Lightning radiative transfer in realistic convective clouds

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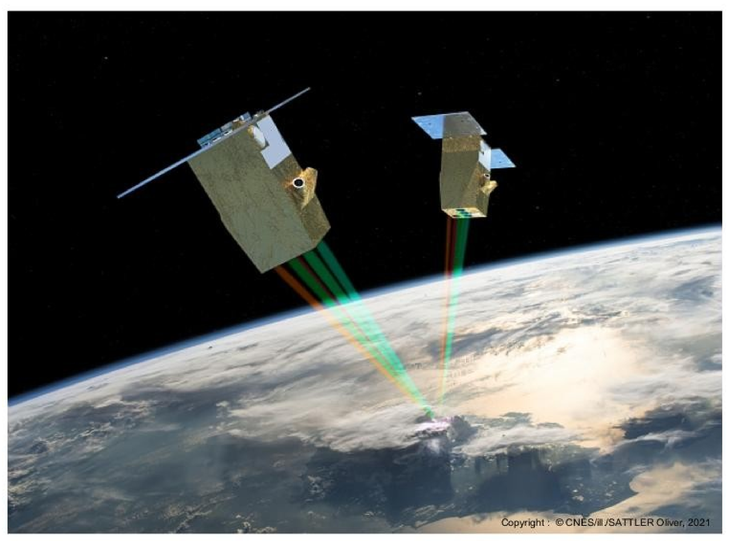
Abstract: Atmospheric scattering and absorption of flash radiations in thunderclouds is more or less important depending on the microphysics and density of the cloud, the spatio-temporal characteristics of the flash, or the wavelength of observation. To better understand the lightning flash and cloud interactions, a flash source has been introduced in the "Three-dimensional polarized Monte-Carlo atmospheric radiative transfer model" (3DMCPOL). We present a realistic simulation of lightning radiation as the French-Israeli space-mission C3IEL cameras should sense. The same simulation is adapted for the MTG-LI mission. This 3DMCPOL code can the be used as a reference to study the propagation of the lightning light through the clouds, enabling a better interpretation of the new measurements observed by operational space-borne instruments.

1. C³IEL SPACE MISSION AND LOIP INSTRUMENTS



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Publication Presse, Scientifique, Educative et Pédagogique.

System	LOI (Camera)	LP (Photometer)
FOV (km)	360 x 302	360 x 360
Pixel size	140 m	360 km
Frame rate	≤ 10 ms	50 µs

C³IEL space mission project overview (CNES & ISA):

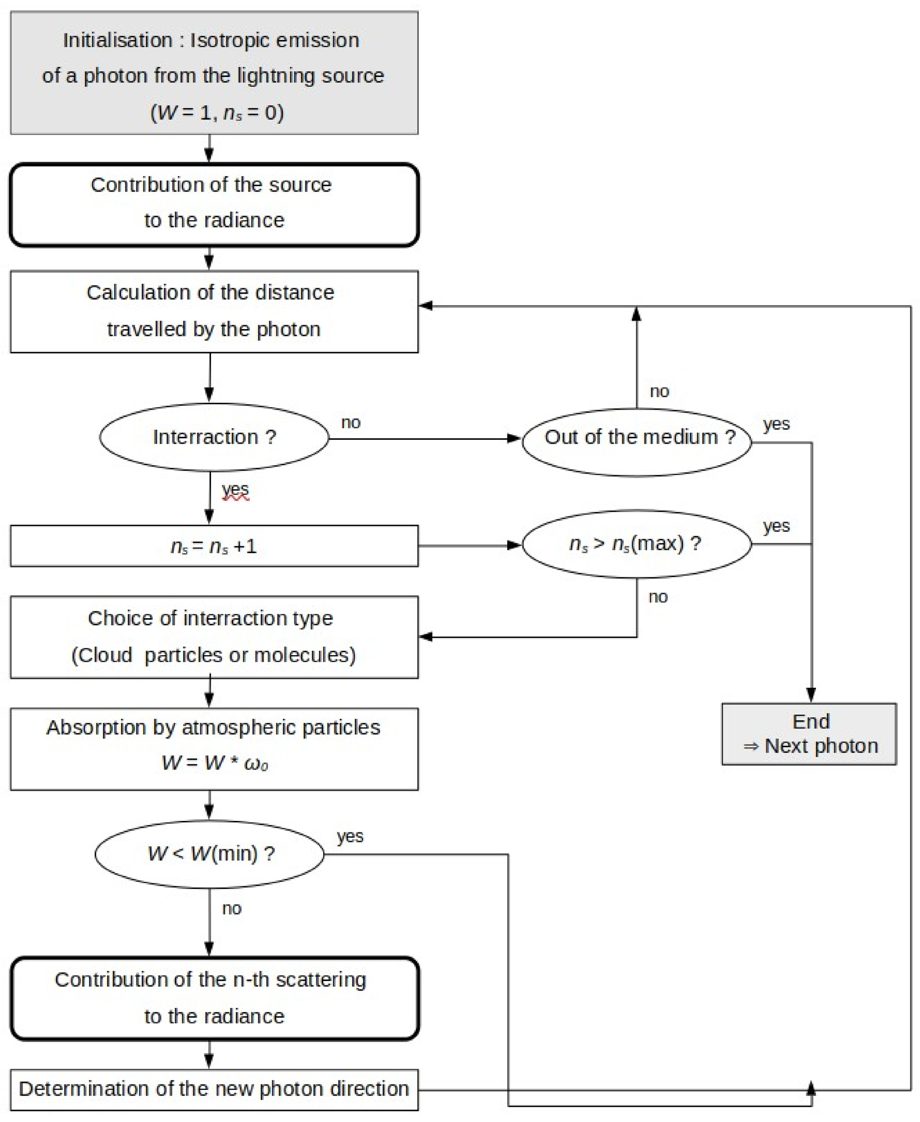
- 2/3 nano-sats flying in train observing the same cloudy scene
- Study of convective clouds at a high spatial and temporal resolution
- Polar orbit, 13:30 LT, 600 km

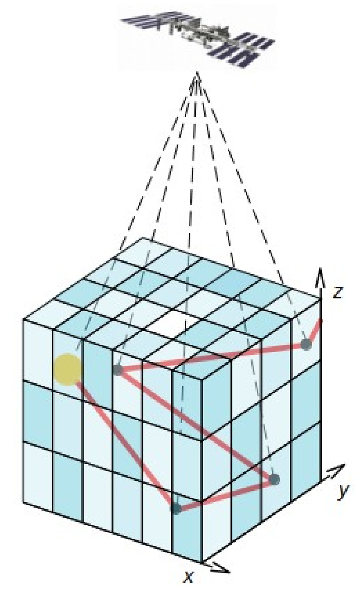
Optical instruments:

- **CLOUD** (20m, 0.670 µm) and **WV** (water vapor, 1.04 µm; 1,13 µm; 1.37 µm) imagers
- **Lightning Optical Imagers and Photometers** (**LOIP**) (777.4 nm)

→ **Links between the electrical activity and the dynamic, microphysical properties of the cloud**

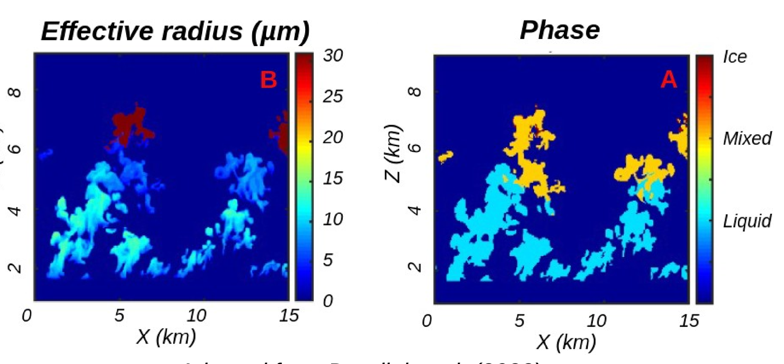
2. LIGHTNING RADIATIVE TRANSFER WITH 3DMCPOL



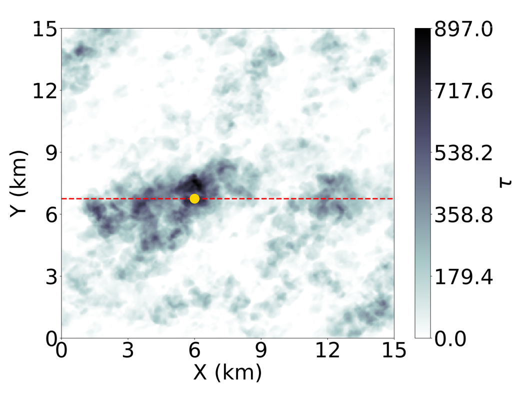


The 3DMCPOL code (Cornet et al. 2010) allows to solve the radiative transfer equation with the Monte-Carlo method and is widely used in the remote sensing community to simulate the radiative effects of heterogeneous clouds in a 3D atmosphere. 3DMCPOL has been validated by intercomparisons with other 3D reference codes (Emde et al. 2018), for an external solar source. A lightning source has been introduced inside the medium and its observations by on-board and ground-based photometers and cameras (Rimboud et al. 2023).

3. CLOUD MICROPHYSICS AND OPTICAL PROPERTIES



Adapted from Dandini et al. (2022)



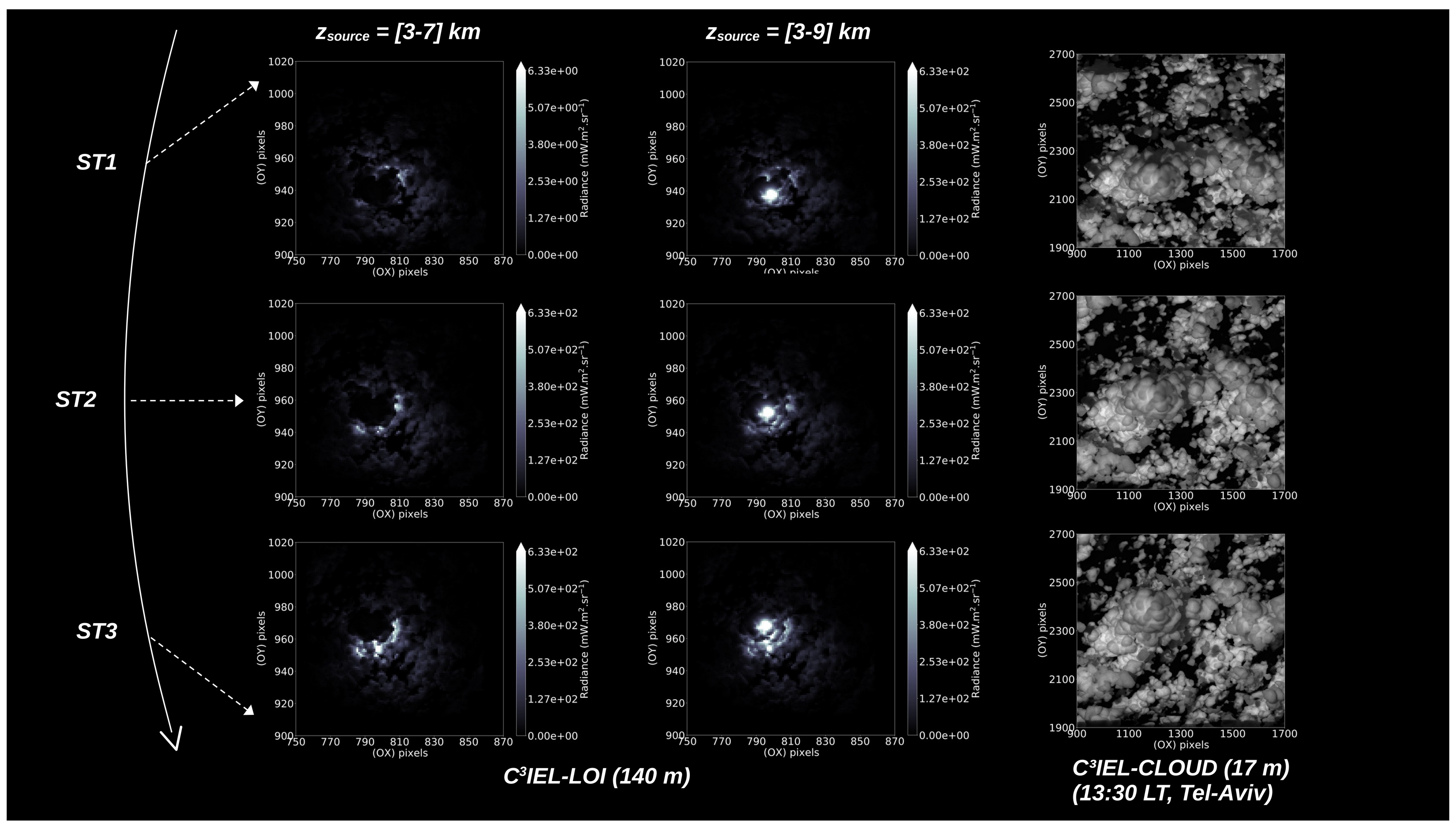
Cloud configuration:

- **Convective cloud** (Strauss et al., 2019) generated via the atmospheric research model **Meso-NH** (snow, ice crystals, graupel, cloud droplets, rain drops)
- **50 m spatial resolution**
- Cloud top at about 9 km and horizontal extent around 10 km

Optical properties:

- **Mie theory** for **cloud droplets**
- **Baran parametrisation** for **ice crystals**

4. VERTICAL LIGHTNING FROM LOIP SIMULATIONS: DIRECT vs SCATTERED RADIATION at 777.4 nm (Night-time)



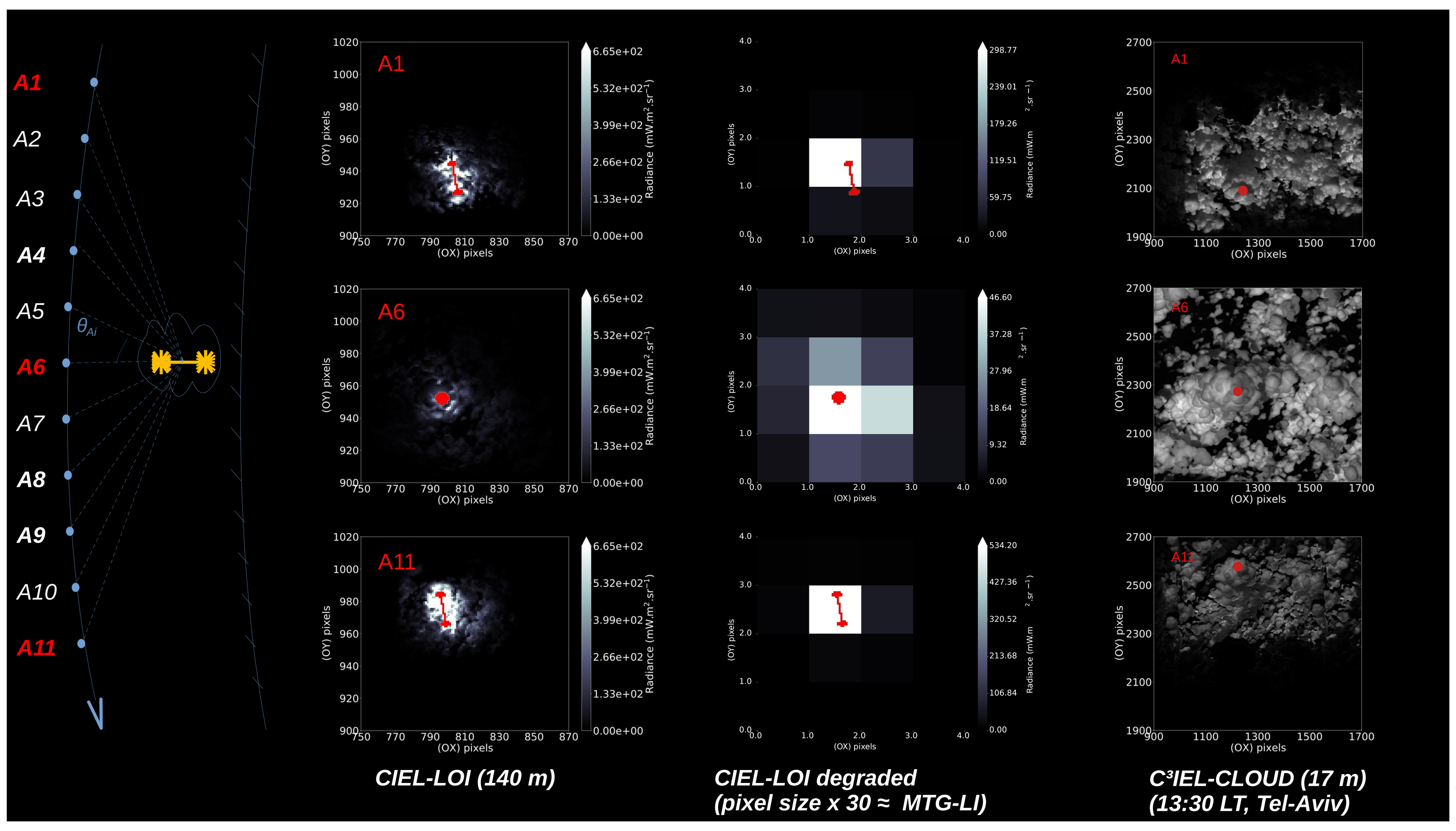
Direct Radiation (z_{source} = *vertical segment [3 – 9] km*):

- Optical depth τ between lightning top and cloud top is low ($\simeq 40$)
- Lightning light escapes from the top of the cloud, lightning structure potentially retrievable

Scattered Radiation (z_{source} = *vertical segment [3 – 7] km*):

- As the source top deeper into the cloud, τ is higher ($\simeq 290$)
- Lightning light escapes from the cloud sides, illuminated pixels more distant from the flash source

5. VARIATION OF THE VIEWING ANGLE (LOIP AND MTG-LI): PARALLAX EFFECTS AND LIGHTNING SEEN FROM THE TOP AND THE SIDE



MTG-LI (Geostationary orbit):

- 84 % of the Earth disk observable
- Day and night-time lightning detection at 777.4 nm
- 1 ms temporal resolution, 4.5 x 4.5 km spatial resolution at nadir

Nadir and tilted viewings of the same radiative transfer calculations result in different images (LOI and MTG-LI):

- Detection of the cloud region illuminated by lightning in the observed direction θ_{Ai}:
  → Cloup top in A6, upper and lower regions in A1 and 11
- Illuminated pixels are emanating from different lightning segments when θ_{Ai} varies

Conclusion:

3DMCPOL: A reference code to study scattering of flash light

- Simulations of heterogeneous clouds in 3D and observations from cameras and photometers
- Temporal variations of the lightning sources (not shown here)

Direct/scattered radiation

- Imagery: Lightning light escapes / doesn't escape from the cloud top in the observation direction
- Photometry: Peaked / Broadened waveforms (not shown here)

Perspectives:

Mapping the flash source:

- Use of stereoscopic methods (Dandini et al., 2022) to reconstruct the lightning position
- Construction of a library with numerous simulated cases (variation in observation angles, source depth, lightning branch sizes, cloud shapes ...)
  → Identification of lightning positions by matching observations to simulated cases

Realistic lightning skeleton:

- Position defined from the electrical charge distribution influenced by the cloud microphyscis (Barthe and Pinty, 2007)

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