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

Yingjie Wang\textsuperscript{a}, O. Regaieg\textsuperscript{a, b}, N. Lauret\textsuperscript{a}, J. Guilleux\textsuperscript{a}, E. Chavanon\textsuperscript{a}, Z. Zhen\textsuperscript{a, c}, P. Boitard\textsuperscript{a}, R. Démoulin\textsuperscript{a}, T. Nguyen\textsuperscript{a, b}, H. Jin\textsuperscript{d}, X. Yang\textsuperscript{d}, T. Yin\textsuperscript{e}, A. Mkaouar\textsuperscript{f}, R. Janoutova\textsuperscript{g}, R. Paugam\textsuperscript{h}, F. De Boissieu\textsuperscript{i}, A. Kallel\textsuperscript{j}, Z. Malenovský\textsuperscript{b}, J.-P. Gastellu-Etchegorry\textsuperscript{a}

\textsuperscript{a} CESBIO, Toulouse, France
\textsuperscript{b} University of Bonn, Bonn, Germany
\textsuperscript{c} University of Jilin, Jilin, China
\textsuperscript{d} CAS, Beijing, China
\textsuperscript{e} Hongkong Polytechnic University, China
\textsuperscript{f} NASA, USA
\textsuperscript{g} CzechGlobe, Czech Republic
\textsuperscript{h} CERTEC, UPC, Spain
\textsuperscript{i} TETIS, Montpellier, France
\textsuperscript{j} CRNS, ATMS, Sfax, Tunisia
Outline

1. Introduction to DART model
2. DART applications
3. Conclusion
Outline

1. Introduction to DART model
2. DART applications
3. Conclusion
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 $\varepsilon$, RMSE) assessed with:

- Monte Carlo models (RAMI-III experiment): $\varepsilon_p \leq 1\%$ (Widlowski et al., 2007)
- Measurements: $\varepsilon_p \leq 2.5\%$ (Landier et al., 2018), $RMSE_{TB} < 2K$ (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

Yingjie Wang
ATER (UT3)
Atm., polarization

Zhijun Zhen
Lecturer (Univ. Jilin)
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

Since 1992  Radiative transfer: Adaptation of DOM
(Optical and thermal radiometer images and radiative budget, with SIF)

Since 2010  Radiative transfer: forward MC
(LiDAR: waveform, point cloud, photon counting)

Since 2018  Radiative transfer: bidirectional MC
(Optical and thermal radiometer images, LiDAR and radiative budget, with SIF and polarization)

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: $\tau_{\text{gas}}(\lambda)$, ...
  - Surface: optical properties or biochemistry

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

- **3D LAI,**

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,...
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) $\Rightarrow$ simulation of photosynthesis, evapotranspiration, ...

(Gastellu-Etchegorry et al., 1996)
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

(Yin et al., 2015)
**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)
Outline

1. Introduction to DART model
2. DART applications
3. Conclusion
DART applications

Research works with indication of projects:

- Vegetation functioning (hyperspectral): RedEdge, HyPOS (ESA)
- Urban radiative budget: H2020 UrbanFluxes, ERC Urbisphere (EU)
- AI algorithms: DIAPPOS (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, ...

<table>
<thead>
<tr>
<th>Maize stage (BBCH scale)</th>
<th>LAI 1</th>
<th>LAI 2</th>
<th>LAI 3</th>
<th>LAI 4</th>
<th>LAI 5</th>
<th>LAI 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plant height</td>
<td>0.92</td>
<td>1.28</td>
<td>1.55</td>
<td>1.79</td>
<td>2.04</td>
<td>2.24</td>
</tr>
<tr>
<td>Number of leaves</td>
<td>14</td>
<td>14</td>
<td>19</td>
<td>19</td>
<td>22</td>
<td>22</td>
</tr>
<tr>
<td>LAI</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
</tr>
<tr>
<td>Leaf max. area</td>
<td>0.105</td>
<td>0.21</td>
<td>0.315</td>
<td>0.42</td>
<td>0.525</td>
<td>0.63</td>
</tr>
</tbody>
</table>
Remote sensing images

DART scenes used as ref. $\Leftrightarrow$ High resolution images. Project S2 NG (ESA) 
(Gastellu-Etchegorry et al., 2022)
Remote sensing images

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

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

Δ_{\text{Leaves} - \text{Leaves+Wood}} \%

- \( f_{\text{APAR}}_{\text{green}} \) 17% ↓
- SIF emitted 17% ↓
- SIF exitance 24% ↓

(Malenovský et al., 2021)
**Atmosphere**

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

(DART - MODTRAN5) Residuals - 2

Mean absolute error of $T_b^{TOA}$: < 1.0K

TOA brightness temperature $T_b^{TOA}$ over France

Reference: MODTRAN5

Solar

(DART - MODTRAN5) Residuals - 2

TOA MODTRAN5

TOA DART
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: nadir (15/06/2012, 9am)  NASA G-LiHT Lidar Reference

DART: scene-leaf off  Canopy height from DART stereo pair

DART: 400x400m SERC forest  DART -20° (15/06/2012, 9am)
Polarization

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

Future polarimetric satellite missions:
- METOP-SG-A (ESA)
- OTB-2 (NASA)

(Wang Yingjie, 2022)
Inversion

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

DART

DART: total radiance

Satellite S2
(865nm): 24/6/2016

Reflectance

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

New OP maps of roofs, streets,...

Solving linear equations using DART Jacobian

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

(Zhen et al., 2021)
Inversion

(Zhen et al., 2021)

Sentinel 2 (B2, B3, B4)

DART simulation with OP maps

Resolution: 10 m

5 km
Deep learning

Training an **AI algorithm** to detect palm trees in high resolution satellite images. Project DIAPPOS (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 $\Rightarrow$ 3D temperature distribution
3D soot/gas density

**DART** $\Rightarrow$ Remote sensing observations (TIR camera, satellite)

$\Rightarrow$ Study the **fire radiative power** from satellite observation

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

Front view
(Grassland fire, Australia)
Urban surface temperature

**SOLENE** model $\Rightarrow$ 3D energy balance (2 broad bands) $\Rightarrow$ LST + $T_{air}$

**DART** model $\Rightarrow$ hyperspectral RTM (more accurate RB) $\Rightarrow$ RS observations

Impact of urban surface heterogeneity on LST estimation from TIR satellites (**TRISHNA, LSTM**)
1. Introduction to DART model

2. DART applications

3. Conclusion
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:

jean-philippe.gastellu@iut-tlse3.fr  (J.-P. Gastellu-Etchegorry)
nicolas.lauret@univ-tlse3.fr        (Nicolas Lauret)
yingjie.wang@univ-tlse3.fr          (Yingjie Wang)