Radiative transfer model (VIS – TIR) for natural and urban surfaces

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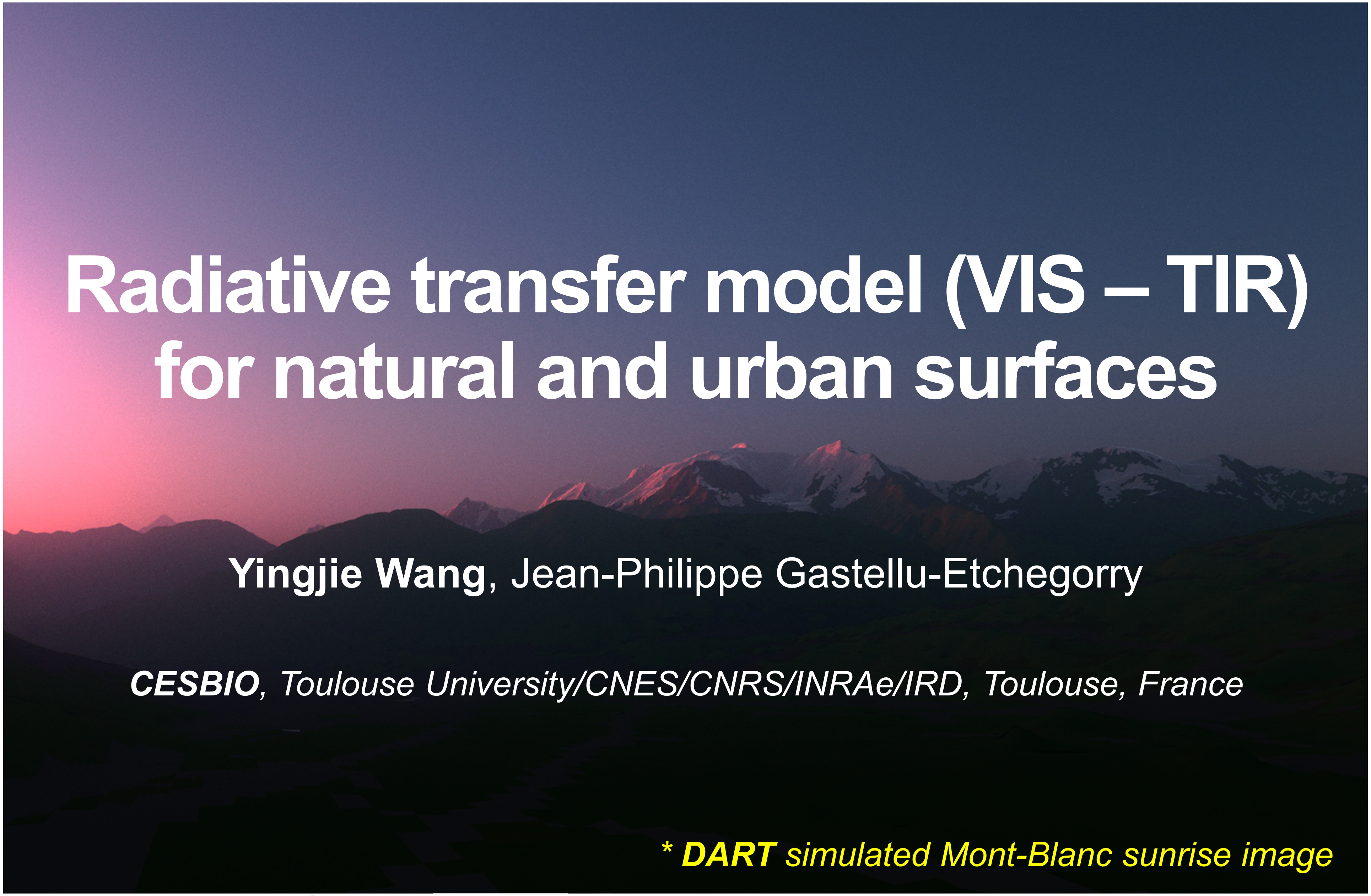

** **DART** simulated Mont-Blanc sunrise image*

Outline

1. Introduction
2. Physical principles
3. Surface 3D RTMs
4. Applications
5. Perspectives

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3. Surface 3D RTMs
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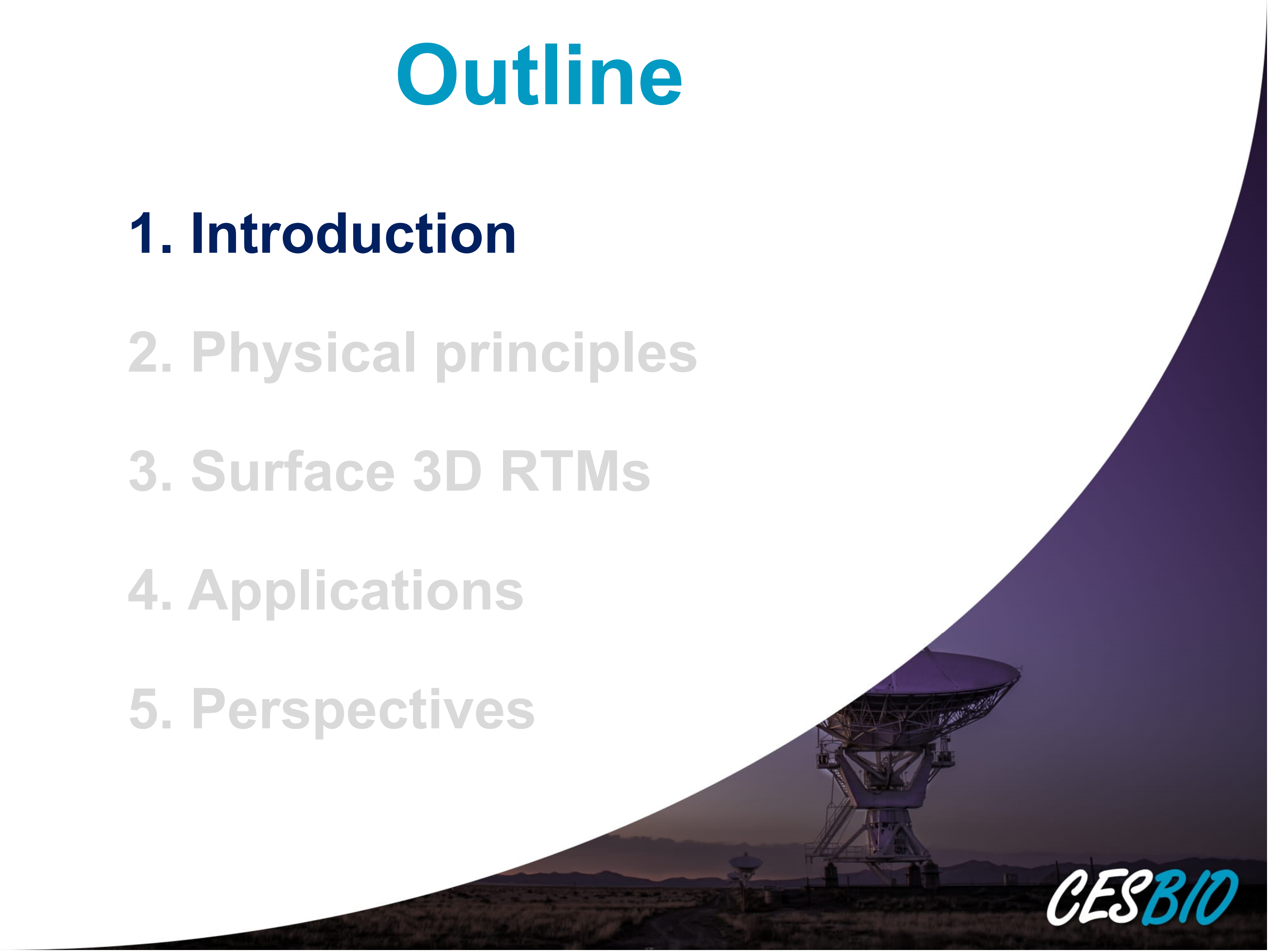
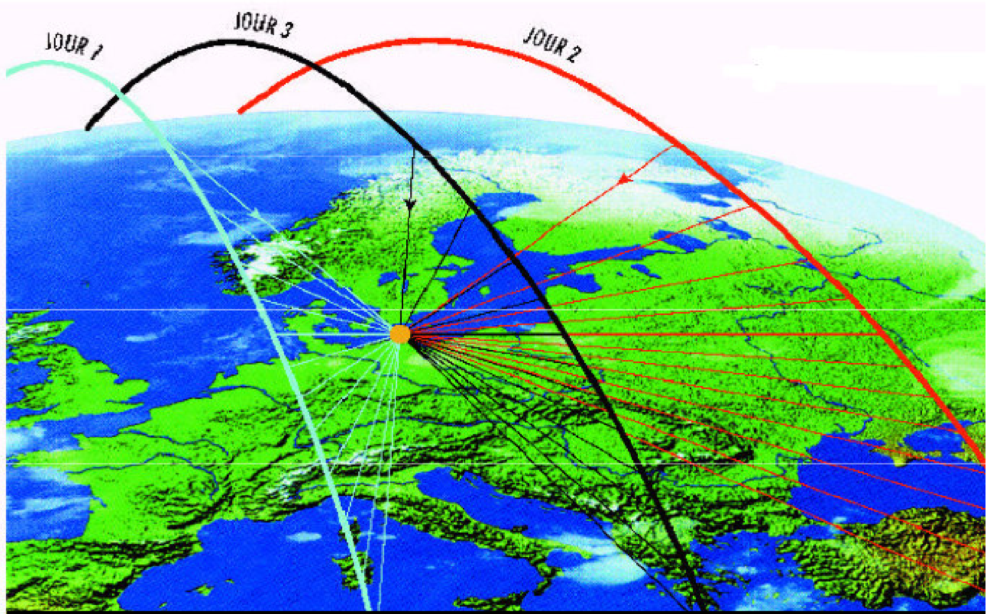


Remote Sensing & Challenges

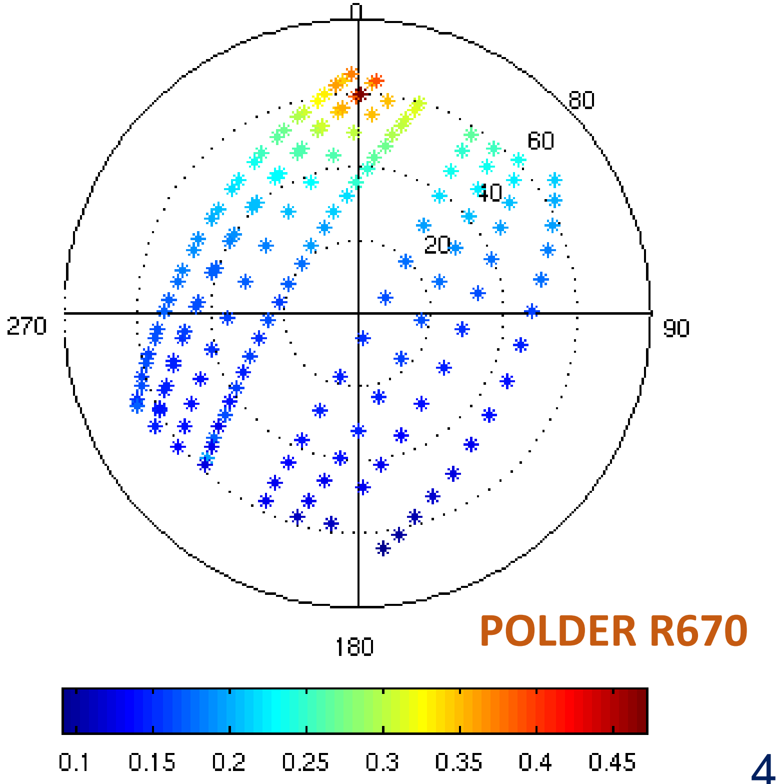
Directional effect: Observed reflectance ρ_{BOA} changes with Ω_s, Ω_v



POLDER (Polarization and Directionality of Earth Reflectances) - **114° FOV, nadir resolution 6km**

(*E. Vermote, C. Justice and Breon, NASA supported Land LTDR Project*)

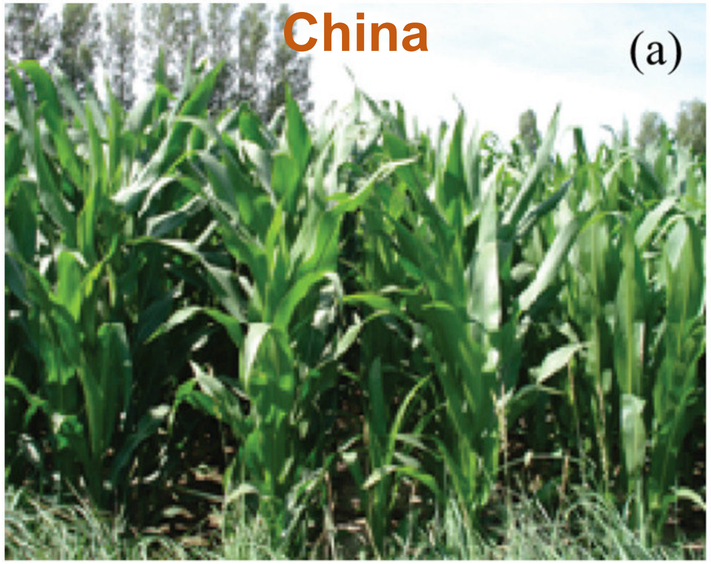
incident direction Ω_s: local time
view direction Ω_v: sensor position



Remote Sensing & Challenges

Directional effect: Observed thermal radiance BT_{BOA} changes with Ω_s, Ω_v

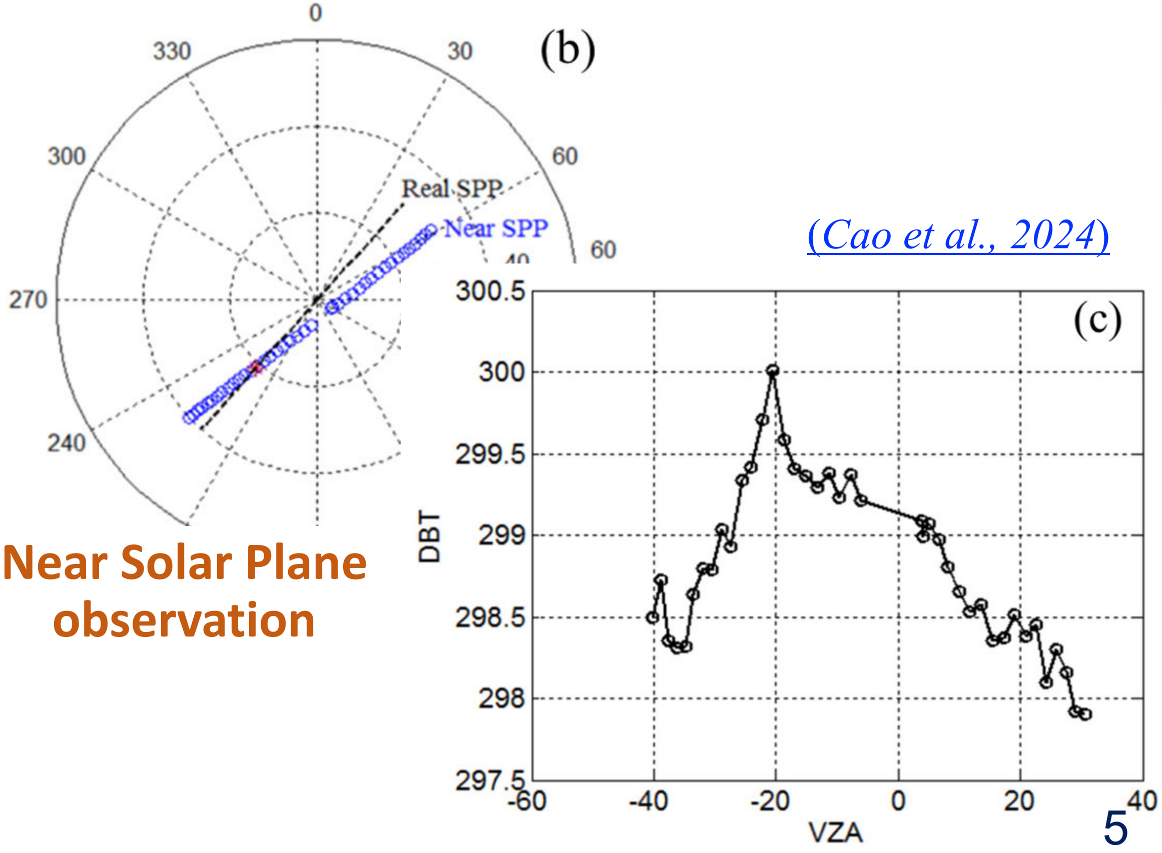
Zhangye city, Gansu, China



Airborne TIR camera

40° wide FOV

Spectral domain 8-11 μm

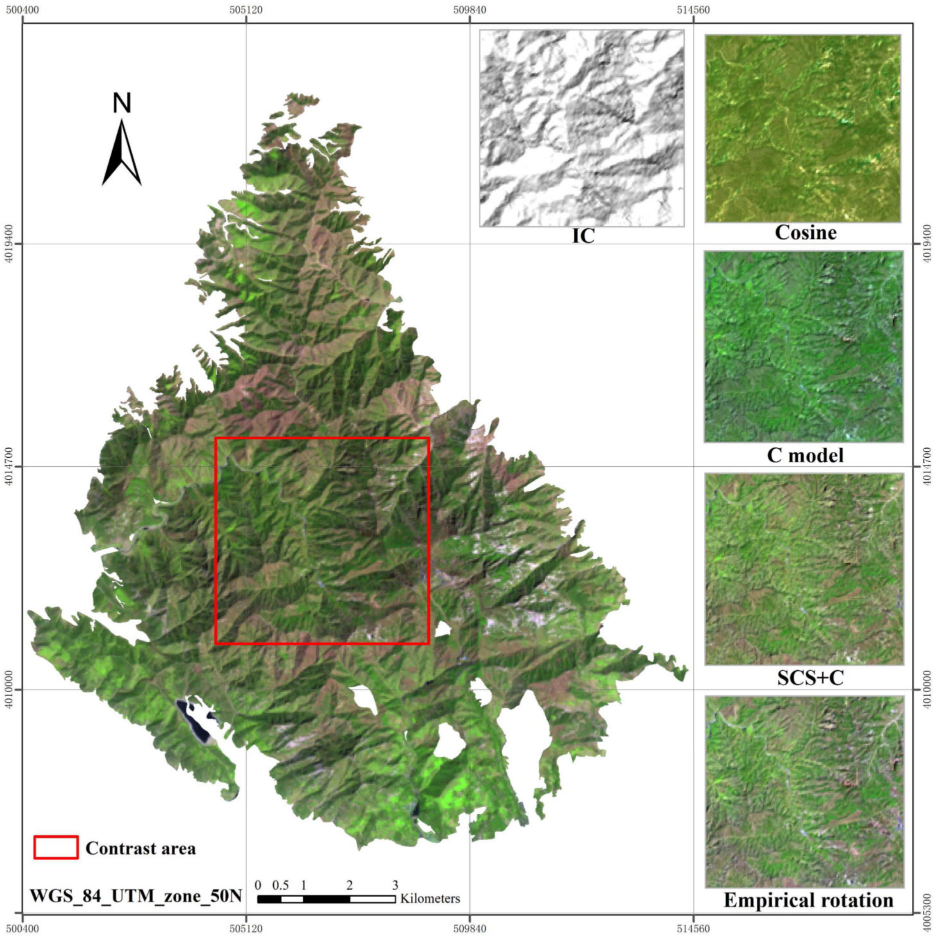


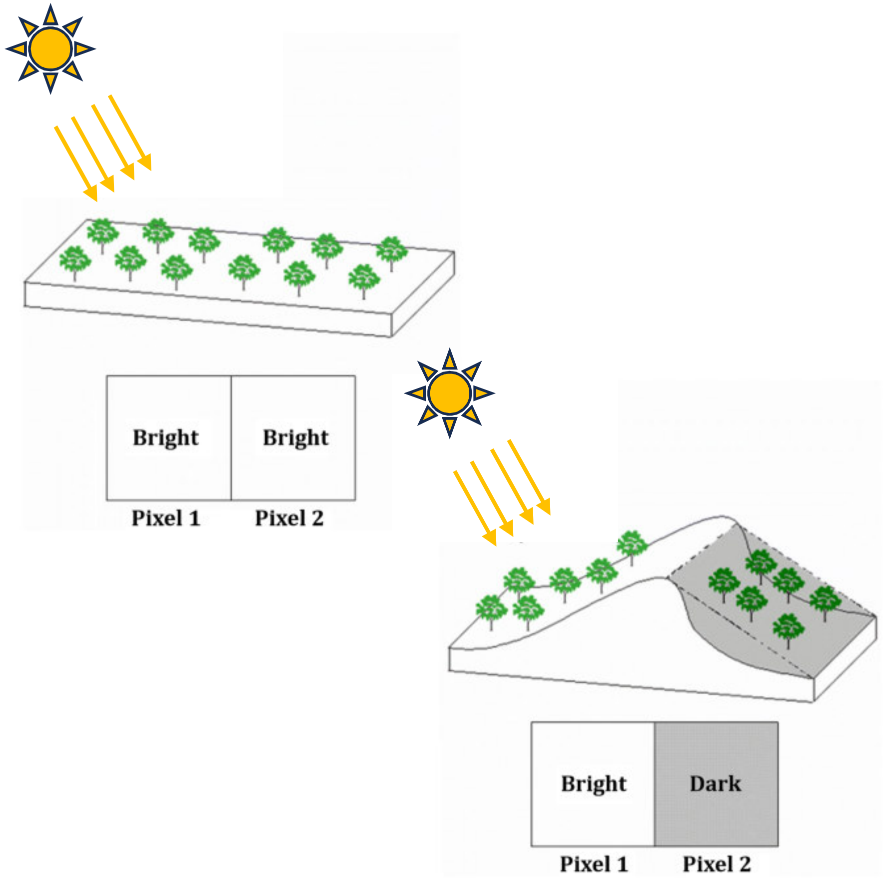
Near Solar Plane observation

(Cao et al., 2024)

Remote Sensing & Challenges

Topographic effect: Observation changes with slope aspect

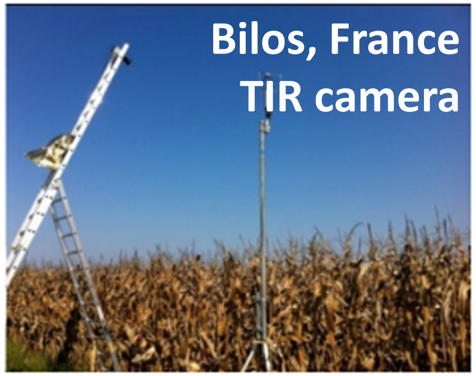


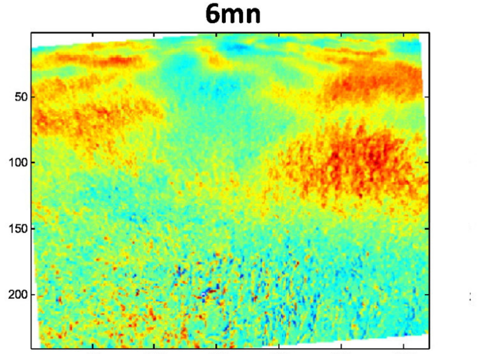


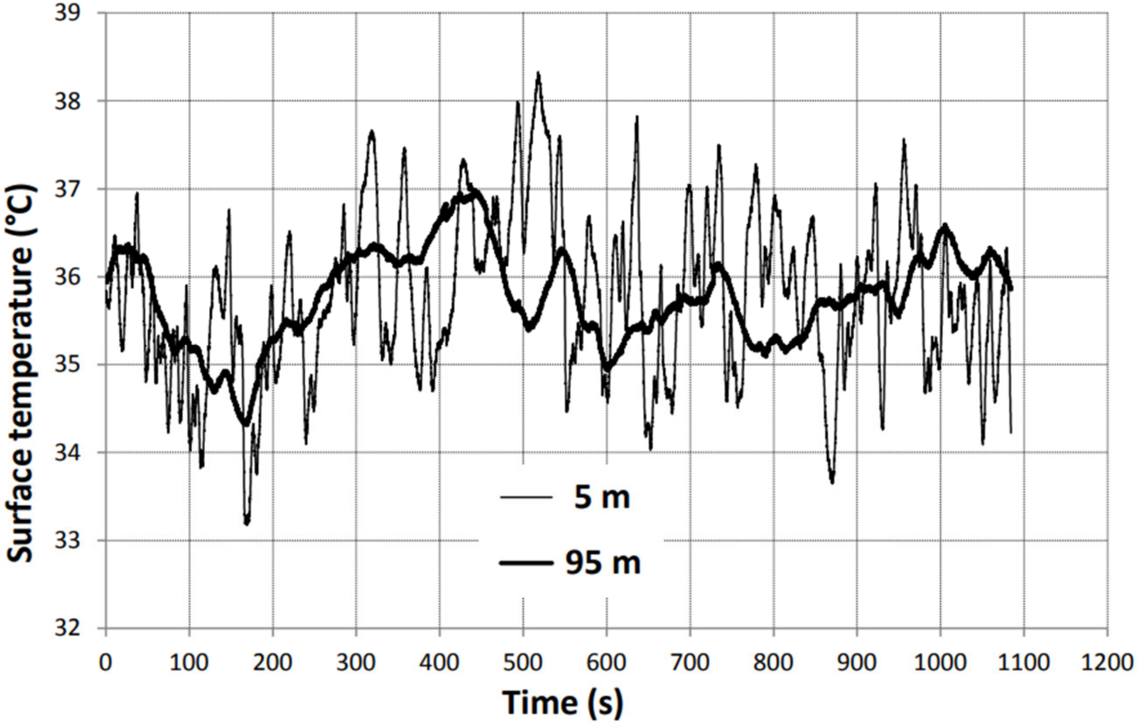
(*Chao et al., 2020*)

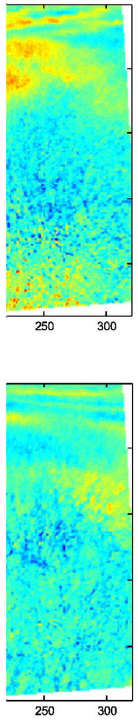
Remote Sensing & Challenges

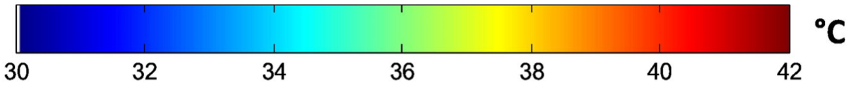
Natural processes: Observation changes with local microclimate







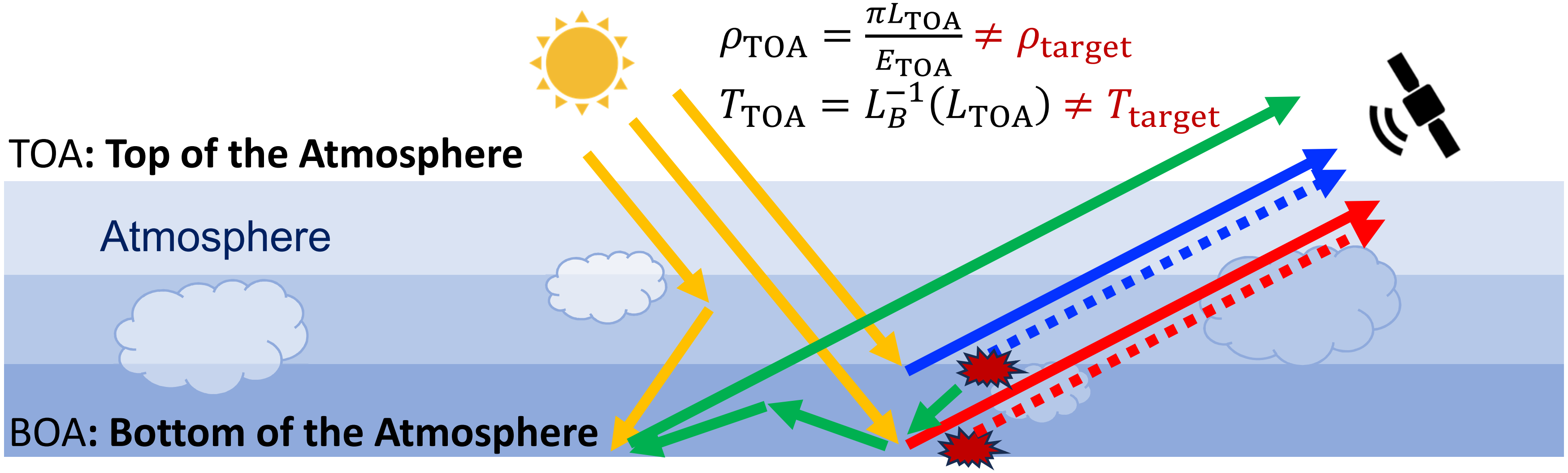




→ **Turbulence induced errors on LST**

(Lagouarde et al., 2015)

Physics of Remote Sensing



$$\rho_{\mathrm{TOA}} = \frac{\pi L_{\mathrm{TOA}}}{E_{\mathrm{TOA}}} \neq \rho_{\mathrm{target}}$$

$$T_{\mathrm{TOA}} = L_B^{-1}(L_{\mathrm{TOA}}) \neq T_{\mathrm{target}}$$

L_{TOA} = **Radiance due to scattering of solar flux and emission by the Earth (Only)**
+ Radiance due to scattering of solar flux and emission by the Atmosphere (Only)
+ Radiance due to scattering of flux by {Earth + Atmosphere} (Multiple scattering)

Physical models

Forward: RS = $f(\pi_1, \pi_2, \ldots)$
Inverse: VAR $\pi_i = f^{-1}(\mathrm{RS})$

⇨

Design space missions according to scientific objectives
Derive surface variables from remote sensing observation
Study surface RB to understand land processes and climate

Outline

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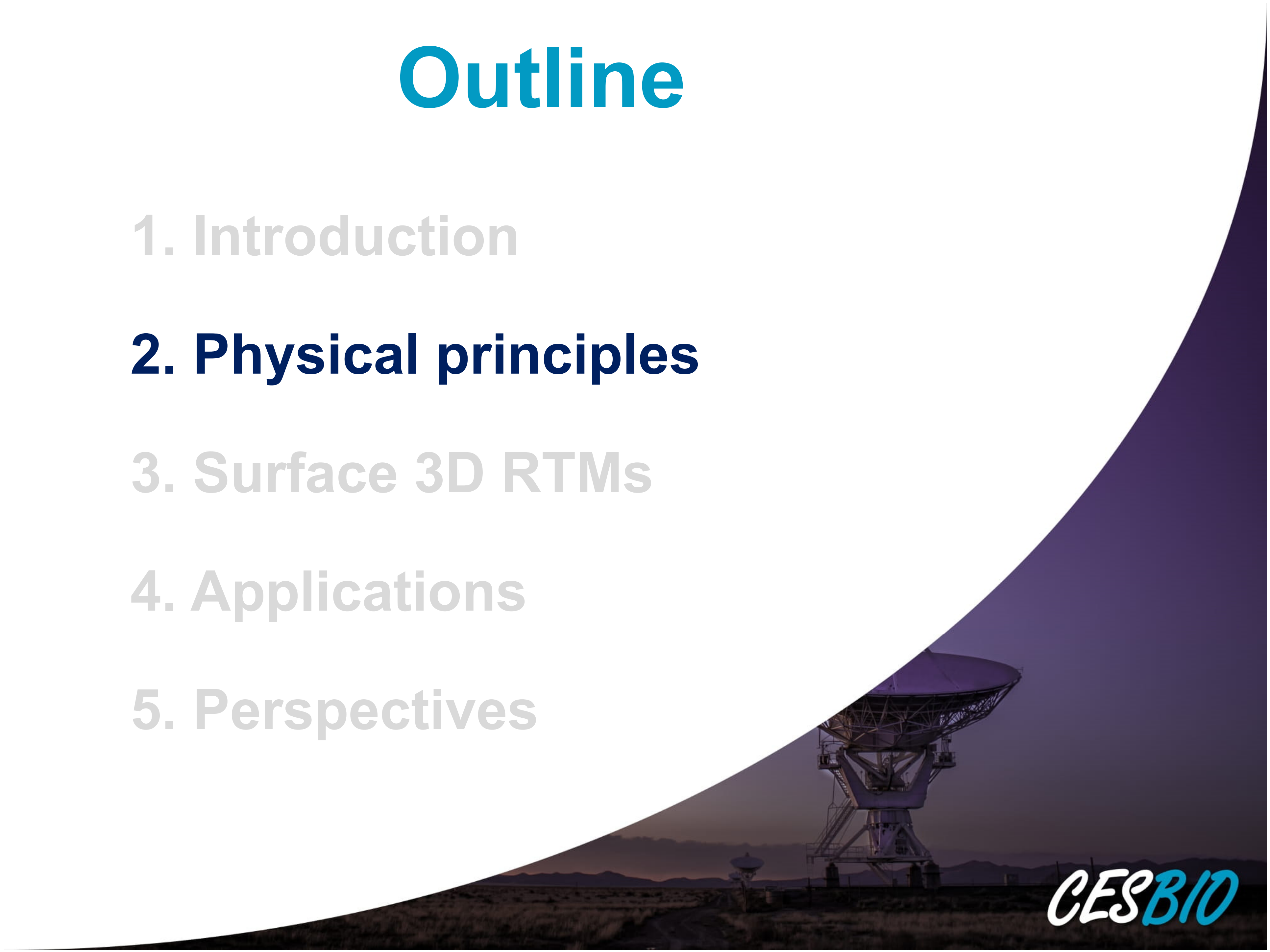
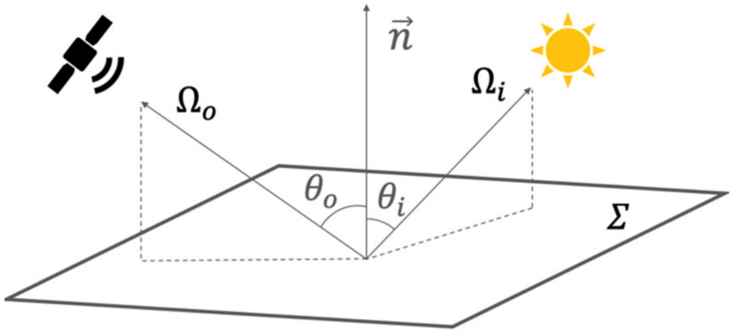


Physical principles

Light transport equation (surface)

$$L(r,\Omega_o) = L_e(r,\Omega_o) + \int L(r,-\Omega_i)\cdot f(r,\Omega_i,\Omega_o)\cdot|\cos\theta_i|\,d\Omega_i$$



$$f(\Omega_i,\Omega_o) = \frac{dL(\Omega_i,\Omega_o)}{dE_i(\Omega_i\,)}$$

$$\int f(r,\Omega_i,\Omega_o)\cdot|\cos\theta_i|\,d\Omega_i \le 1$$

$L_e(r,\Omega_o)$: emitted radiance (e.g., light source, thermal emission)

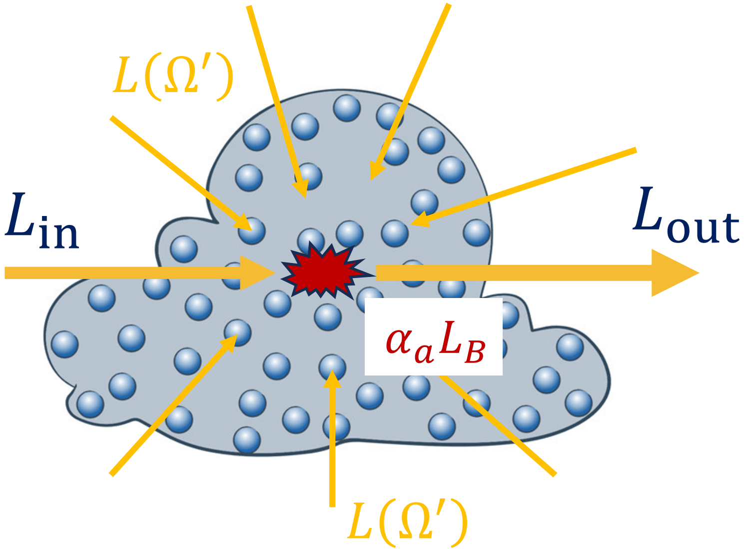
$f(r,\Omega_i,\Omega_o)$: bidirectional scattering distribution function (BSDF)

$$f(r,\Omega_i,\Omega_o) = \begin{cases} BRDF\colon \dfrac{\rho(r,\Omega_i,\Omega_o)}{\pi}, & \text{if } (\vec{n}\cdot\Omega_i)\cdot(\vec{n}\cdot\Omega_o) \ge 0 \\ BTDF\colon \dfrac{\tau(r,\Omega_i,\Omega_o)}{\pi}, & \text{otherwise} \end{cases}$$

Physical principles

Radiative transfer equation RTE (volume: atmosphere, turbid, fluid)

$$\frac{dL(\Omega)}{ds} = -\alpha_t L(\Omega) + \frac{\alpha_s}{4\pi} \cdot \int_{4\pi} L(\Omega') \cdot P(\Omega' \rightarrow \Omega)\, d\Omega' + \alpha_a L_B(T, \Omega)$$



$$d\tau = \alpha_t ds$$

$-\alpha_t L$: Attenuation due to **absorption** and **out-scattering**

$\frac{\alpha_s}{4\pi} \cdot \int_{4\pi} L(\Omega') \cdot P(\Omega' \rightarrow \Omega)\, d\Omega'$: Contribution due to **in-scattering** into the line of sight

$\alpha_a L_B$: Contribution due to **thermal emission**

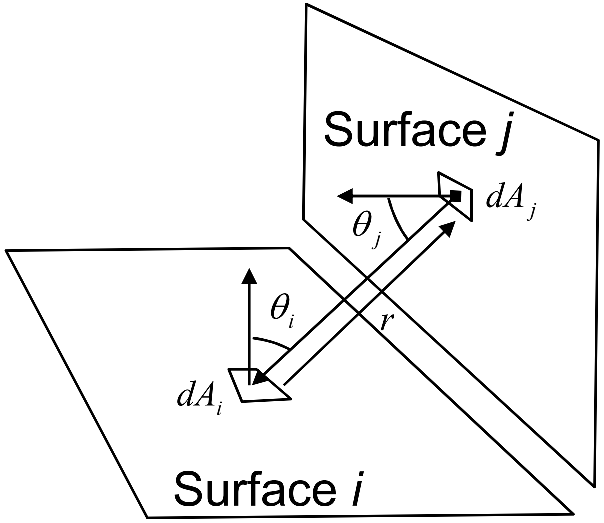
Also expressed as: $\frac{dL(\Omega)}{d\tau(\Omega)} = -L(\Omega) + \frac{\omega}{4\pi} \int_{4\pi} L(\Omega') P(\Omega' \rightarrow \Omega)\, d\Omega' + (1 - \omega) L_B(T, \Omega)$

Numerical solution

Radiosity method: Radiant energy conservation.

$$B_i = E_i + \sum_{j=1, j\neq i}^{N} \xi_i \cdot F_{i,j} \cdot B_j \text{, with } \xi_i = \rho_i \text{ or } \tau_i$$

$$F_{ij} = \frac{1}{A_i} \int_{A_i} \int_{A_j} \frac{\cos\theta_i \cos\theta_j}{\pi |r|^2} dA_i dA_j$$



B_i: Radiant flux leaving a facet *i (N facets in total)*

E_i: Emitted flux from a facet *i*

ρ_i (reflectance): fraction of an incident flux reflected by facet *i*

τ_i (transmittance): fraction of an incident flux reflected by facet *i*

$F_{i,j}$ (view factor): fraction of flux leaving facet *j* and reaching facet *i*

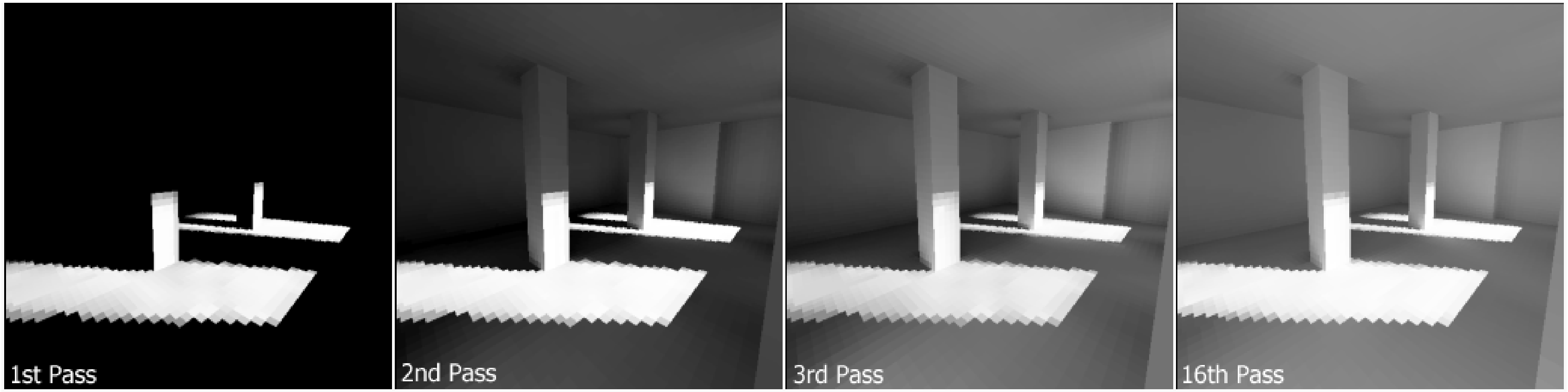
Numerical solution

Radiosity method: Transformation and solution

$$B_i = E_i + \xi_i \sum_{j=1, j\neq i}^{N} F_{i,j} \cdot B_j \quad \Rightarrow \quad B_i - \xi_i \sum_{j=1, j\neq i}^{N} F_{i,j} \cdot B_j = E_i$$

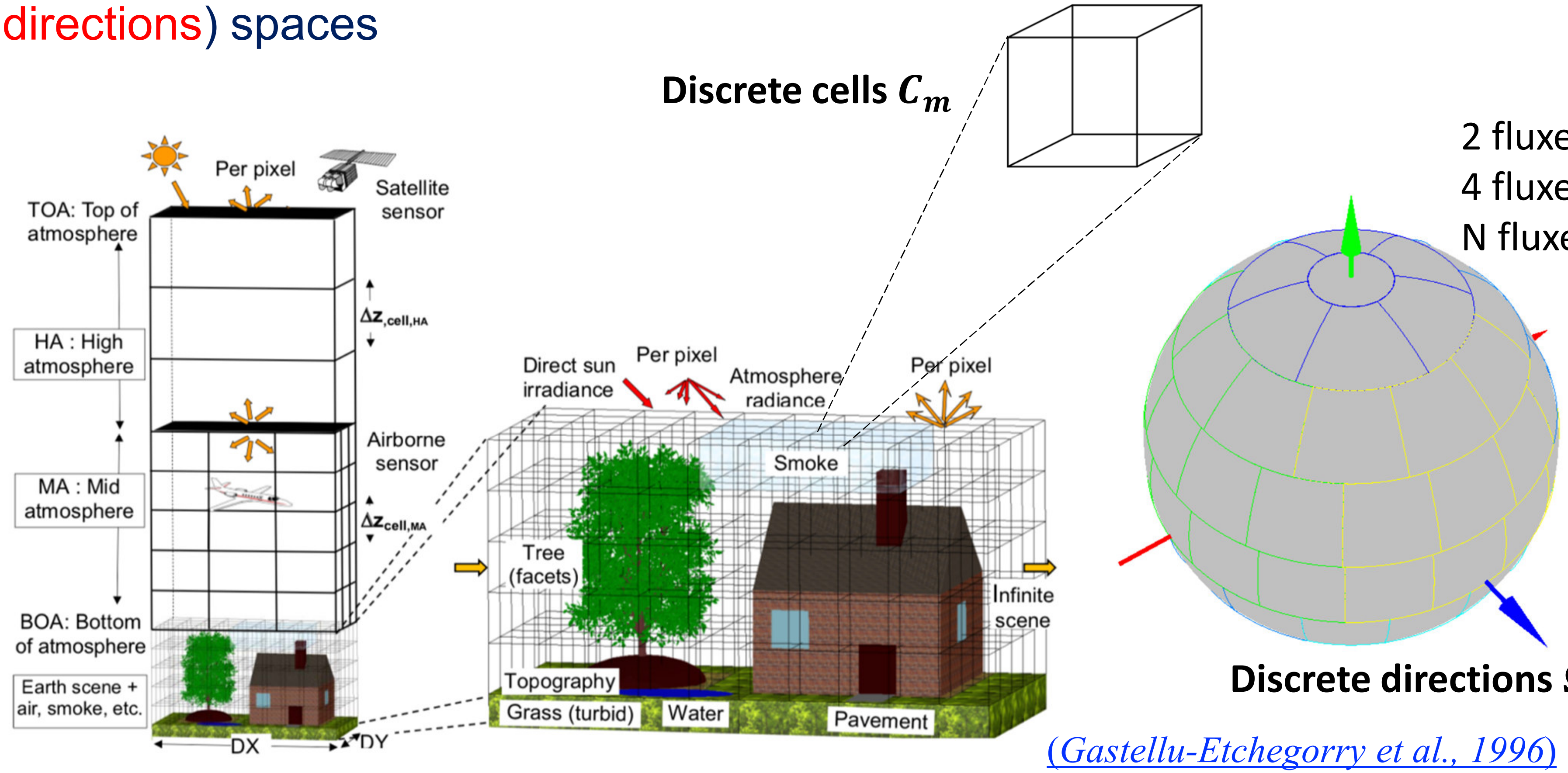
N equations
N unknowns

$$\begin{bmatrix} 1 & -\xi_1 F_{1,2} & \dots & -\xi_1 F_{1,N} \\ \vdots & & & \vdots \\ -\xi_N F_{N,1} & -\xi_N F_{N,2} & \dots & 1 \end{bmatrix} \cdot \begin{bmatrix} B_1 \\ \vdots \\ B_N \end{bmatrix} = \begin{bmatrix} E_1 \\ \vdots \\ E_N \end{bmatrix}$$



Numerical solution

Discrete Ordiantes method: Discretisation of XYZ (M cells) and angular (N directions) spaces



Discrete cells C_m

2 fluxes
4 fluxes
N fluxes

Discrete directions Ω_n

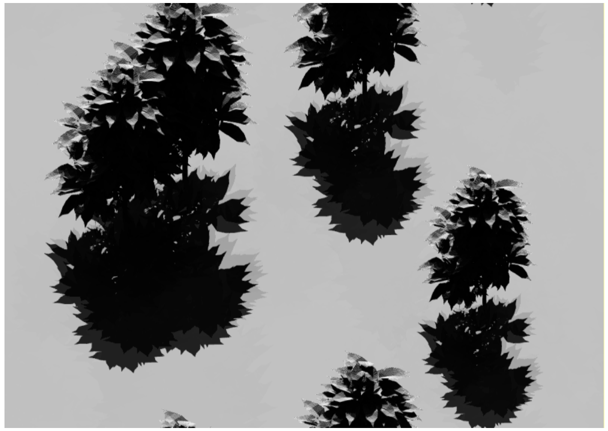
(Gastellu-Etchegorry et al., 1996)

Numerical solution

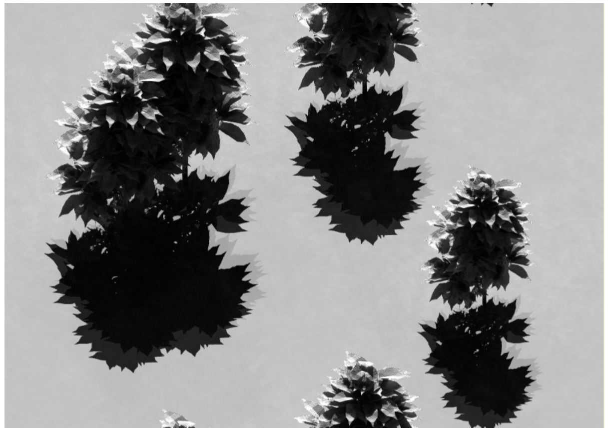
Discrete Ordiantes method: N equations per cell, for M cells

$$L_{\text{out}}(\Omega_m) = \mathcal{T}(\Omega_m) L_{\text{in}}(\Omega_m) + L_{\text{e}}(\Omega_m) + \sum_{i=1}^{M} \phi_{i,m} \, L_{\text{in}}(\Omega_i)$$

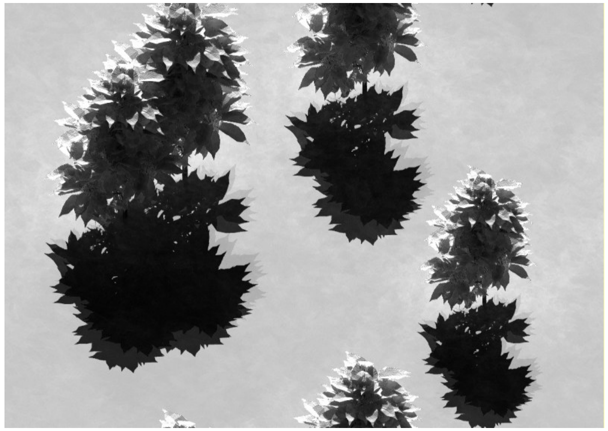
M x N equations per Pass



1st Pass



2nd Pass

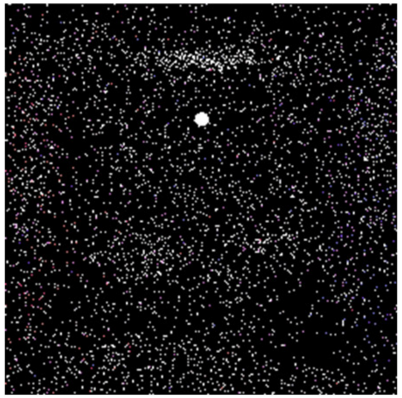


20th Pass

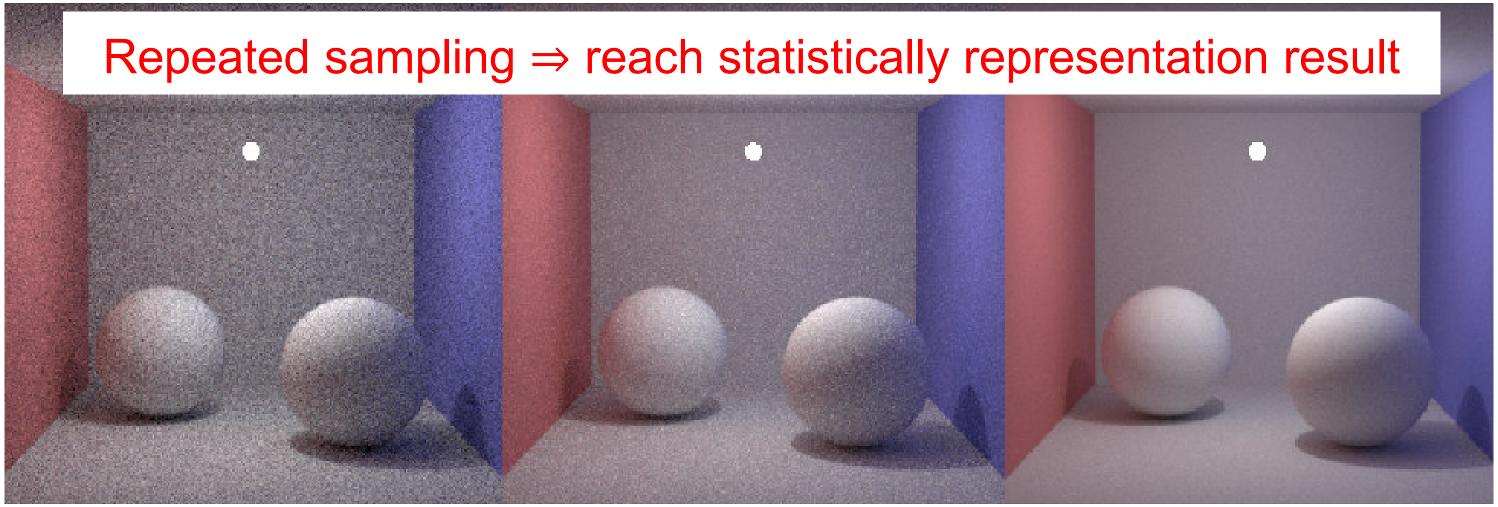
Numerical solution

Monte Carlo method: probability of interception and scattering

- **Forward approach:** scene illumination by tracking rays from the source
- **Backward approach:** scene illumination by tracking rays from the sensor
- **Bi-directional approach:** scene illumination by tracking rays from sensor & source



MC.gif



Repeated sampling ⇒ reach statistically representation result

10 samples / pixel **100 samples / pixel** **1000 samples / pixel**

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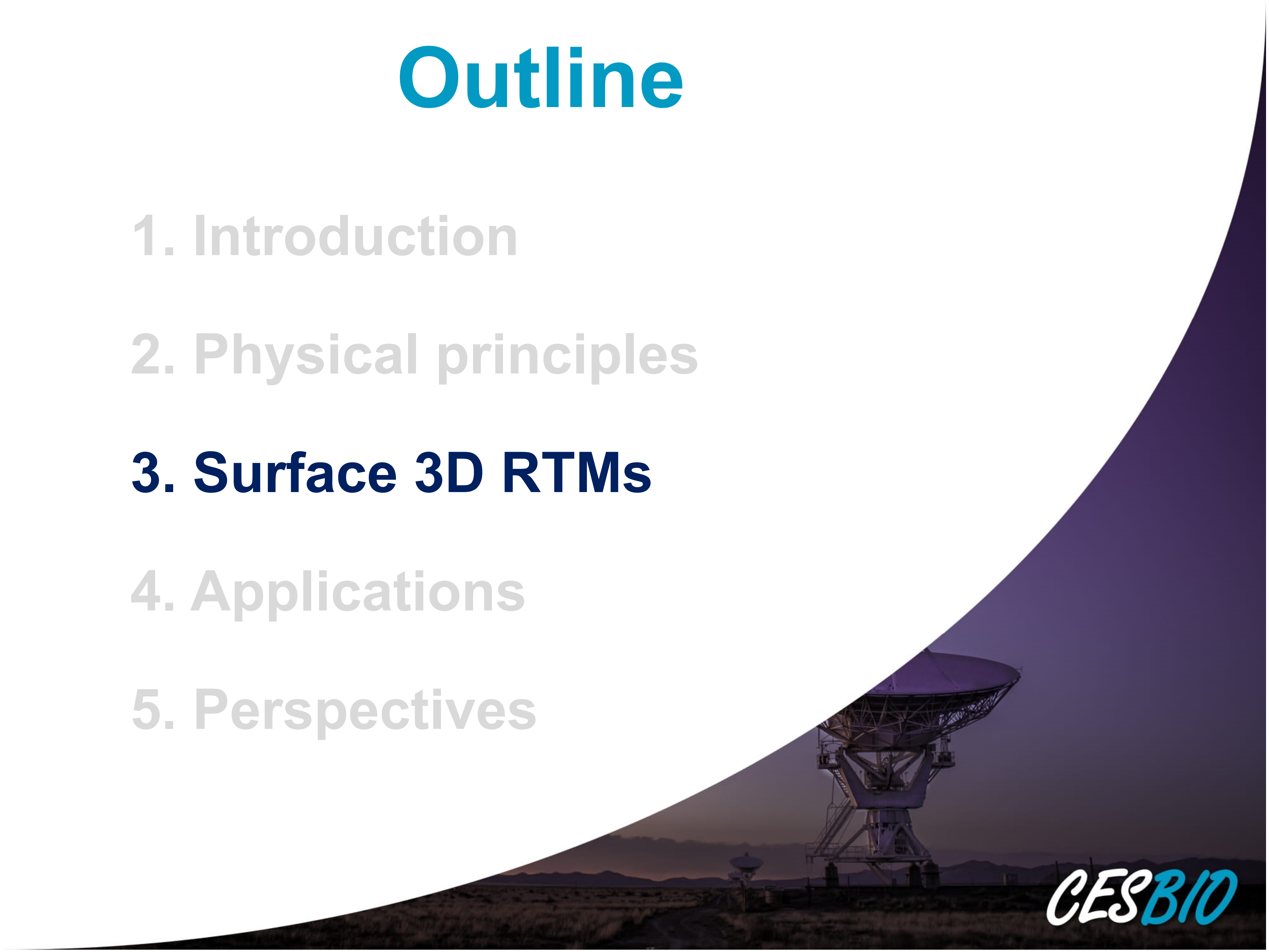
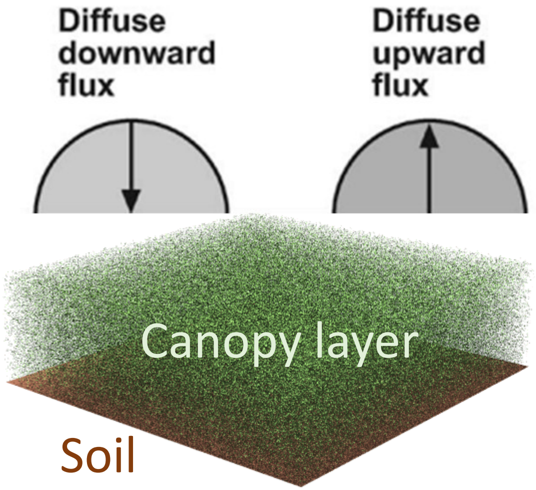


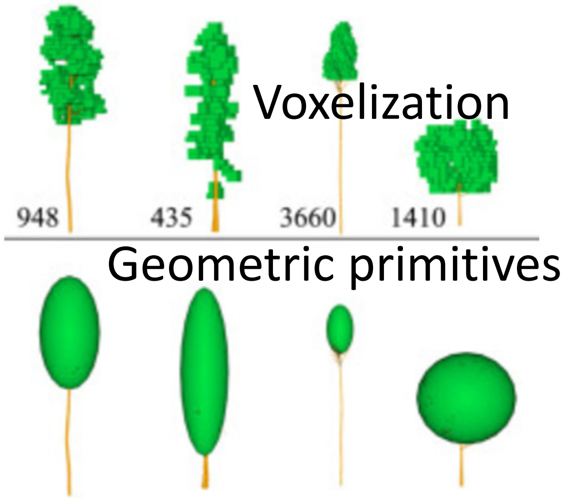
Radiative transfer modelling

Evolution of Physical Models

RT and landscape modeling complexity



SAIL 1980s
(2 fluxes)



DART, FLIGHT, etc. 1990s
(DOM, MC, Radiosity)


© European Union

DART, LESS, etc. 2020s
(MC)

Close to reality reference;
Validate other models

Accuracy

3D radiative transfer models

(Survey on 09/2022, Wang Yingjie, 2022)

🟩 Yes 🟥 No 🟨 Possible

		DART	DIRSIG	Eradiate	FLiES	FLIGHT	LCVRT	LESS	Librat	MCScene	RAPID	Raytran	WPS
Radiative transfer	Mode (**MC**, **DOM**, **R**adiosity)	M/D	M	M	M	M	M	M	M	M	R	M	M
	Short wave [12]	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
	Thermal emission [7]	🟩	🟩	🟥	🟩	🟥	🟥	🟩	🟥	🟩	🟩	🟥	🟩
	SIF emission [6]	🟩	🟥	🟥	🟩	🟩	🟩	🟩	🟥	🟥	🟥	🟥	🟩
	LiDAR [7]	🟩	🟩	🟥	🟥	🟩	🟥	🟩	🟩	🟥	🟩	🟥	🟩
	Surface anisotropic scattering [9]	🟩	🟩	🟥	🟥	🟩	🟩	🟩	🟩	🟥	🟩	🟩	🟩
	Surface specular reflection [8]	🟩	🟩	🟥	🟥	🟩	🟩	🟩	🟥	🟥	🟩	🟩	🟩
	Polarization [3]	🟩	🟨	🟥	🟥	🟥	🟩	🟥	🟥	🟥	🟥	🟥	🟥
	3D radiative budget [8]	🟩	🟩	🟥	🟩	🟩	🟥	🟩	🟥	🟩	🟥	🟩	🟩
Light source	Parallel sunlight [12]	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
	Spherical sun [8]	🟩	🟩	🟥	🟩	🟩	🟩	🟩	🟩	🟥	🟥	🟩	🟥
	BOA anisotropic atmosphere [10]	🟩	🟨	🟥	🟩	🟩	🟩	🟩	🟩	🟩	🟨	🟥	🟩
	Multi light sources [8]	🟩	🟩	🟥	🟥	🟩	🟥	🟩	🟩	🟩	🟥	🟩	🟩

(Survey on 09/2022, Wang Yingjie, 2022)

🟩 Yes 🟥 No 🟨 Possible

		DART	DIRSIG	Eradiate	FLiES	FLIGHT	LCVRT	LESS	Librat	MCScene	RAPID	Raytran	WPS
Sensor	Orthographic camera [9]	🟩	🟩	🟥	🟩	🟩	🟥	🟩	🟩	🟩	🟩	🟥	🟩
	Perspective camera [10]	🟩	🟩	🟩	🟥	🟨	🟥	🟩	🟩	🟩	🟩	🟩	🟩
	Hemispheric camera [9]	🟩	🟩	🟥	🟩	🟨	🟥	🟩	🟩	🟩	🟩	🟩	🟥
	Pushbroom [8]	🟩	🟩	🟥	🟥	🟨	🟥	🟩	🟩	🟩	🟨	🟩	🟥
Land surface	Turbid medium (vegetation) [11]	🟩	🟩	🟥	🟩	🟩	🟩	🟩	🟨	🟨	🟩	🟩	🟩
	Solid surface (buildings, *etc*.) [11]	🟩	🟩	🟩	🟥	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
	Fluids (gas, aerosol, etc.) [7]	🟩	🟩	🟩	🟩	🟥	🟥	🟥	🟥	🟩	🟥	🟩	🟩
	Topography [9]	🟩	🟩	🟩	🟥	🟨	🟥	🟩	🟩	🟩	🟩	🟩	🟥
	Spherical Earth surface [5]	🟩	🟩	🟩	🟥	🟥	🟥	🟥	🟨	🟩	🟥	🟥	🟥
Atmos.	Plane parallel [9]	🟩	🟩	🟩	🟩	🟨	🟥	🟩	🟥	🟩	🟩	🟥	🟩
	Spherical [3]	🟩	🟥	🟩	🟥	🟥	🟥	🟥	🟥	🟩	🟥	🟥	🟥
	3D clouds [3]	🟩	🟩	🟥	🟥	🟥	🟥	🟥	🟥	🟩	🟥	🟥	🟥
Energy balance	Photosynthesis, thermal conduction, *etc*. [5]	🟨	🟥	🟥	🟩	🟩	🟥	🟥	🟥	🟥	🟥	🟩	🟩

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4. **Applications**
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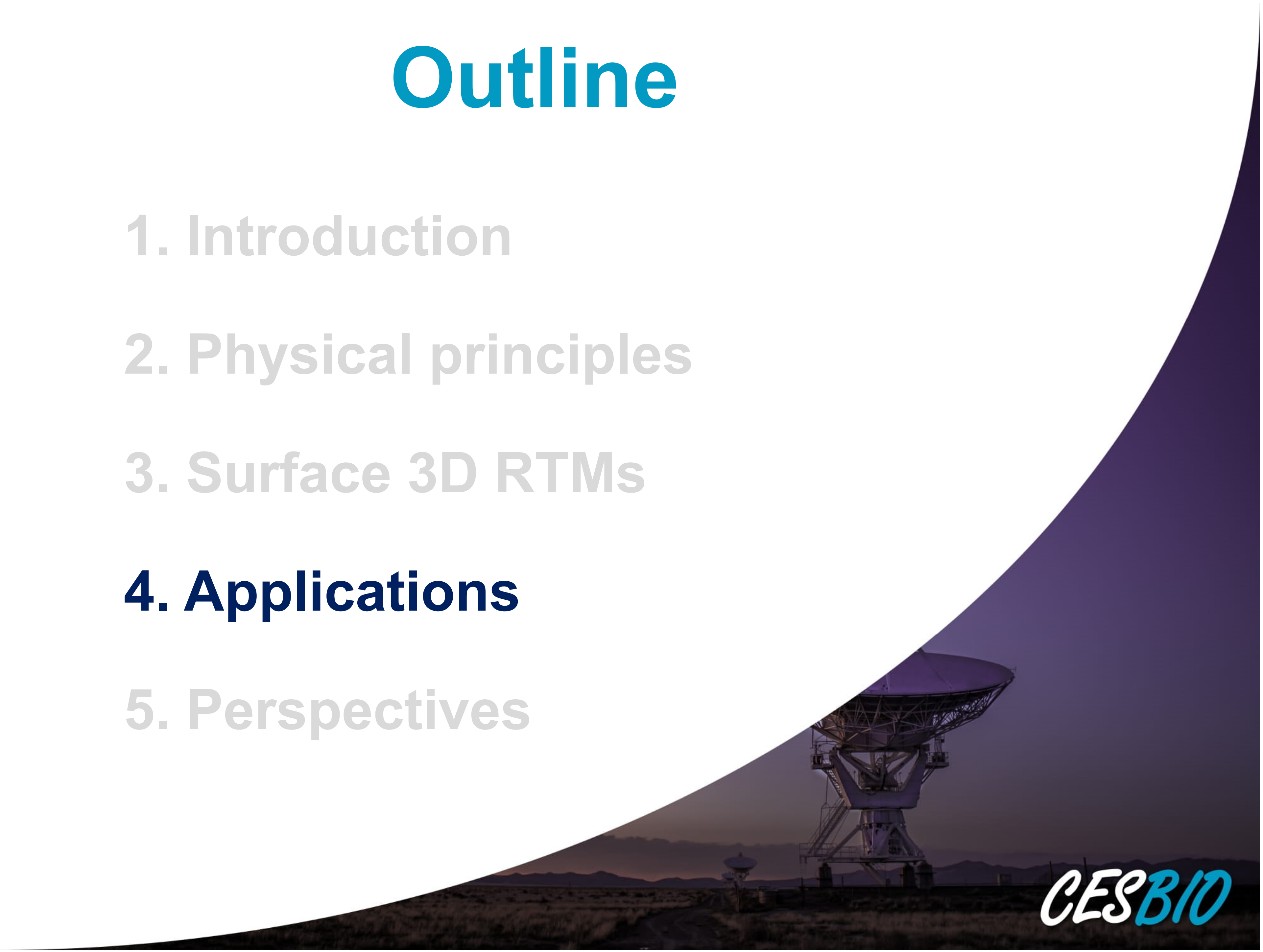


DART model (CESBIO, FR)

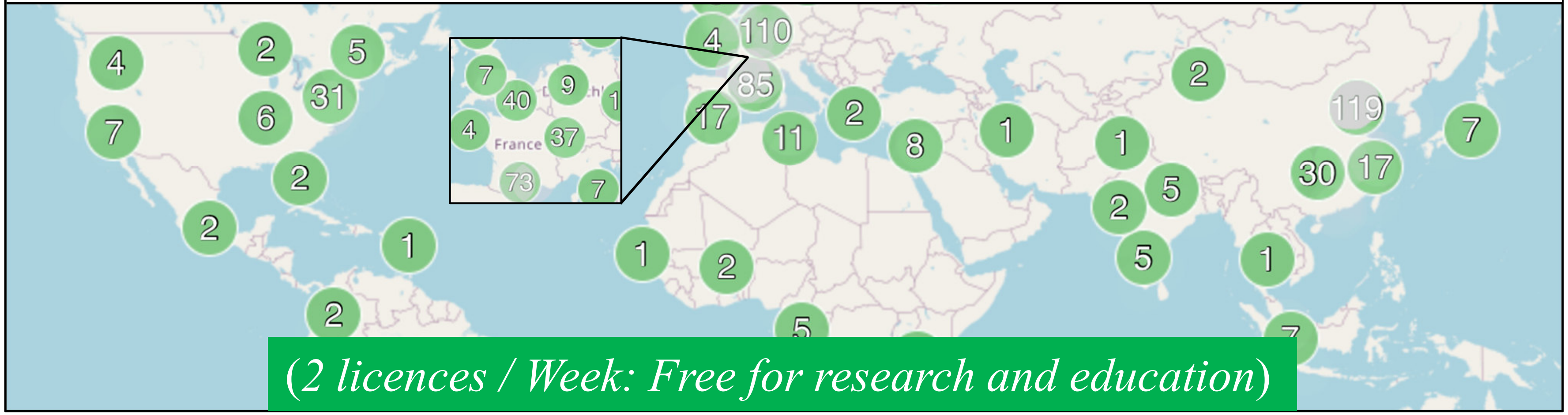
History: developed in CESBIO since 1992 by 10 scientists. Patented in 2003

Code: 500,000 lines **C++ (Core)**, 100,000 lines **Java (GUI)** and **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*)

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



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

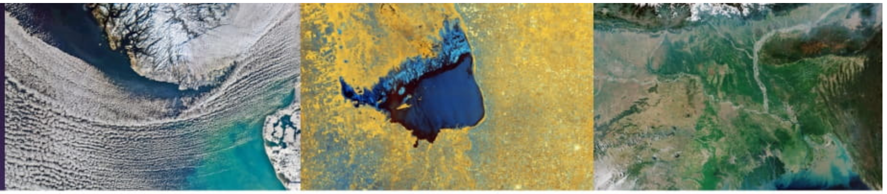
Sentinel-2 NG (ESA)

DART scenes used as reference ⇒ Trade-off "several satellite" *vs* "large FOV".

Project Sentinel-2 NG (ESA) *(Gastellu-Etchegorry et al., 2022)*

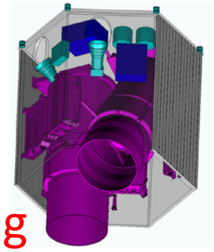
Google map (Ripperdan, USA, Sept. 2018)

DART Simulation



STV (NASA)

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

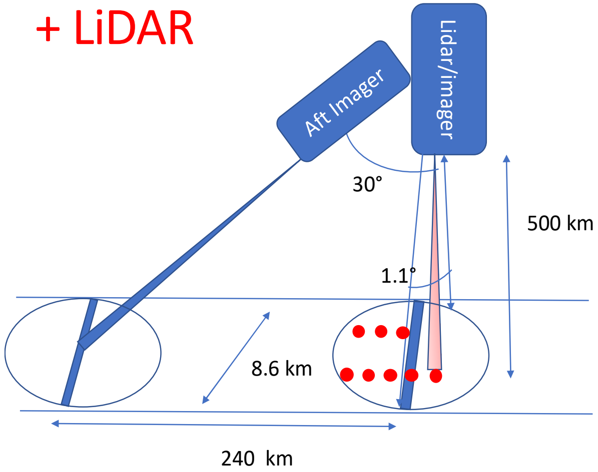


DART gives images and (x, y, z) coordinates of scene elements

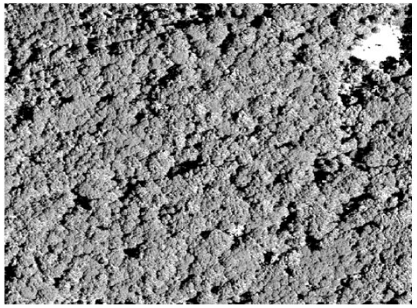
⇒ NASA uses DART to define the optimal satellite configuration

Stereo imaging

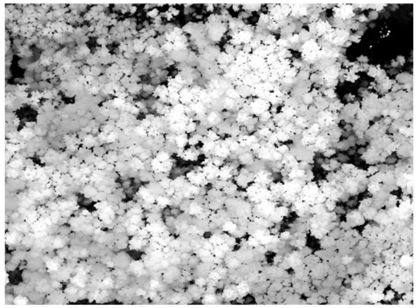
+ LiDAR



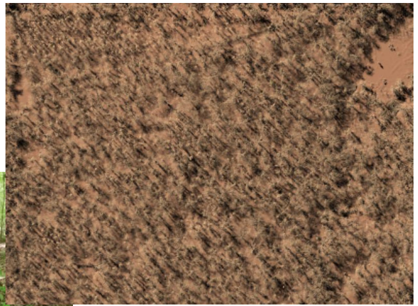
DART: 400x400m SERC forest



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

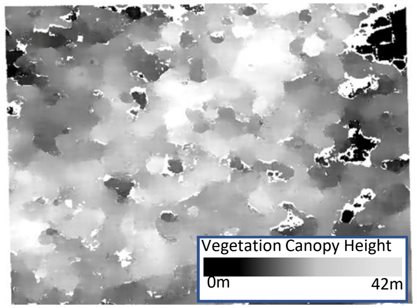


NASA G-LiHT Lidar Reference



DART: scene-leaf off

DART -20° (15/06/2012, 9am)



Canopy height from DART stereo pair

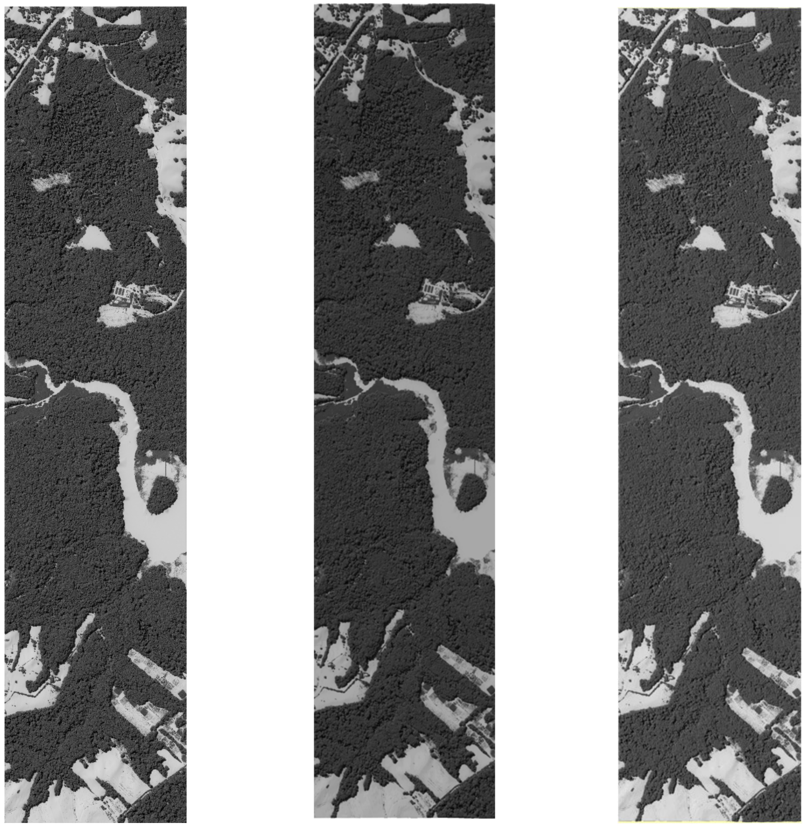
Image processing algorithm

DART Large-Scale Simulations of Stereogrammetry

Google map (4.5km×1km)

meter-scale

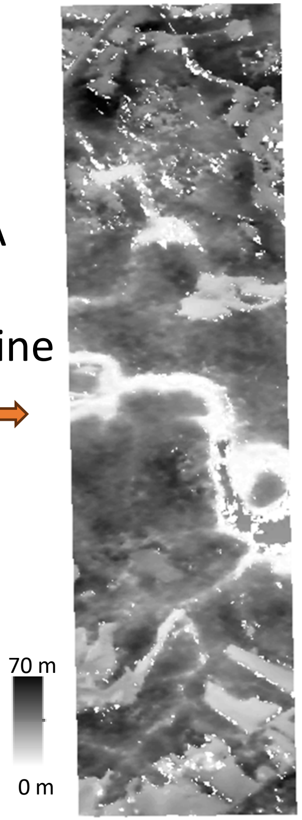
DART simulated images

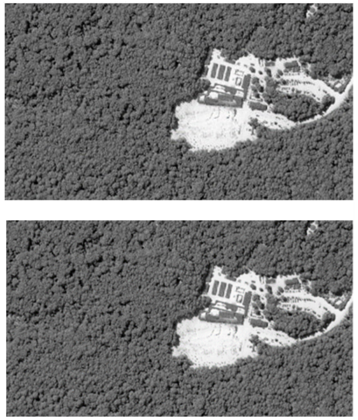


(a) Nadir (b) 10° to 40° forward (c) -10° to -40° backward

NASA ASP pipeline →

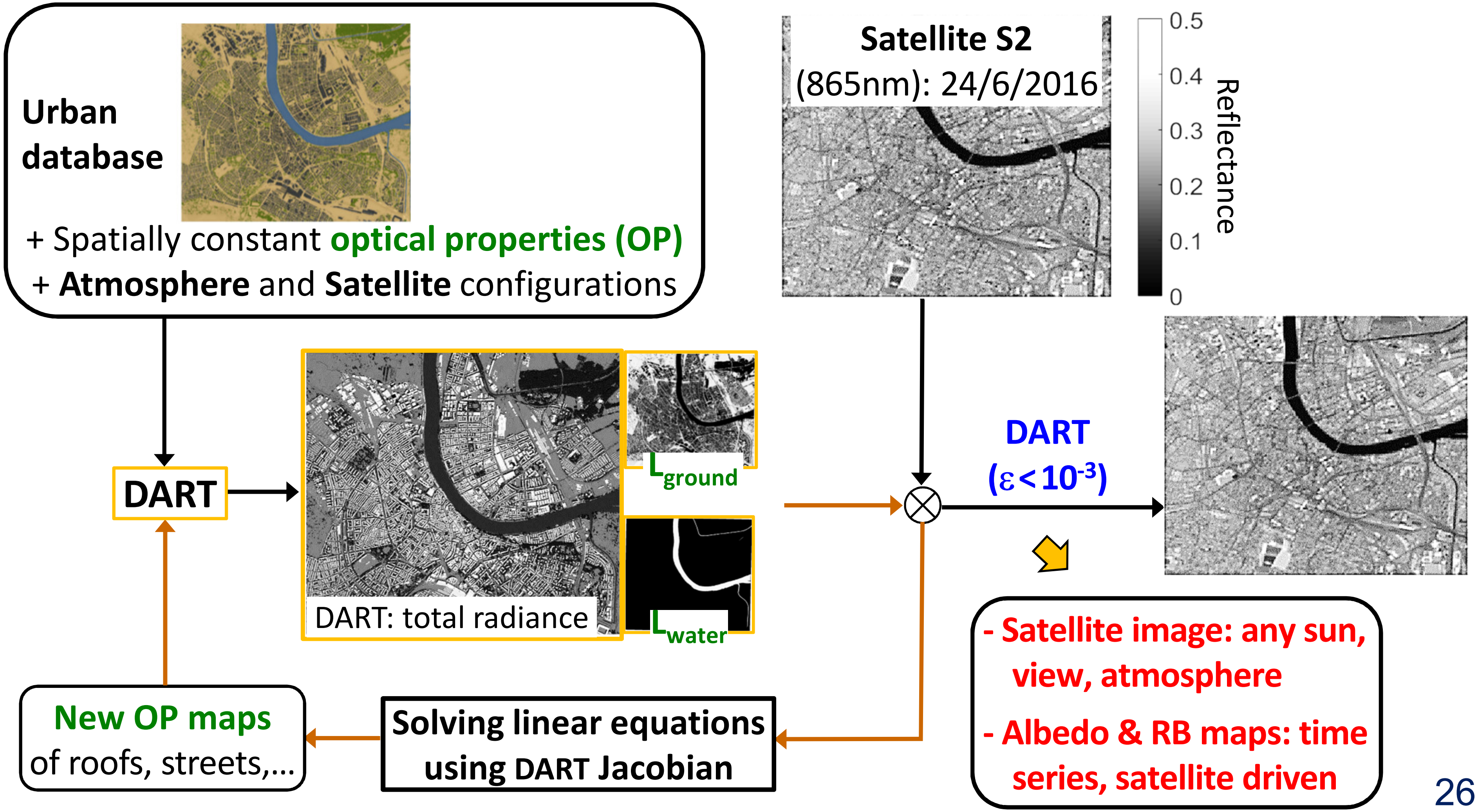
Generated DSMs





Jitter simulation

Inversion



Urban database

+ Spatially constant **optical properties (OP)**

+ **Atmosphere** and **Satellite** configurations

DART

DART: total radiance

Satellite S2

(865nm): 24/6/2016

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

Solving linear equations using DART Jacobian

New OP maps of roofs, streets,...

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

Inversion

Sentinel 2 RGB (B2, B3, B4) - **VIS**

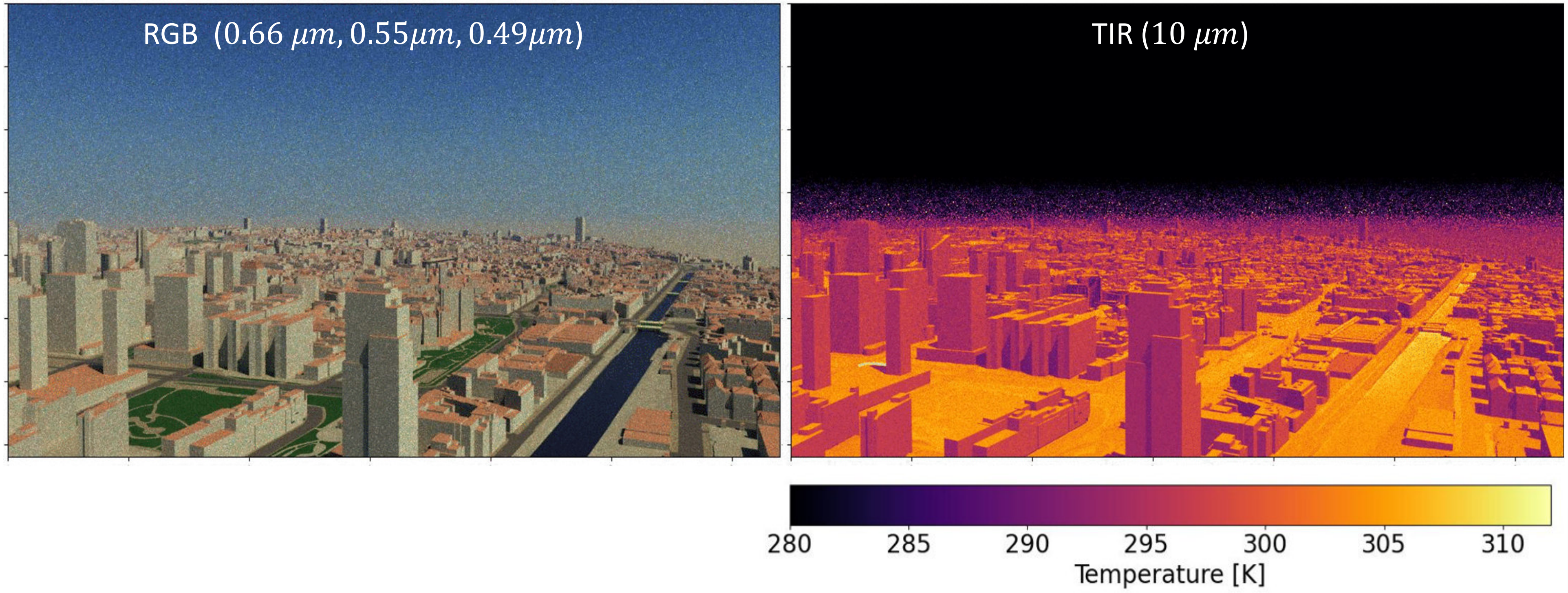
5 km

DART simulation with ρ/τ maps

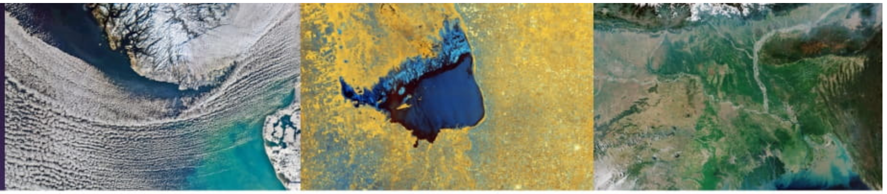
(Zhen et al., 2021)

Urban heat island

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



DART image: Brussels city. Land parameters from inversion S2/ASTER



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

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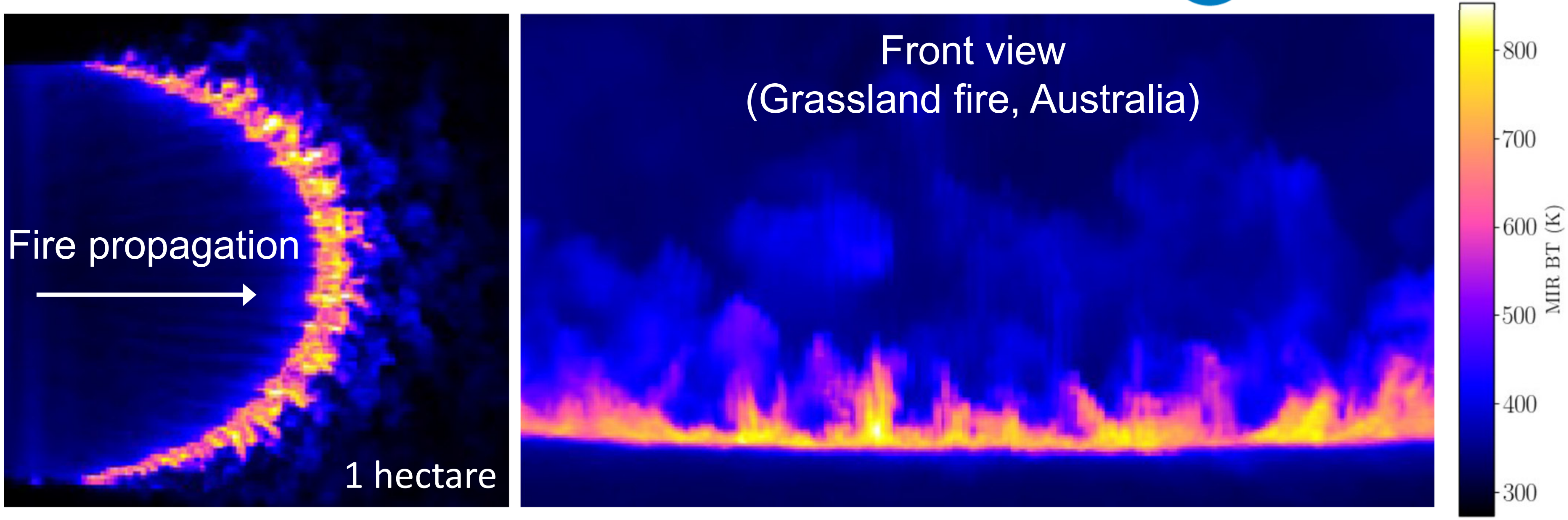
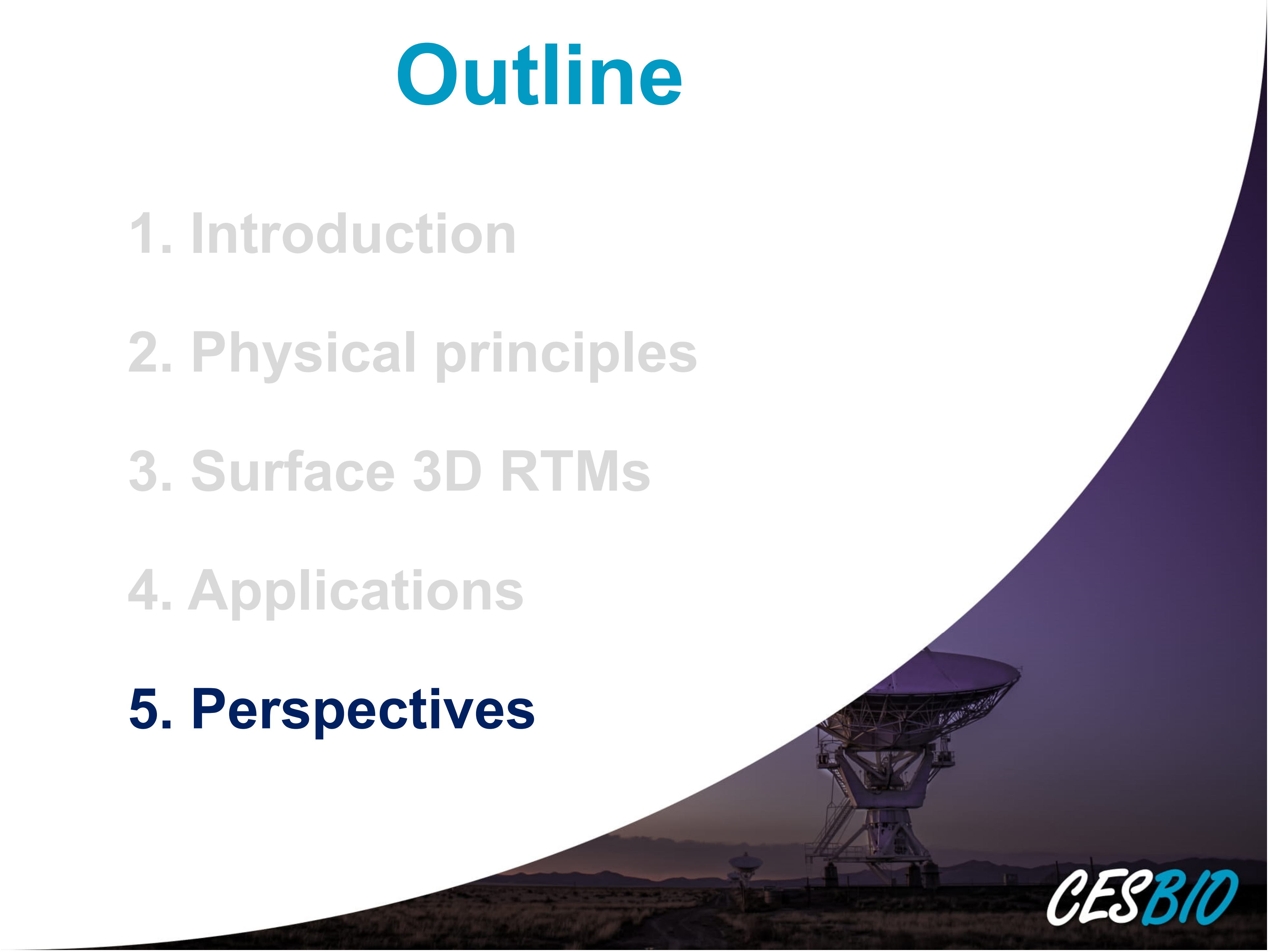
DE CATALUNYA
BARCELONATECH



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

Outline

1. Introduction
2. Physical principles
3. Surface 3D RTMs
4. Applications
5. **Perspectives**



Multi-scale modelling

Forest reconstruction with TLS and QSM: 1ha, 559 trees

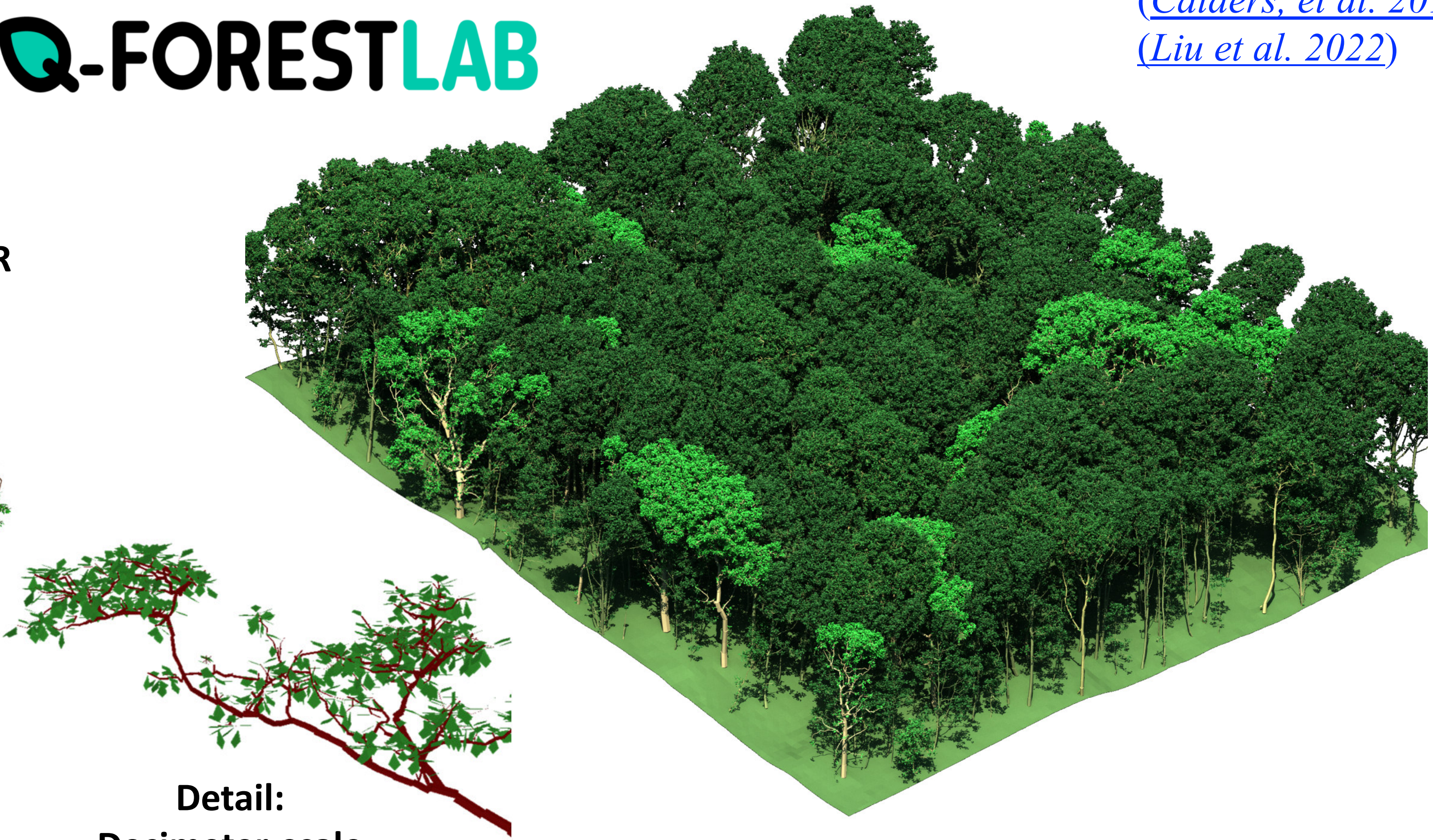
(Calders, et al. 2018)
(Liu et al. 2022)

Q-FORESTLAB

Terrestrial LiDAR point cloud

⇩

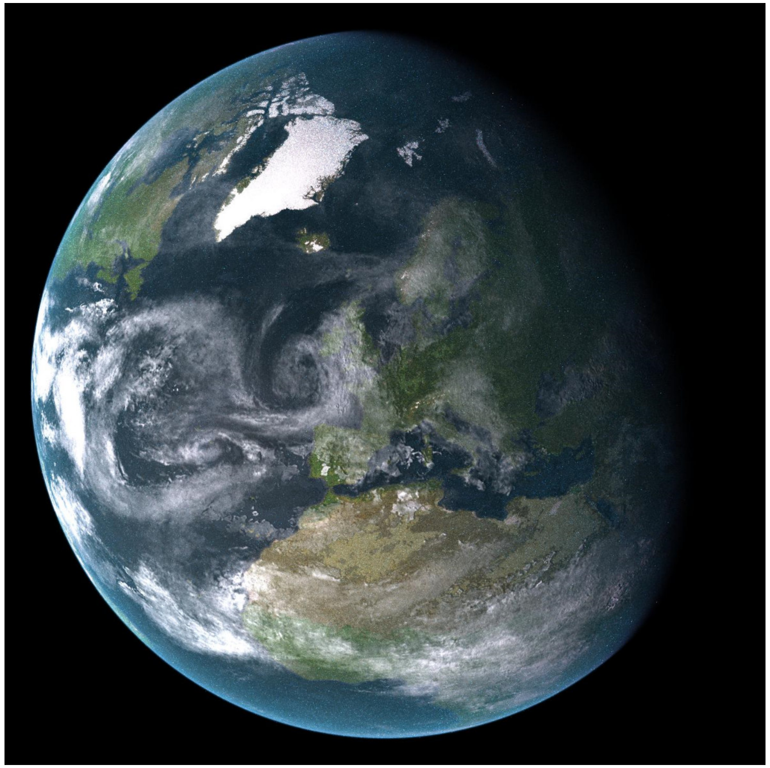
Reconstructed 3D tree model



Detail: Decimeter-scale

Multi-scale modelling

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

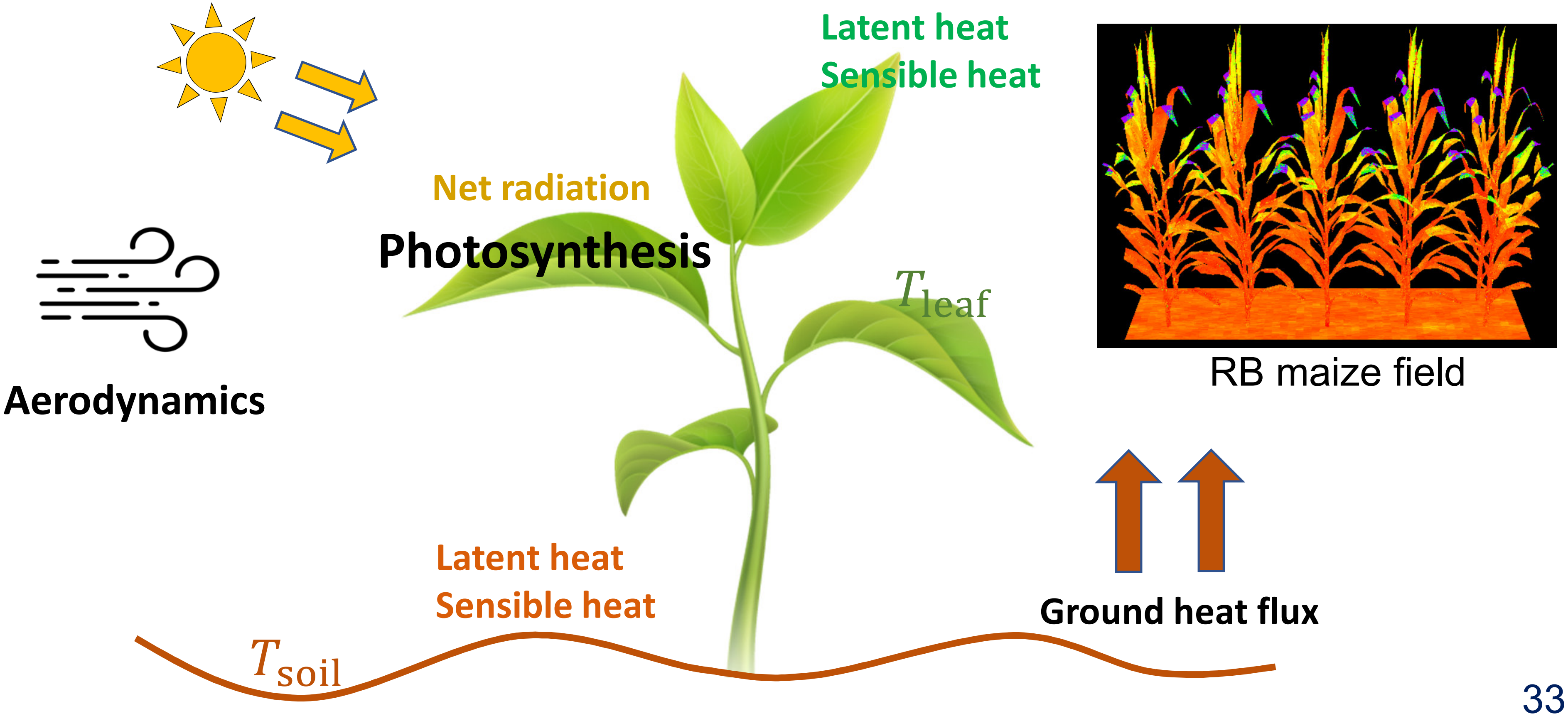


DART simulation (E. Chavanon), resolution = 10 km (1° x 1°)

Energy balance

EB modelling: Photosynthesis, heat flux, turbulence, *etc*. + Radiative Transfer

Products: Temperature distribution, evapotranspiration, *etc*.



Latent heat

Sensible heat

Net radiation

Photosynthesis

T_{leaf}

Aerodynamics

RB maize field

Latent heat

Sensible heat

Ground heat flux

T_{soil}

Other improvements

(1) **Uncertainty (Jacobian):** Modelling the propagation of Uncertainties/Errors

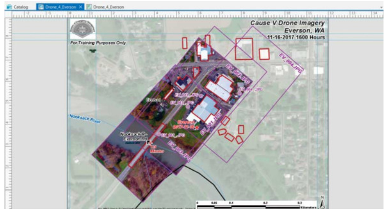
(2) **Georeferencing:** Import georeferenced scenes and export georeferenced images

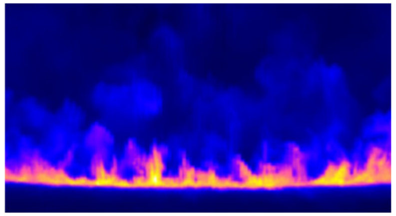
(3) **RT acceleration for volume:** Turbid representation of vegetation, Fire, Pollutants,…

(4) **Measurements:** Import measurements (optical/thermal properties, 3D structure, …)

(5) **Surface process:** Coupling with climate/process models (SCOPE, SOLENE, …), …

$$\mathbf{J}_{\mathbf{f}} = \left[\frac{\partial \mathbf{f}}{\partial x_1} \quad \cdots \quad \frac{\partial \mathbf{f}}{\partial x_n} \right]$$





THANK YOU

DART is freely available for research and education.

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Tutorial DART 17:00 – 18:00

sDrive

sdrive.cnrs.fr/s/Y9bMZqGsbBKmDMf

CESBIO