DART: Improvement of Thermal Infrared Radiative Transfer Modelling

for simulating top of atmosphere radiance

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Overview

- Context: why 3D RT modelling ?
- DART model and its initial accuracy
- Improvements of TIR RT modelling
- Results and consistency tests
- Conclusion

Context

Satellite sensor TIR spectral bands and sensitivity

Satellite	Launch date	Organization	Center wavelength	Bandwidth	Sensitivity (NeDT)
Trishna	foreseen 2024-2025	CNES+ISRO	8.6 µm	0.35 µm	0.3 K@300 K
			9.1 µm	0.35 µm	0.3 K@300 K
			10.3 µm	1.0 µm	0.3 K@300 K
			11.5 µm	1.0 µm	0.3 K@300 K
Landsat 9	foreseen 2020	NASA	10.9 µm	0.6 µm	0.4 K@300 K
			12.0 µm	1.0 µm	0.4 K@300 K
Sentinel 3	2016	ESA	8.8 µm	0.6 µm	0.25 K@293 K
			10.8 µm	0.6 µm	0.25 K@293 K
			12.0 µm	0.6 µm	0.25 K@293 K

Irons et al., 2012, Donlon et al., 2012, Lagouarde et al., 2018, McCorkel et al, 2018

Accuracy requirement for LST applications:

accuracy < **1 K**

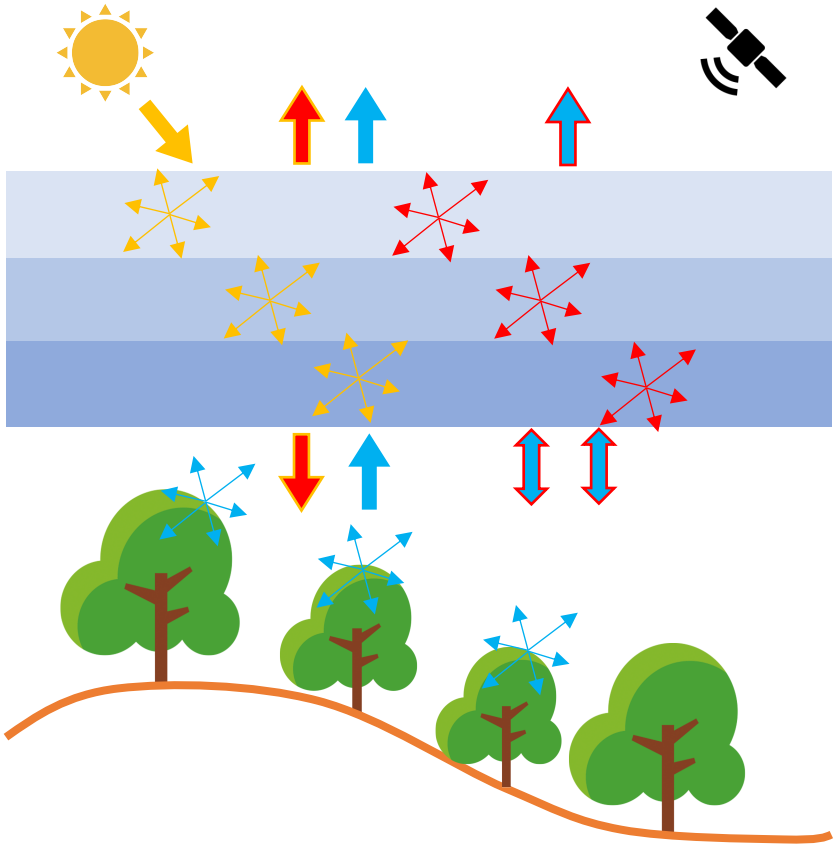
Sobrino et al., 2016

Context

Difficulties to interpret RS data

- Instrumental configuration:
spectral resolution, viewing direction, sensor FOV, …
- Experimental configuration:
topography, surface / atmosphere conditions,…

→ **3D RT Modelling**



Solar radiation

Atmosphere thermal emission

Atmosphere scattering

Direct+Diffuse radiation

Landscape thermal emission

Landscape emission + scattering

Earth-Atmosphre radiative coupling

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DART model

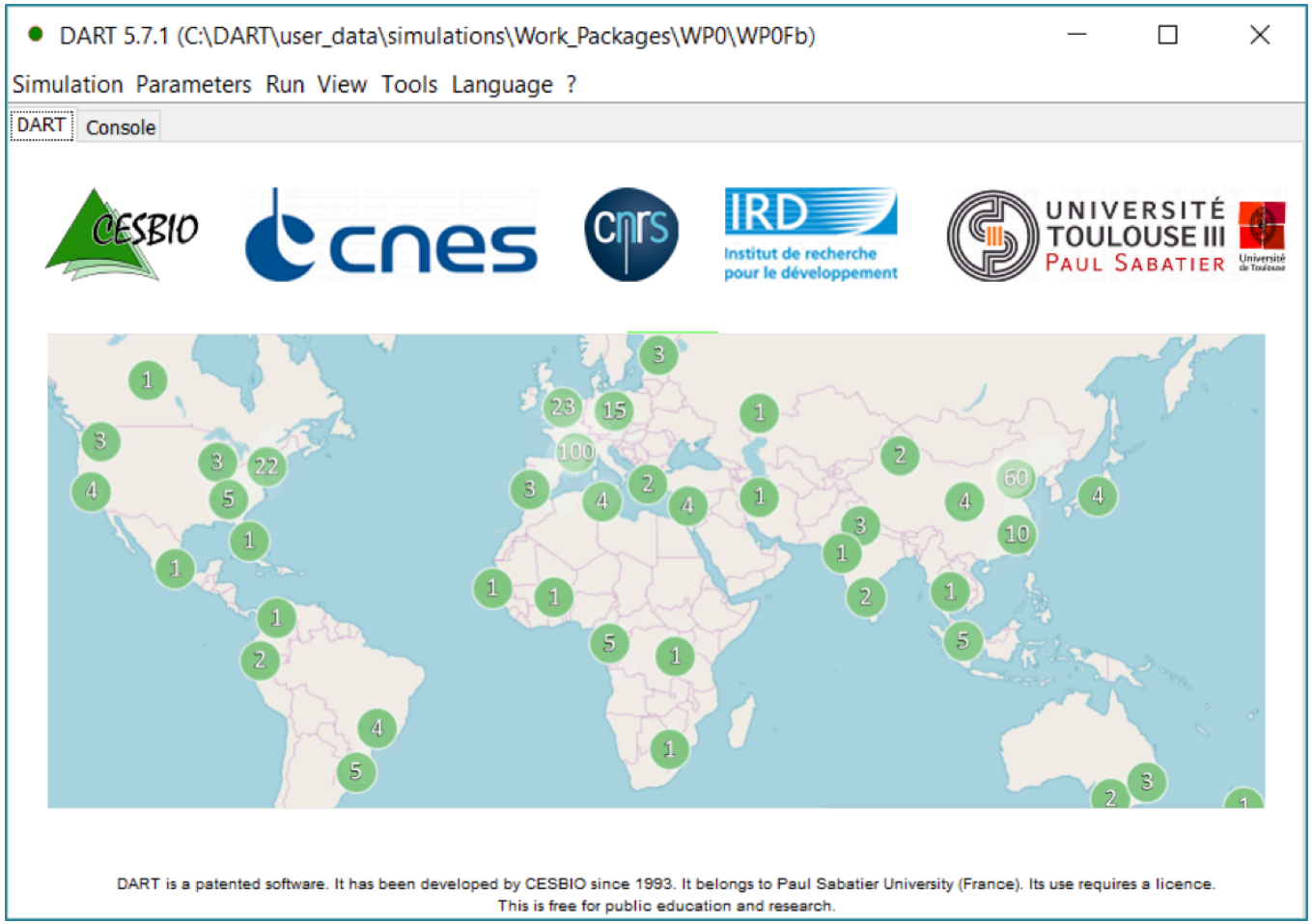
History:

Developed since 1992 by 7-10 physicists / computer scientists. Patented in 2003.

License:

Free for research & education (*http://www.cesbio.ups-tlse.fr/dart/license/*)

DART GUI (Graphical User Interface) and licence distribution



Users: 399 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.
...

DART model

Representation of 3D scene elements

- Turbid medium: vegetation
- Triangles / facets: vegetation, buildings, DEM,…
- Fluids: air, smoke, water.

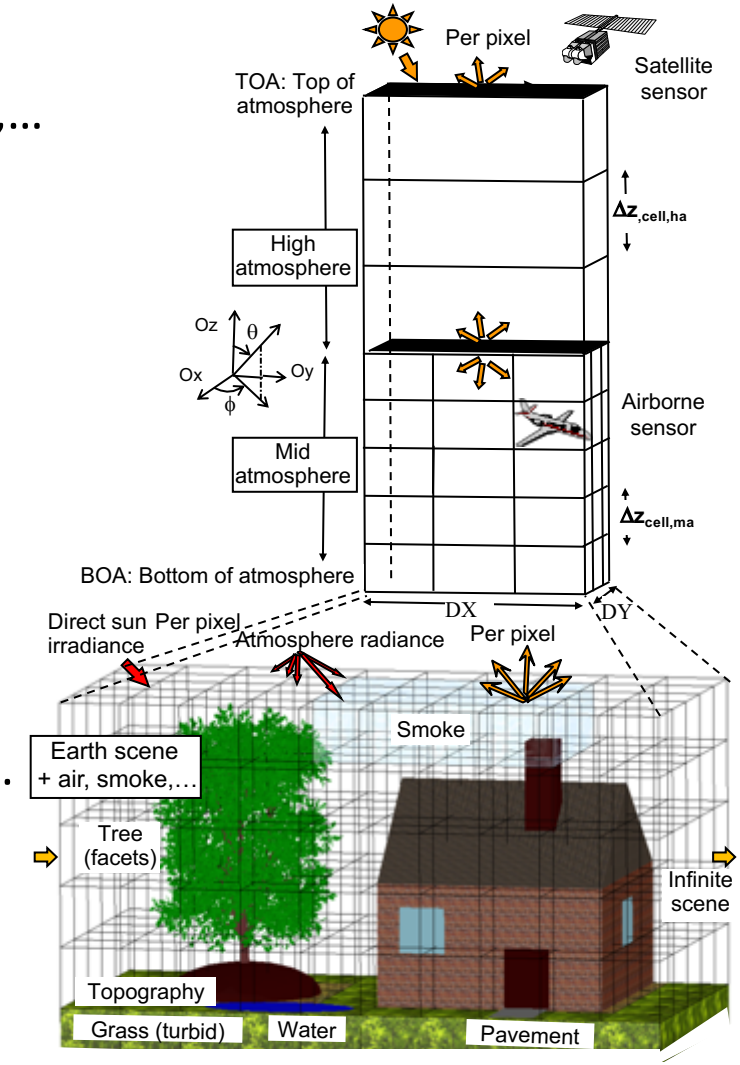
Results for any:

- Spectral band ([0.25 µm 100 µm])
- Viewing direction
- Spatial resolution,…

Different types of products:

- BOA/TOA image, polarisation: satellite, UAV,…
- LiDAR
- Fluorescence
- Radiative budget
- LUT for inversion and sensitivity studies (LAI,…)

DART Earth-Atmosphere mock-up.



Gastellu-Etchegorry et al., 2017

DART atmosphere RT modelling

Atmosphere Geometry

User defined geometry:

- atmosphere altitude
- layer thickness: $\Delta z_l = z_{l+1} - z_l$

$\Rightarrow$ *L* atmosphere layers

Layer Properties

Constant layer properties per layer $l \in [1, L]$:

- Temperature T_l
- Extinction coefficient $\alpha_{l,i}(\lambda)$ per gas *i* per band λ

$$\alpha_{l,i}(\lambda) = \frac{-\log(T_{atm,i,\lambda})}{z_{l+1} - z_l} \cdot \frac{\int_{z_l}^{z_{l+1}} \sigma_{a,i}(\lambda) \cdot N_i(z).\,dz}{\int_0^{\infty} \sigma_{a,i}(\lambda) \cdot N_i(z).\,dz}$$

normalized $\alpha_{l,i}(\lambda) \Rightarrow T_{atm,DART} = T_{atm,MODTRAN}\ \forall \lambda, i$

Thermal Emission

Beer's law:

$\Rightarrow$ transmittance $T_{atm}(\Omega) \approx e^{-\Delta\tau(\Omega)}$

Thermal radiative energy (*W*) along direction $(\Omega, \Delta\Omega)$:

$$W(\Omega, \lambda) = L_B(T_l, \lambda) \cdot \left[1 - e^{-\frac{\alpha_l(\lambda) \cdot \Delta z_l}{\mu}}\right] \cdot \mu \cdot \Delta S \cdot \Delta\Omega$$

$\omega(z, \lambda) \approx 0$

DART accuracy in TIR region

Landscape TIR RT modelling

ESA projects ⇒ accurate 3D landscape thermal emission and scattering modelling

DART recent improvements: Embree library, parallel computation, memory demand

Atmosphere RT modelling in TIR region (i.e. [3.5 µm 20 µm])

Mean Absolute Error (MAE) of TOA & BOA BT: DART vs. MODTRAN5 (1 cm^{-1})

Gas Model	TOA	BOA
USSTD76	3.1 K	2.1 K
TROPICAL	4.7 K	1.7 K
MIDLATSUM	3.8 K	1.6 K
MIDLATWIN	2.3 K	1.5 K
SUMARCSUM	2.9 K	1.7 K
SUMARCWIN	1.8 K	1.2 K
AVERAGE	3.1 K	1.6 K

MODTRAN5 accuracy: thermal BT < 1 K (*Berk et al, 2008*)

Accurate TOA radiance ⇒ atmosphere TIR RT modelling improvement

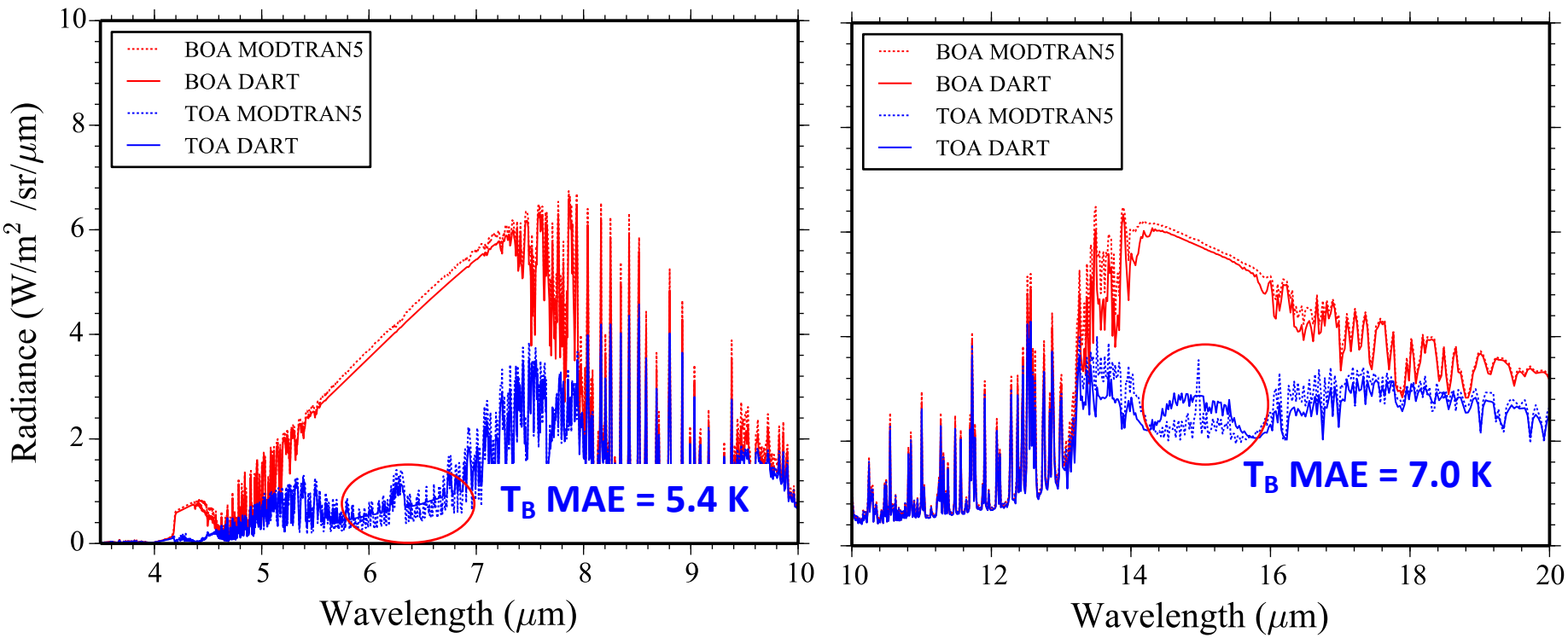
⇒ atmosphere thermal BT MAE < 1 K

DART accuracy in TIR region

Atmosphere TIR RT modelling in initial DART:

- Independence of gas absorption cross-section $\sigma_{a,i}(\lambda)$ on $T(z)$ and $P(z)$
- Unique temperature T_l and extinction coefficient $\alpha_{l,i}(\lambda)$ per atmosphere layer l
- Use of Beer's law to simulate radiation transmission in spectral bands

TOA & BOA TIR radiance : DART vs. MODTRAN5. USSTD76 gas model



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Improvements of TIR RT modelling

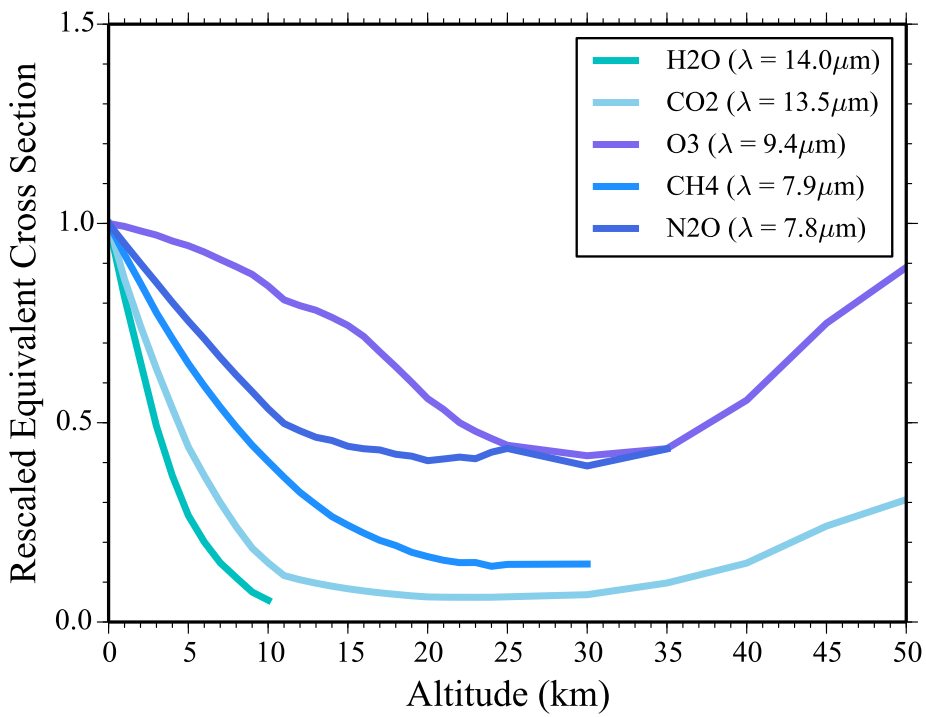
Introduction of "Equivalent absorption cross-section":

$$T_{i,z,\lambda,\Delta L} = \exp(-\sigma_{a,i,\Delta L}(z,\lambda) \cdot N_i(z) \cdot \Delta L) \Rightarrow \sigma_{a,i,\Delta L}(z,\lambda) = \frac{-\log(T_{i,z,\lambda,\Delta L})}{N_i(z) * \Delta L}$$

$\sigma_{a,i}(z,\lambda)$ is derived from MODTRAN5 simulations:

- 5 most absorbing gases i = H_2O, CO_2, O_3, CH_4, N_2O (gas density $N_i(z)$)
- transmittance $T_{i,z,\lambda,\Delta L}$ along equal-paths $\Delta L = 6$ km at 36 altitudes z.

Vertical profile of rescaled $\sigma_{a,i,\Delta L}(z,\lambda)$ for 5 most absorbing gases. USSTD76 gas model.



Scaling: $\sigma^*_{a,i}(z,\lambda) = \frac{\sigma_{a,i}(z,\lambda)}{\sigma_{a,i}(0,\lambda)}$

MODTRAN decimal precision:
ε = 5E-5

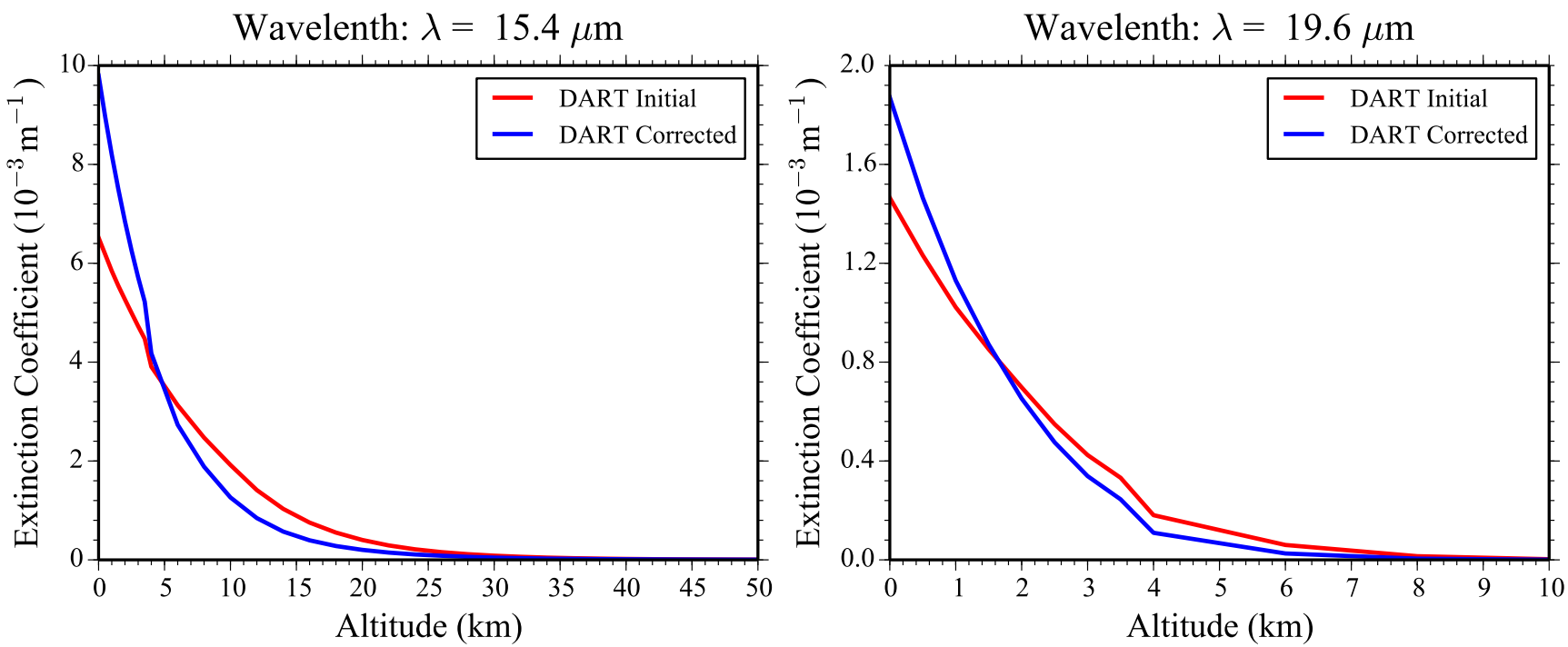
$T_{i,z,\lambda,\Delta L}$ >= 0.9999
$\Rightarrow$ meaningless $\sigma_{a,i}(z,\lambda)$

Improvements of TIR RT modelling

New normalized extinction coefficient per layer *l*

$$\alpha_{l,i}(\lambda)=\begin{cases}\dfrac{-\log(T_{atm,i,\lambda})}{z_{l+1}-z_l}\cdot\dfrac{\int_{z_l}^{z_{l+1}}\sigma_{a,i}(z,\lambda).N_i(z).dz}{\int_0^{\infty}\sigma_{a,i}(z,\lambda).N_i(z).dz}, i=H_2O, CO_2, O_3, CH_3, N_2O \\ \dfrac{-\log(T_{atm,i,\lambda})}{z_{l+1}-z_l}\cdot\dfrac{\int_{z_l}^{z_{l+1}}\sigma_{a,i}(\lambda).N_i(z).dz}{\int_0^{\infty}\sigma_{a,i}(\lambda)\cdot N_i(z).dz}, gases\ other\ than\ H_2O, CO_2, O_3, CH_3, N_2O\end{cases}$$

DART initial and corrected absorption extinction coefficients profiles. USSTD76 gas model



Improvements of TIR RT modelling

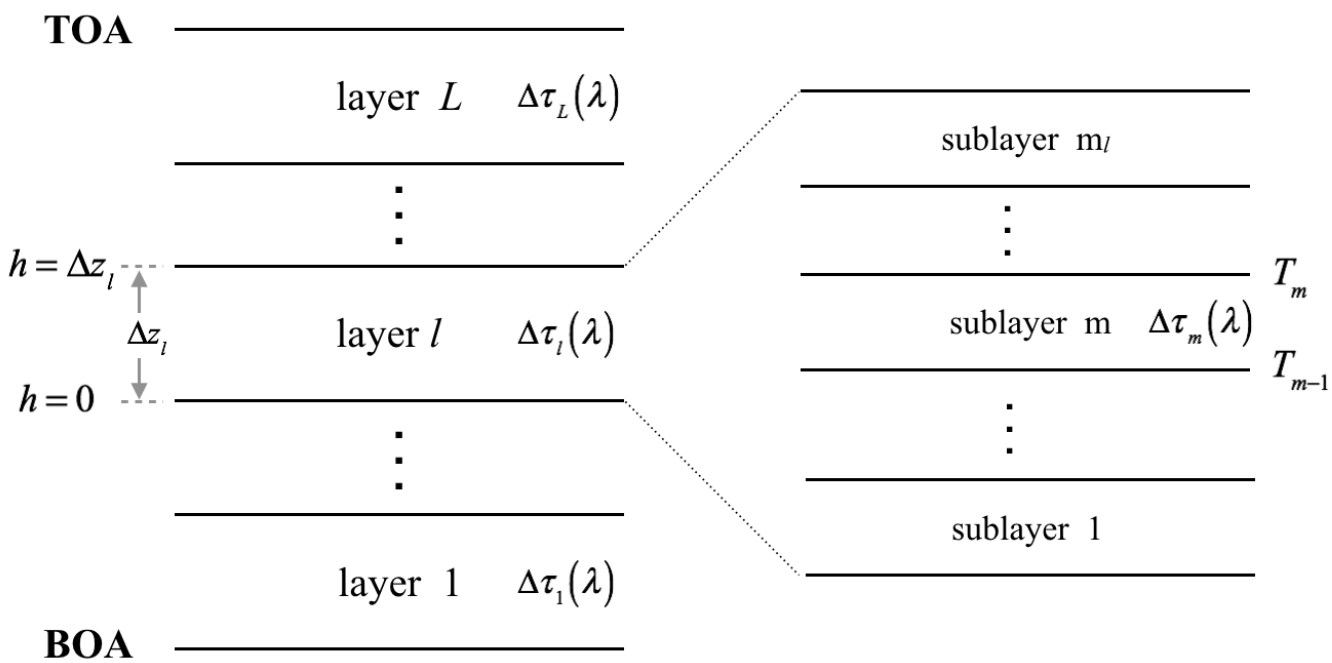
Design of continuous T(z) and $\alpha(z,\lambda)$ within and between atmosphere layers

$$\alpha(h,\lambda) = -3A_l(\lambda)\cdot h^2 - 2B_l(\lambda)\cdot h + C_l(\lambda)$$

$$T(h) = K_{1l}.h + K_{2l}$$

h = relative altitude in each atmosphere layer l;
A_l, B_l, C_l, K_l = constants per layer l.

Each atmosphere layer l is divided into m_l sub-layers.



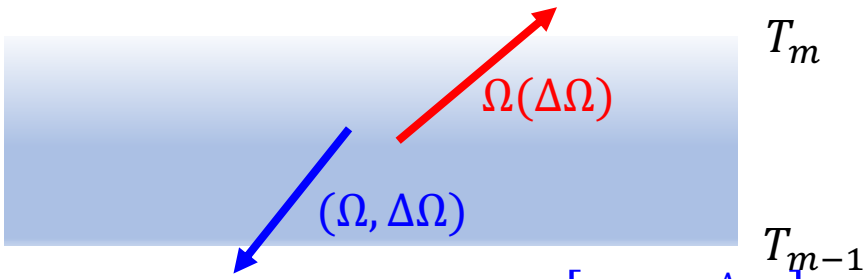
Improvements of TIR RT modelling

Numerical integration in order to compute layer thermal emission.

Four conditions to verify:

a. Constant temperature $T_m = T_{m-1}$

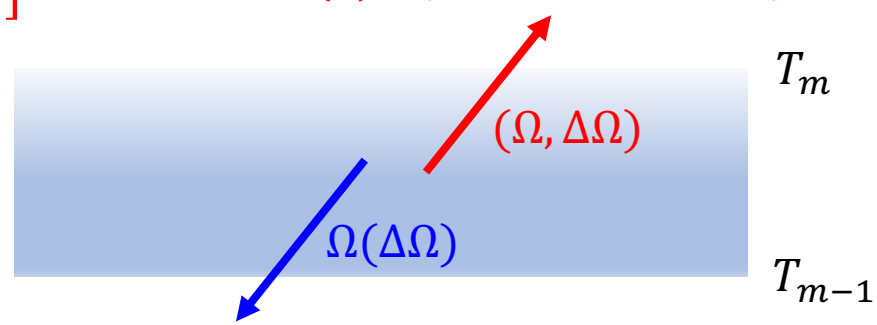
$$(1)\ L_m^{\uparrow}(\Omega, \Delta\Omega) = L_B(T_m, \lambda) \cdot \left[1 - e^{-\frac{\Delta\tau_m}{\mu}}\right]$$



$$(2)\ L_m^{\downarrow}(\Omega, \Delta\Omega) = L_B(T_m, \lambda) \cdot \left[1 - e^{-\frac{\Delta\tau_m}{\mu}}\right]$$

b. Infinite $\Delta\tau_m$:

$$(3) L_m^{\uparrow}(\Omega, \Delta\Omega) = L_B(T_m, \lambda)$$



$$(4)\ L_m^{\downarrow}(\Omega, \Delta\Omega) = L_B(T_{m-1}, \lambda)$$

⇒ **Final expression:**

$$W_l^{\uparrow}(\Omega, \Delta\Omega) = \sum_{m=1}^{m_l} \left[L_B(T_{m-1}, \lambda).\, e^{-\frac{\Delta\tau_m}{2\mu}} + L_B(T_m, \lambda)\right].\left[1 - e^{-\frac{\Delta\tau_m}{2\mu}}\right].\, e^{-\frac{\tau_m}{\mu}}.\, \mu.\, \Delta S.\, \Delta\Omega$$

$$W_l^{\downarrow}(\Omega, \Delta\Omega) = \sum_{m=1}^{m_l} \left[L_B(T_{m-1}, \lambda) + L_B(T_m, \lambda).\, e^{-\frac{\Delta\tau_m}{2\mu}}\right].\left[1 - e^{-\frac{\Delta\tau_m}{2\mu}}\right].\, e^{-\frac{(\tau_{l-1} - \tau_{m-1})}{\mu}}.\, \mu.\, \Delta S.\, \Delta\Omega$$

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Results

Mean Absolute Error (MAE) of TOA & BOA BT: DART vs. MODTRAN5. In [3.5 µm, 20 µm] region.

Gas Model	Initial TOA	Improved TOA	Initial BOA	Improved BOA
USSTD76	3.1 K	0.70 K	2.1 K	0.85 K
TROPICAL	4.7 K	1.02 K	1.7 K	0.59 K
MIDLATSUM	3.8 K	0.91 K	1.6 K	0.59 K
MIDLATWIN	2.3 K	0.60 K	1.5 K	0.70 K
SUMARCSUM	2.9 K	0.75 K	1.7 K	0.68 K
SUMARCWIN	1.8 K	0.48 K	1.2 K	0.60 K
AVERAGE	**3.1 K** ➡	**0.74 K**	**1.6 K** ➡	**0.67 K**

Atmosphere thermal BT MAE < 1 K !

Results

TOA BT difference (DIFF): DART vs. MODTRAN5. USSTD76 gas model.

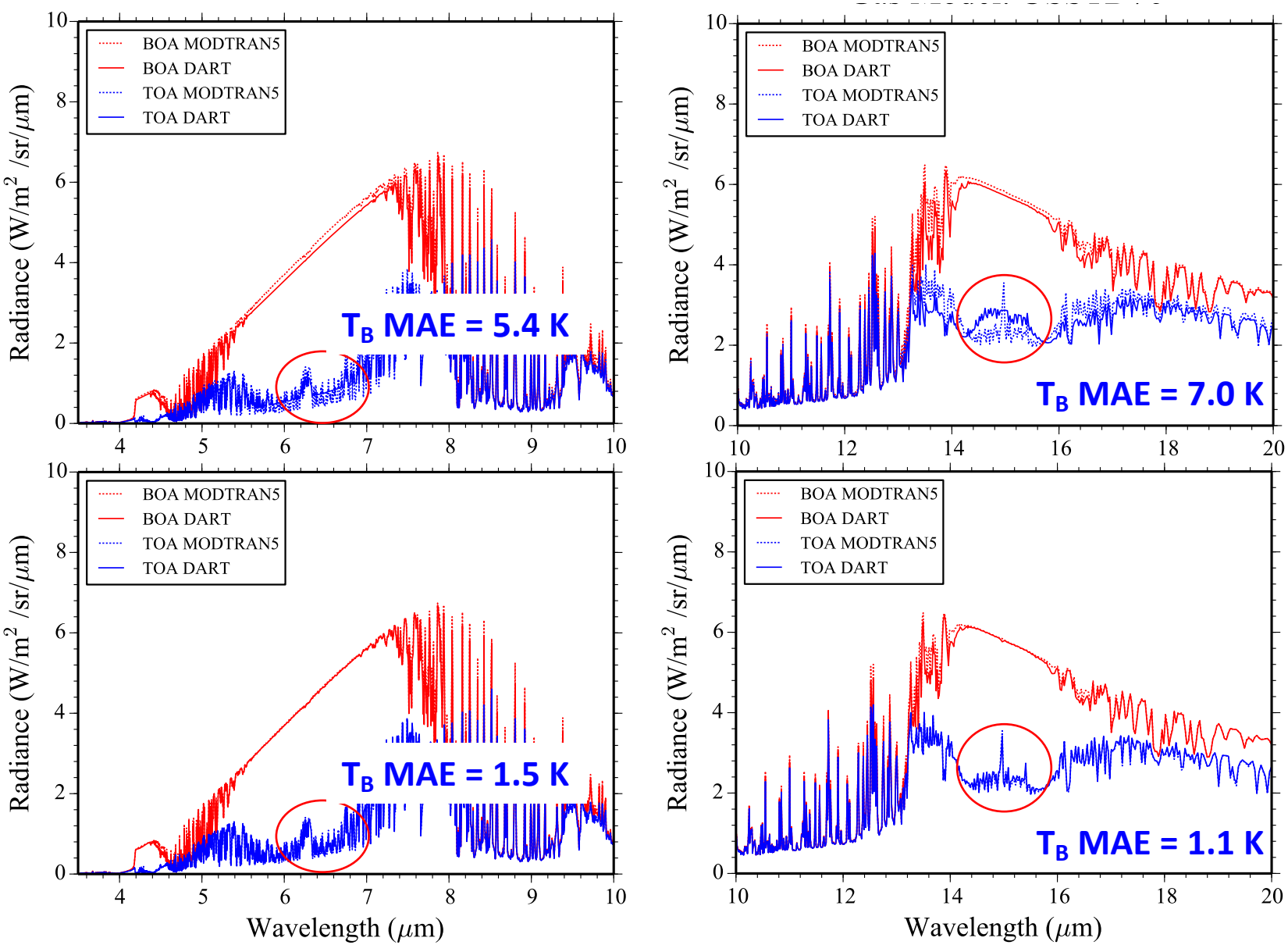
Satellite	Center wavelength	Bandwidth	Sensitivity (NeDT)	Initial	Improved
Trishna	8.6 μm	0.35 μm	**0.3 K**@300 K	0.65 K	**0.179 K**
	9.1 μm	0.35 μm	**0.3 K**@300 K	1.56 K	**0.079 K**
	10.3 μm	1.0 μm	**0.3 K**@300 K	2.60 K	**0.233 K**
	11.5 μm	1.0 μm	**0.3 K**@300 K	1.49 K	**0.032 K**
Landsat 9	10.9 μm	0.6 μm	**0.4 K**@300 K	1.95 K	**0.002 K**
	12.0 μm	1.0 μm	**0.4 K**@300 K	1.71 K	**0.055 K**
Sentinel 3	8.8 μm	0.6 μm	**0.25 K**@293 K	0.46 K	**0.210 K**
	10.8 μm	0.6 μm	**0.25 K**@293 K	2.09 K	**0.008 K**
	12.0 μm	0.6 μm	**0.25 K**@293 K	1.65 K	**0.019 K**

Results

TOA & BOA TIR radiance : DART vs. MODTRAN5. USSTD76 gas model, spectral resolution 1 cm-1.

Before

After



Consistency test

Measurements:
thermal emission spectra of Sahara and Mediterranean region from IRIS-D on Nimbus 4. Spectral resolution 2.8 cm^{-1} *Hanel et al. 1971*

DART simulation configurations:

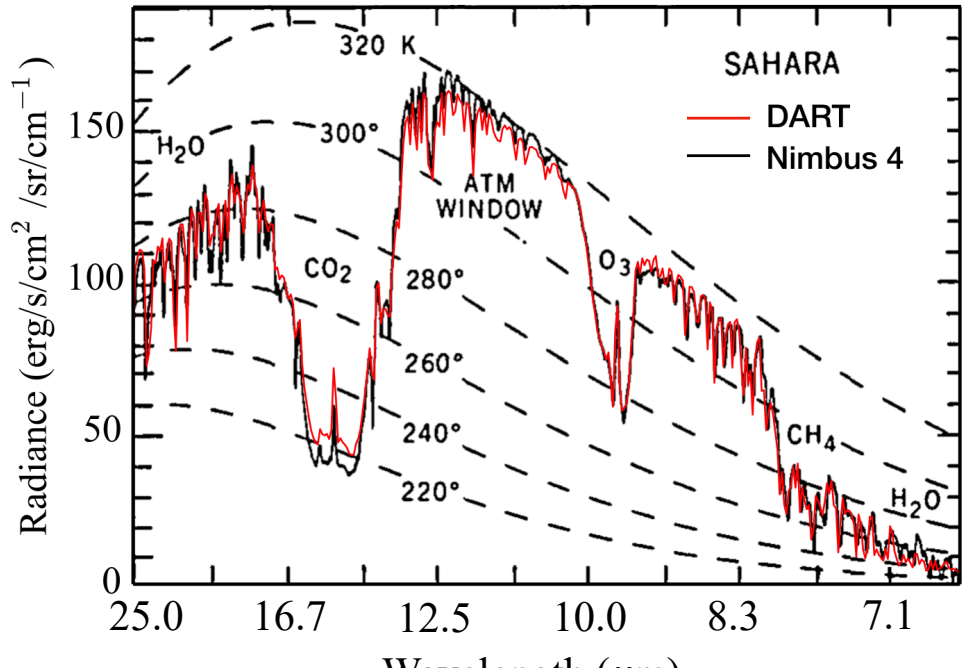
Sahara region:

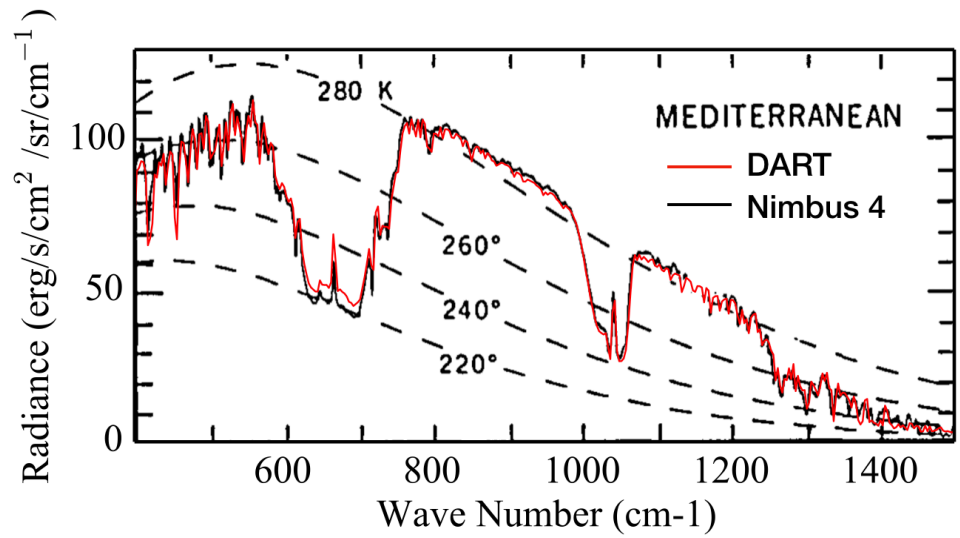
Gas = TROPICAL + ↓50% H_2O
Aerosol = DESERT_V76km
CO_2 ratio = 340 ppm
ρ_{ground} = yellowish loamy sand
$T_{surface}$ = 325 K

Mediterranean sea region:

Gas = USSTD76 + ↑ 50% H_2O
Aerosol = MARITIME_V23km
CO_2 ratio = 380 ppm
ρ_{sea} = 0.0
T_{sea} = 285 K

TOA TIR radiance : DART vs. Nimbus 4





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Conclusion:

DART TIR RT modelling accuracy is greatly improved with the introduction of:

- equivalent absorption cross-section
- continuous $T_l\ (z)$ and $\alpha_{l,i}(z,\lambda)$ per atmosphere layer l

$\Rightarrow$ DART TIR BT MAEs are reduced: - from 3.1 K to **0.74 K** at TOA

- from 1.6 K to **0.67 K** at BOA

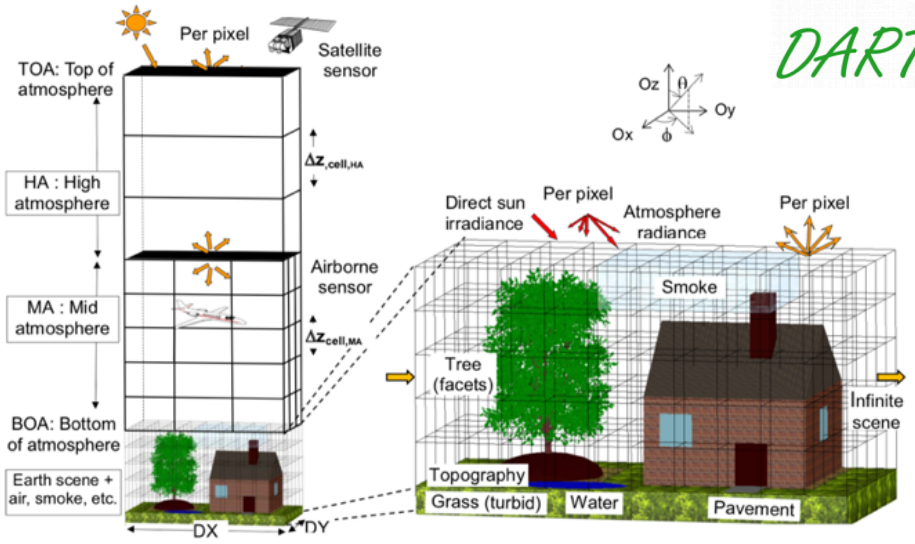
$\Rightarrow$ Improvements are much larger in TIR absorption regions.

$\Rightarrow$ DART TOA radiance accuracy reaches LST accuracy requirement

Perspective:

Improvement of radiative coupling of atmosphere over sloping terrain.

Thanks


Per pixel
Satellite sensor
TOA: Top of atmosphere
HA : High atmosphere
MA : Mid atmosphere
Airborne sensor
BOA: Bottom of atmosphere
Earth scene + air, smoke, etc.
DX
DY
Oz
Oy
Ox
Direct sun irradiance
Per pixel
Atmosphere radiance
Per pixel
Smoke
Tree (facets)
Infinite scene
Topography
Grass (turbid)
Water
Pavement