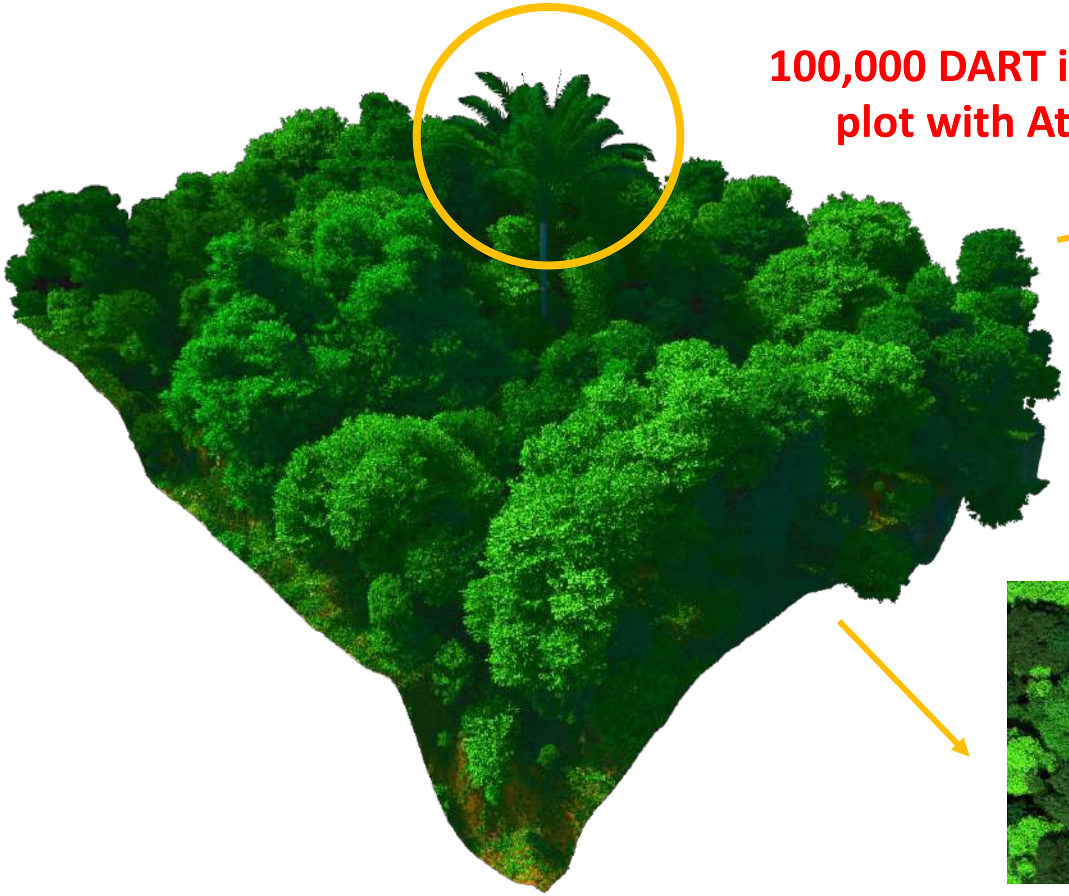
5 km

DART simulation with OP maps

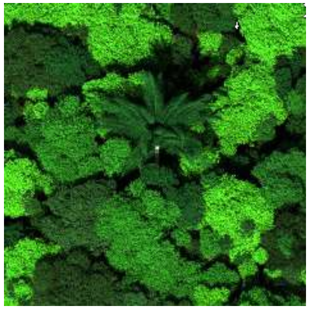


Deep learning

Training an **AI algorithm** to detect palm trees in high resolution satellite images. Project DIAPOS (CNES)

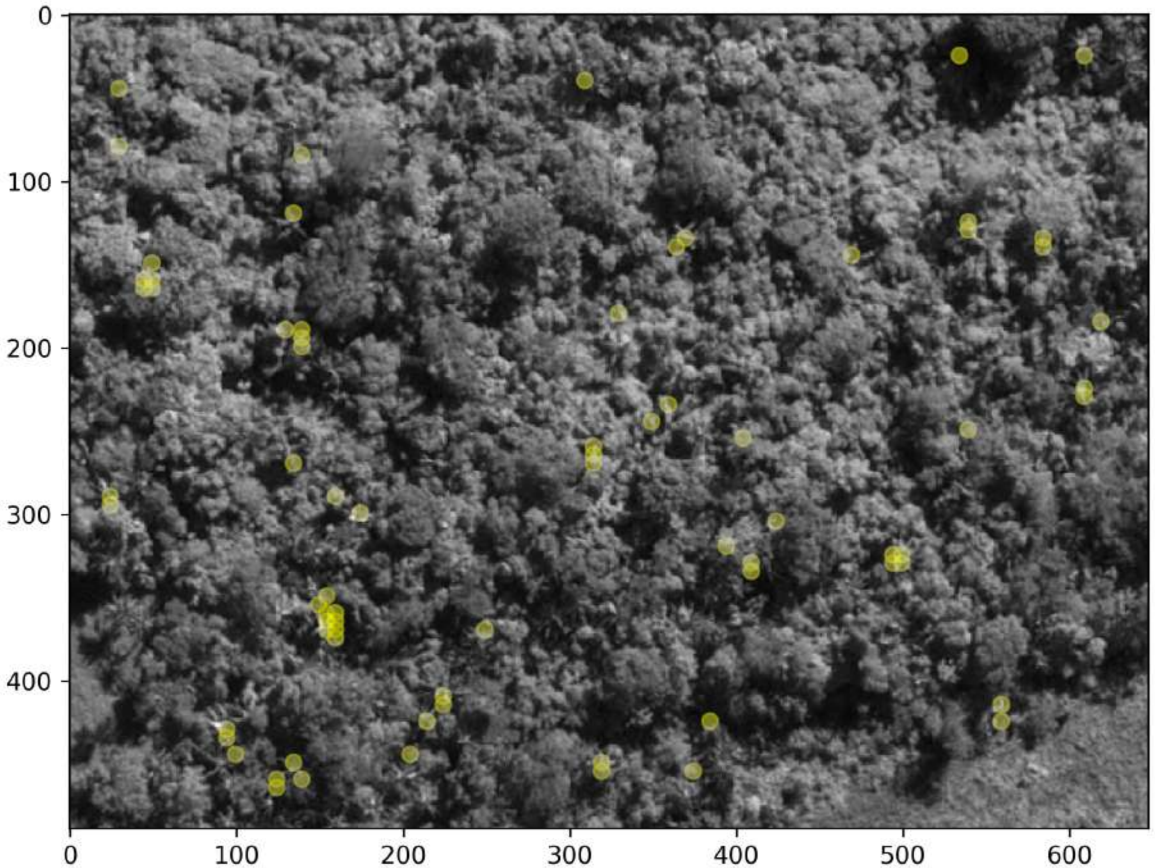


100,000 DART image of a forest plot with Attalea Maripa



Deep learning

Preliminary evaluation: Detection precision 75 %



Automatic detection of palm tree in high spatial resolution satellite image.

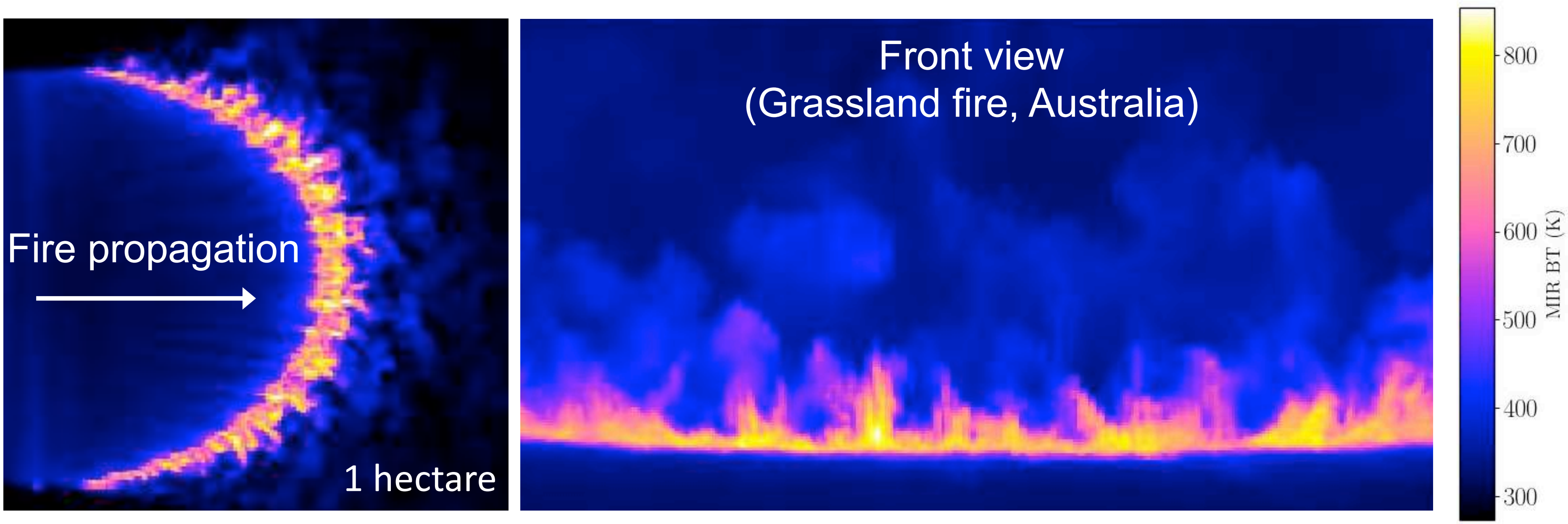
(Data from ESPACE-DEV, IRD)

Fire

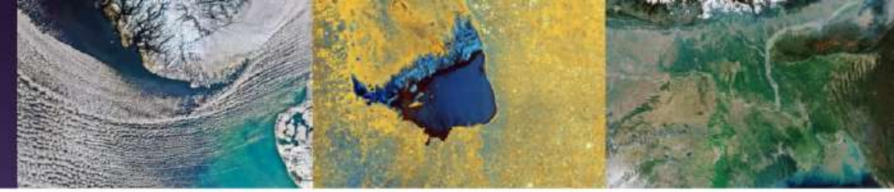
FDS (Fire Dynamics Simulator) model ⇒ 3D temperature distribution
3D soot/gas density

DART ⇒ Remote sensing observations (TIR camera, satellite)

⇒ Study the **fire radiative power** from satellite observation



DART simulation from R. Paugam (UPC), 50s after fire ignition



Urban surface temperature

SOLENE model ⇒ 3D energy balance (2 broad bands) ⇒ LST + T*air*

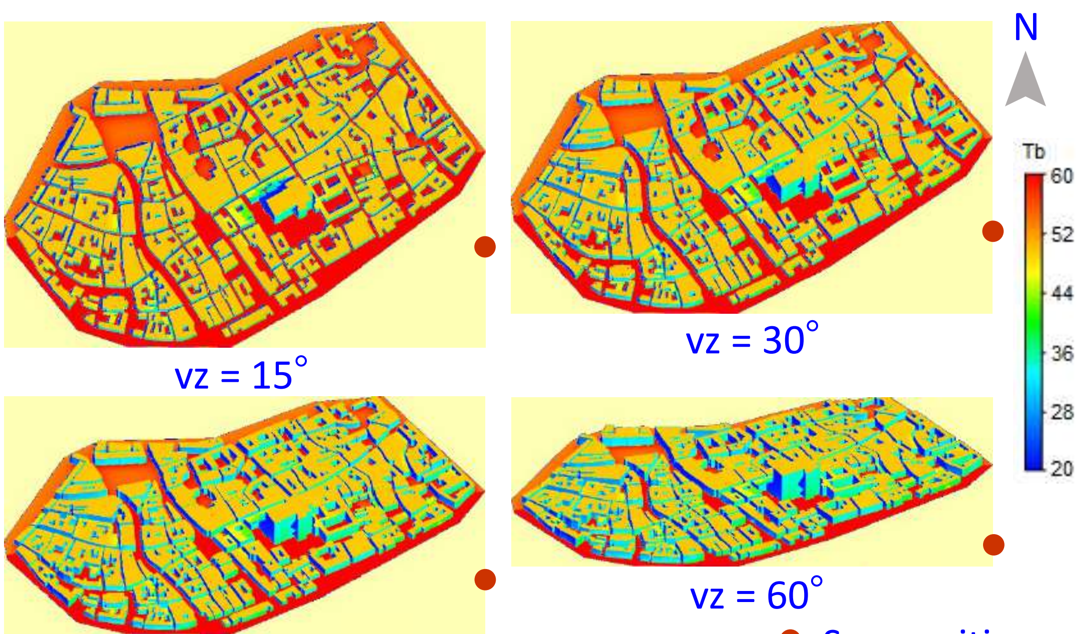
DART model ⇒ hyperspectral RTM (more accurate RB) ⇒ RS observations

Impact of urban surface heterogeneity on LST estimation from TIR satellites (**TRISHNA, LSTM**)

LST – SOLENE microclimate

Strasbourg, cathedral district, 15th June 2021, 9h UTC

Brightness temperature at 4 view zenith (vz) angles



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Conclusion

DART:

1) Efficient & accurate for simulating 3D surface observations (TIR, SIF,…) and radiative budget at various spatial and time scales

2) Adapted to a wide range of applications: inversion of satellite data, preparation of satellite mission, AI, fire, …

3) Easy to chain with process models (SOLENE, SCOPE,…)

On-going work

(1) 3D modelling of energy balance of vegetation (DART-EB) (temperature distribution ⇒ TIR obs., RB)

(2) Differentiable radiative transfer (Jacobian) (uncertainties, better inversion)

(3) Technical: georeference, NetCDF format, GPU, … (preparing satellite missions, massive simulation)

THANK YOU

DART is freely available for research and education.

Contact:

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