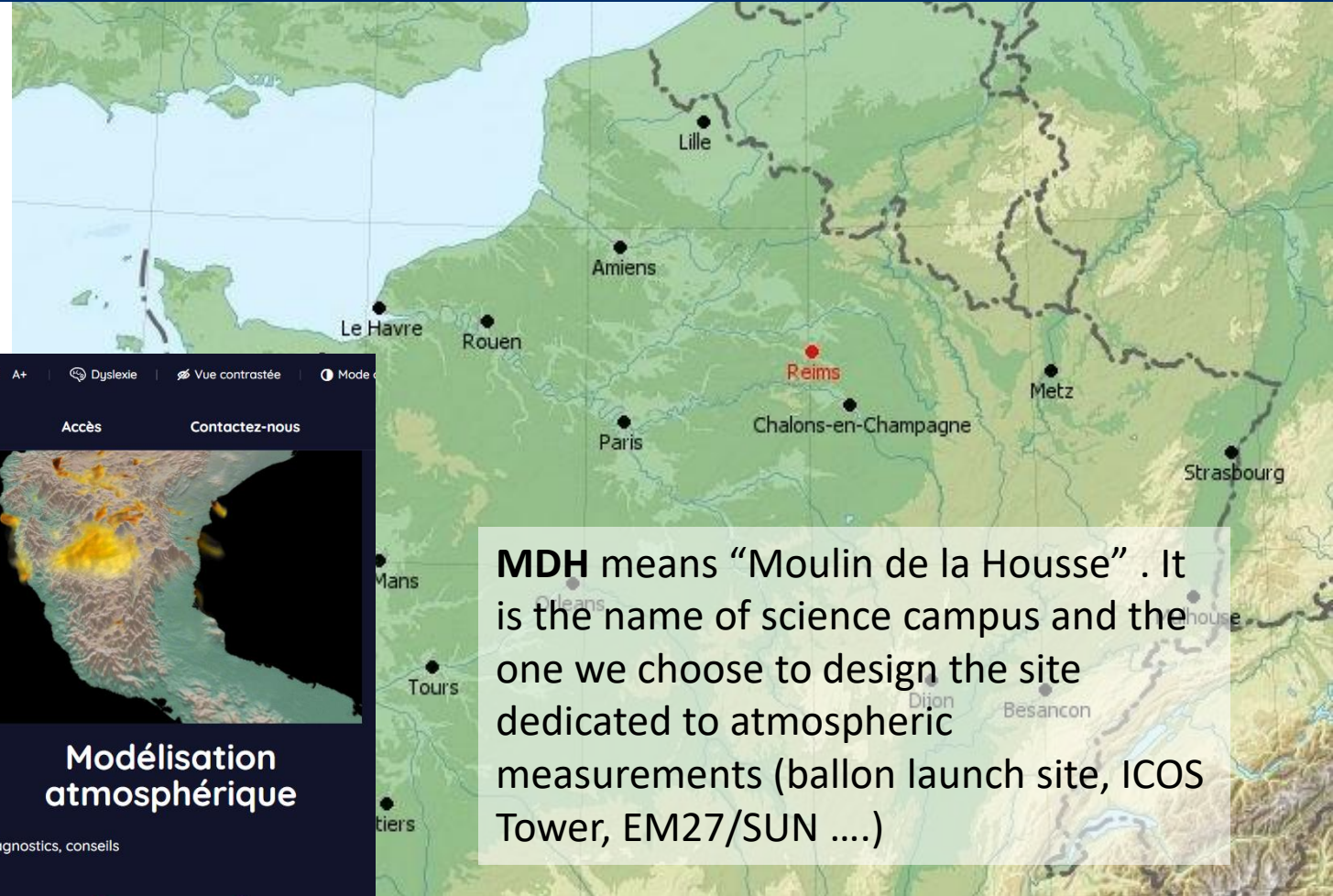


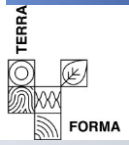
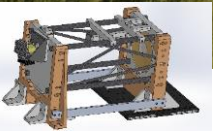
# AEROLAB and « MDH » site @REIMS (France) 1/2

- AEROLAB = A research structure to provide expertise and solutions for monitoring and analyzing atmospheric emissions
- AEROLAB was born from the GSMA
- <https://www.aerolab-innovation.com>

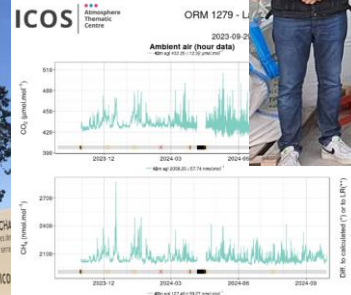


# AEROLAB and « MDH » site @REIMS (France) 2/2

## SURFACE



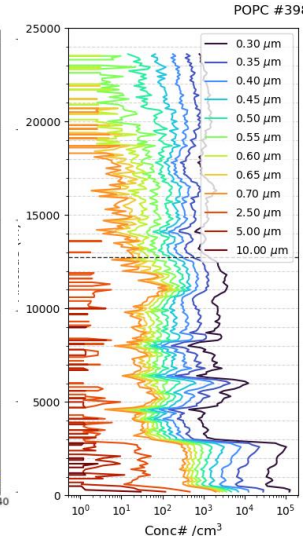
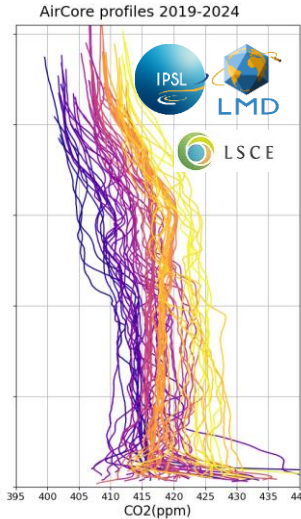
Member of  
"ICOS-  
atmosphere  
FRANCE"  
(2025)



## ATMOSPHERIC



**AERONET**  
AEROSOL ROBOTIC NETWORK



GHG (AirCore) + aerosol (POPC)



Nasa  
achievement  
award (2025)

<https://science.larc.nasa.gov/balneo>

## COLUMN



## Des avions et des ballons au-dessus de Reims pour étudier la pollution atmosphérique

Depuis ce lundi 10 octobre, des avions et des ballons atmosphériques survolent la Cité des sares. Pendant quinze jours ces manœuvres à basse ou haute altitude vont permettre de quantifier les émissions de gaz à effet de serre. Une cinquantaine de scientifiques du monde entier sont à Reims (Marne) pour cette campagne unique.



<https://magic.aeris-data.fr/magic2022/#logbook>



# Monitoring of greenhouse gases at the MDH location and assessment of the informative capabilities of the EM27/SUN with the ARAHMIS algorithm

Presented by : **EL HABCHI EL FENNIRI Hajar**

# Context and Objectives of the Thesis

## Scientific Context

- EM27/SUN spectrometers: key tools for calibration and validation of satellite GHG observations. Part of the European strategy for high-precision carbon monitoring ( $\approx 1$  ppm, errors  $< 0.5$  ppm; Ciais et al., 2021).
- Thesis: use the ARAHMIS inversion model to analyze information content and identify sensitive spectral channels.

## Objectives

- Investigate the information content of the EM27/SUN instrument.
- Propose potential improvements to PROFFAST or validate its current settings.
- Develop a unified inversion framework applicable to EM27/SUN data as well as satellite or other instruments (e.g., CHRIS).

# ARAHMIS Algorithm

## Context:

- Developed at LOA (H. Herbin & F. Ducos)
- Reference code for space mission preparation:  
IASI-NG, Biodiversity, FORUM, MicroCarb [1]

## Collaboration:

- Access obtained during WS Magic 2023 (16/05/2023)
- Collaboration initiated with Prof. H. Herbin

## Operates in Two Steps :

ARAHMIS

Forward model

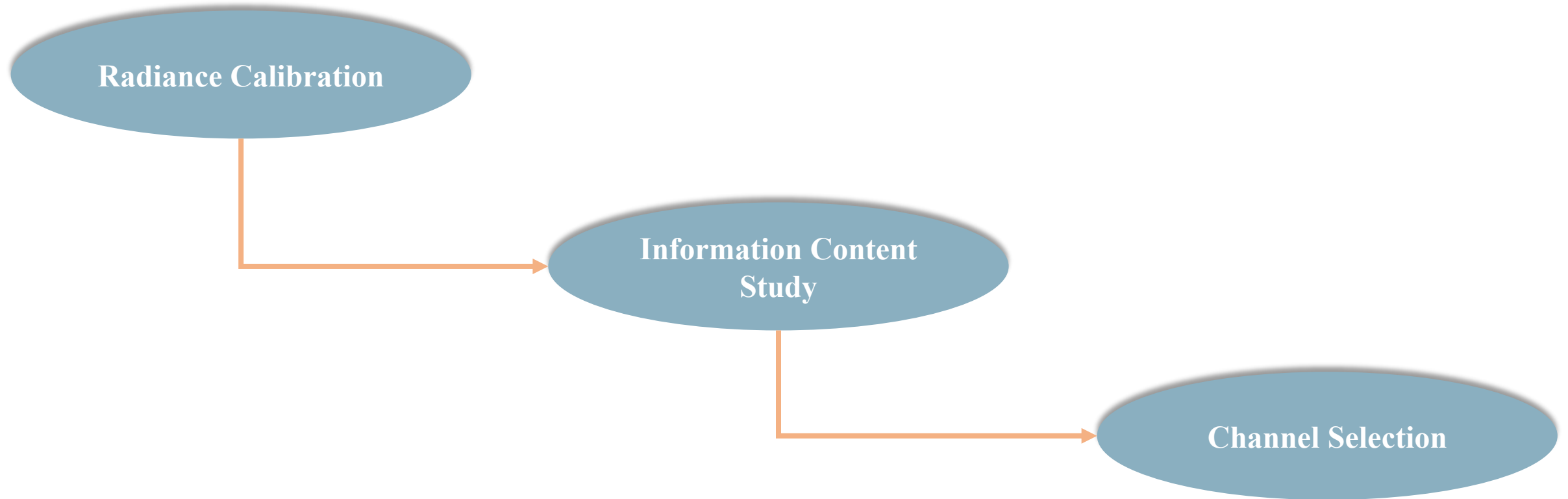
Retrieval

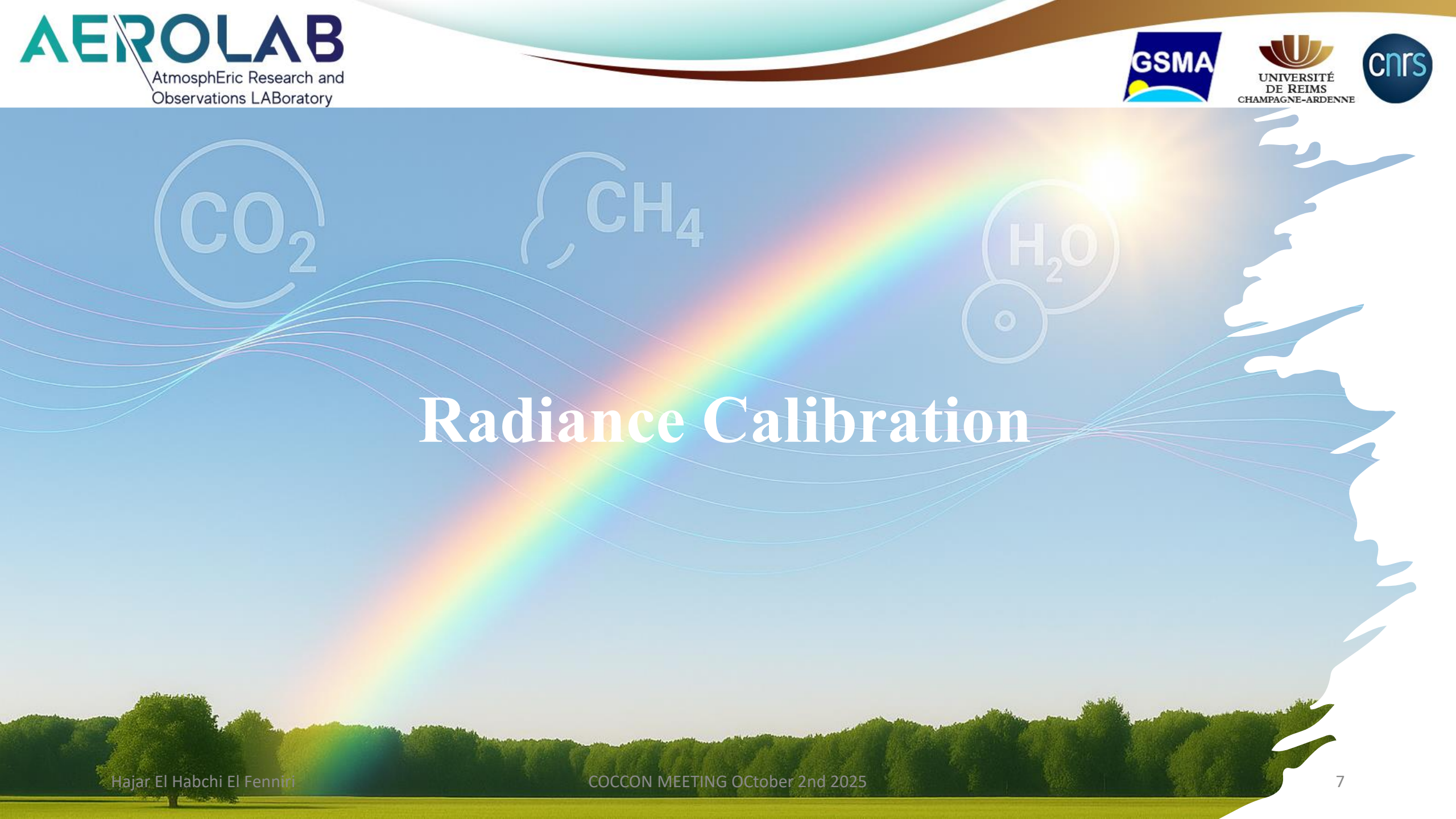
## Inversion Method with ARAHMIS



| Advantages                                    | Drawbacks                                  |
|-----------------------------------------------|--------------------------------------------|
| SF & ETR                                      | Requires Radiance Calibration              |
| Inclusion of Aerosols                         | Time-consuming                             |
| Sandbox Mode – Adaptable to Observation Needs | <b>! Spectrum Calibrated in Radiance !</b> |

## Steps to Achieve ARAHMIS





The background of the slide features a landscape with a green field and a line of trees under a blue sky. A vibrant rainbow arches across the sky. Overlaid on the sky are several faint, stylized chemical formulas:  $\text{CO}_2$  inside a circle,  $\text{CH}_4$  inside a cloud-like shape, and  $\text{H}_2\text{O}$  inside a circle with a smaller circle below it. Thin, wavy lines in shades of blue and purple flow across the scene, connecting the chemical formulas to the rainbow and the title.

# Radiance Calibration

# Radiance Calibration

## Why calibrate?

- The EM27/SUN records FTIR spectra of direct solar radiation.
- High radiometric accuracy is required to retrieve reliable atmospheric column amounts (CO<sub>2</sub>, CH<sub>4</sub>, etc.).
- Calibration errors directly affect the quality of trace gas retrievals.

## Current status (Transfer Function step):

- For now, the Transfer Function (TF) is performed using OPUS.

## Method used:

- Method is based on the calculation of two parameters (Revercomb et al., 1988, adapted):

**m** (slope of the instrument response) & **b** (offset of the instrument response)

$$m = \frac{S_c - S_h}{B_{\vartheta}(T_c) - B_{\vartheta}(T_h)} \quad b = \frac{S_c \cdot B_{\vartheta}(T_h) - S_h \cdot B_{\vartheta}(T_c)}{B_{\vartheta}(T_h) - B_{\vartheta}(T_c)}$$

**$S_c$**  spectrum at **1523 K**, recorded using the LOA blackbody

**$S_h$**  EM27/SUN solar spectrum (maximum), recorded under optimal conditions (clean mirror, clear sky, solar noon).

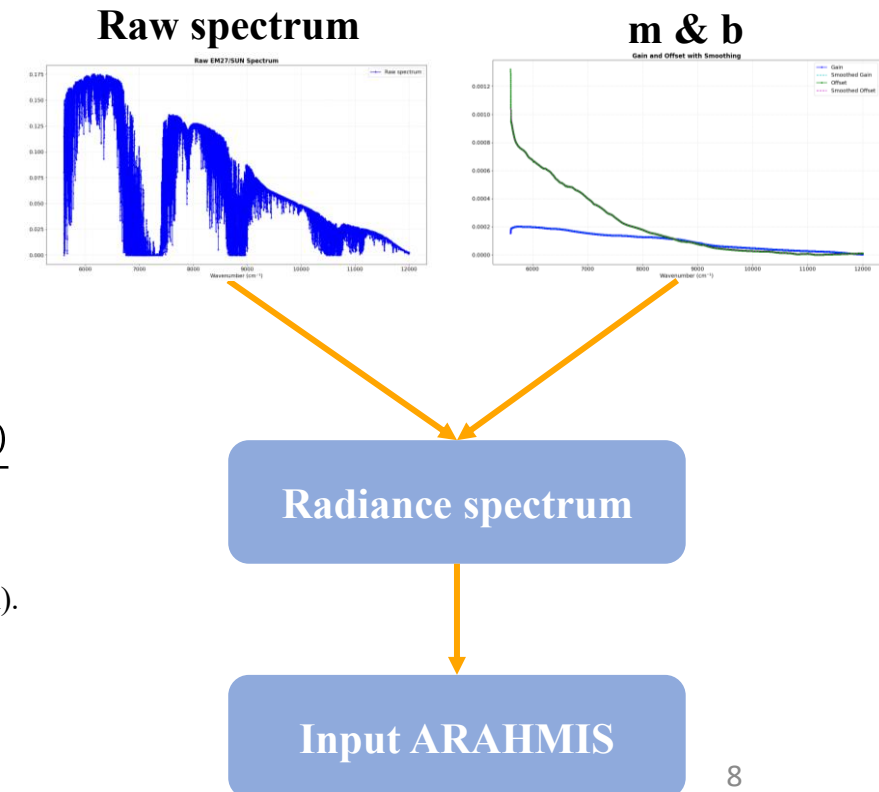
**$B_{\vartheta}(T_c)$**  blackbody radiance at **1523 K**, calculated using Planck's law

**$B_{\vartheta}(T_h)$**  blackbody radiance at **6011 K**, from LATMOS (recent solar reference spectrum).

## Calibrated solar spectrum:

Hajar El Habchi El Fenniri

$$L = \frac{S - b}{m}$$



# Blackbody Spectrum Recording – EM27/SUN

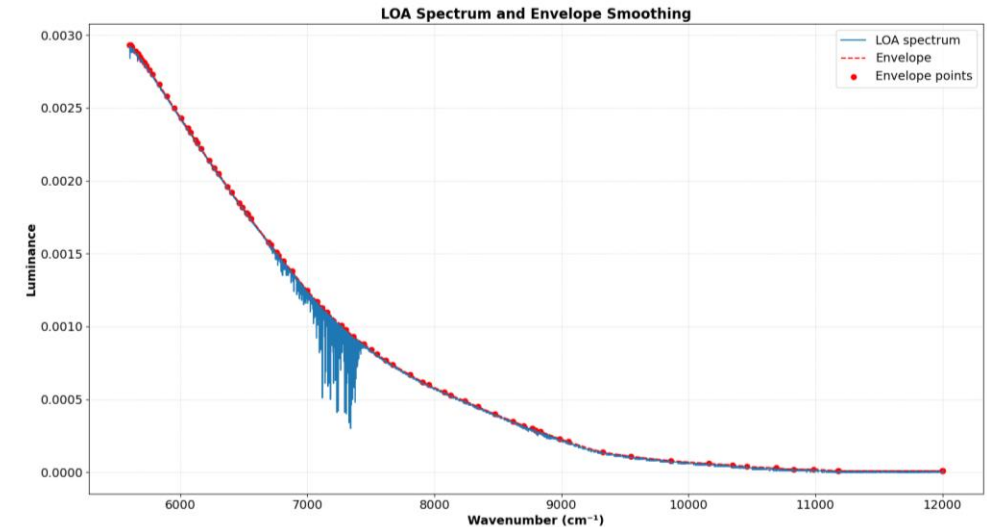
- Cold blackbody spectrum (1523 K) recorded at LOA with the EM27/SUN → used as reference (radiometrically calibrated)

## Processing of the 1523 K spectrum:

- Applied smoothing using an upper-envelope modeling approach.

Method:

- Manually selected control points.
- PCHIP interpolation (Piecewise Cubic Hermite Interpolating Polynomial) → Code Python
- Advantages: Avoids oscillations & Preserves monotonicity of the data.



# Solar Spectrum Correction and Smoothing

## Reference spectrum:

- The new solar spectrum from LATMOS ([doi: 10.21413/SOLAR-V-DATABASE-SSI.L3.V1\\_SOLSPEC-LATMOS](https://doi.org/10.21413/SOLAR-V-DATABASE-SSI.L3.V1_SOLSPEC-LATMOS)), measured by the SOLAR/SOLSPEC instrument on the ISS.

## Attenuation at ground level:

- The solar spectrum is attenuated by: Rayleigh scattering (ROD) & Aerosols (AOD) (Casinière et al., 2005)

$$AOD = \cos(SZA) \ln \left( \frac{K_d I_{0\lambda}}{I_\lambda} \right) - ROD - k_0 \Omega$$

## Assumptions:

- Seasonal Sun–Earth variation negligible  $\rightarrow K_d = 1$
- NIR: ozone absorption negligible  $\rightarrow k_0 \Omega \approx 0$

## Corrected spectrum:

$$I_\lambda = I_{0\lambda} \cdot e^{\left( -\frac{(AOD+ROD)}{\cos(SZA)} \right)}$$

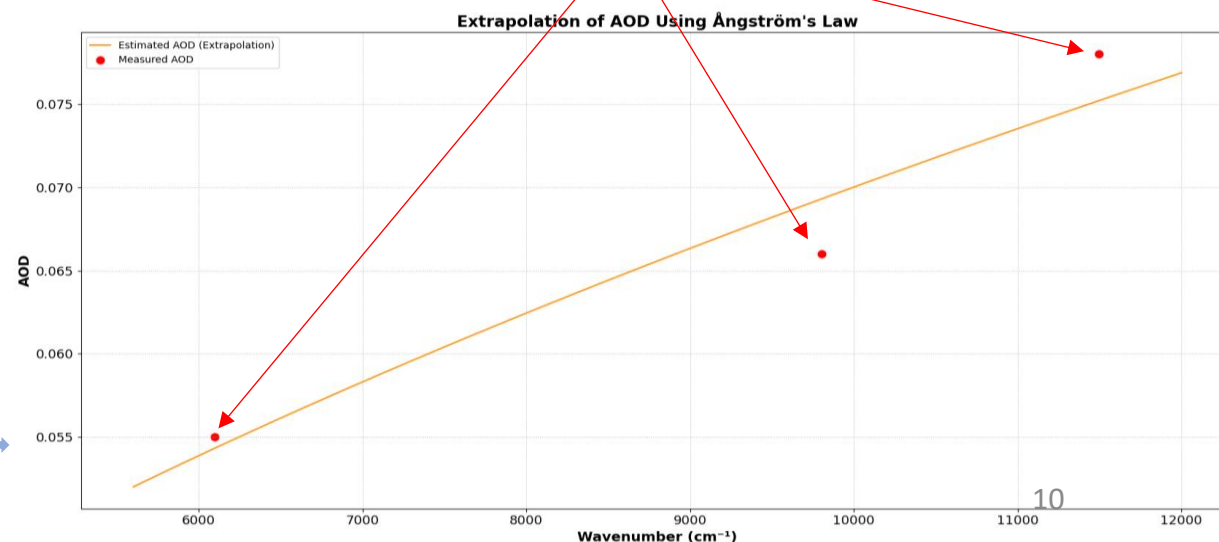
## Rayleigh optical depth (ROD):

$$ROD = 0.008569(\lambda)^{-4} (1 + 0.0113(\lambda)^{-2} + 0.00013(\lambda)^{-4})$$

## Aerosol Optical Depth (AERONET data: the three red points):

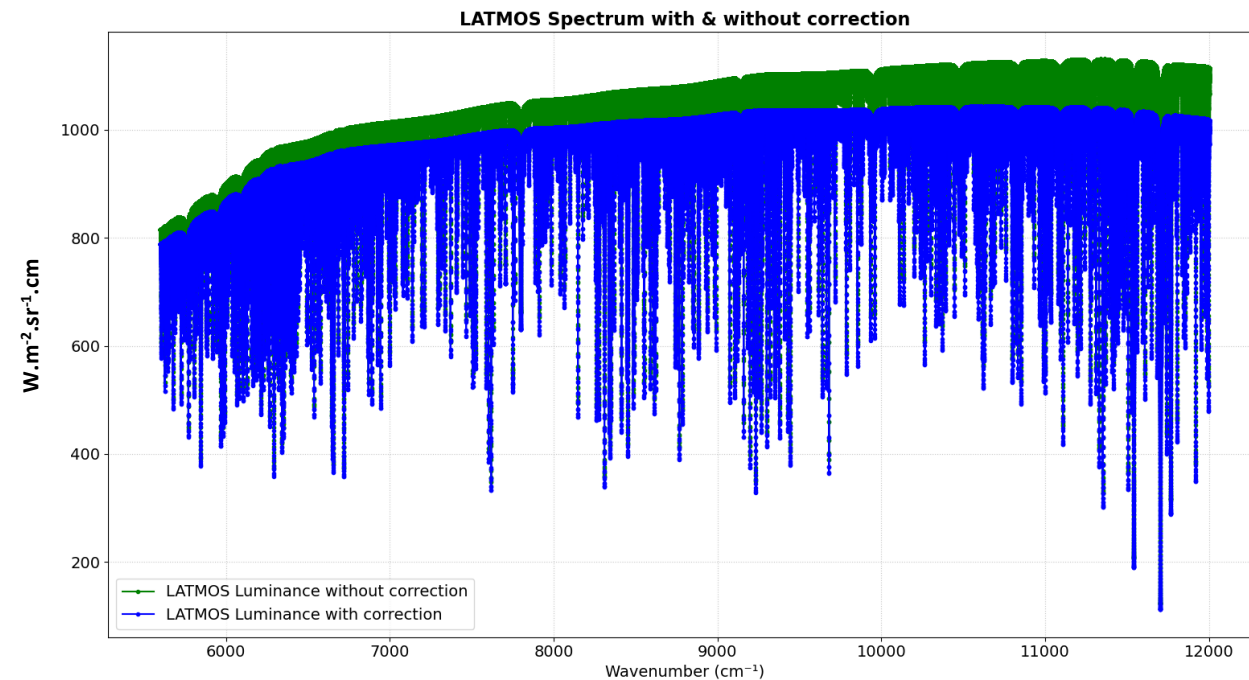
- Extrapolated using Ångström's law : —————→

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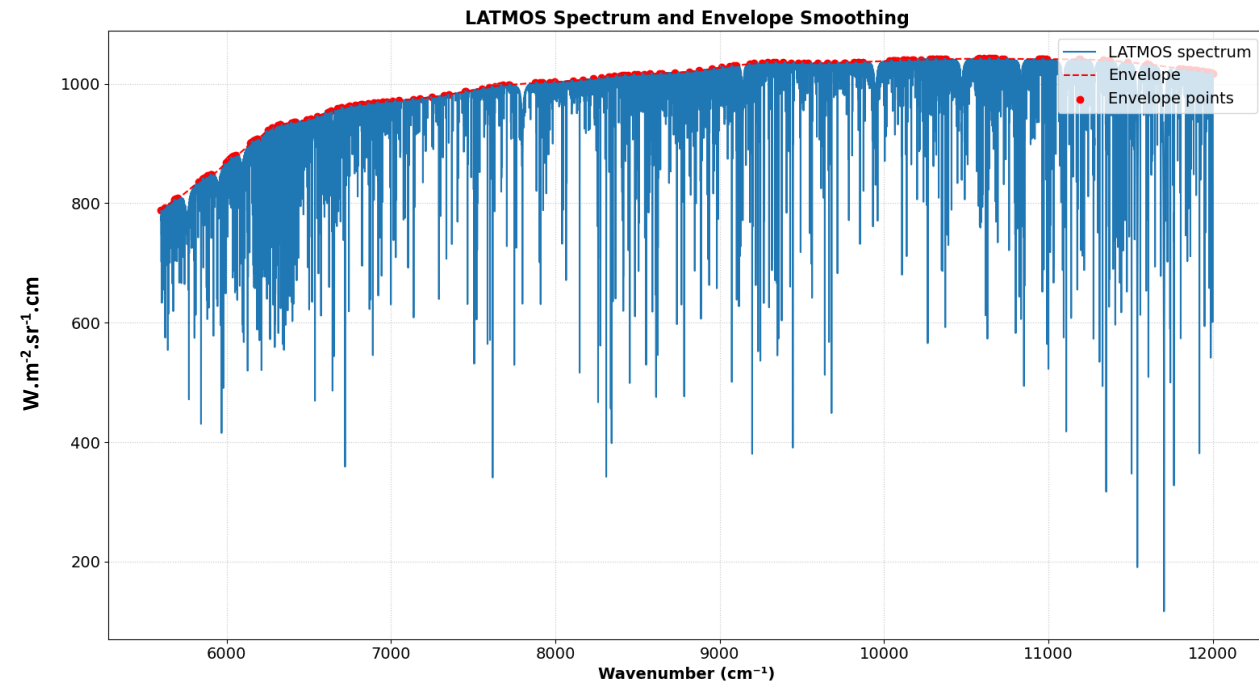


# Solar Spectrum Correction and Smoothing

## Comparison between solar spectrum before and after correction



## Corrected spectrum with smoothing (PCHIP interpolation), same method as before



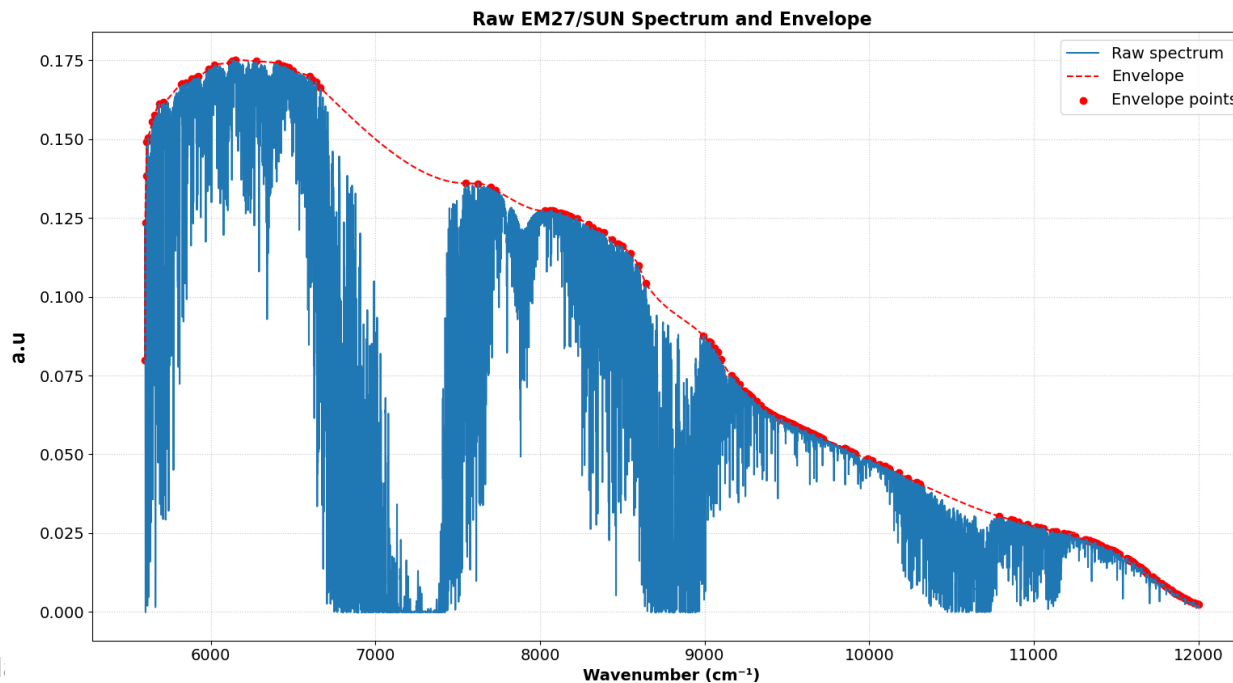
## Selection of the EM27/SUN Spectrum

### Acquisition conditions:

- Sunny day – June 13, 2023
- Selected spectrum: maximum recorded during the day

### Processing applied:

- Spectre brut de l'EM27/SUN (Blue curve).
- Smoothing using PCHIP (red curve).



Hajar El H.

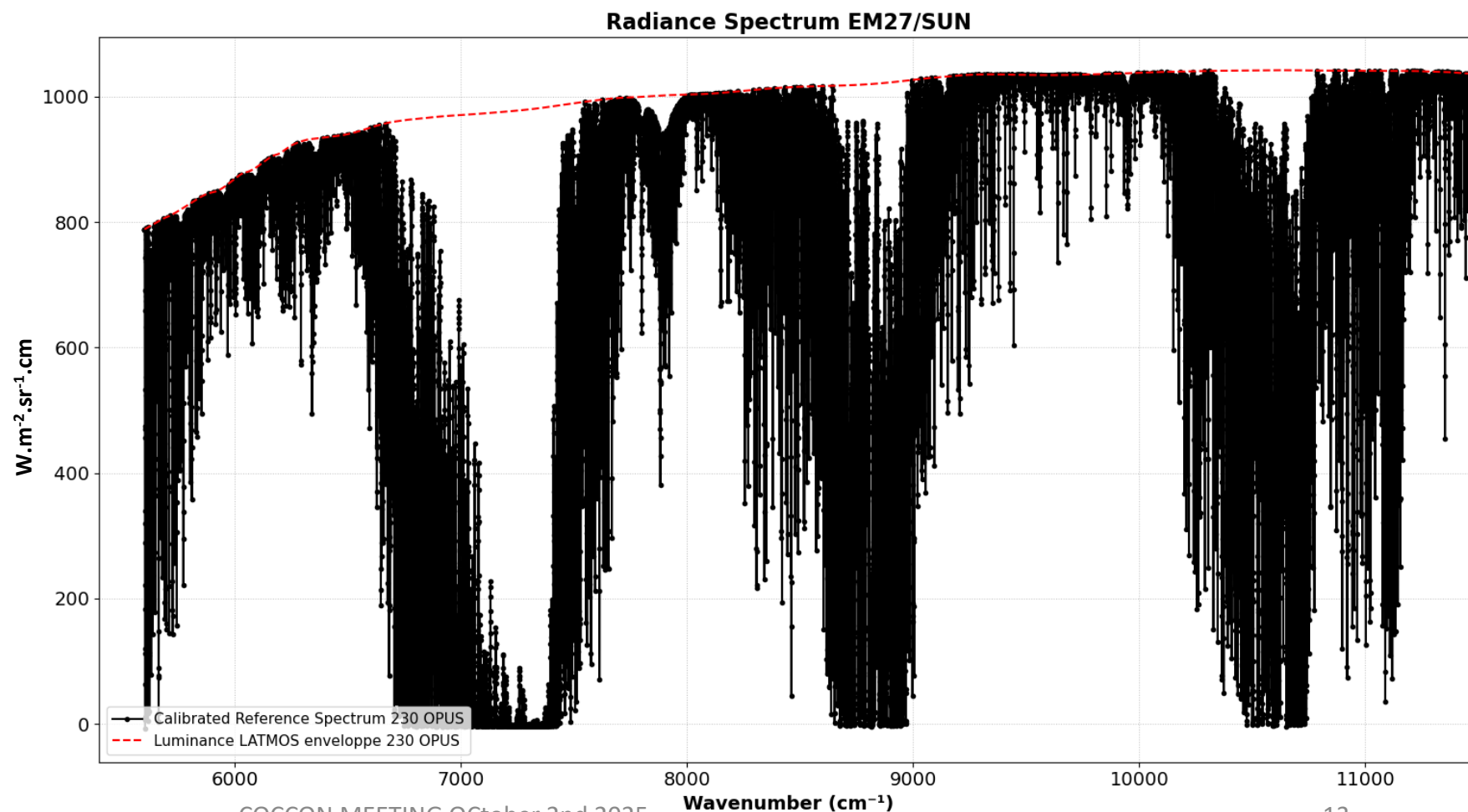


## Calibrated Solar Spectrum – EM27/SUN

Final spectrum obtained after:

- Radiometric calibration (two-point method).
- Correction for Rayleigh scattering (ROD) and aerosols (AOD).
- Smoothing with PCHIP interpolation.

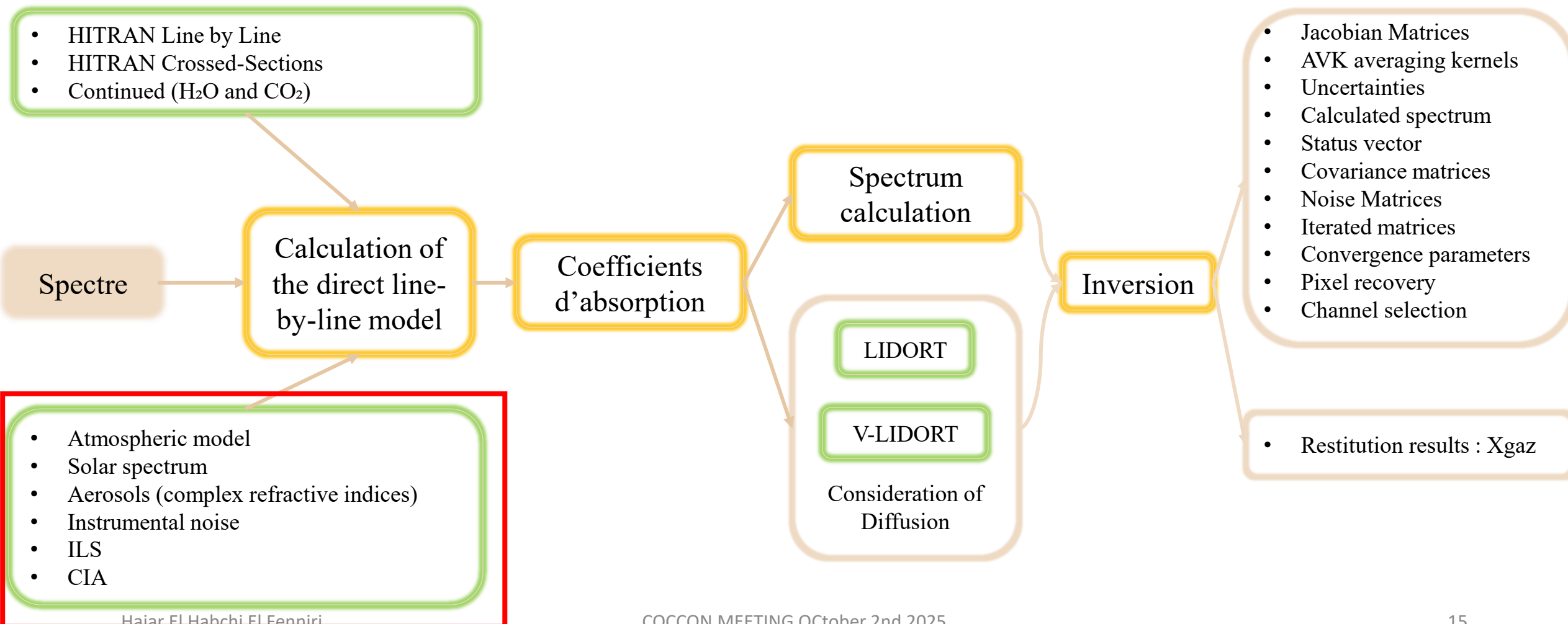
Spectrum is now ready to be used  
for ARAHMIS





# Input Data for ARAHMIS

## Input Data for ARAHMIS



# Adaptation of the GGG2020 Atmospheric Profile to ARAHMIS Requirements with In Situ Correction

Same a priori profile as PROFFAST

Ensures consistency in future comparisons (ARAHMIS vs PROFFAST)

Development of a Restructuring Code

Converts GGG2020 profile (default format → ATM format)

Lowest layer

T & P replaced with in situ measurements (at spectrum time)

```
12 13
rh_40h_004E_2023061300Z.nag
GINPUT Version 1.0.6 JLL, SR, HK
Please see https://tcccon-wiki.caltech.edu for a complete description of this file and its usage.
NOTE: The gas concentrations (including H2O) are in mole FRACTIONS. If you require dry mole fractions,
you must calculate [H2O]_dry = ([H2O]_wet - 1)/[H2O] and then [gas]_dry = ([gas]_wet - 1) + [H2O]_dry.
Avogadro (molecules/mole): 6.022141e+23
Mass_Dry_Air (kg/mole): 0.028964
Mass_H2O (kg/mole): 0.01801534
Latitude (degrees): 49.243
Height, Temp, Pressure, Density, h2o, hdo, co2, n2o, co, ch4, hf, co2, gravity
km, K, hPa, molecules, cm3, parts, parts, ppm, ppb, ppb, ppt, parts, n_s2
0.000, 297.655, 0.1011E+04, 0.2466E+20, 0.1149E-01, 0.9752E-02, 409.146, 333.031, 0.329E+03, 1911.8, 0.099, 0.2071, 9.810
0.420, 293.218, 0.9635E+03, 0.2380E+20, 0.1068E-01, 0.9808E-02, 411.191, 333.200, 0.317E+03, 1912.3, 0.099, 0.2071, 9.809
0.880, 289.144, 0.9130E+03, 0.2287E+20, 0.9088E-02, 0.7593E-02, 414.399, 333.739, 0.255E+03, 1913.5, 0.099, 0.2076, 9.808
1.380, 285.021, 0.8604E+03, 0.2186E+20, 0.7722E-02, 0.6377E-02, 416.559, 334.199, 0.222E+03, 1915.1, 0.099, 0.2079, 9.806
1.920, 281.706, 0.8061E+03, 0.2073E+20, 0.4668E-02, 0.3799E-02, 419.835, 335.158, 0.154E+03, 1919.0, 0.100, 0.2085, 9.805
2.500, 278.266, 0.7513E+03, 0.1955E+20, 0.2554E-02, 0.1953E-02, 420.723, 335.040, 0.121E+03, 1922.1, 0.100, 0.2090, 9.803
3.120, 275.197, 0.6961E+03, 0.1832E+20, 0.9983E-03, 0.0997E-03, 421.879, 336.264, 0.104E+03, 1924.1, 0.100, 0.2091, 9.801
3.780, 271.484, 0.6412E+03, 0.1711E+20, 0.1176E-02, 0.8399E-03, 422.203, 336.284, 0.102E+03, 1922.8, 0.100, 0.2093, 9.799
4.480, 268.409, 0.5869E+03, 0.1584E+20, 0.9028E-03, 0.6718E-03, 422.593, 336.276, 0.104E+03, 1922.2, 0.100, 0.2093, 9.797
5.220, 263.171, 0.5337E+03, 0.1469E+20, 0.1212E-02, 0.8637E-03, 422.687, 336.192, 0.106E+03, 1920.6, 0.100, 0.2092, 9.794
6.000, 257.318, 0.4819E+03, 0.1356E+20, 0.6722E-03, 0.4570E-03, 423.016, 336.274, 0.106E+03, 1920.7, 0.100, 0.2094, 9.792
6.820, 250.782, 0.4316E+03, 0.1246E+20, 0.3979E-03, 0.2563E-03, 423.232, 336.366, 0.105E+03, 1920.2, 0.100, 0.2094, 9.789
7.680, 243.344, 0.3835E+03, 0.1141E+20, 0.3754E-03, 0.2406E-03, 423.341, 336.374, 0.104E+03, 1919.3, 0.100, 0.2094, 9.787
8.580, 235.944, 0.3378E+03, 0.1036E+20, 0.3039E-03, 0.1910E-03, 423.371, 336.398, 0.105E+03, 1919.4, 0.100, 0.2094, 9.784
9.520, 228.557, 0.2947E+03, 0.9329E+19, 0.1950E-03, 0.1179E-03, 423.418, 336.434, 0.992E+02, 1918.6, 0.100, 0.2095, 9.781
10.500, 221.138, 0.2539E+03, 0.8306E+19, 0.0881E-03, 0.5802E-04, 423.386, 336.237, 0.460E+02, 1916.5, 0.121, 0.2095, 9.778
11.520, 216.483, 0.2165E+03, 0.7244E+19, 0.4564E-04, 0.2340E-04, 422.814, 335.251, 0.263E+02, 1904.2, 0.294, 0.2095, 9.772
12.580, 219.288, 0.1834E+03, 0.6046E+19, 0.3022E-04, 0.1494E-04, 421.087, 332.457, 0.453E+02, 1868.9, 0.329, 0.2095, 9.772
13.680, 221.862, 0.1491E+03, 0.5049E+19, 0.9295E-05, 0.3874E-05, 419.296, 329.497, 0.314E+02, 1832.0, 0.576, 0.2095, 9.768
14.820, 218.877, 0.1197E+03, 0.4291E+19, 0.6072E-05, 0.2370E-05, 417.330, 319.098, 0.269E+02, 1783.3, 0.119, 0.2095, 9.765
16.000, 210.524, 0.1079E+03, 0.3574E+19, 0.4070E-05, 0.1033E-05, 416.531, 317.531, 0.120E+02, 1771.0, 0.120, 0.2095, 9.761
17.220, 217.287, 0.8897E+02, 0.2867E+19, 0.4507E-05, 0.1675E-05, 415.331, 301.266, 0.175E+02, 1703.0, 0.203, 0.2095, 9.758
18.480, 217.287, 0.7283E+02, 0.2428E+19, 0.4348E-05, 0.1686E-05, 412.131, 250.566, 0.152E+02, 1529.3, 0.420, 0.2095, 9.754
19.780, 210.271, 0.5952E+02, 0.1974E+19, 0.4448E-05, 0.1649E-05, 410.265, 234.599, 0.143E+02, 1435.0, 0.545, 0.2095, 9.750
21.120, 210.363, 0.4835E+02, 0.1597E+19, 0.4078E-05, 0.1749E-05, 409.631, 204.766, 0.136E+02, 1344.0, 0.608, 0.2095, 9.746
22.500, 220.483, 0.3981E+02, 0.1281E+19, 0.4046E-05, 0.1822E-05, 407.798, 178.866, 0.139E+02, 1248.7, 0.772, 0.2095, 9.741
23.920, 222.341, 0.3125E+02, 0.1018E+19, 0.5002E-05, 0.1899E-05, 407.465, 164.099, 0.147E+02, 1213.7, 0.814, 0.2095, 9.737
25.380, 223.369, 0.2305E+02, 0.8123E+18, 0.5137E-05, 0.1949E-05, 407.298, 149.799, 0.163E+02, 1174.7, 0.864, 0.2095, 9.733
26.880, 224.594, 0.1996E+02, 0.6436E+18, 0.5278E-05, 0.2012E-05, 406.731, 126.332, 0.184E+02, 1100.3, 0.967, 0.2095, 9.728
28.420, 227.136, 0.1578E+02, 0.5040E+18, 0.5440E-05, 0.2087E-05, 406.298, 100.299, 0.206E+02, 1000.0, 0.1089, 0.2095, 9.723
30.000, 231.188, 0.1244E+02, 0.3898E+18, 0.5663E-05, 0.2183E-05, 405.998, 76.110, 0.222E+02, 905.3, 0.1224, 0.2095, 9.719
31.620, 234.916, 0.9844E+01, 0.3036E+18, 0.5873E-05, 0.2277E-05, 405.898, 56.093, 0.237E+02, 810.3, 0.1347, 0.2095, 9.714
33.280, 236.485, 0.7640E+01, 0.2360E+18, 0.6080E-05, 0.2337E-05, 405.898, 43.627, 0.256E+02, 737.7, 0.1441, 0.2095, 9.709
34.980, 242.820, 0.6101E+01, 0.1822E+18, 0.6098E-05, 0.2378E-05, 405.765, 31.140, 0.258E+02, 647.6, 0.1557, 0.2095, 9.703
36.720, 248.021, 0.4785E+01, 0.1399E+18, 0.6222E-05, 0.2434E-05, 405.697, 21.500, 0.258E+02, 541.9, 0.1693, 0.2095, 9.698
38.500, 253.353, 0.3747E+01, 0.1071E+18, 0.6392E-05, 0.2510E-05, 405.630, 14.223, 0.263E+02, 431.6, 0.1835, 0.2095, 9.693
40.320, 258.645, 0.2935E+01, 0.8222E+17, 0.6574E-05, 0.2594E-05, 405.630, 9.450, 0.272E+02, 350.4, 0.1941, 0.2095, 9.687
```

```
Atmospheric level 7 ("GGG2020")
Number of levels
51
Altitudes (km)
0.130 0.420 0.880 1.380 1.920 2.500 3.120 3.780 4.480 5.220
6.000 6.820 7.680 8.580 9.520 10.500 11.520 12.580 13.680 14.820
16.000 17.220 18.480 19.780 21.120 22.500 23.920 25.380 26.880 28.420
30.000 31.620 33.280 34.980 36.720 38.500 40.320 42.180 44.080 46.020
48.000 50.020 52.080 54.180 56.320 58.500 60.720 62.980 65.280 67.620
70.000
Pressures (hPa)
996.990 993.935+03 91330E+03 0.8604E+03 0.8063E+03 0.7513E+03 0.6961E+03 0.6412E+03 0.5869E+03 0.5337E+03
0.4819E+03 0.4316E+03 0.3835E+03 0.3378E+03 0.2947E+03 0.2539E+03 0.2165E+03 0.1834E+03 0.1597E+03
0.1356E+03 0.1141E+03 0.9329E+02 0.7283E+02 0.5952E+02 0.4835E+02 0.3981E+02 0.3125E+02 0.2305E+02 0.1996E+02 0.1579E+02
0.1244E+02 0.9844E+01 0.7764E+01 0.6101E+01 0.4785E+01 0.3747E+01 0.2935E+01 0.2308E+01 0.1811E+01 0.1418E+01
0.1104E+01 0.8546E+00 0.6554E+00 0.4974E+00 0.3729E+00 0.2756E+00 0.2002E+00 0.1428E+00 0.1008E+00 0.7026E+01
0.4826E-01
Temperature (K)
307.490 293.218 289.144 285.021 281.706 278.266 275.197 271.494 268.409 263.171
257.318 250.782 243.344 235.944 228.557 221.138 216.483 210.288 204.077
210.524 217.287 217.287 218.271 219.361 220.483 222.341 223.369 224.594 227.136
231.168 234.916 238.485 242.820 248.021 253.353 258.645 264.213 268.544 270.159
269.271 266.175 261.075 256.025 249.492 242.118 234.498 227.261 220.562 214.881
210.048
Number of molecules
8
H2O (1)
1.149E+04 1.068E+04 9.888E+03 7.722E+03 4.668E+03 2.554E+03 9.983E+02 1.17E+03 9.628E+02 1.212E+03
6.722E+02 3.979E+02 3.754E+02 3.039E+02 1.950E+02 9.881E+01 4.504E+01 3.482E+01 9.295E+00 6.072E+00
4.070E+00 4.507E+00 4.348E+00 4.448E+00 4.078E+00 4.486E+00 5.002E+00 5.137E+00 5.278E+00 5.448E+00
5.463E+00 5.878E+00 6.088E+00 6.098E+00 6.222E+00 6.392E+00 6.574E+00 6.714E+00 6.828E+00 6.888E+00
6.926E+00 6.923E+00 6.894E+00 6.821E+00 6.725E+00 6.610E+00 6.459E+00 6.303E+00 6.177E+00 6.140E+00
6.129E+00
```

# Noise Handling in ARAHMIS

## Two options:

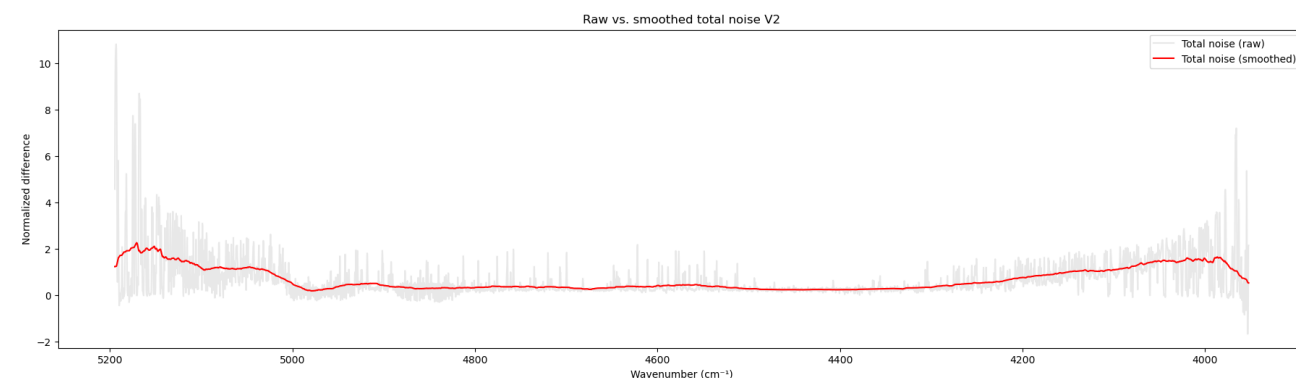
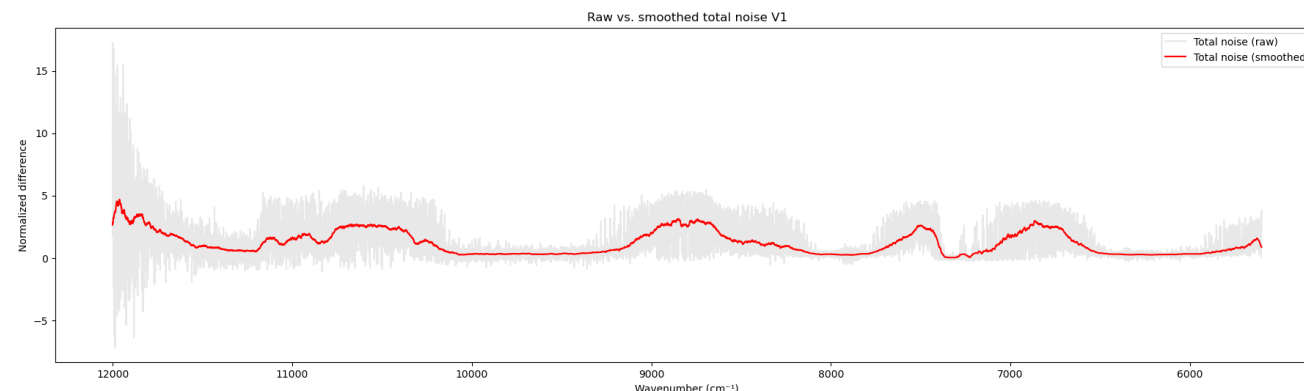
- Provide a single SNR value (fixed across the spectrum)
- Provide a noise profile file (wavenumber-dependent)

## In this study:

Noise calculated for our instrument as:

$$Noise = \frac{std(S_1 - S_2)}{\sqrt{2}}$$

- Used directly as noise profile input in ARAHMIS



# Instrument Line Shape (ILS) in ARAHMIS

## ARAHMIS capabilities:

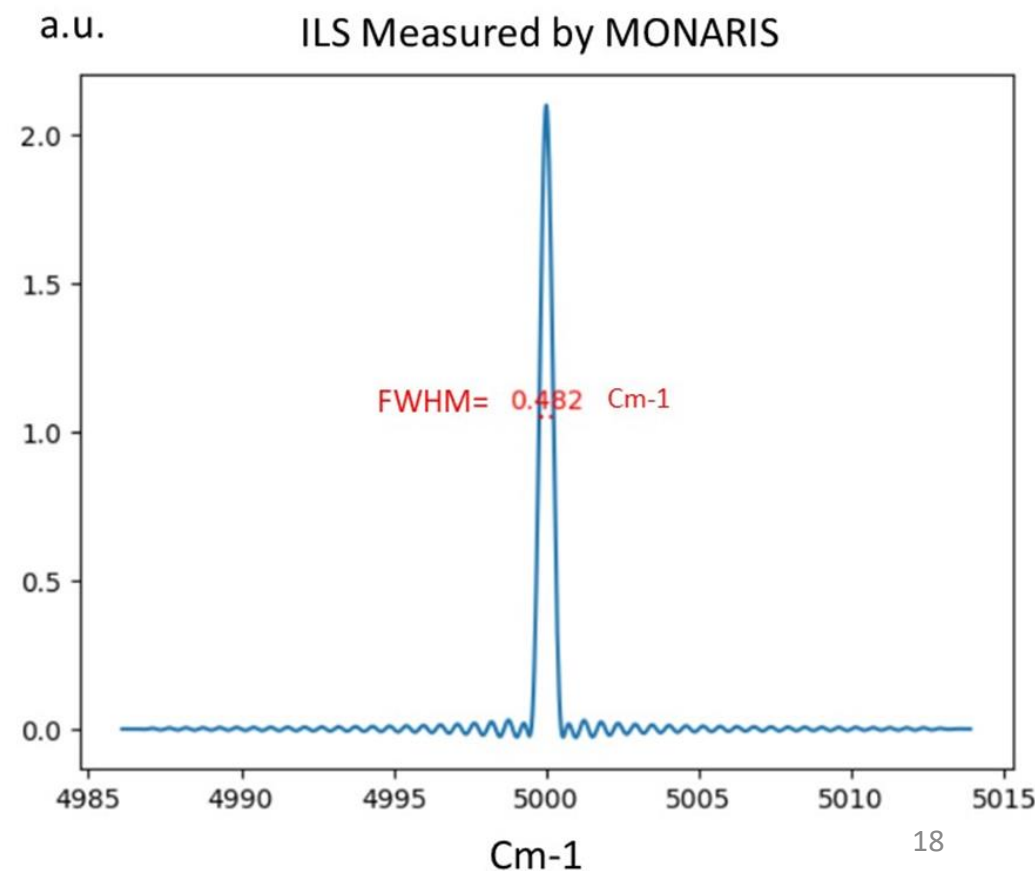
- Simulation of different apodization functions (sinc, gaussian, triangle, Lorentz, Norton-Beer weak, Norton-Beer medium, Norton-Beer strong Or direct ils file)

## In this study:

- Measured **instrument ILS** file employed
- Extracted with **LINEFIT (v14.8)**
- Methodology: **Frey et al. (2015)**
- Modulation & phase parameters: **Alberti et al. (2022)**
- File provided by the **MONARIS team**

## Application:

- Measured ILS used as **convolution kernel** in ARAHMIS
- Ensures accurate reproduction of observed spectra



# Collision-Induced Absorption (CIA)

## Definition / Importance

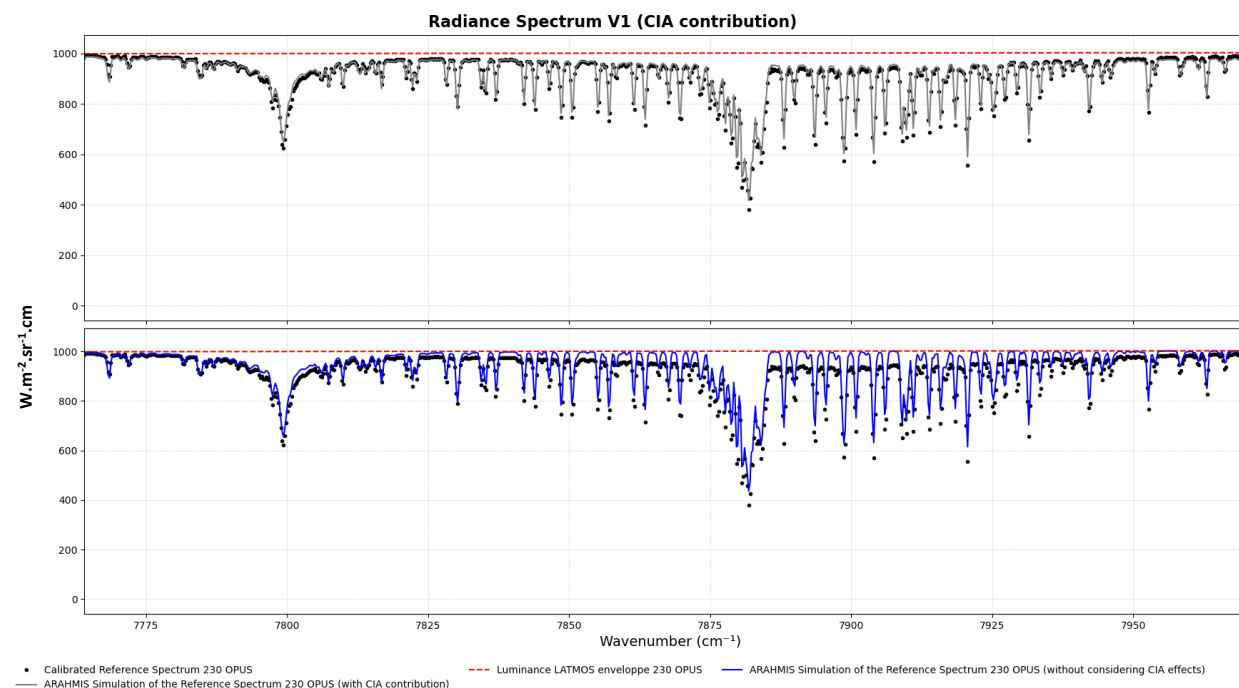


- Absorption due to transient dipoles created during molecular collisions.
- Crucial for an accurate simulation of measured spectra, especially in spectral regions affected by molecular interactions.
- Implemented in ARAHMIS according to the observation path used by EM27/SUN.

## CIA Pairs Used



- Detector 1 (O<sub>2</sub>): O<sub>2</sub>-O<sub>2</sub>, O<sub>2</sub>-air
- Detector 2 (N<sub>2</sub>): N<sub>2</sub>-N<sub>2</sub>, N<sub>2</sub>-air





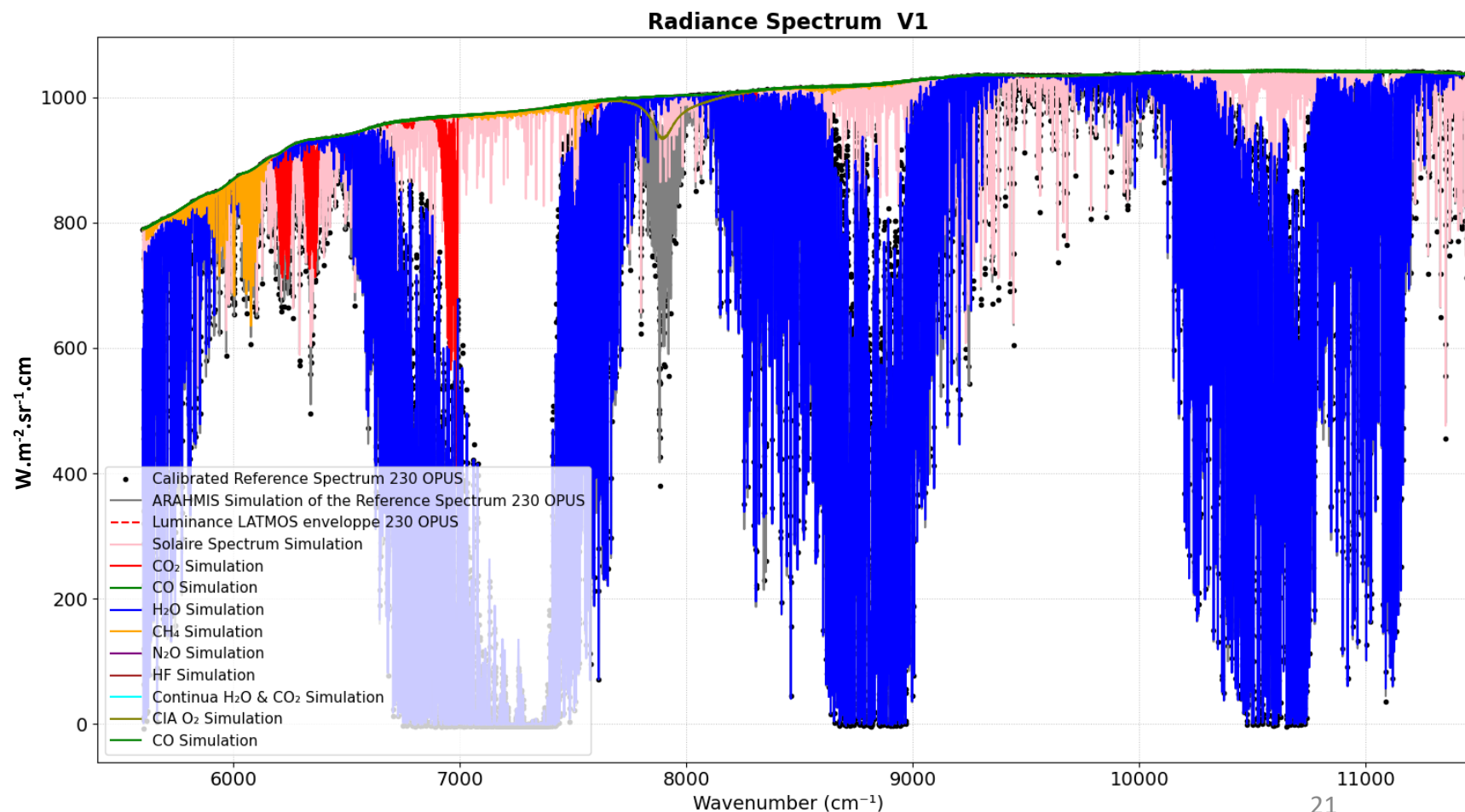
# ARAHMIS Simulation

## Comparison: Calibrated Spectrum vs ARAHMIS Simulation - Detector 1 (EM27/SUN)

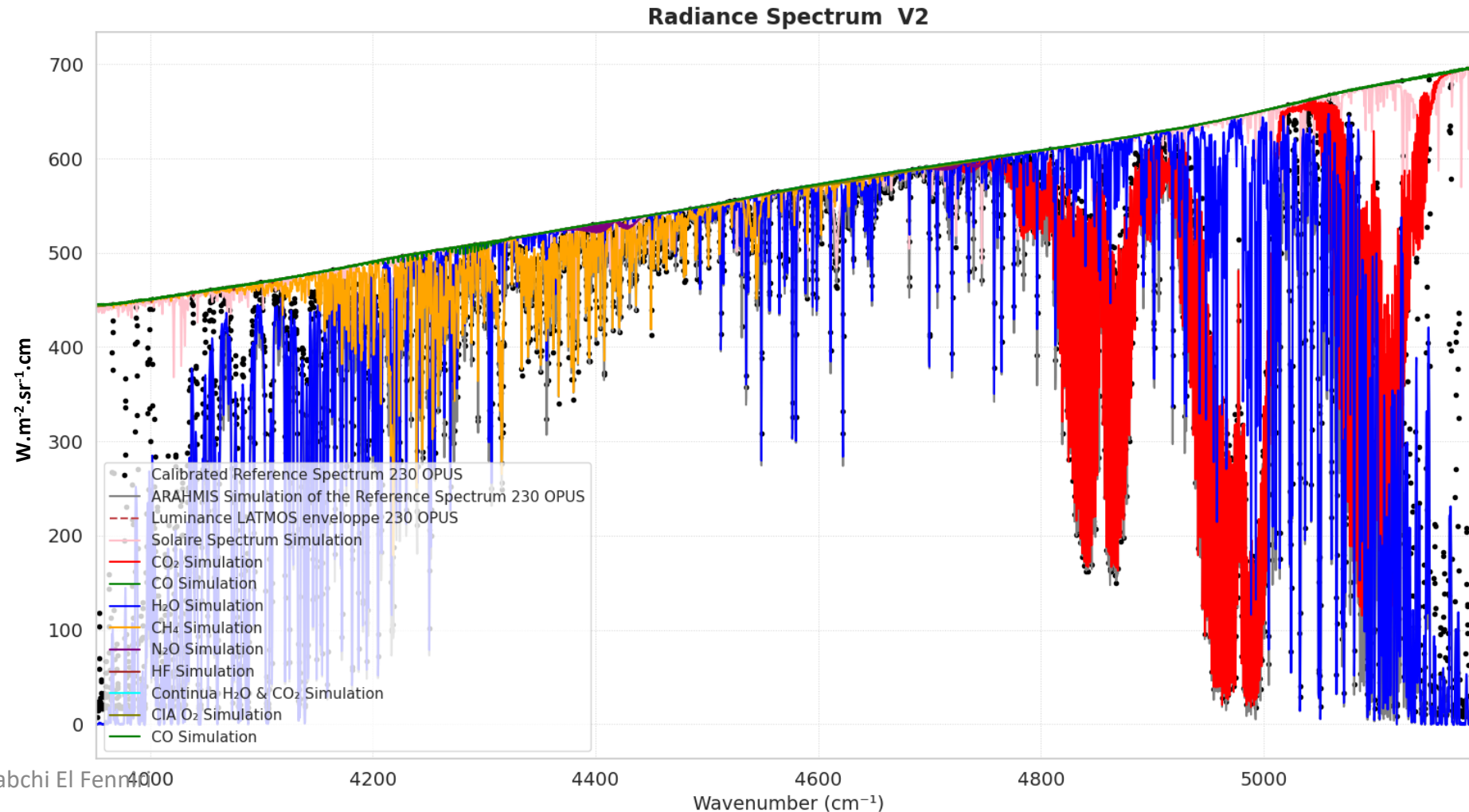
- Calibrated EM27/SUN spectrum
- ARAHMIS simulated spectrum (total)

Individual contributions:

- Molecular absorption ( $\text{CO}_2$ ,  $\text{H}_2\text{O}$ ,  $\text{CH}_4$ ,  $\text{O}_2$ , ...)
- CIA (Collision Induced Absorption)
- $\text{H}_2\text{O}$  and  $\text{CO}_2$  continua
- Solar reference spectrum



# Comparison: Calibrated Spectrum vs ARAHMIS Simulation – Detector 2 (EM27/SUN)





# Information Content Analysis

# Information Content Analysis – Rodgers (2000) Framework

## General framework:

Rodgers' formalism (2000) quantifies the information content of measurements and the associated uncertainties.

The analysis is based on (for more details, see chapter 3 of [Rodgers(2000)] C D Rodgers. Inverse Methods for Atmospheric Sounding. WORLD SCIENTIFIC, 2000.):

- Averaging Kernel (AVK) matrices.
- Different error sources in the retrieval.

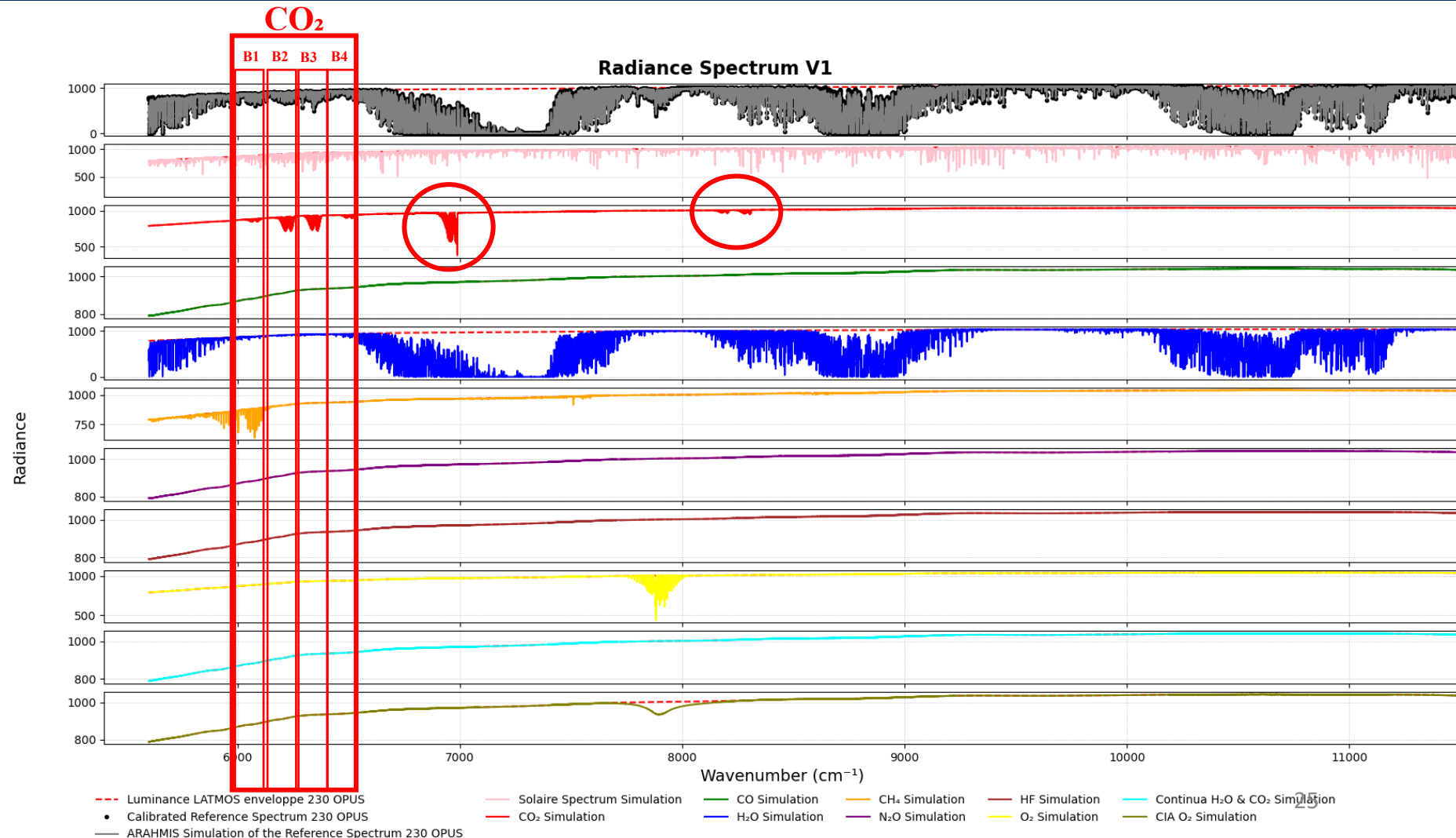
## Error sources considered:

- **Smoothing error:** due to the influence of the a priori on the retrieved profile.
- **Model error:** approximations in the radiative transfer representation.
- **Measurement error:** instrumental uncertainties and measurement noise.
- **A priori error:** linked to the choice of the assumed initial profile.

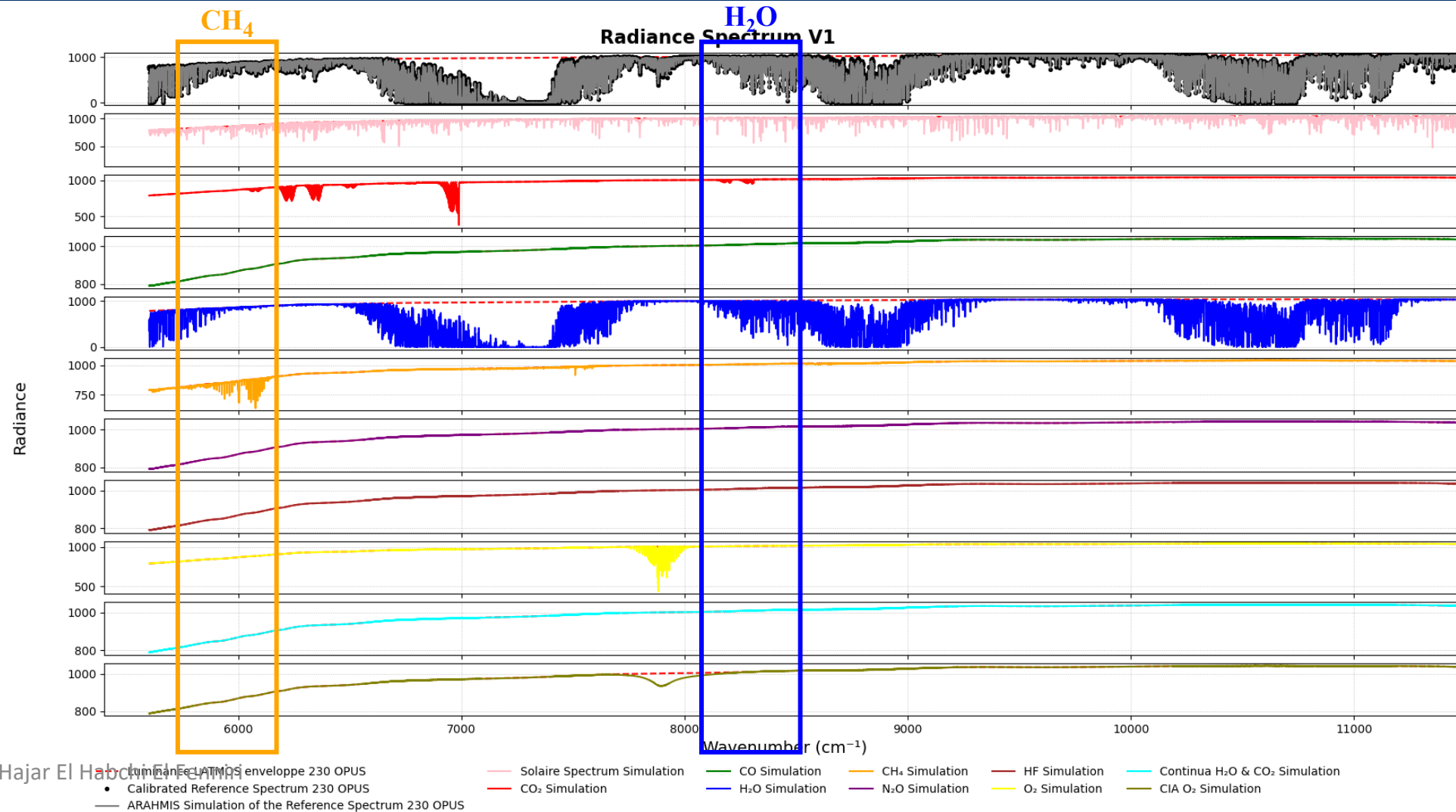
# Identification of Absorption Features – ARAHMIS Simulation - Detector 1 (EM27/SUN)

## Objective:

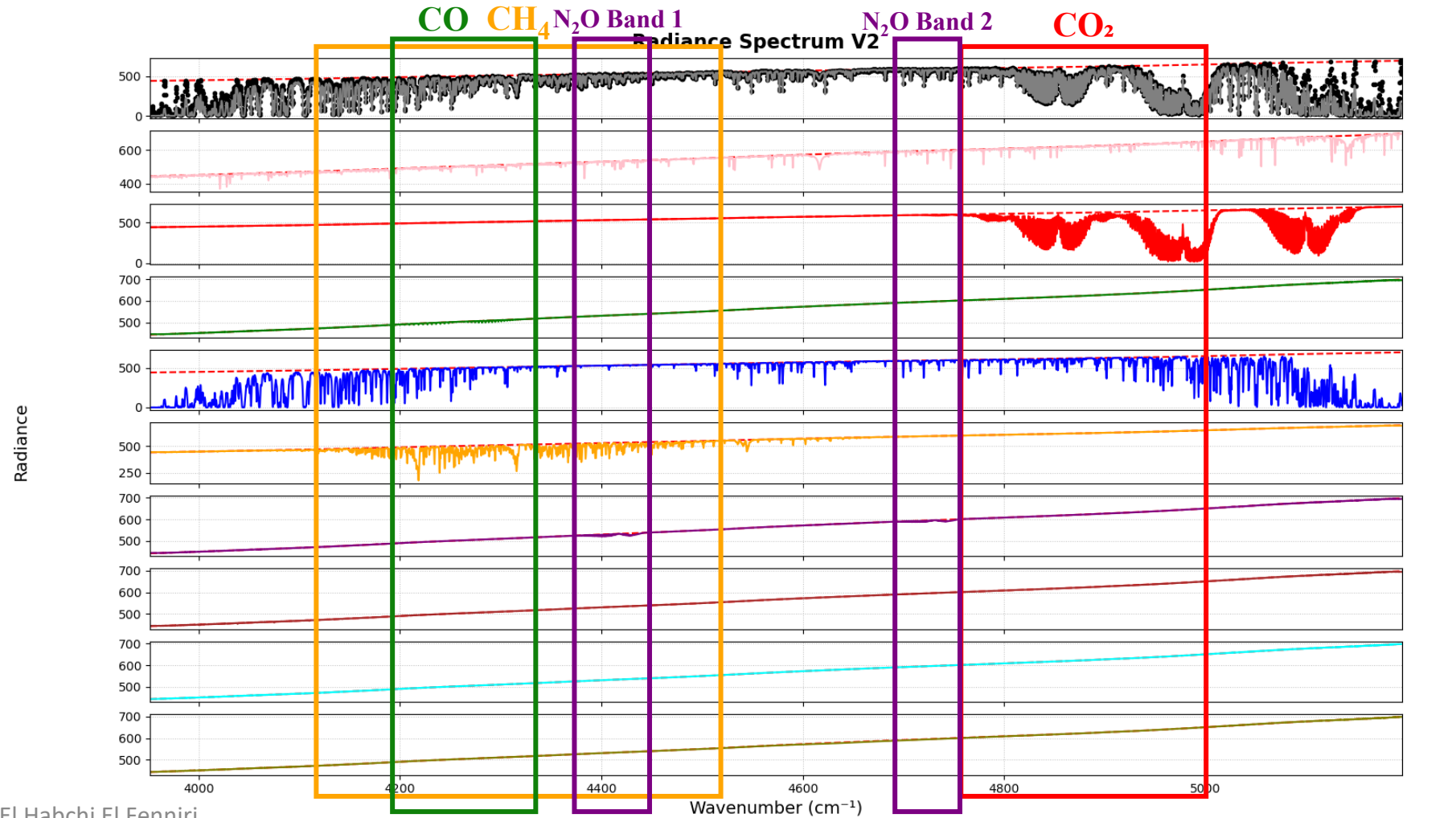
- Identify absorption bands of each molecule.
- Detect overlapping regions where several species absorb simultaneously.



# Identification of Absorption Features – ARAHMIS Simulation - Detector 1 (EM27/SUN)



# Identification of Absorption Features – ARAHMIS Simulation - Detector 2 (EM27/SUN)



## Summary of Entries

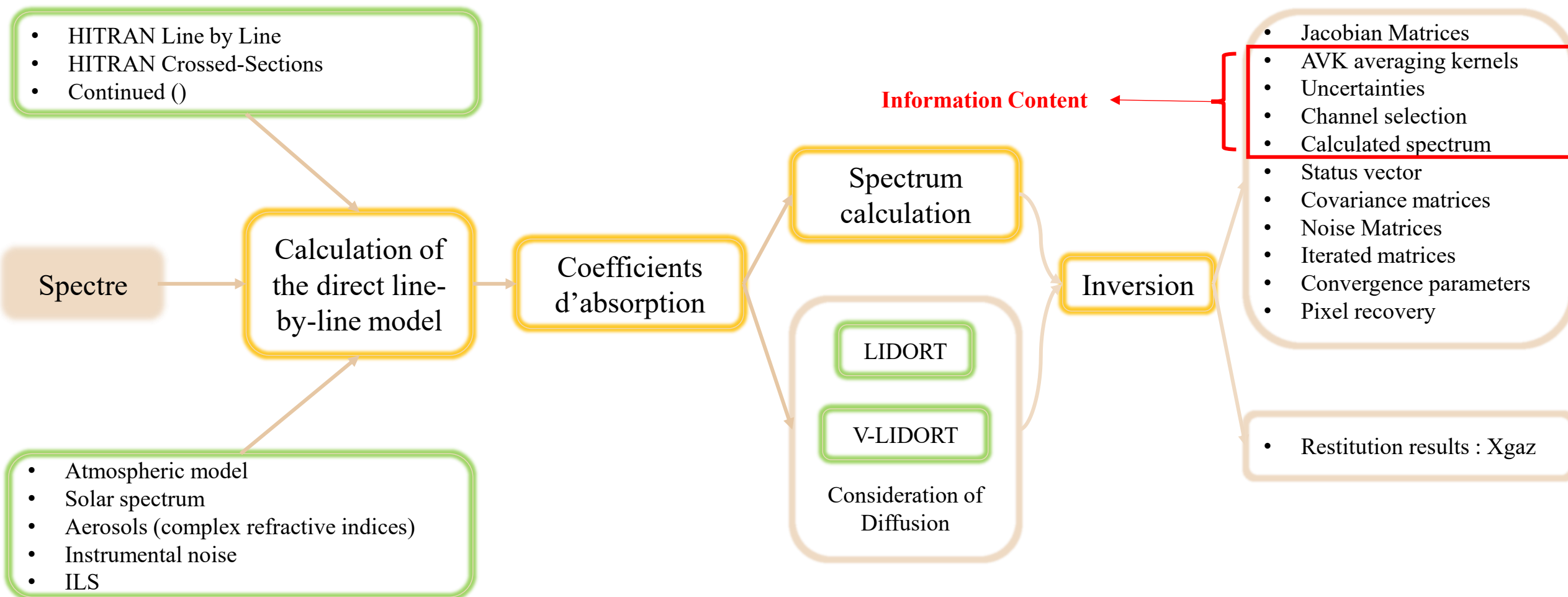
### Detector 1 :

|                  |                                    | A priori | CIA O <sub>2</sub> -O <sub>2</sub> ,<br>O <sub>2</sub> -air | Noise | ILS | Solar<br>Spectrum<br>Correction | H <sub>2</sub> O | CO <sub>2</sub> | CH <sub>4</sub> |
|------------------|------------------------------------|----------|-------------------------------------------------------------|-------|-----|---------------------------------|------------------|-----------------|-----------------|
| CO <sub>2</sub>  | Band 1 :<br>6038.21709, 6107.88233 | ✓        | ✓                                                           | ✓     | ✓   | ✓                               | ✓                | ✓               | ✓               |
|                  | Band 2 :<br>6166.21794, 6259.02458 | ✓        | ✓                                                           | ✓     | ✓   | ✓                               | ✓                | ✓               |                 |
|                  | Band 3 :<br>6293.01351, 6379.79374 | ✓        | ✓                                                           | ✓     | ✓   | ✓                               | ✓                | ✓               |                 |
|                  | Band 4 :<br>6463.92236, 6533.82866 | ✓        | ✓                                                           | ✓     | ✓   | ✓                               | ✓                | ✓               |                 |
| CH <sub>4</sub>  | Band :<br>5741.2358, 6170.0748     | ✓        | ✓                                                           | ✓     | ✓   | ✓                               | ✓                | ✓               | ✓               |
| H <sub>2</sub> O | Band :<br>8318.12676, 8598.2340    | ✓        | ✓                                                           | ✓     | ✓   | ✓                               | ✓                |                 |                 |

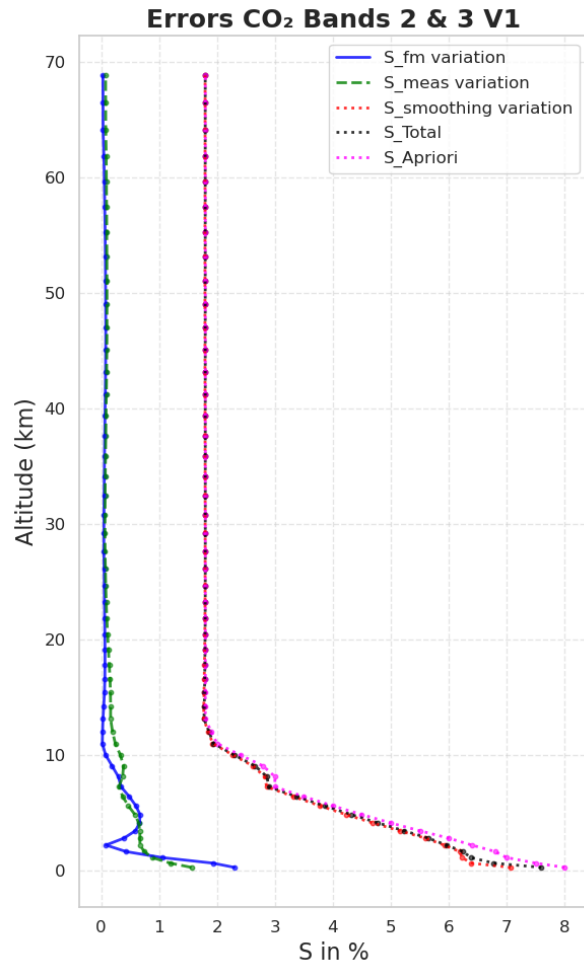
### Detector 2 :

|                  |                                   | A priori | CIA N <sub>2</sub> -N <sub>2</sub> , N <sub>2</sub> -<br>air | Noise | ILS | Solar<br>Spectrum<br>Correction | H <sub>2</sub> O | CO <sub>2</sub> | CH <sub>4</sub> | CO | N <sub>2</sub> O |
|------------------|-----------------------------------|----------|--------------------------------------------------------------|-------|-----|---------------------------------|------------------|-----------------|-----------------|----|------------------|
| CO <sub>2</sub>  | Band :<br>4722.0501, 5002.1574    | ✓        | ✓                                                            | ✓     | ✓   | ✓                               | ✓                | ✓               |                 |    | ✓                |
| CH <sub>4</sub>  | Band :<br>4179.1915, 4675.7673    | ✓        | ✓                                                            | ✓     | ✓   | ✓                               | ✓                |                 | ✓               | ✓  | ✓                |
| CO               | Band :<br>4187.1464, 4326.9590    | ✓        | ✓                                                            | ✓     | ✓   | ✓                               | ✓                |                 | ✓               | ✓  |                  |
| N <sub>2</sub> O | Band 1 :<br>4371.0723, 4442.9070  | ✓        | ✓                                                            | ✓     | ✓   | ✓                               | ✓                |                 | ✓               |    | ✓                |
|                  | Band 2 :<br>4699.14982, 4756.7622 | ✓        | ✓                                                            | ✓     | ✓   | ✓                               | ✓                | ✓               |                 |    | ✓                |

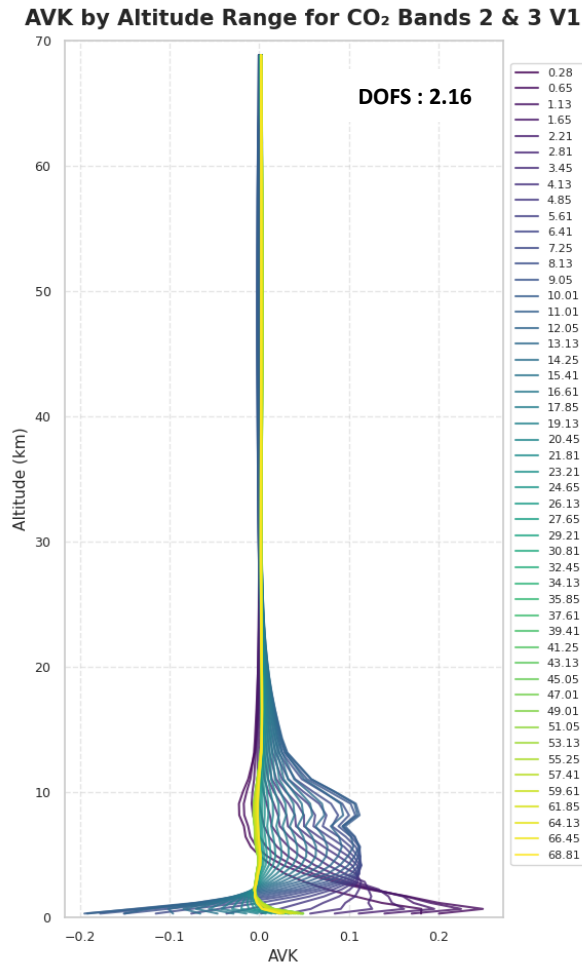
## Output Data for ARAHMIS



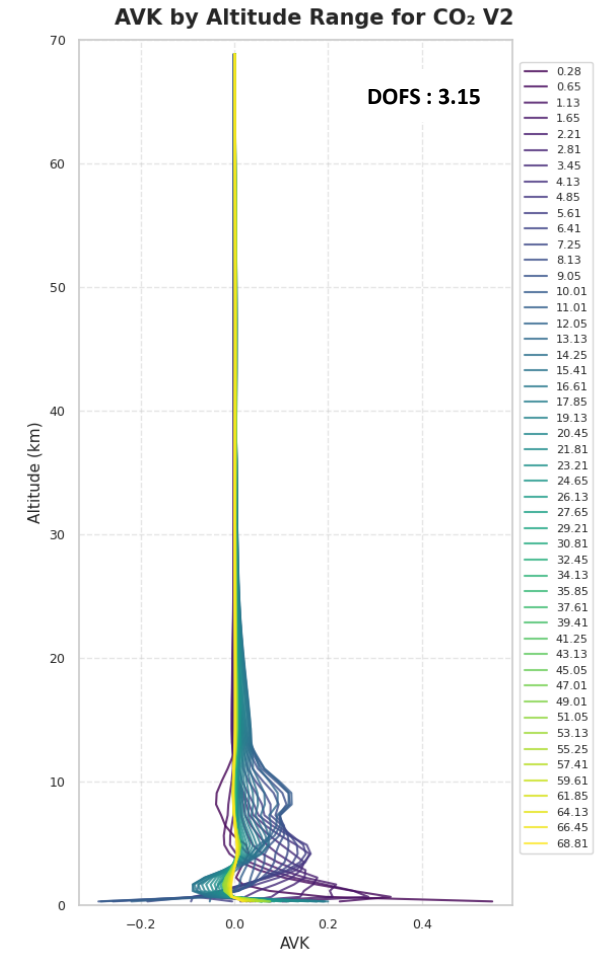
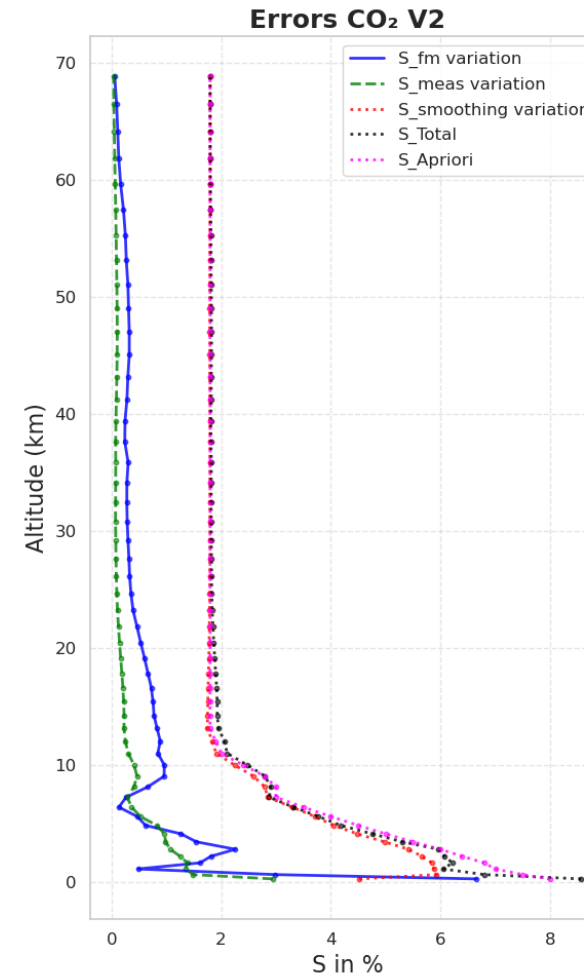
# Example Plots of Errors and AVKs



Hajar El Habchi El Fenniri



COCCON MEETING OCTober 2nd 2025



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## Summary of DOFS and Errors

- Detector 1: the combination of bands 2 & 3 represents an optimal compromise:
  - Provides as much information as using all 4 bands (DOFS  $\approx$  2.16 vs 2.22).
  - AVKs and posterior errors are nearly identical  $\rightarrow$  no significant loss of quality.
  - Reduces computation time and avoids spectral redundancy.
- Detector 2: more performant (DOFS = 3.15)  $\rightarrow$  provides greater independent information.
- Sensitivity altitude: EM27/SUN is mainly sensitive to CO<sub>2</sub> in the lower troposphere, consistent with its use for total column monitoring.
- Dominant error: smoothing error  $\rightarrow$  highlights the importance of a robust a priori.

| CO <sub>2</sub> |                                    |             |                       |          |               |          |
|-----------------|------------------------------------|-------------|-----------------------|----------|---------------|----------|
|                 | Band                               | DOFS        | Smoothing uncertainty |          | Total Error   |          |
|                 |                                    |             | S_smooth % max        | Altitude | S_total % max | Altitude |
| Detector 1      | Band 1 :<br>6038.21709, 6107.88233 | 1,01        | 7.750120              | 0.28     | 7.858250      | 0.28     |
|                 | Band 2 :<br>6166.21794, 6259.02458 | 1,93        | 7.18440               | 0.28     | 7.53491       | 0.28     |
|                 | Band 3 :<br>6293.01351, 6379.79374 | 1,90        | 7.20534               | 0.28     | 7.51155       | 0.28     |
|                 | Band 4 :<br>6463.92236, 6533.82866 | 0,98        | 7.756640              | 0.28     | 7.936460      | 0.28     |
|                 | Bands 1 et 2                       | 1,98        | 7.19798               | 0.28     | 7.61311       | 0.28     |
|                 | Bands 2 et 3                       | <b>2,16</b> | 7.07130               | 0.28     | 7.59874       | 0.28     |
|                 | Bands 3 et 4                       | 1,94        | 7.20179               | 0.28     | 7.55248       | 0.28     |
|                 | Bands 1 à 4                        | 2,22        | 7.05730               | 0.28     | 7.72628       | 0.28     |
| Detector or 2   | Band :<br>4722.0501, 5002.1574     | <b>3,15</b> | 5.93085               | 0.65     | 8.56782       | 0.28     |

# Summary of DOFS and Errors

- Detector 2 is clearly more efficient for CH<sub>4</sub>:
  - Higher DOFS (2.30 vs 1.82).
  - Sensitivity concentrated in the lower troposphere, more suitable for monitoring surface emissions.

- High information content (DOFS = 2.5) with strong sensitivity in the lower troposphere.
- Stable errors (~5%) → EM27/SUN provides robust retrievals of water vapor.

- Very limited information (DOFS = 0.37).
- Absorption lines are too weak, as clearly confirmed in the simulations.
- Although CO retrievals are often mentioned in the literature, these results show that EM27/SUN provides poor sensitivity for CO.

- Provides non-negligible information (DOFS ~0.9), with sensitivity in both the lower and upper troposphere.
- N<sub>2</sub>O retrievals from EM27/SUN have not been addressed in the literature

| CH <sub>4</sub> |                             |             |                       |          |                   |          |
|-----------------|-----------------------------|-------------|-----------------------|----------|-------------------|----------|
|                 | Band                        | DOFS        | Smoothing uncertainty |          | Total uncertainty |          |
|                 |                             |             | S_smooth % max        | Altitude | S_total % max     | Altitude |
| Detector 1      | Band : 5741.2358, 6170.0748 | 1,82        | 5                     | 51.05    | 5.030900          | 17.85    |
| Detector 2      | Band : 4179.1915, 4675.7673 | <b>2,30</b> | 5                     | 53.13    | 5.039280          | 0.28     |

|            | Band                                            | DOFS        | Smoothing uncertainty |          | Total Error   |          |
|------------|-------------------------------------------------|-------------|-----------------------|----------|---------------|----------|
|            |                                                 |             | S_smooth % max        | Altitude | S_total % max | Altitude |
| Detector 1 | H <sub>2</sub> O Band : 8318.12676, 8598.2340   | <b>2,5</b>  | 5.000040              | 13.13    | 5.000470      | 7.25     |
| Detector 2 | CO Band : 4187.1464, 4326.9590                  | <b>0,37</b> | 5                     | 35.85    | 5.37858       | 0.65     |
| Detector 2 | N <sub>2</sub> O Band 1 : 4371.0723, 4442.9070  | <b>0,94</b> | 5                     | 35.85    | 5             | 34.13    |
| Detector 2 | N <sub>2</sub> O Band 2 : 4699.14982, 4756.7622 | 0,69        | 5                     | 34.13    | 5.101910      | 2.21     |

# Construction of the A Priori Covariance Matrix

## Objective:

- Provide an a priori profile together with its variance and covariance matrix (including vertical correlations).
- In ARAHMIS, this matrix goes beyond variance: It introduces covariance, linking the levels and allowing the inversion to optimally weight information from both the a priori and the measurements.

## Principle:

- Use AirCore profiles as the basis.
- AirCore data limited to 20–25 km altitude.
- Completed with CAMS outputs to extend up to 70 km (EM27/SUN grid).

## Methodology:

- Constructed from 19 days of data around the reference date:
  - ✓ June 13, 2023 (day of the studied spectrum).
- Provides a realistic representation of atmospheric variability during the study period.

## Summary of DOFS with and without the covariance matrix

- Covariance significantly reduces DOFS → much of the raw information is redundant.
- Detector 2 remains more efficient, especially for CH<sub>4</sub>.
- Sensitivity shifts upward, reducing constraints near the surface.
- CH<sub>4</sub> retains more independent information than CO<sub>2</sub>, even with covariance.

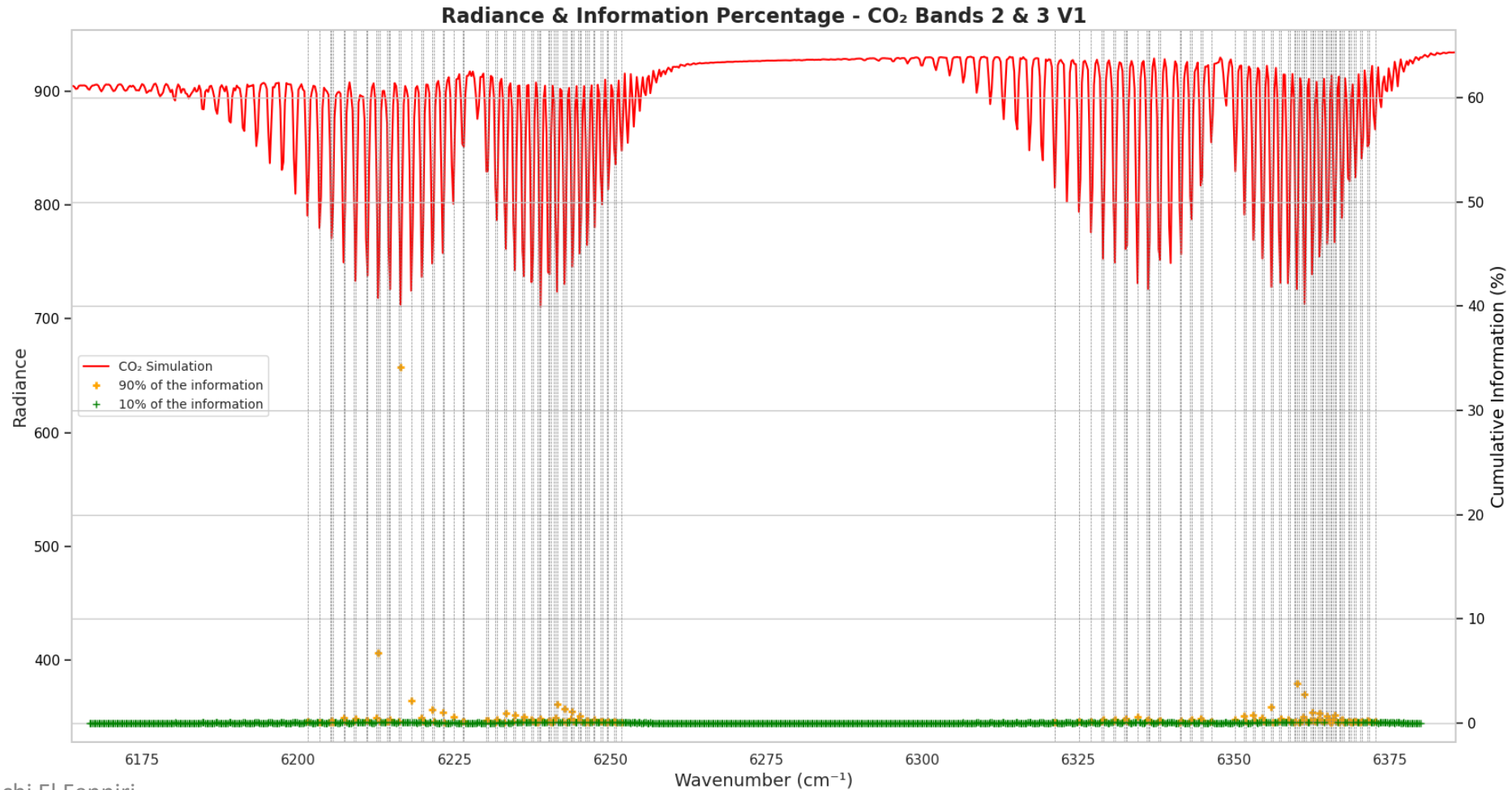
| Detector 1 | CO2                                   |                           |                |          |                        |                |          |
|------------|---------------------------------------|---------------------------|----------------|----------|------------------------|----------------|----------|
|            |                                       | Without covariance matrix |                |          | With covariance matrix |                |          |
|            | Fenêtre                               | DOFS                      | S_smooth % max | Altitude | DOFS with Covariance   | S_smooth % max | Altitude |
|            | Fenêtre 1 : 6038.21709, 6107.88233    | 1,01                      | 7.750120       | 0.28     | 0,440                  | 3.26277        | 0.275    |
|            | Fenêtre 2 : 6166.21794, 6259.02458    | 1,93                      | 7.18440        | 0.28     | 0,979                  | 1.88078        | 13.13    |
|            | Fenêtre 3 : 6293.01351, 6379.79374    | 1,90                      | 7.20534        | 0.28     | 0,980                  | 1.88071        | 13.13    |
|            | Fenêtre 4 : 6463.92236, 6533.82866    | 0,98                      | 7.756640       | 0.28     | 0,508                  | 2.91026        | 0.275    |
|            | Fenêtre 2 et 3                        | 2,16                      | 7.07130        | 0.28     | 0,997                  | 1.87477        | 13.13    |
| Detector 2 | CH4                                   |                           |                |          |                        |                |          |
|            | Fenêtre : 5741.2358300, 6170.07483765 | 1,82                      | 5              | 51.05    | 1,099                  | 0.06545        | 21.81    |
|            | CO2                                   |                           |                |          |                        |                |          |
|            | Fenêtre CO2                           | 3,15                      | 5.93085        | 0.65     | 1,047                  | 1.82914        | 13.13    |
|            | CH4                                   |                           |                |          |                        |                |          |
|            | Fenêtre CH4                           | 2,30                      | 5              | 53.13    | 1,424                  | 0.060426       | 21.81    |



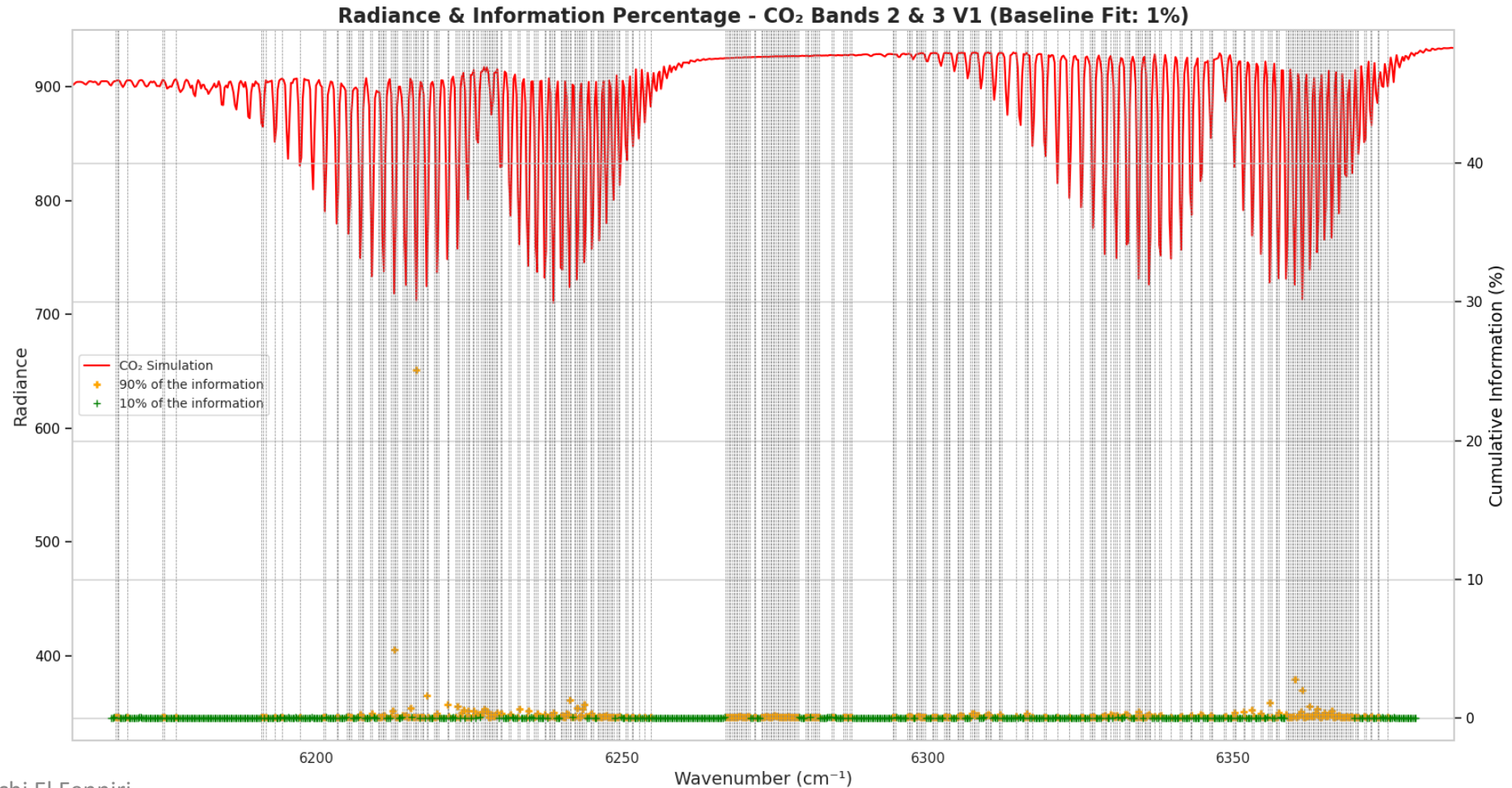
The background features a landscape with a green field and a line of trees under a blue sky. A vibrant rainbow arches across the sky. Faint, stylized chemical formulas are visible:  $\text{CO}_2$  in a circle on the left,  $\text{CH}_4$  in a cloud-like shape in the center, and  $\text{H}_2\text{O}$  in a circle on the right. A white silhouette of the map of France is on the right side. Thin, wavy lines in blue and purple connect the chemical formulas to the title.

# Channel Selection

# Channels and corresponding percentages



# Channels and corresponding percentages



## Summary of the channels

- Without baseline freedom:  
Fewer channels, but more concentrated and reliable → information is better attributed to the gases.
- With 1% baseline freedom:  
Much higher number of channels, but with redundancy and dilution of the real information (baseline compensation).
- Indicates where to find information — by molecule and by bandwidth (LB)

| CO <sub>2</sub>      |                                         |                                                               |
|----------------------|-----------------------------------------|---------------------------------------------------------------|
| Bands                | Number of channels with 90% information | Number of channels with 90% information (Baseline fit = 0.01) |
| Band 1               | 48                                      | 170                                                           |
| Band 2               | 73                                      | 177                                                           |
| Band 3               | 69                                      | 165                                                           |
| Band 4               | 48                                      | 162                                                           |
| Bands 2 & 3          | 145                                     | 370                                                           |
| CH <sub>4</sub>      |                                         |                                                               |
| Band CH <sub>4</sub> | 42                                      | 394                                                           |

## Conclusion

- Coupling bands 2 & 3 for CO<sub>2</sub> confirms the PROFFAST choice (Detector 1).
- The PROFFAST choice for CH<sub>4</sub> is also validated (Detector 1).
- With Detector 2, an additional degree of information is obtained for both CO<sub>2</sub> and CH<sub>4</sub>.
- The selected H<sub>2</sub>O band (Detector 1) matches PROFFAST → choice confirmed.
- CO shows very poor sensitivity (DOFS  $\approx 0.37$ ), not usable.
- N<sub>2</sub>O provides non-negligible information (DOFS  $\approx 0.9$ ), rarely explored.
- The covariance matrix reduces DOFS but removes redundancy and introduces vertical correlations.
- Without baseline freedom: fewer but more reliable channels. With 1% baseline freedom: more channels but redundancy and dilution.

## Perspectives

- Extend H<sub>2</sub>O analysis (two detectors, multiple bands).
- Explore the potential of N<sub>2</sub>O retrievals.
- Automate ARAHMIS for daily full-spectrum inversions and compare outputs with PROFFAST.



Thank you for your attention