DART: a 3D radiative transfer model for urban studies

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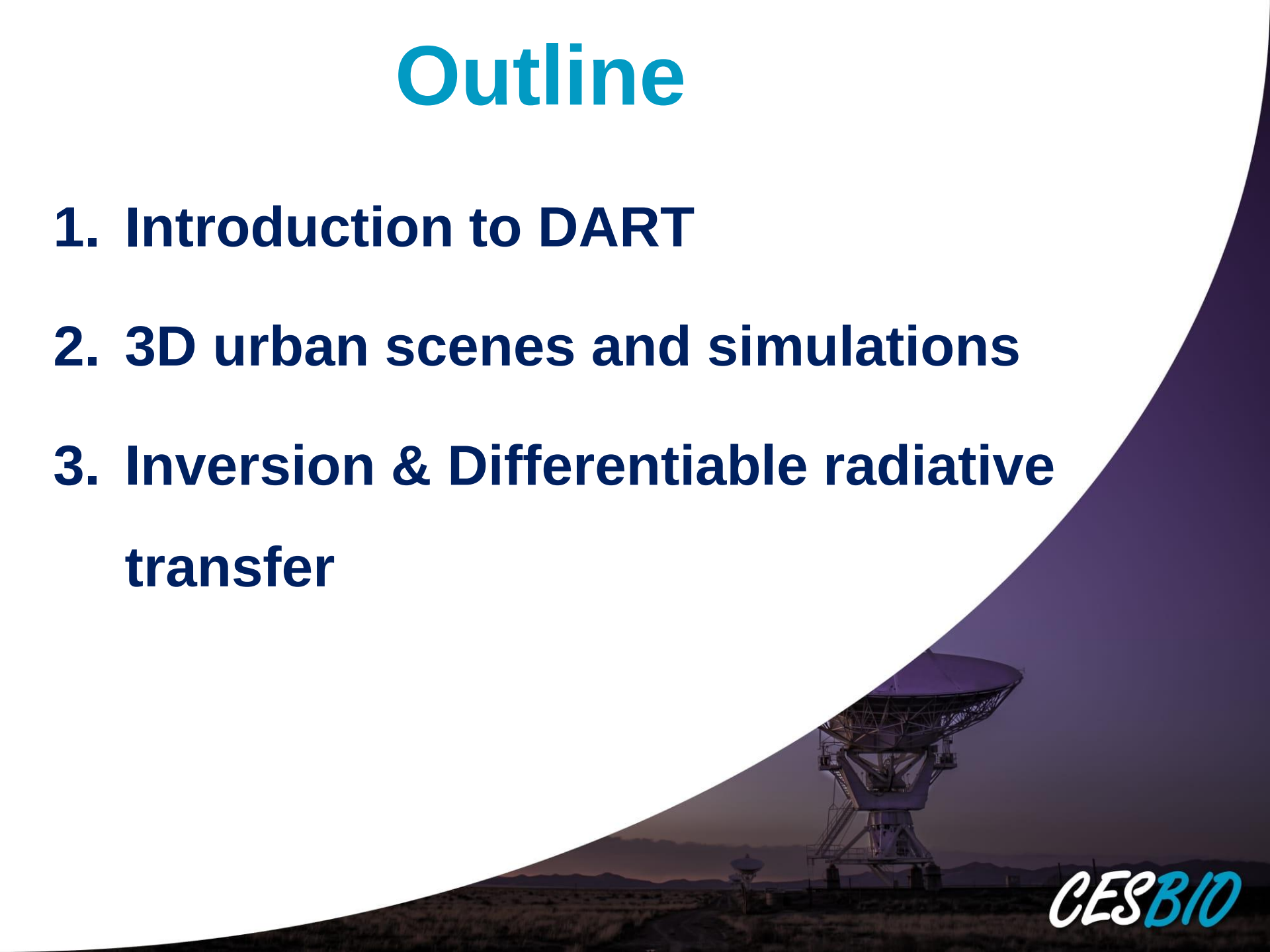
DART since 1992 Discrete Anisotropic Radiative Transfer

CESBIO

Outline

1. Introduction to DART
2. 3D urban scenes and simulations
3. Inversion & Differentiable radiative transfer



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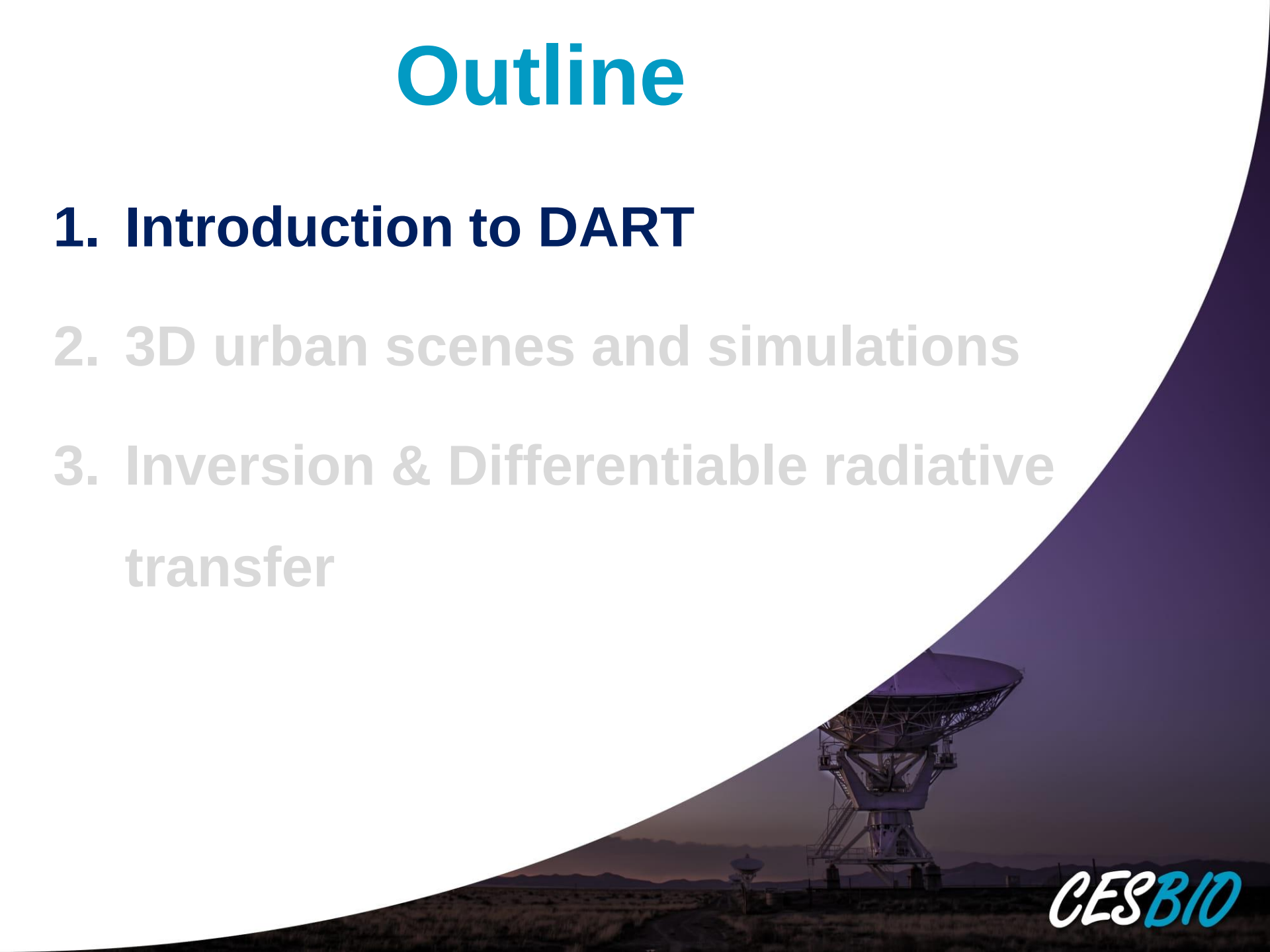
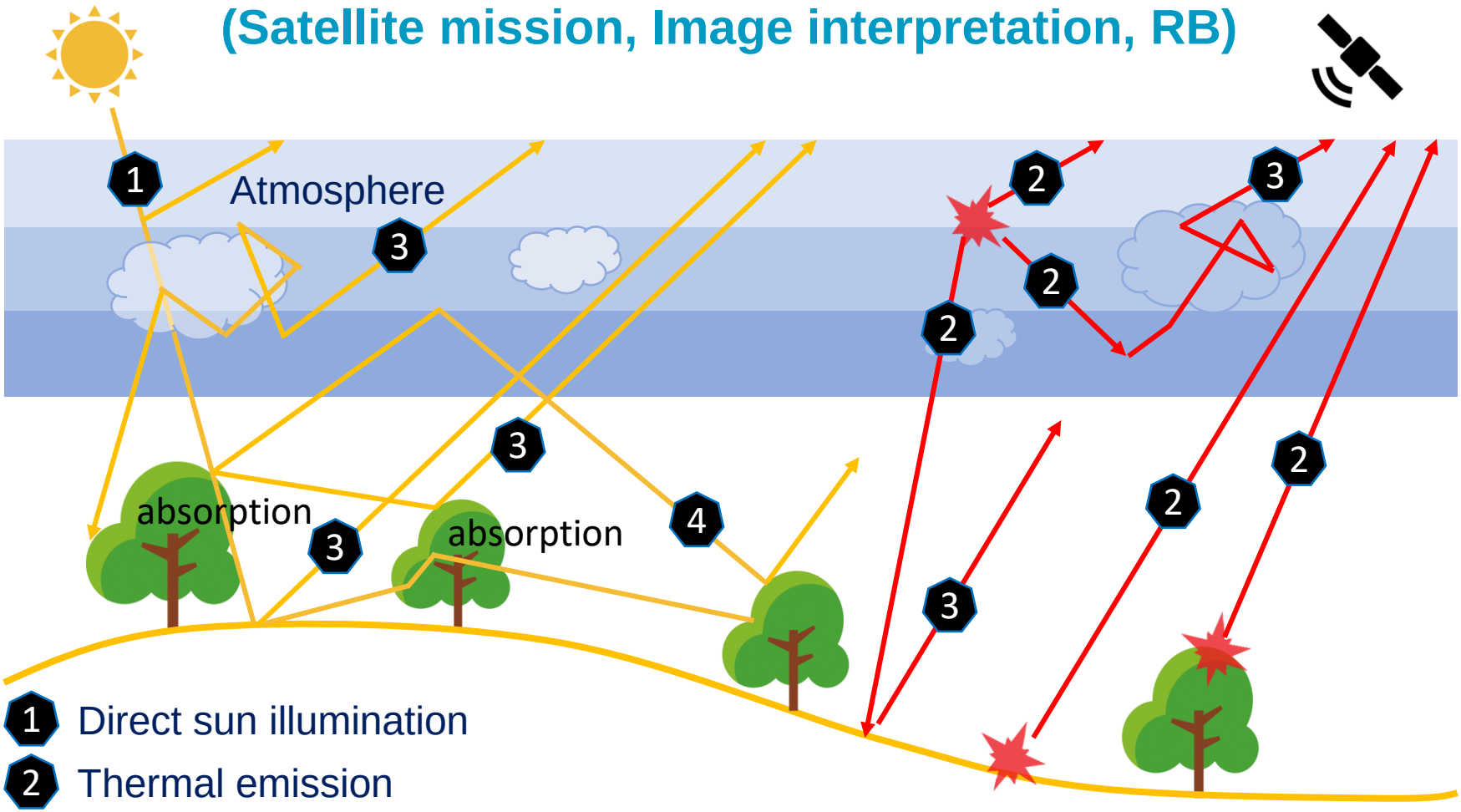


Radiative transfer modelling

(Satellite mission, Image interpretation, RB)



1 Direct sun illumination

2 Thermal emission

3 Single & multiple scattering

4 Surface-Atmosphere coupling

DART model: an overview

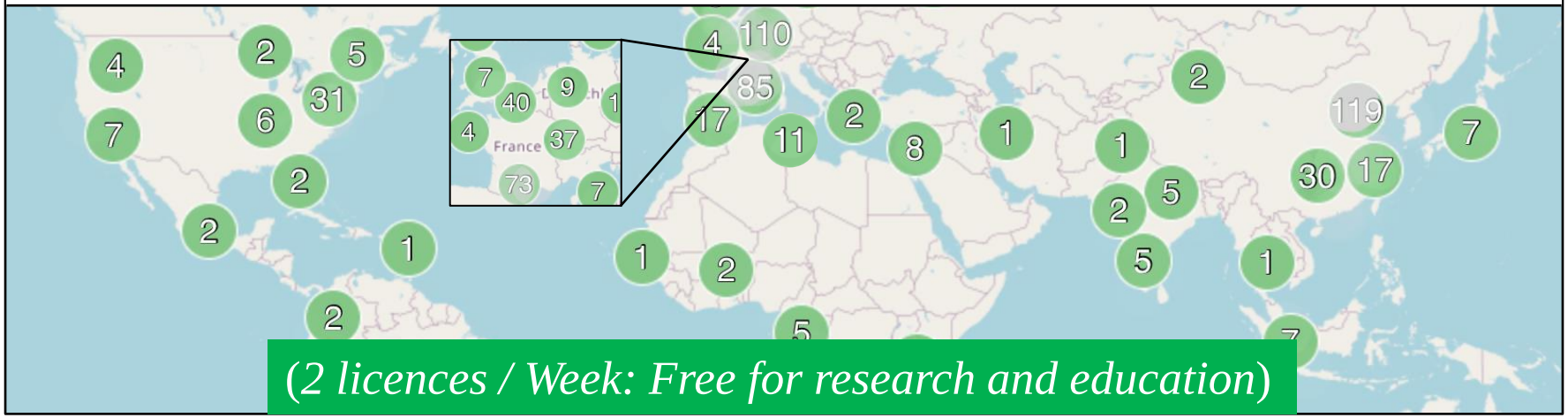
History: developed in CESBIO since 1992 by 10 scientists. Patented in 2003

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*)

Community code certification: enhence research collaboration using DART.

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



DART Discrete Anisotropic Radiative Transfer



DART Team (CESBIO)

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Scientific leader

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Science

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Space mission

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Energy balance

Computer science

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Engineer (CNRS)
Interfaces, databases, ….

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

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

Pytools4dart: https://gitlab.com/pytools4dart

Outside CESBIO:

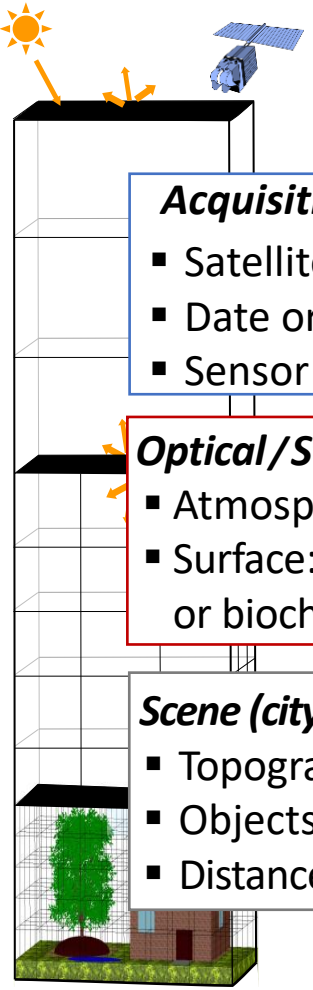
Z. Malenovsky, O. Regaieg, T. Nguyen *(Univ. Bonn, Germany): SIF, TIR, RB.*

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

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

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

DART model: 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,...

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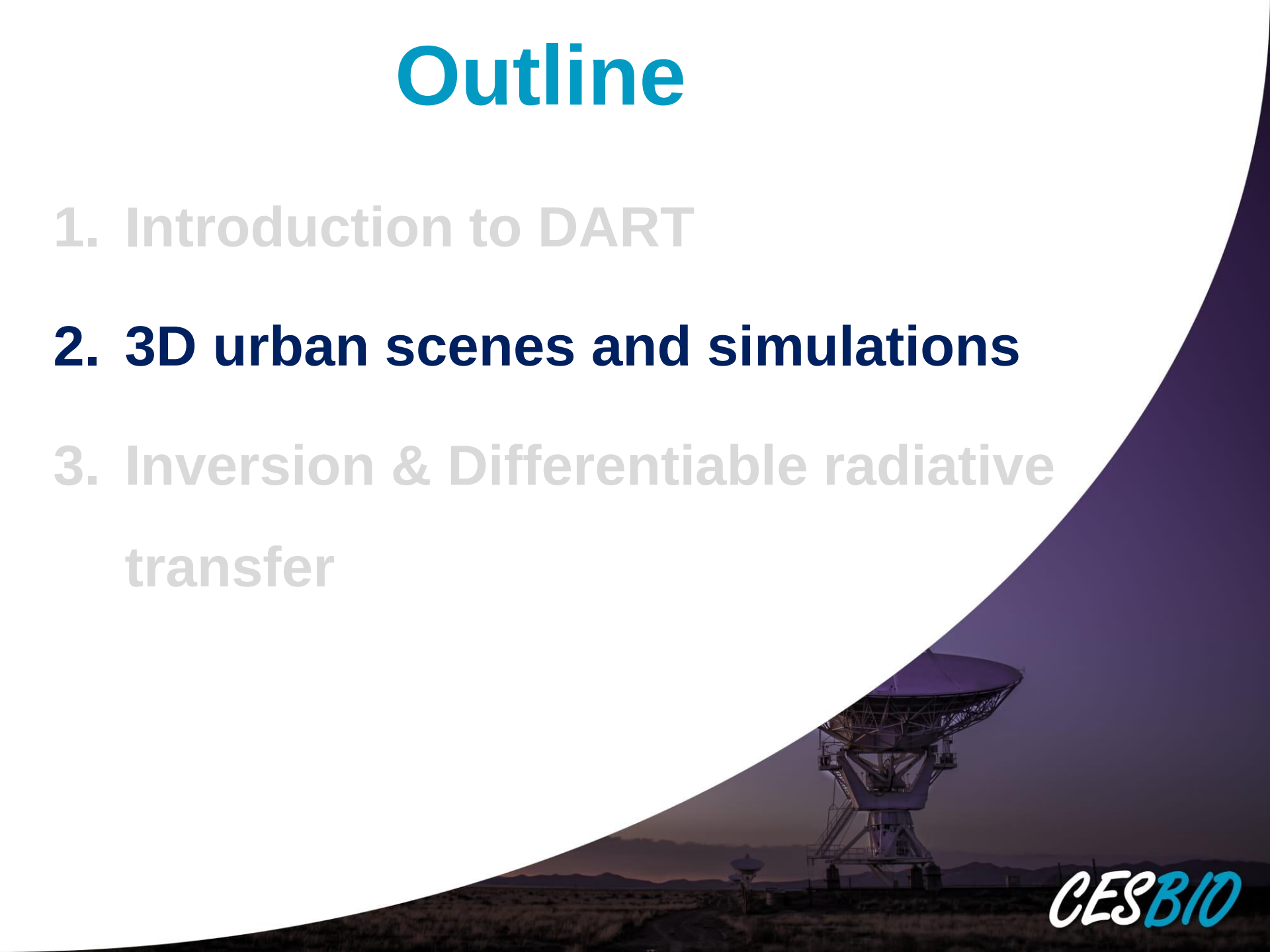


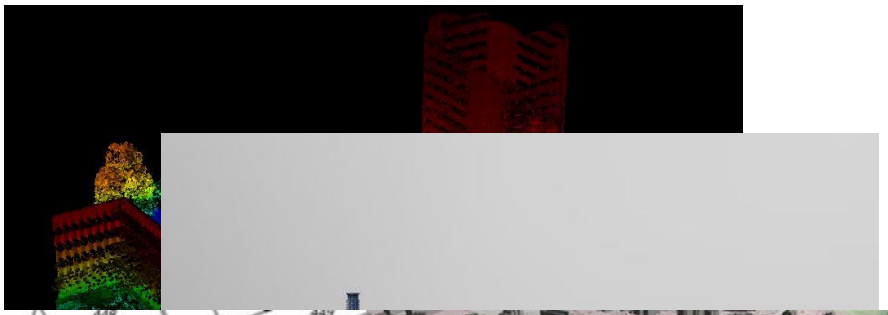
3D city representation

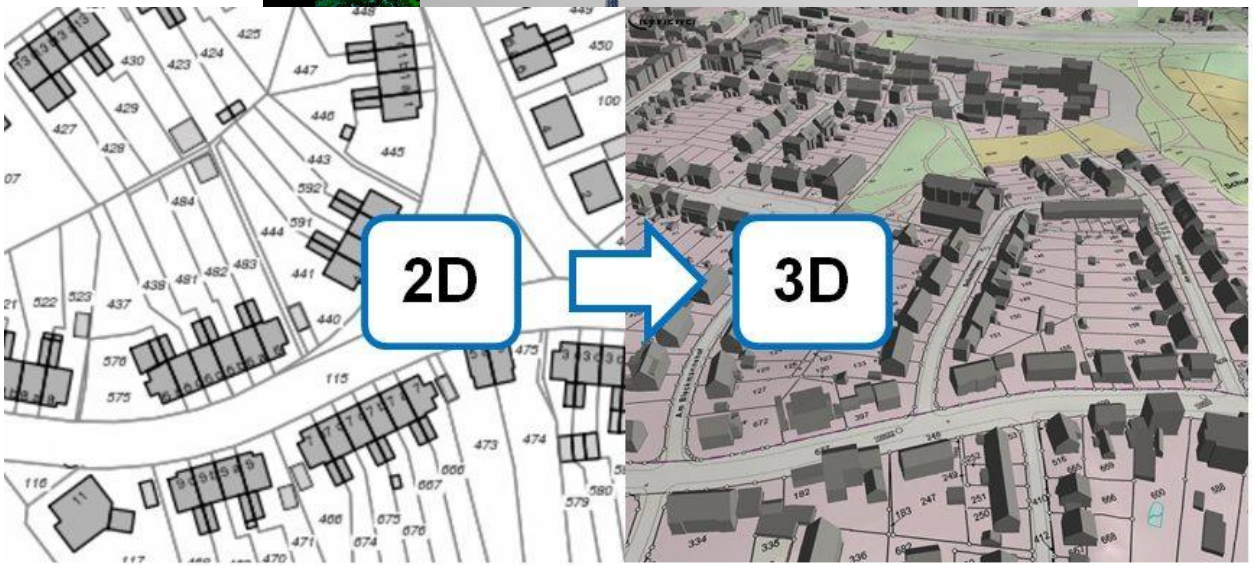
Common techniques for 3D city construction:

(1) LiDAR point clouds

(2) Photogrammetry

(3) Cadastre

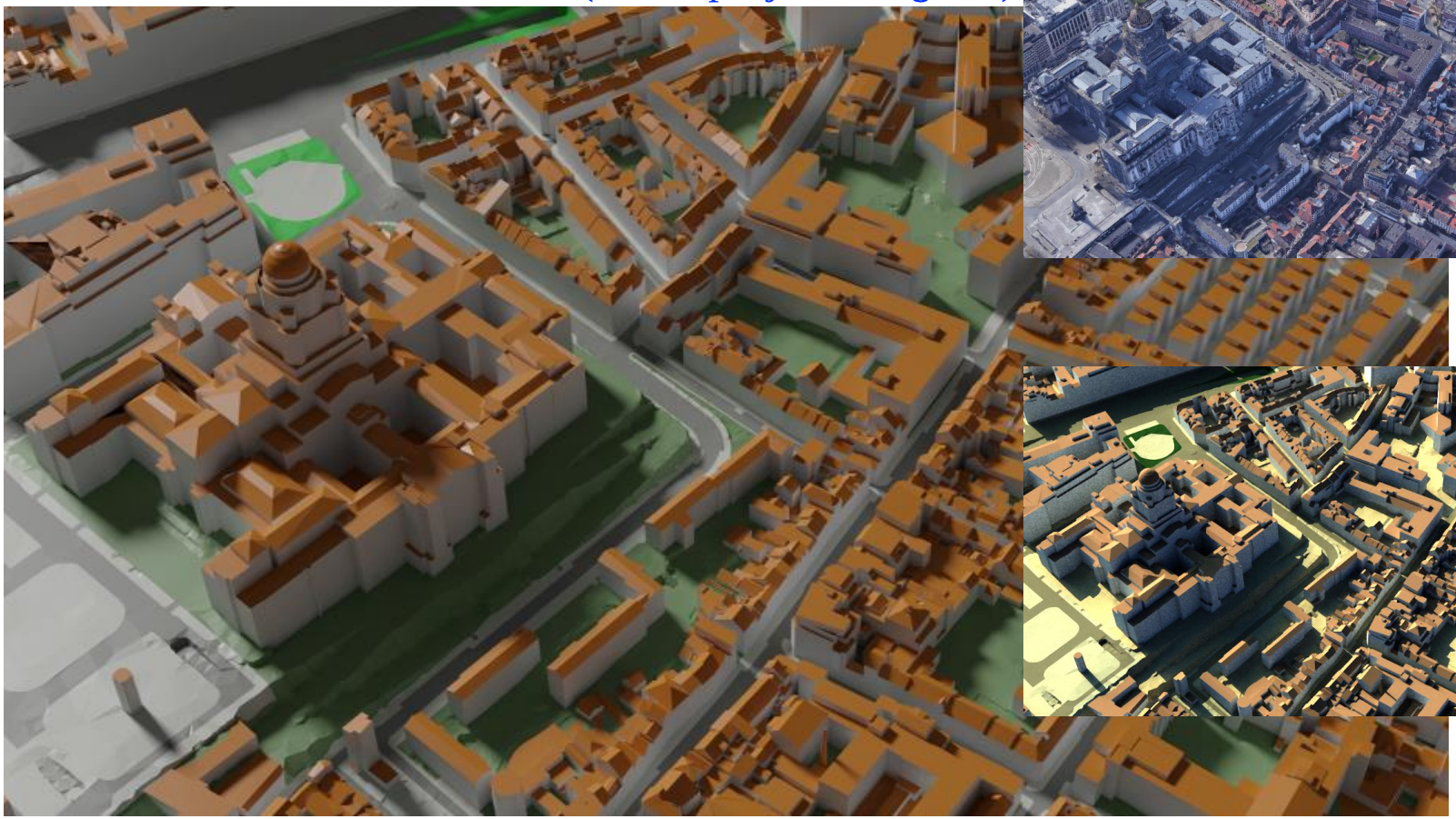




3D city representation

Brussels city 3D mock-up (17 x 17 km).
(Suabe project, Belgium)

Google Map



DART simu

3D city representation

Basel city 3D mock-up (10 x 11 km).

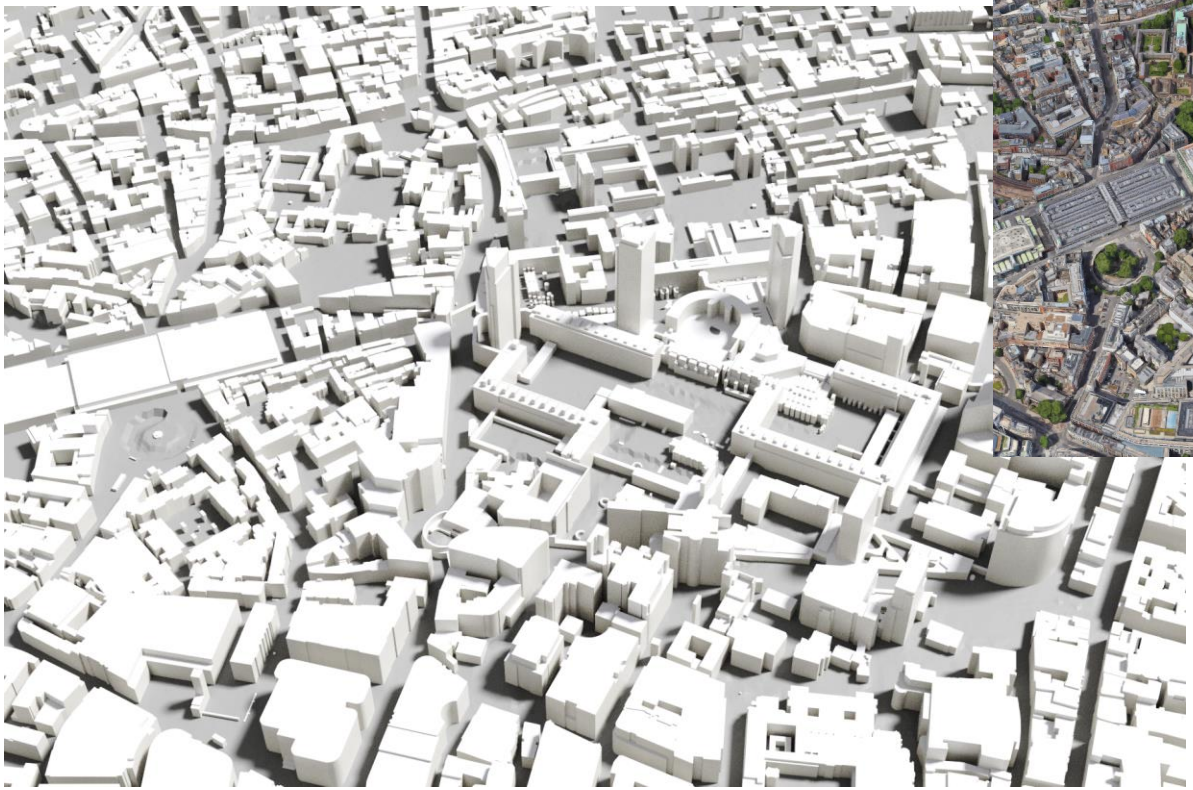
(UrbanFluxes, Horizon2020, EU)

Google Map

3D city representation

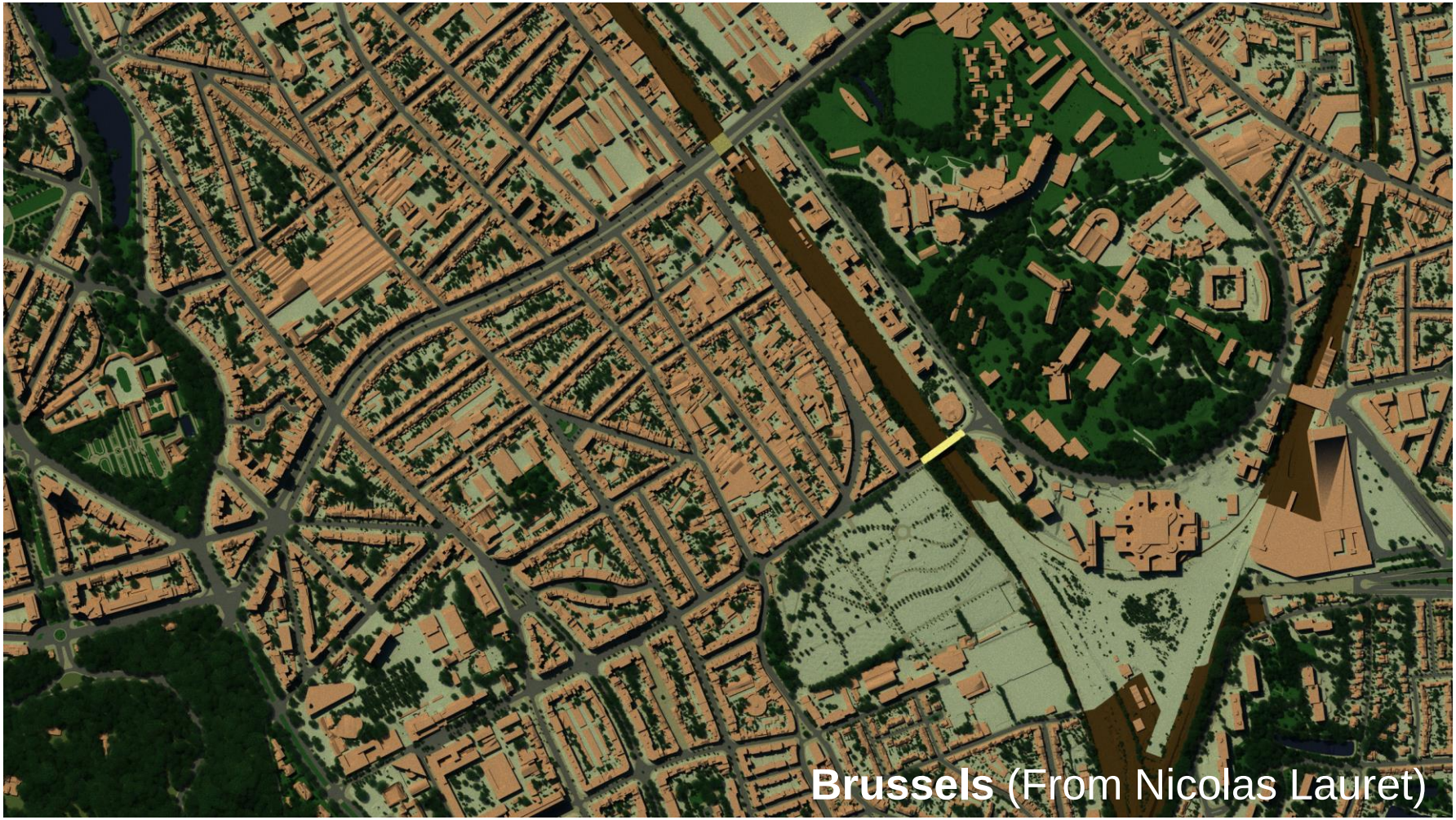
London city 3D mock-up (5 x 4 km).

(UrbanFluxes, Horizon2020, EU)



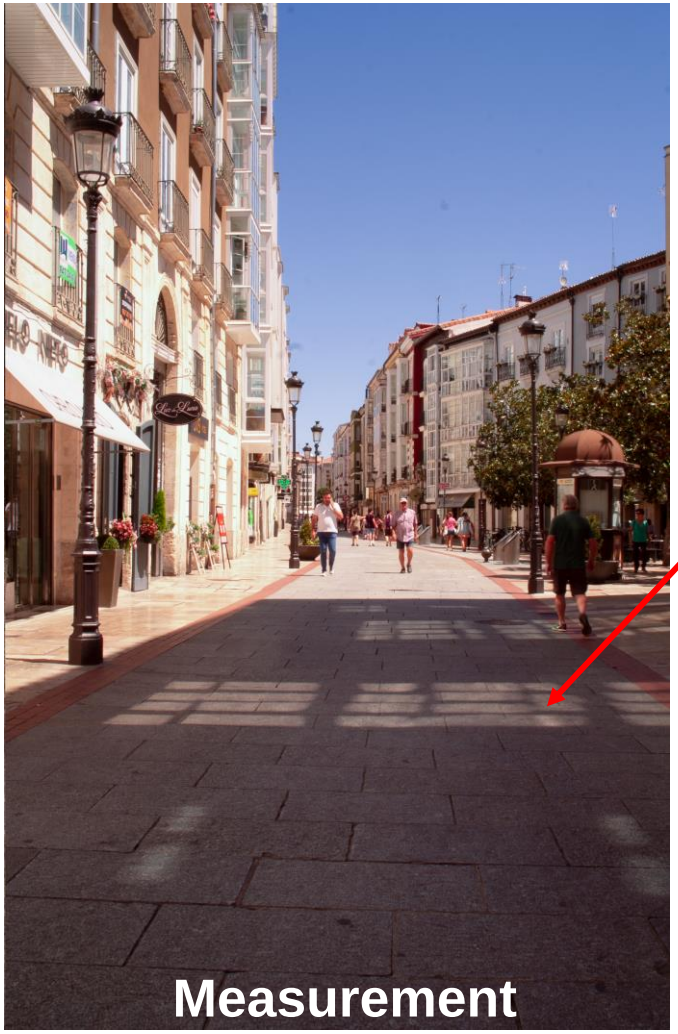
Google Map

DART urban simulations



Brussels (From Nicolas Lauret)

DART urban simulations



Reflection from windows

Work from **Diego Granados Lopez**
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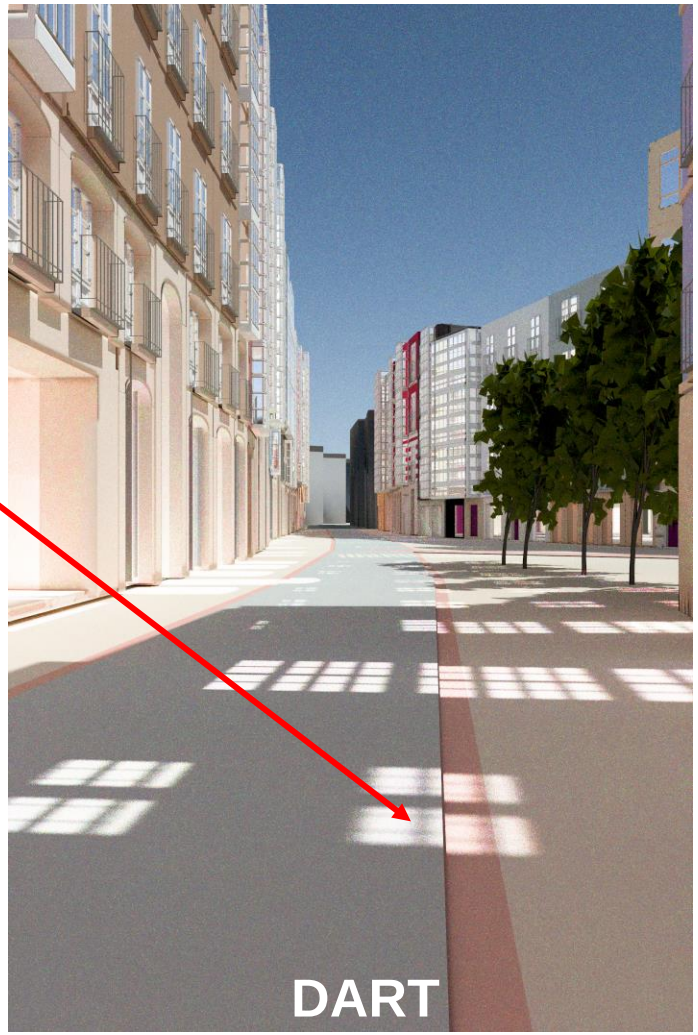
UNIVERSIDAD DE BURGOS



DART urban simulations

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

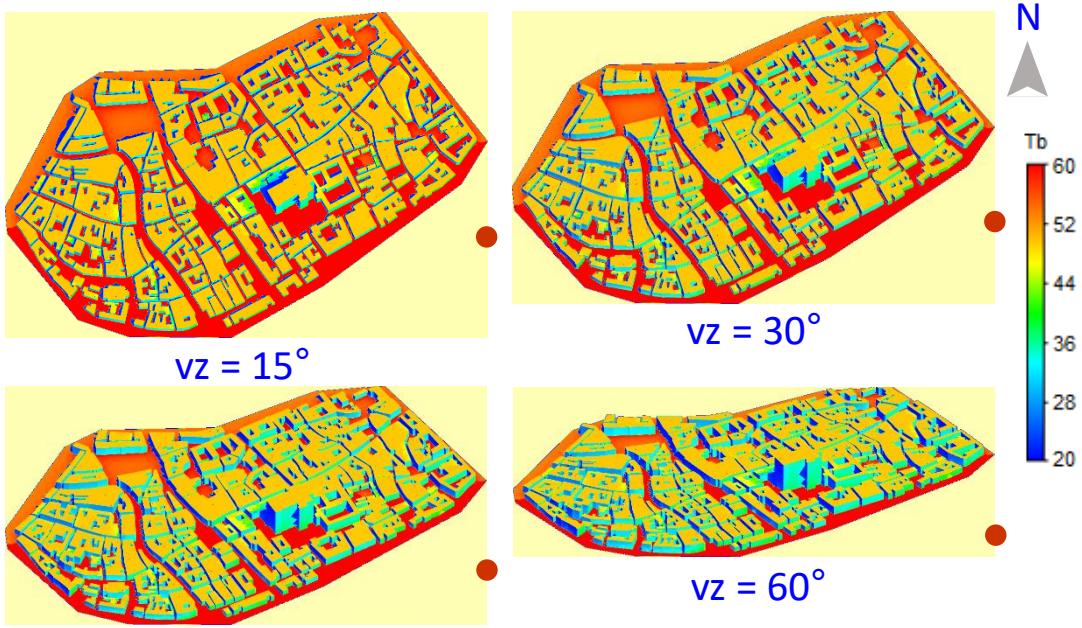
DART model ⇒ hyperspectral RTM (more accurate RB) ⇒ RS observations

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

LST – SOLENE microclimate

Strasbourg, cathedral district,

Brightness temperature at 4 view zenith (vz) angles



ONERA THE FRENCH AEROSPACE LAB

Cerema CLIMAT & TERRITOIRES DE DEMAIN

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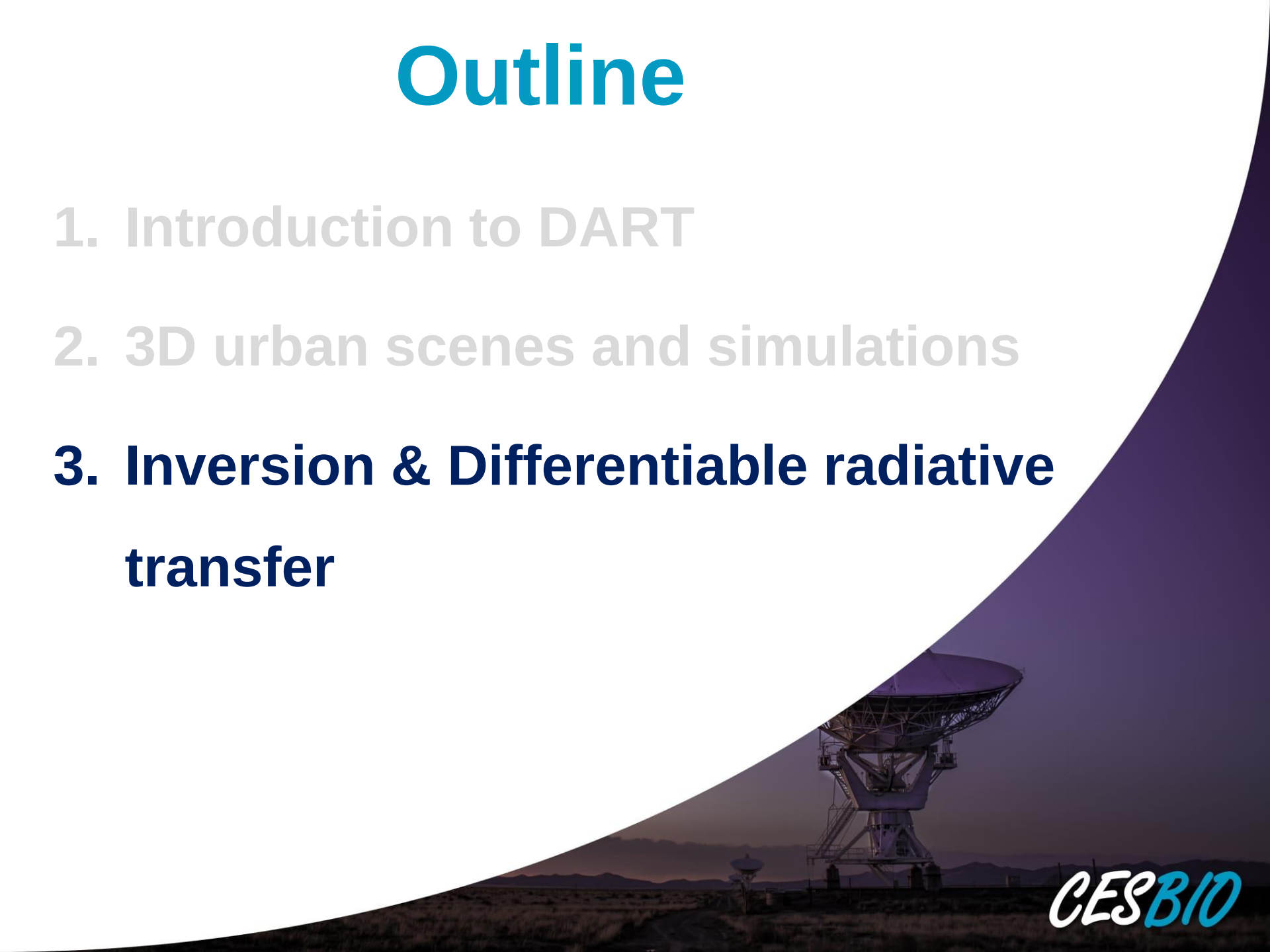


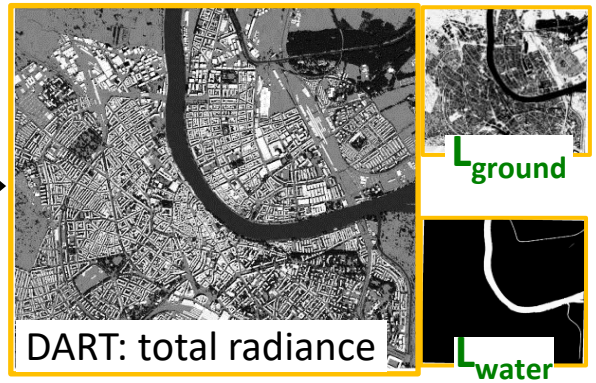
Inversion

(Zhen et al., 2021)

Urban database

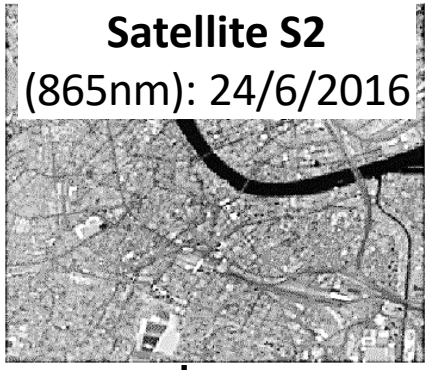
+ Spatially constant **optical properties (OP)**
+ **Atmosphere** and **Satellite** configurations

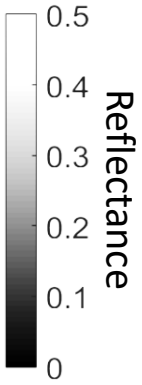
DART



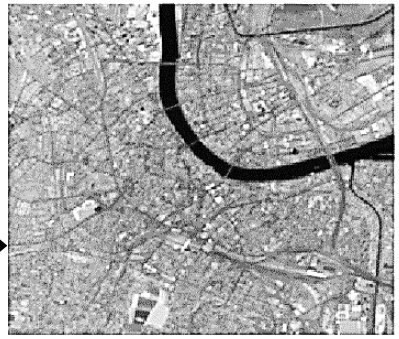
New OP maps of roofs, streets,...

Solving linear equations using DART Jacobian





DART ($\varepsilon < 10^{-3}$)



- **Satellite image: any sun, view, atmosphere**
- **Albedo & RB maps: time series, satellite driven**

Inversion

(*Zhen et al., 2021*)

5 km

Sentinel 2 (B2, B3, B4)

DART simulation with OP maps

Jacobian matrix

What is Jacobian matrix ?

The derivatives of measurements F to a series of parameters $\hat{\pi} = [\pi_1, \pi_2, \dots, \pi_k, \dots, \pi_N]$.

$$J = \left[\frac{\partial F}{\partial \pi_1}, \frac{\partial F}{\partial \pi_2}, \dots, \frac{\partial F}{\partial \pi_k}, \dots, \frac{\partial F}{\partial \pi_N}\right]$$

Jacobian matrix quantifies the change of RS signal due to the change of parameters:

(a) Retrieve parameters $\hat{\boldsymbol{\pi}}$ from RS obervation $\boldsymbol{F}$

(b) Estimate uncertainties of remote sensing products $\boldsymbol{u(\hat{\pi})}$ from $\boldsymbol{u(F)}$

(c) Estimate uncertainties of radiative transfer modelling $\boldsymbol{u(F)}$ from $\boldsymbol{u(\hat{\pi})}$

(d) …

DART since 1992

Finite difference method

FD method: straightforward Jacobian matrix computation.

$$\frac{\partial F(\hat{\pi})}{\partial \pi_k} = \frac{F(\pi_1, \dots, \pi_k + h\pi_k, \dots, \pi_N) - F(\pi_1, \dots, \pi_k - h\pi_k, \dots, \pi_N)}{2h\pi_k}$$

$F(\hat{\pi}) \Longrightarrow$ Radiative transfer modelling

Advantages: Acceptable accuracy + Easy to chain with RT code (Current implementation in DART)

Disadvantages:

(1) Efficiency: N derivatives $\Longrightarrow$ 2N simulations.

(2) Accuracy: Non-linearity between $\hat{\pi}$ and $F(\hat{\pi})$.

Large *h* $\Rightarrow$ baised derivative (error of approximation)

Small *h* $\Rightarrow$ baised derivative (error of RT modelling)

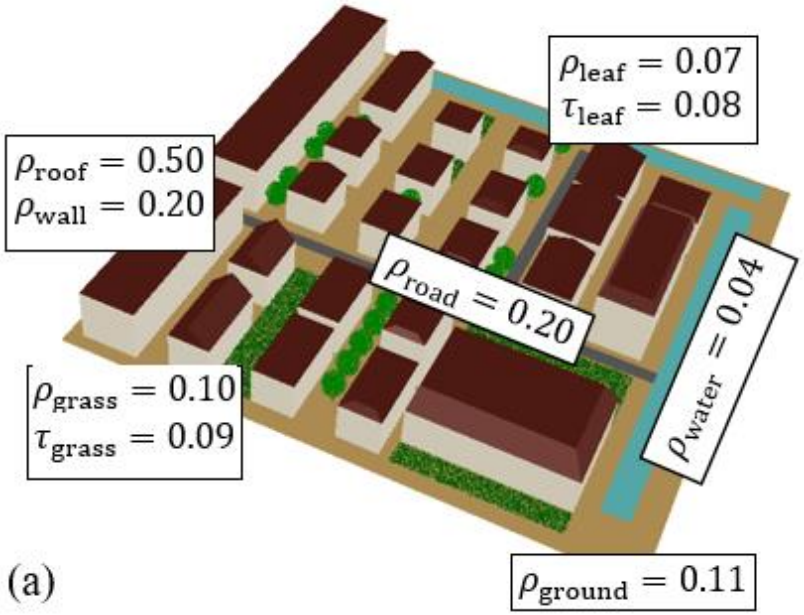
$\twoheadrightarrow$ **Forward modelling of Jacobian Matrix**

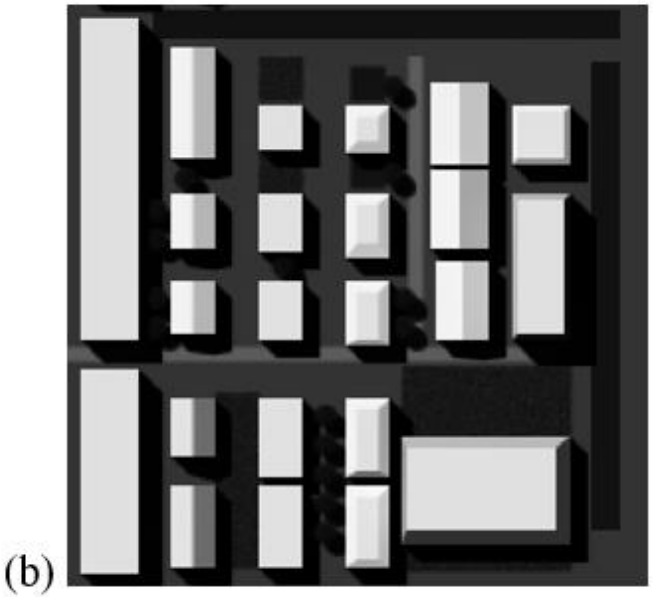
DART since 1992

Differentiable radiative transfer

Differentiable radiative transfer modelling with DART

⇒ DART scene consists of 7 elements (roof, wall, roads, tree, grass, ground, water)

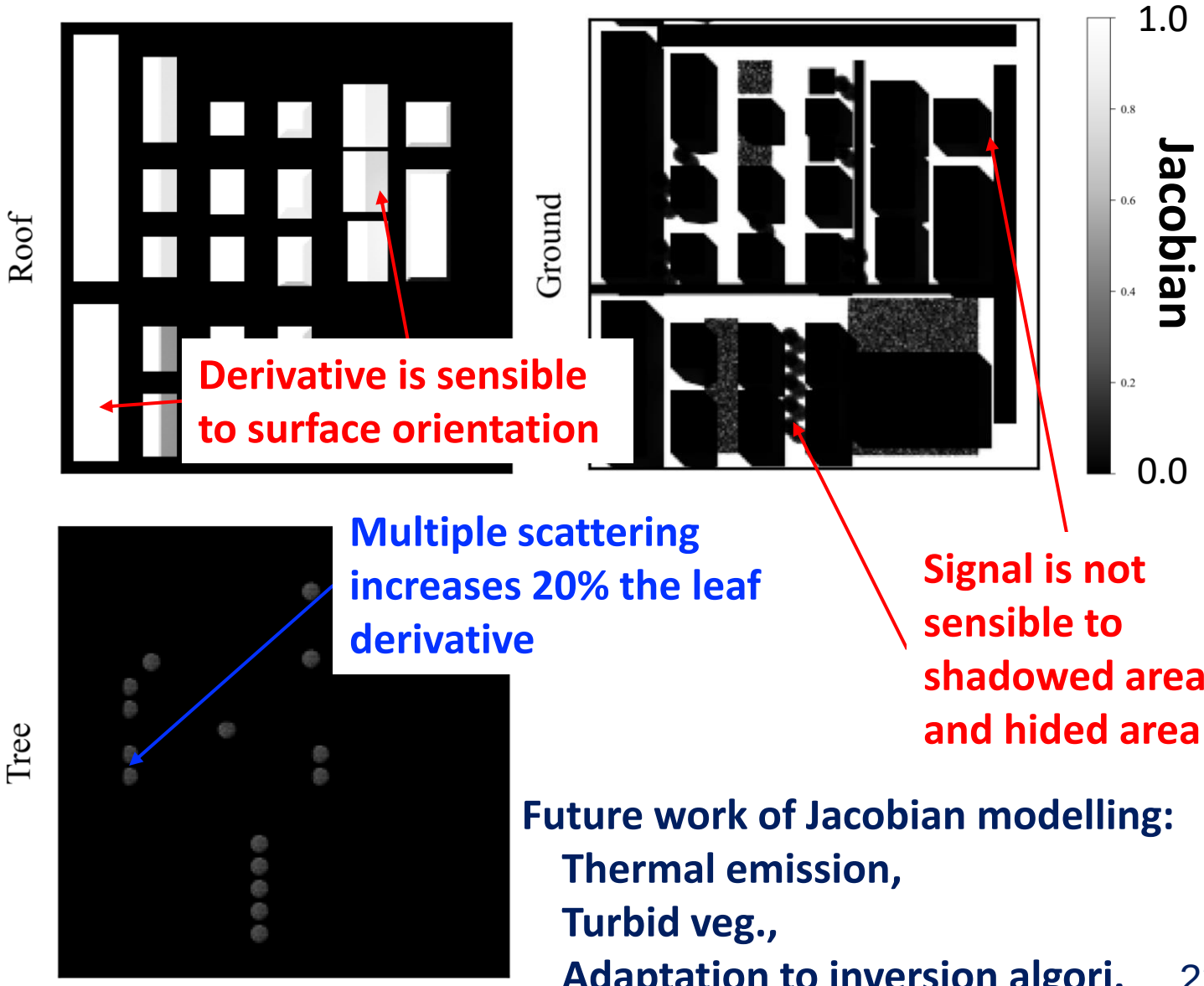




DART Scene **Nadir image**

DART since 1992

Differentiable radiative transfer



Future work of Jacobian modelling:

- Thermal emission,
- Turbid veg.,
- Adaptation to inversion algori.

DART since 1992