Recent progress of the long-wave infrared instrument for atmosphere monitoring within the StarDICE experiment

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Definitions and notations

- **LWIR :** Long-Wave Infrared band ~ 7 - 14 µm
- **Radiance :** radiant flux emitted, reflected, transmitted, or received by a surface, per unit solid angle per unit projected area = **L** in $W/m^2/sr$
- **Spatial noise :** standard deviation of a single complete image
- **Temporal noise :** standard deviation of a single pixel value on consecutive images for a supposed constant scene radiance
- **Cloud optical depth τ** : measure of the attenuation of light due to cloud particles along a given path
- **Radiometric** ⇒ LWIR thermal camera (sky measurements)
- **Photometric** ⇒ UV-VIS-NIR w/ CCD camera (stars measurements)

1. Why using an infrared thermal camera ?

1.1 "Gray" extinction as a limiting systematic

$$F_{SD} = \int_\lambda S_\star(\lambda) \times R_{SD}(\lambda) \times \boxed{T_{atm}(\lambda)} \times t_{exp,SD} \times A_{mirror,SD} \times \frac{\lambda d\lambda}{hc}$$

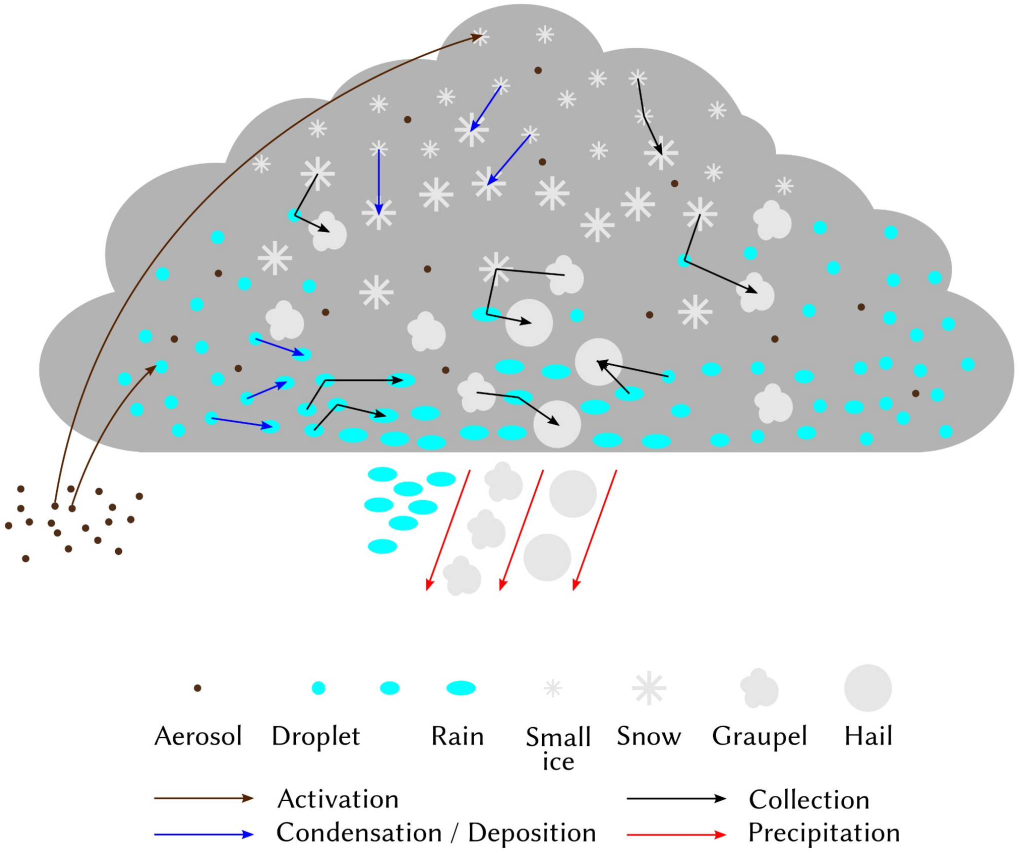
$$T^{atm}(alt,az,t;\lambda) = T_{gray} e^{-z(alt)\cdot\tau_{aerosol}(alt,\, az,\, t;\, \lambda)}$$
$$\times (1.0 - C_{mol}(BP(t)/BP_0) A_{mols}(z(alt);\lambda))$$
$$\times (1.0 - \sqrt{C_{mol} BP(t)/BP_0} A_{mola}(z(alt);\lambda))$$
$$\times (1.0 - C_{O_3} A_{O_3}(z(alt);\lambda))$$
$$\times (1.0 - C_{H_2O}(alt,az,t) A_{H_2O}(z(alt);\lambda)).$$

- Empirical wavelength-independent "gray" normalization T_{gray} is fitted for each observation (Burke et al. 2010) → **insufficient as calibration is limited by a rapidly changing conditions with moving and evolving cloud cover**
- Given by spectra + local measurements + radiative transfer simulations

1.2 What is causing "gray" extinction ?

Ice crystals and water droplets in clouds :

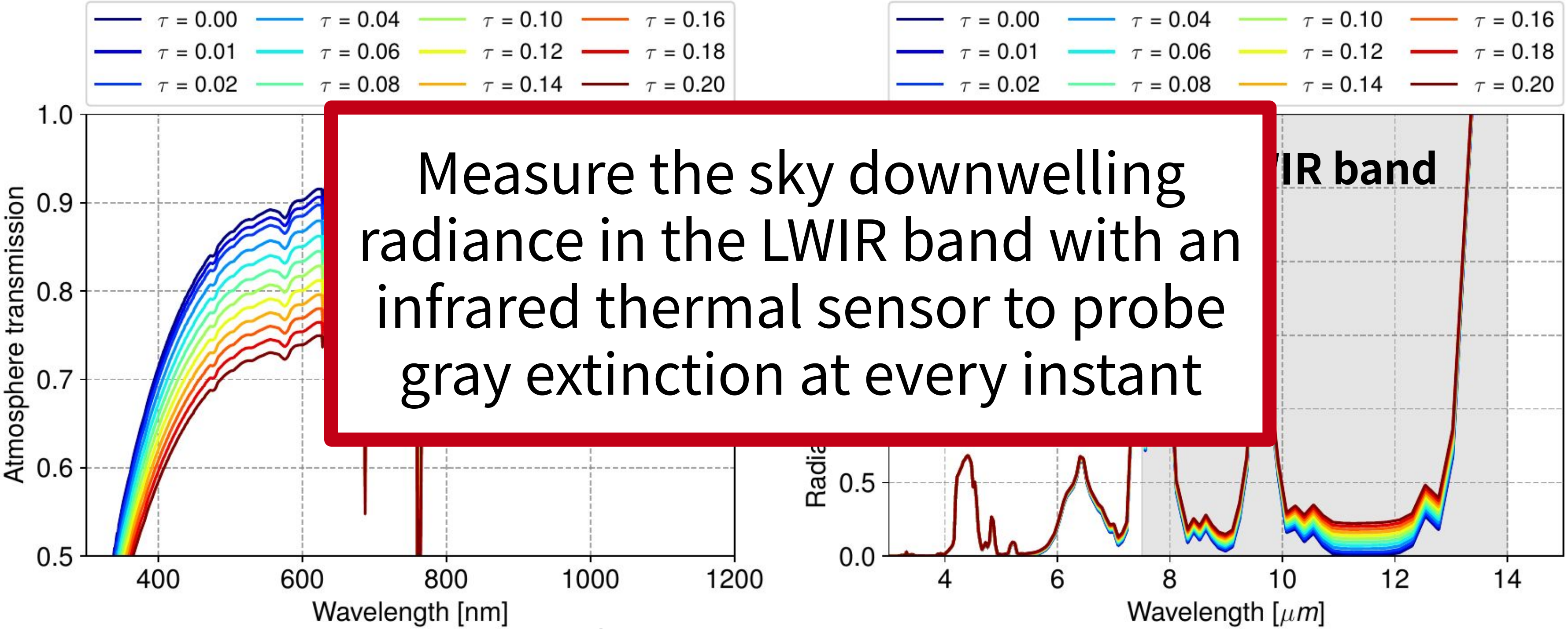
- Produce shadows that appear as "gray" in UV-VIS-NIR (independent of wavelength) ⇒ **decrease in atmosphere transmission** ⇒ decrease in stellar source flux
- Produce thermal emission ⇒ **increase in radiance / brightness temperature**



What's happening in the clouds? Encyclopedia of the Environment [ISSN 2555-0950]

1.3 Effect on UV-VIS-NIR photometry and LWIR radiance

→ Measuring the sky radiance in LWIR band appears as a potential solution

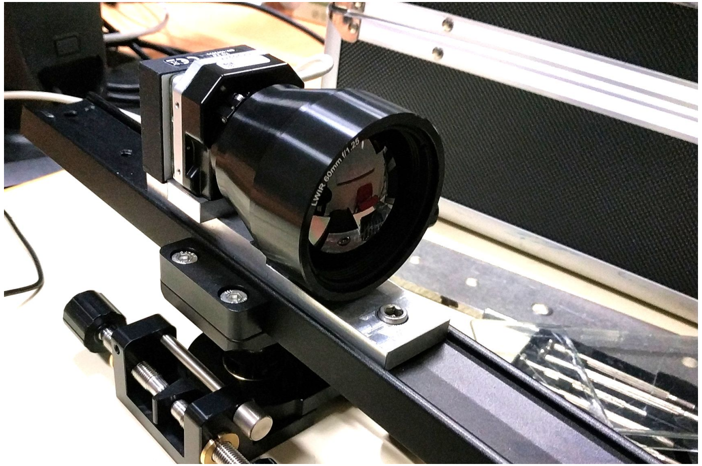


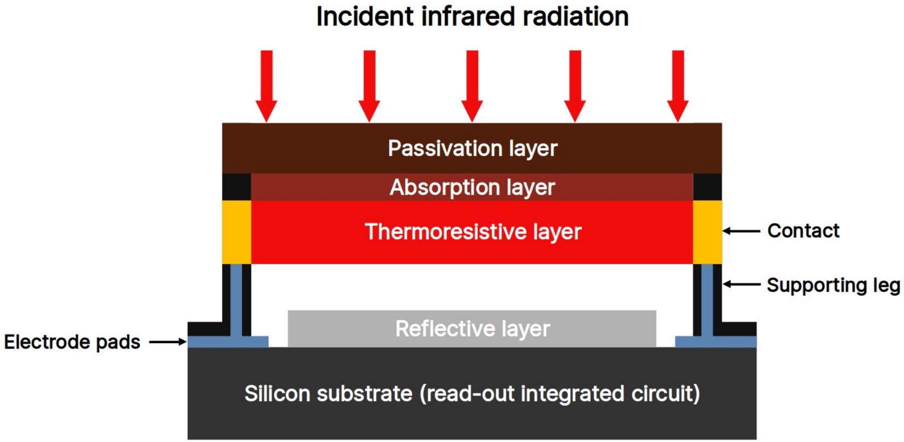
Measure the sky downwelling radiance in the LWIR band with an infrared thermal sensor to probe gray extinction at every instant

Credits: Sylvie Dagoret-Campagne

1.4 Description of the instrument

- 640 x 512 pixels <u>uncooled microbolometers</u> focal plane array
- Large FOV = 10.4 x 8.3 deg
- 8.33 Hz imaging rate ⇒ ~ 80 GB/night
- Radiometrically calibrated radiance images in radiances W/m^2/sr



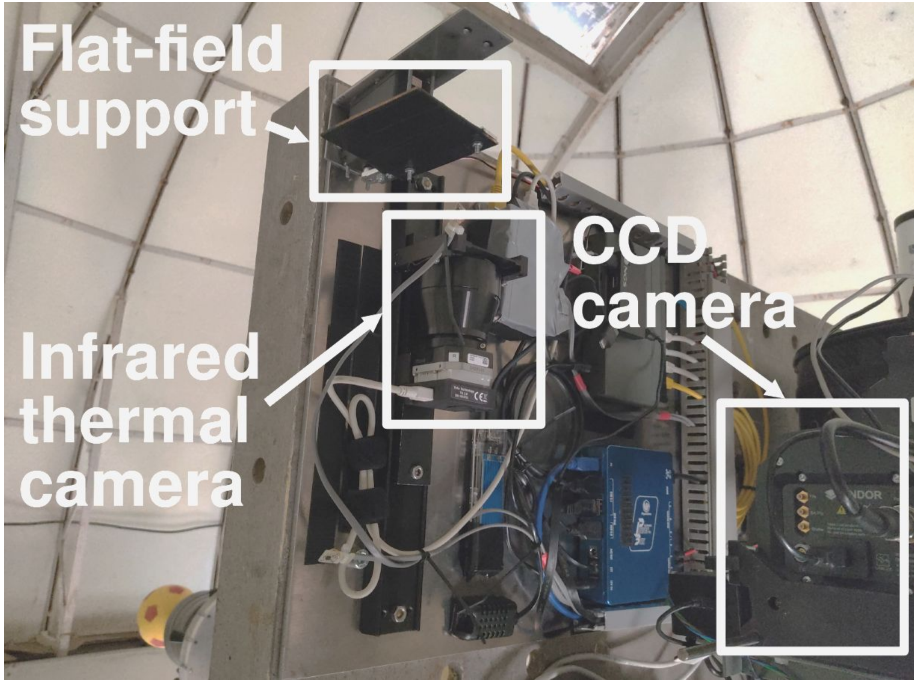


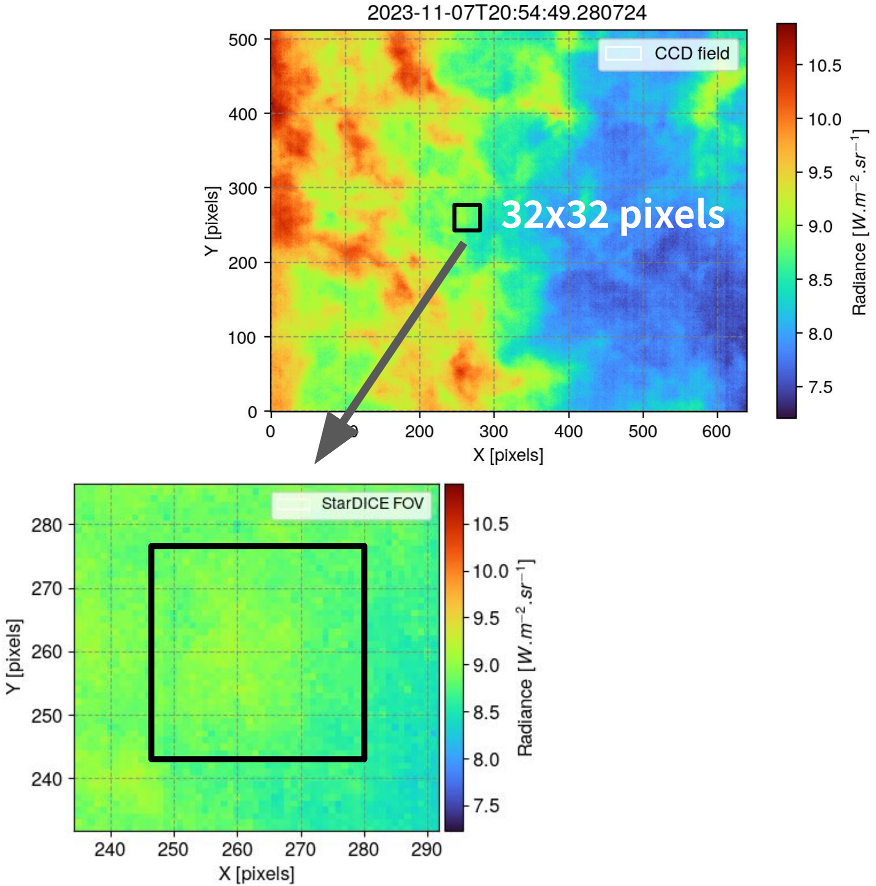
Voltage change | Gain | Scene radiance | Offset

$$\boxed{\Delta V} = \boxed{A} \times \boxed{L_{s2}} + \boxed{B(L_{pix})}$$

Does definitely not work like a photon counting sensor !

1.5 Infrared instrument installed @ OHP





2. Goals

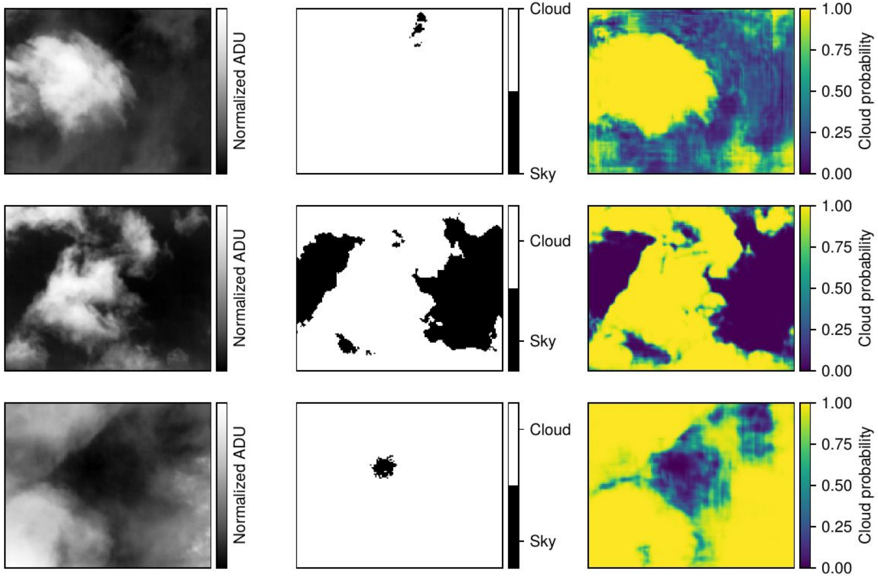
2.1 Short-term goal(s)

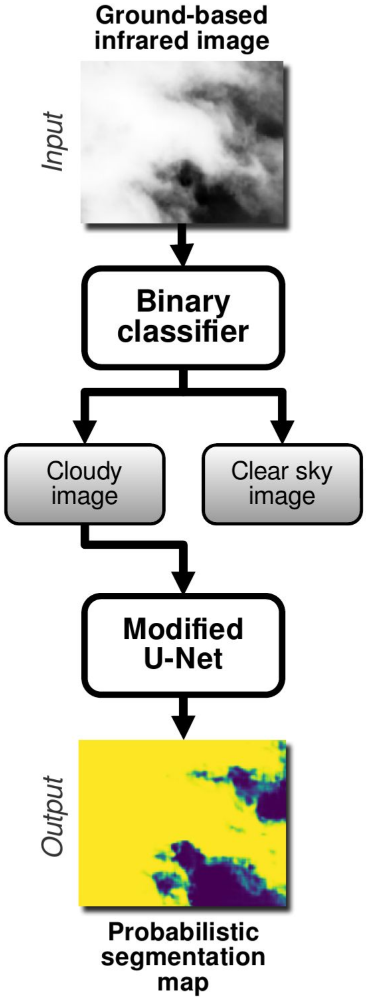
- **Identify spectro/-photometric exposures affected by gray extinction / clouds**

  → classification, cloud structure detection / image segmentation

  → flag them and remove them from the analysis

Infrared Radiometric Image Classification and Segmentation of Cloud Structure Using Deep-learning Framework for Ground-based Infrared Thermal Camera Observations
K. Sommer, **W. Kabalan**, R. Brunet
In prep.
Atmosphere Measurement Techniques, European Geosciences Union (AMT Copernicus)





2.2 Long-term goal(s)

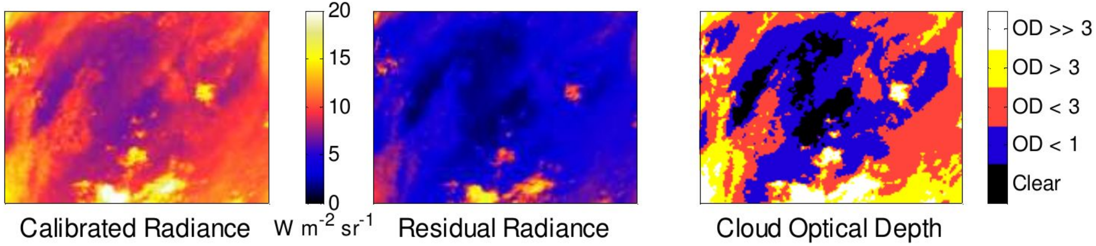
- **Correct photometry for spurious variations**

  → find a method to produce the quantitative metric T_{gray}

  → comparisons with simulations: sky background radiance removal to derive the gray extinction component

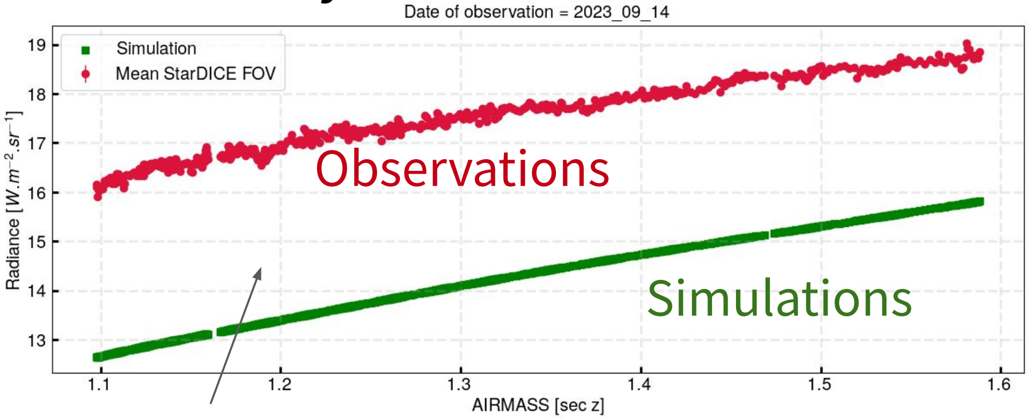
  → joint-analysis with other data: observed spectrum, lidar, AERONET to fit the atmosphere

  → correct sub-regions of CCD images



Source: Nugent et al. 2009

Sky thermal IR radiance

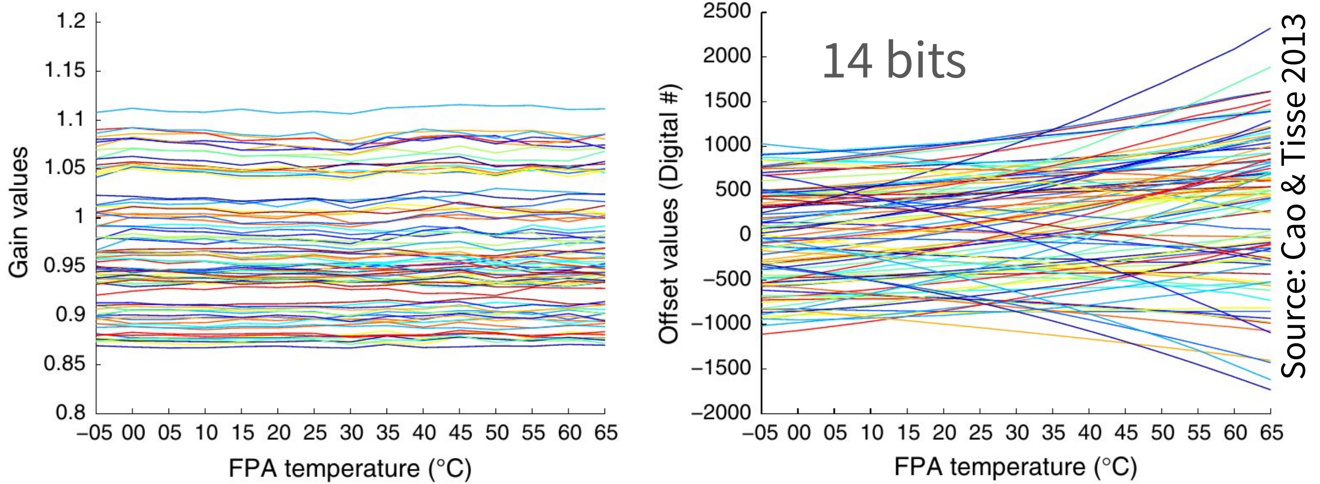


Discrepancy: calibration ? simulation ? both ?
→ work in progress

3. Radiometric calibration

3.1 Motivation

- **Why calibrating the camera ?**
  - Correct for camera gain and offset drifts
  - Compare nights between each other
  - Compare to simulations of sky radiance to evaluate the background level (e.g. libRadTran radiative transfer code)



3.2 Method

- **How ?**
  - Acquire data with a controlled thermal source (e.g. blackbody surface with known temperature and emissivity)
  - Put the camera at different ambient temperatures inside a controlled area
  - Fit a set of calibration parameters θ of the model L_{model} on the expected scene radiance L_{scene}

$$-2ln(\mathcal{L}) = \chi^2 = [L_{scene} - L_{mod}(\theta)]^T \cdot C^{-1} \cdot [L_{scene} - L_{mod}(\theta)]$$

$$L_{scene} = \epsilon_{BB} \times L_{BB} + (1 - \epsilon_{BB}) \times L_{AMB}$$

$$L_{mod} \equiv f(\theta, S, T_{FPA})$$

1 set of fitted parameters **θ** per pixel ⇒ 327,680 regressions

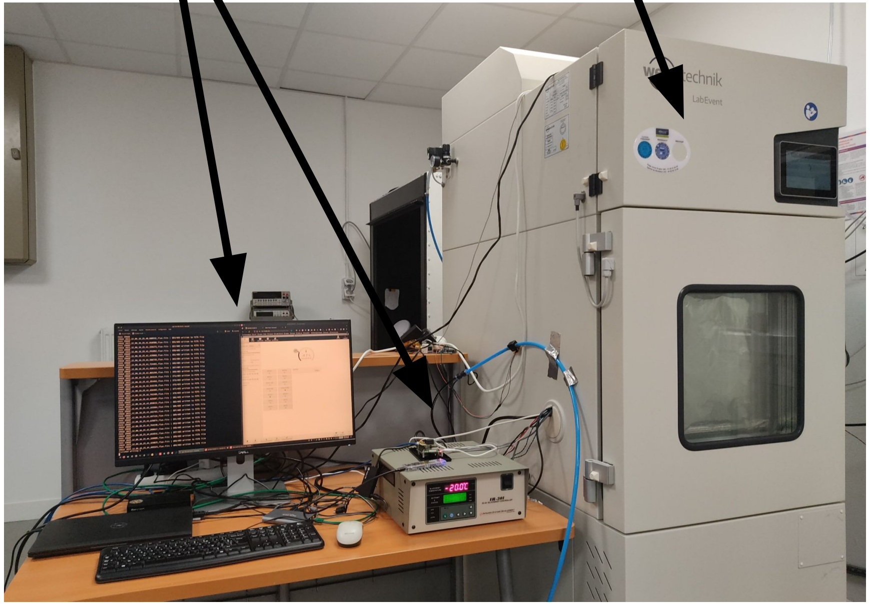
3.3 Experiments @ IJC-Lab

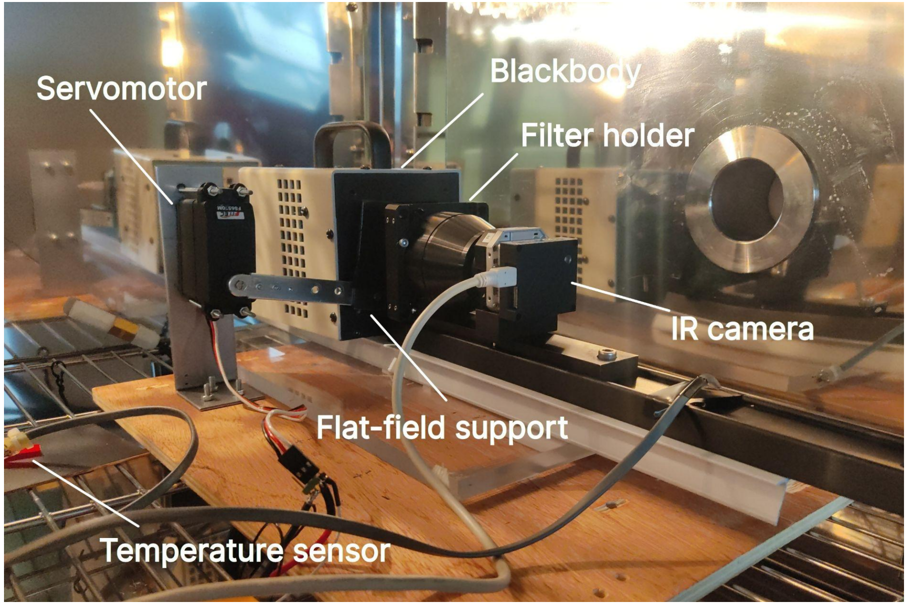
With Sylvie Dagoret-Campagne and Marc Moniez in December 2022

Control-command setup

Climatic chamber for ATLAS ITK experiment

+300k images for multiple camera and low blackbody temperature setpoints

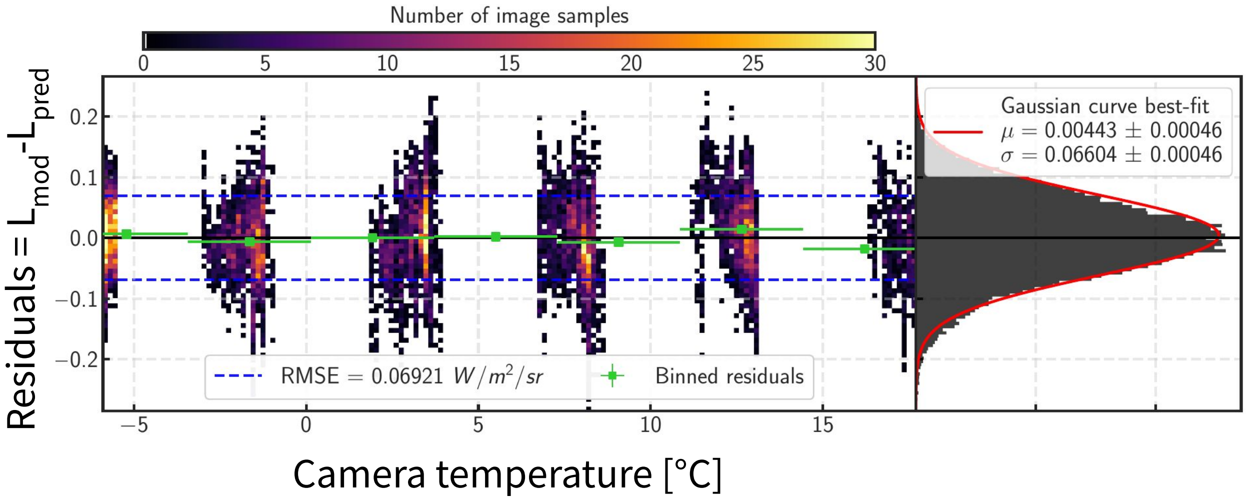


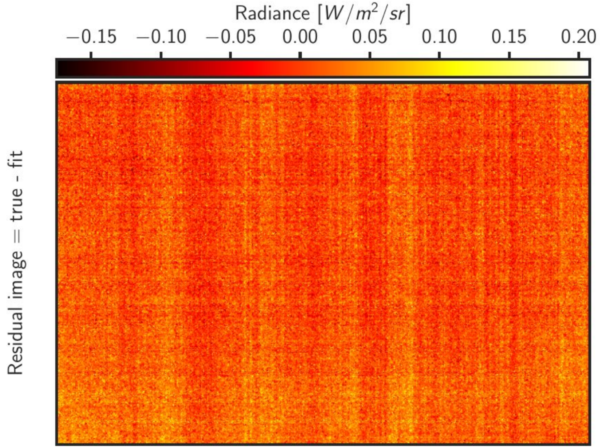


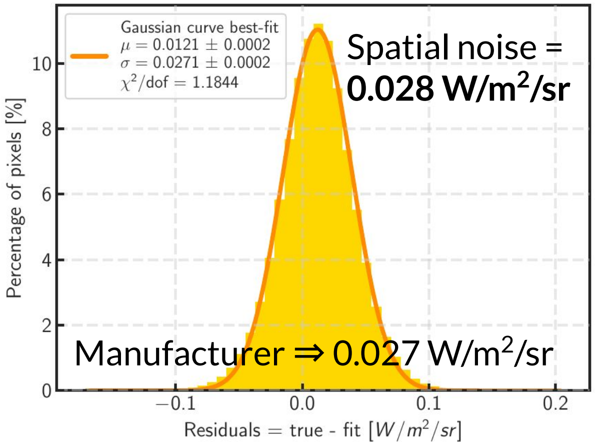
3.4 Preliminary results

Pixel temporal noise = ± 0.067 (stat.) ± 0.042 (syst.)
⇒ ± 0.080 (total) W/m²/sr

* *Best calibration found in the literature : ± 0.36 W/m²/sr (Nugent, 2008, PhD)*



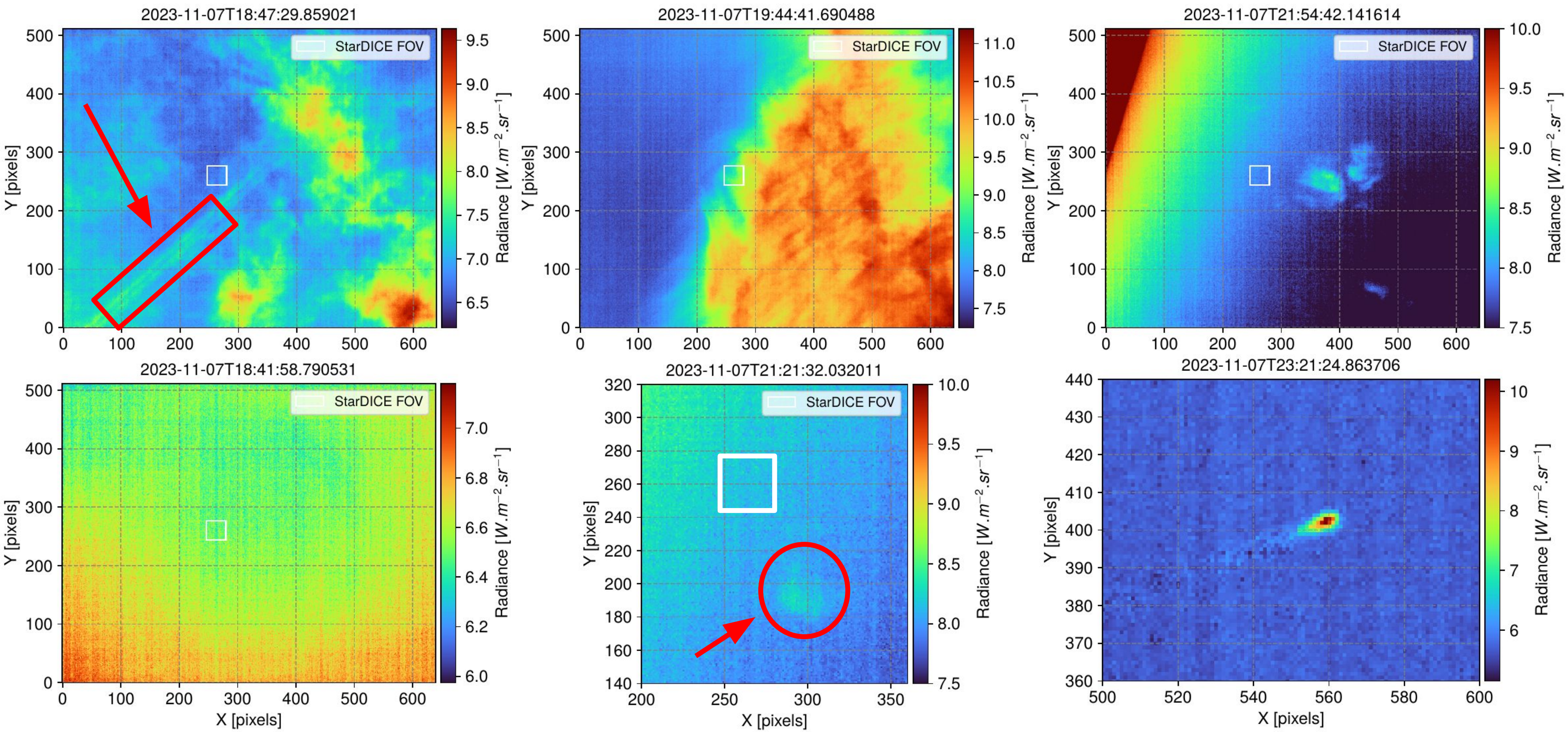




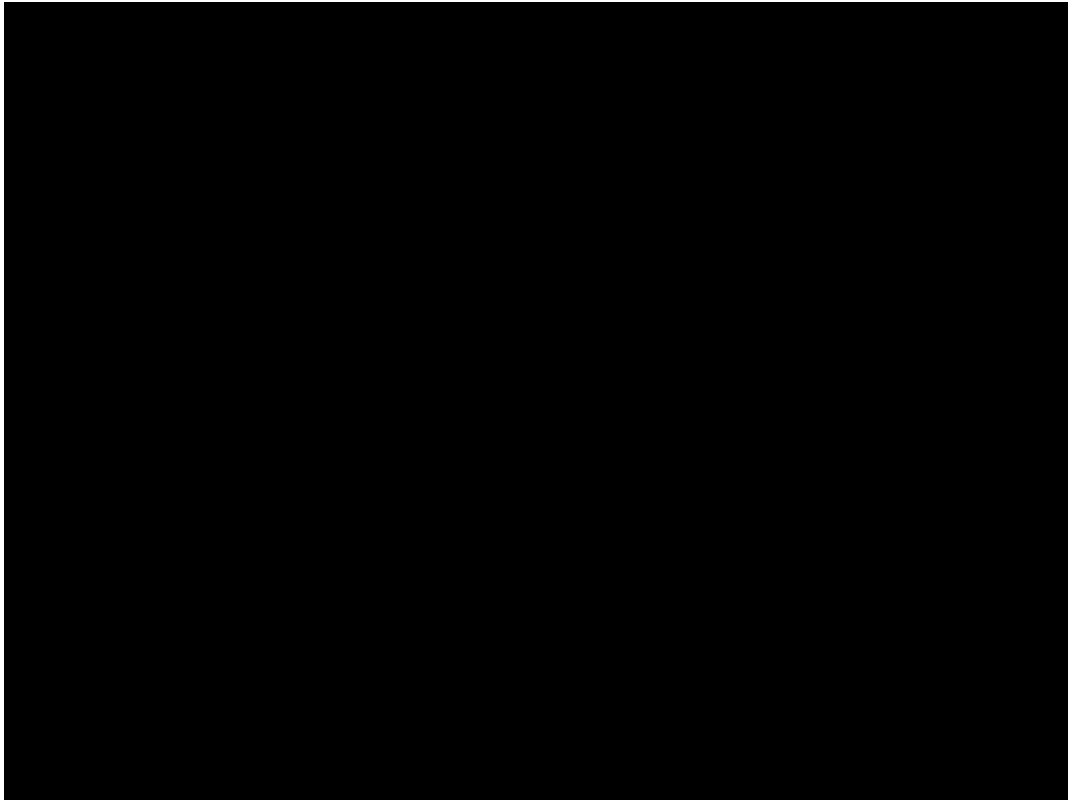
Caveat : extrapolation outside the calibration range (below -30°C)

4. Overview of first observations

4.1 Quick look : a lot of things happen in 4h of imaging…



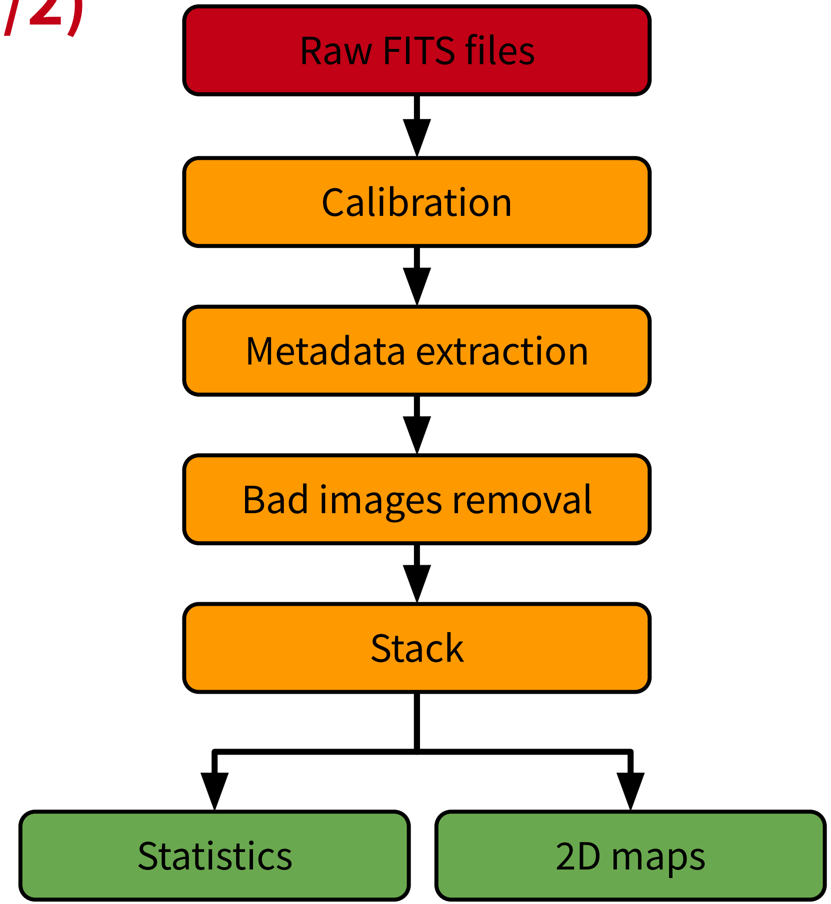
4.2 Night movie animation



https://drive.google.com/file/d/1ddrEIeWxekYS38OtJoGE9FtJotc97m1M/view?usp=sharing

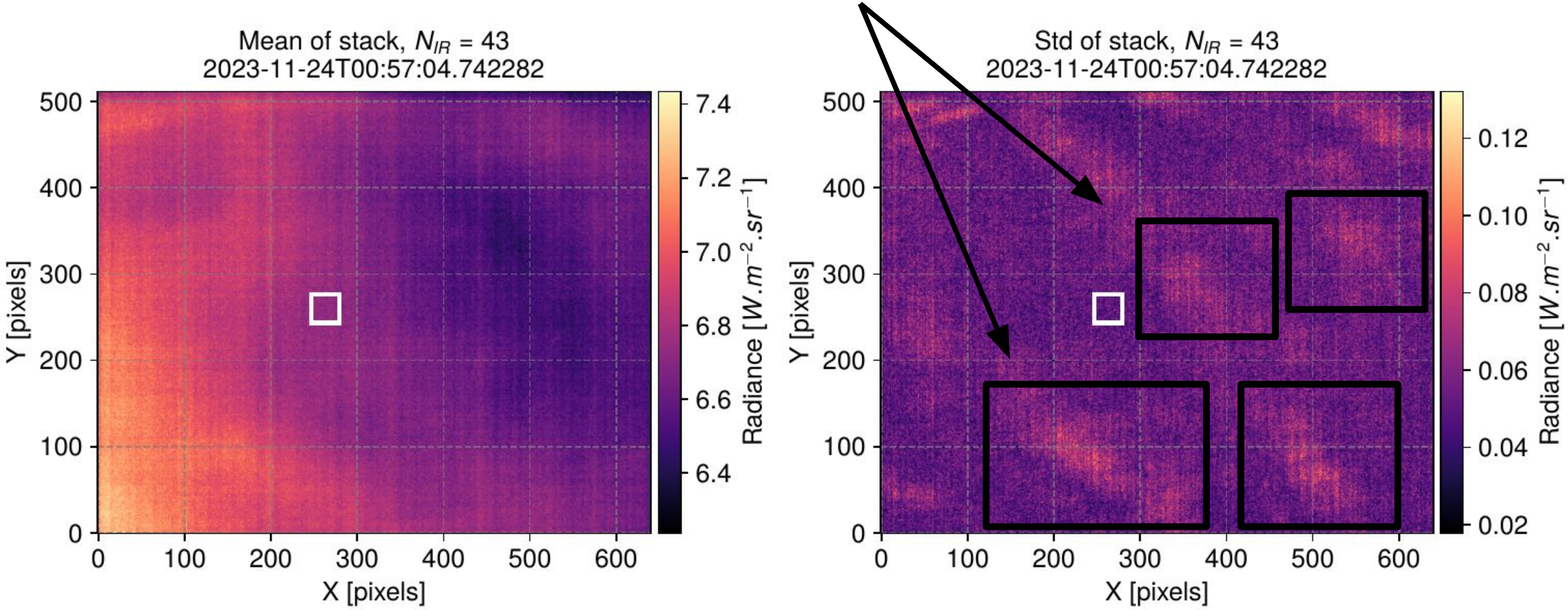
4.3 Pre-processing for DR0 (1/2)

- For each *ugrizG* exposure
  ⇒ N_{obs} infrared images
- Difficult to process all the individual images for analysis
- Statistics : spatial & temporal mean + std of the complete image and the StarDICE FOV
- For now :
  - ~ 80 GB to process per night
  - ~ 1 hours of processing per night on 40-cores server



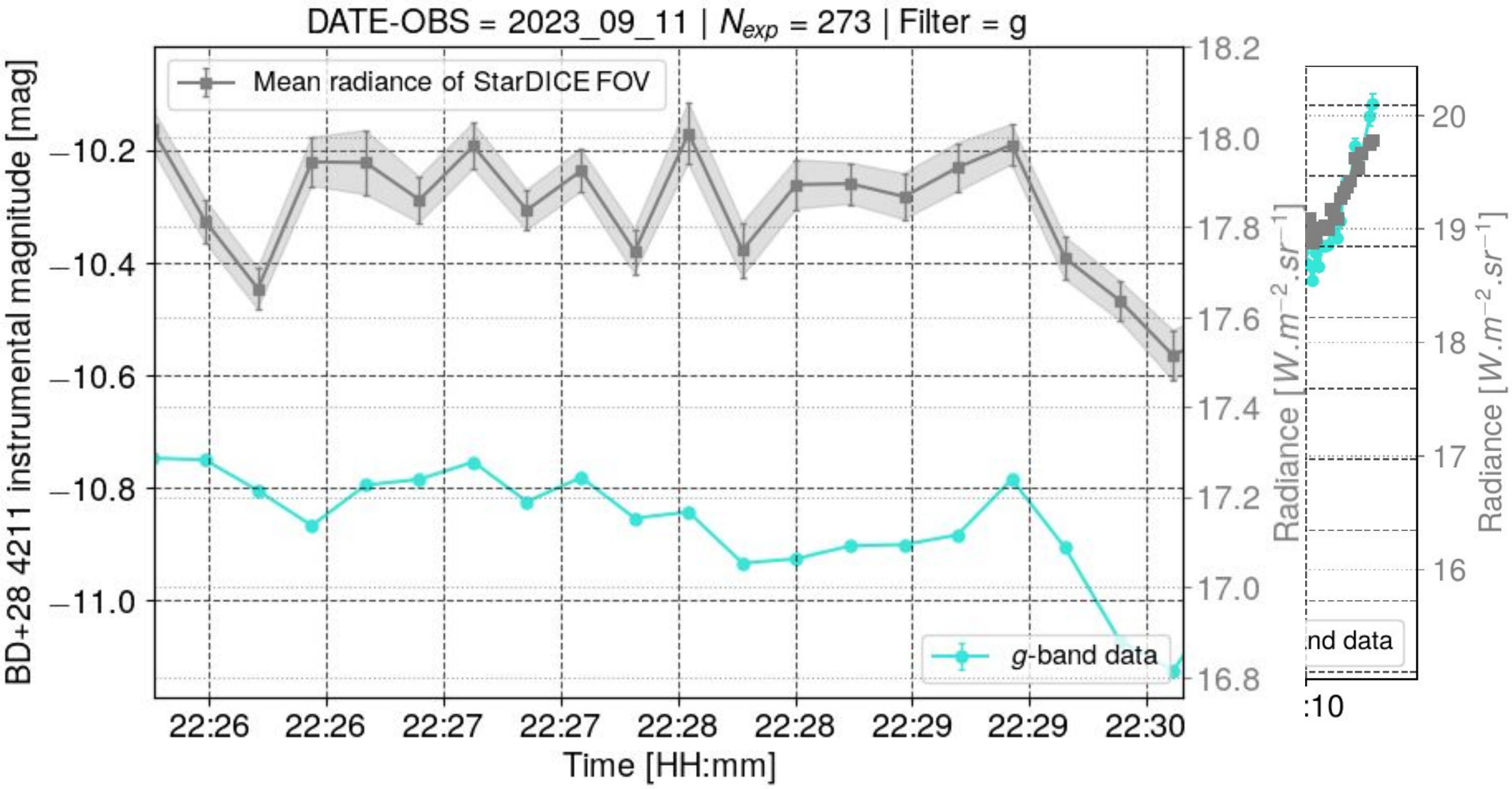
4.3 Pre-processing for DR0 (2/2)

→ Image / cloud structure evolution with time is key



4.4 Preliminary analysis on BD+28 4111 for one night (1/2)

- ~ 1 h from varia conc first
- Only high imag seco



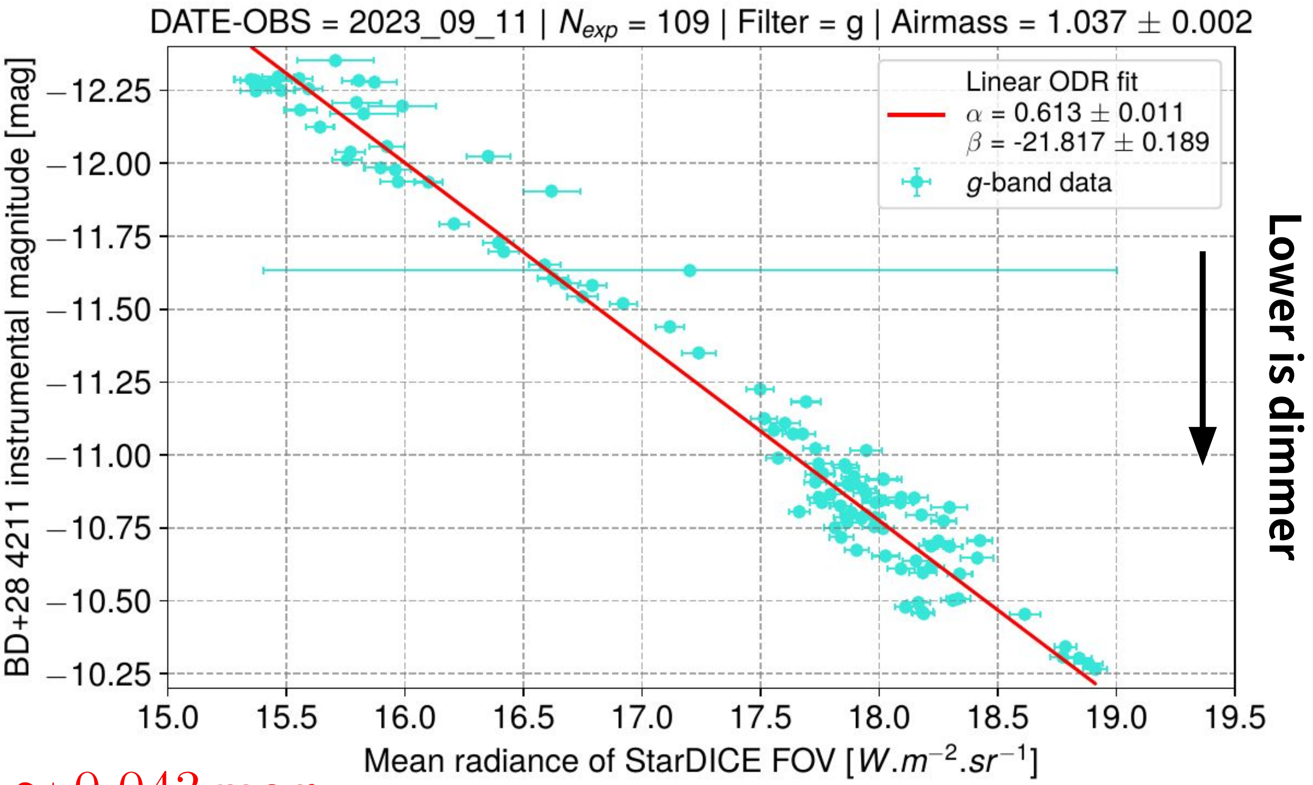
4.4 Preliminary analysis on BD+28 4111 for one night (2/2)

- Strong correlation between magnitude and radiance
- Linear dependence as a first approximation :

$$m_i = \alpha \times L_{i,*} + \beta$$

- With current uncertainty estimation (stat.+syst.) per pixel from calibration :

$$\sigma(m_i) = \alpha \times \sigma(L_{i,*}) \approx 0.043\,\mathrm{mag}$$



Next steps

- **Software :**
  - Complete the final stages of automating the pre-processing pipeline.
  - Anticipate an increase of data flux.
  - Correct for some issues regarding the control-command of the dome position affecting IR images + post-processing
- **Calibration :**
  - Finalize the calibration data analysis → publication
- **Analysis :**
  - Thorough IR and photometry analysis → robust metric for gray extinction.
  - Comparisons with libradtran simulations.
  - Combination of IR and UV-VIS-NIR data for atmosphere fitting.
  - Collaborate with OHP for atmosphere data leveraging lidar, AERONET, and more.

Backup

Summary

- Datasets from StarDICE pre-survey first nights look promising
  - Already +940k images ~ 750 GB
  - ~ 10 nights
- Remote observations of IR instrument @ OHP
- Excellent SNR → low spatial and temporal noise on calibrated images
- Linear dependence between star flux magnitude and IR radiance is confirmed