IRIS: A RADIATIVE TRANSFER SIMULATION TOOL FOR SPACE-BASED GHG OBSERVATION MISSIONS

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PNST

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Outline

I. Introduction

Climate change represents one of the most significant challenge of the 21st century.

Increasing anthropogenic emissions, particularly from fossil fuel burning, have led to an unprecedented rise in the atmospheric concentration of greenhouse gases (GHG), resulting in enhanced trapping of terrestrial infrared radiation and an unbalanced Earth's Radiation Budget (ERB).

The Global Climate Observing System (GCOS) has identified 55 Essential Climate variables (ECVs) that have to be monitored closely as:

➔ Earth Radiative Budget (ERB) and greenhouse gases column are main ECVs that must be monitored,
➔ Greenhouse Gases (GHG) such as carbon dioxide (CO_2) and methane (CH_4).

Requirements for a hypothetical satellite constellation named Terra-F

Parameter	Absolute accuracy	Stability per decade	Spatial resolution	Temporal resolution
TSI	$\pm 0.54\,Wm^{-2}$	$\pm 0.14\,Wm^{-2}$	–	24 hours
OSR	$\pm 1.00\,Wm^{-2}$	$\pm 0.10\,Wm^{-2}$	10 – 100 km	3 hours
OLR	$\pm 1.00\,Wm^{-2}$	$\pm 0.10\,Wm^{-2}$	10 – 100 km	3 hours
EEI	$\pm 1.00\,Wm^{-2}$	$\pm 0.10\,Wm^{-2}$	–	24 hours
CO_2	± 1.0 ppm	± 1.5 ppm	2 – 10 km	3 hours
CH_4	± 10.0 ppb	± 7.0 ppb	2 – 10 km	3 hours

Meftah et al. 2023

I. Introduction

Many space missions have already been launched to monitor GHG from space.

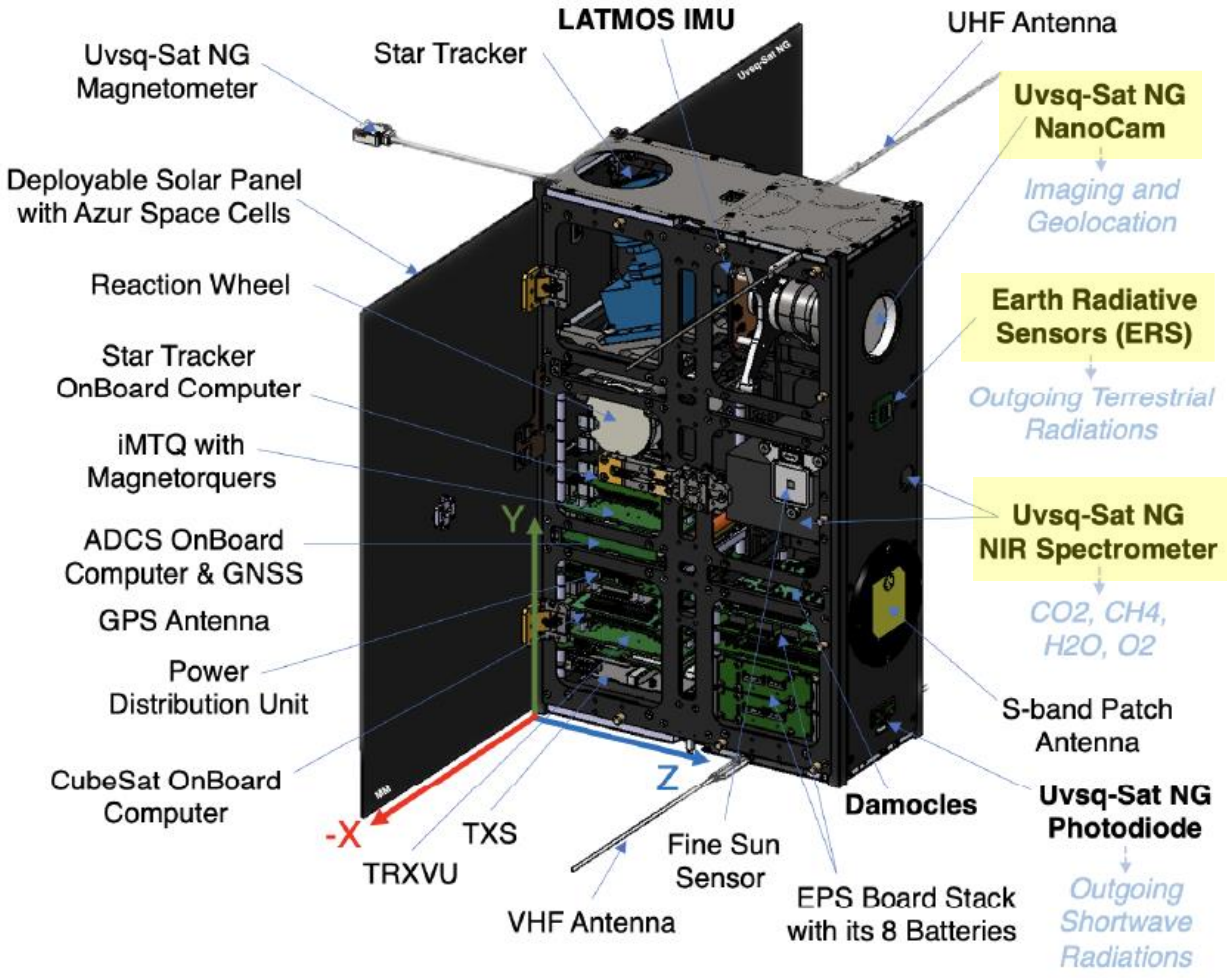
Satellite / Instrument	Satellite Type	Operational Period	XCO_2 Accuracy	XCH_4 Accuracy	References
SCIAMACHY	Large	2002 – 2012	1.2 ppm	20 ppb	Schneising et al. (2012) [9]
GOSAT	Large	2009 – Present	2 ppm	13 ppb	Kuze et al. (2016) [10]
OCO-2	Large	2014 – Present	0.65 ppm	/	Worden et al. (2017) [11]
GHGSat	SmallSat	2016 – Present	4.2 ppm	95 ppb	Jervis et al. (2021) [12]
TROPOMI	Large	2017 – Present	/	< 20 ppb	Lorente et al. (2021) [13]
Uvsq-Sat NG	SmallSat	From 2025	1 ppm	10 ppb	Meftah et al. (2023) [6]
MicroCarb	MicroSat	From 2025	<0.2 ppm	/	Meftah et al. (2023) [14]
Merlin	Large	From 2028	/	3.7 ppb	Ehret et al. (2017) [15]

Scientific requirements for a few key space missions. Clavier et al. 2024 (submitted)

Many space missions have already been launched to monitor GHG from space.
To assess the performance of such space-bases missions, it is necessary to implement simulators.
As part of the Uvsq-Sat NG mission, we have established a tool that provides an insight into the achievable performance of this mission.

Outline

II. Description of the Uvsq-Sat NG mission



Scientific objectives:

- ERB (OSR, OLR)
- GHG (CO_2, CH_4, H_2O)

Main properties:

- Mass: 10.0 kg
- Power: 35 W
- Orbit: Sun-Synchronous Orbit – 535 km

Payloads:

Parameter	Spectrometer	NanoCam	ERS sensors
Field of view	0.15°	13°	180°
Aperture / Surface	15 mm	32 mm	10 × 10 mm
Spectral range	1200 – 2000 nm	390 – 690 nm	0.1 – 100 | 0.1 – 3 μm
Image Size	1 × 256 pixels	2048 × 1536 pixels	1 × 1 element
Pixel size	250 × 50 μm	3.2 × 3.2 μm	10 × 10 mm
Spectral resolution	1 to 6 nm	–	–
Spatial resolution	< 2 km	< 30 m	2500 km

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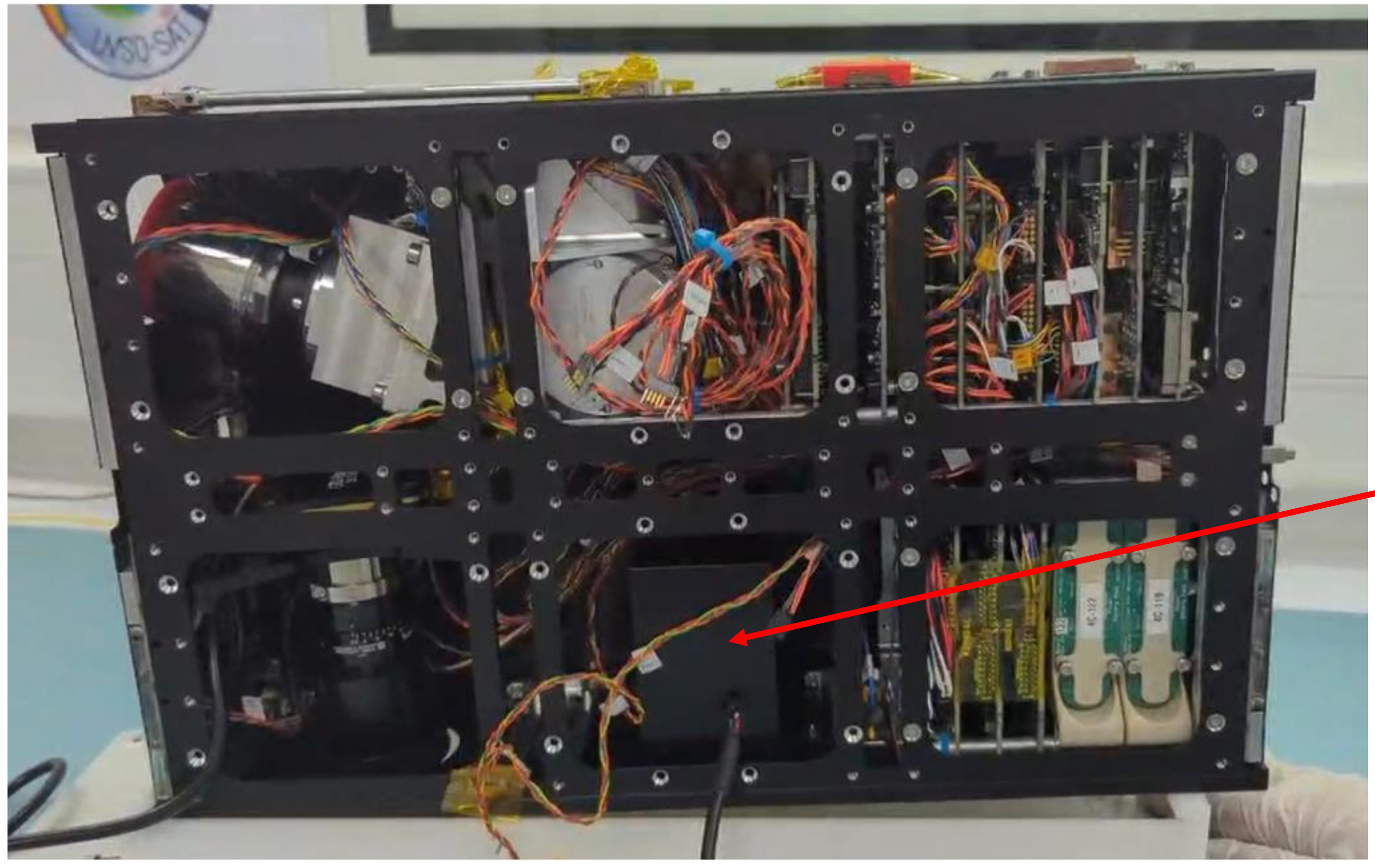
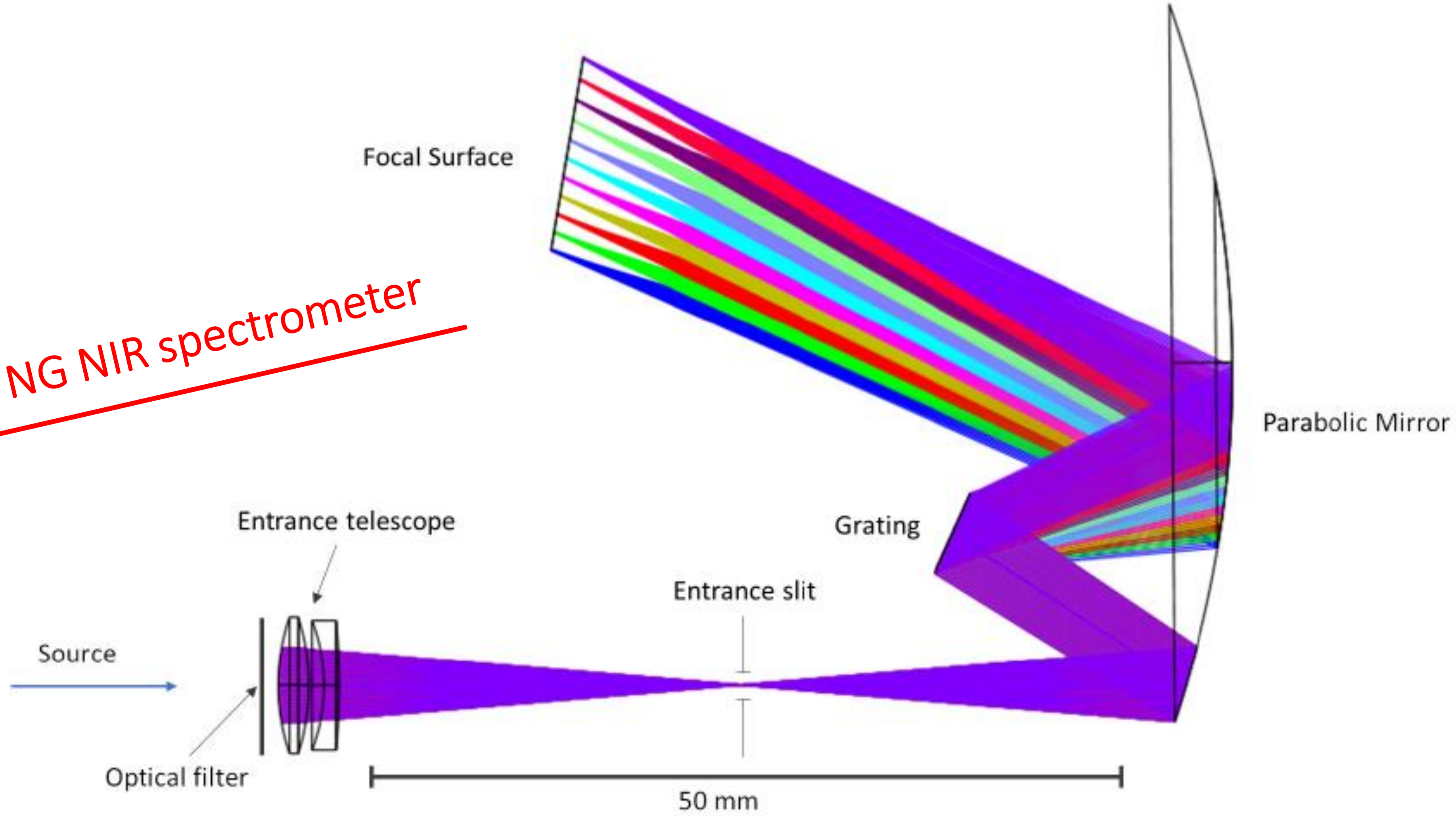


Uvsq-Sat NG NIR spectrometer



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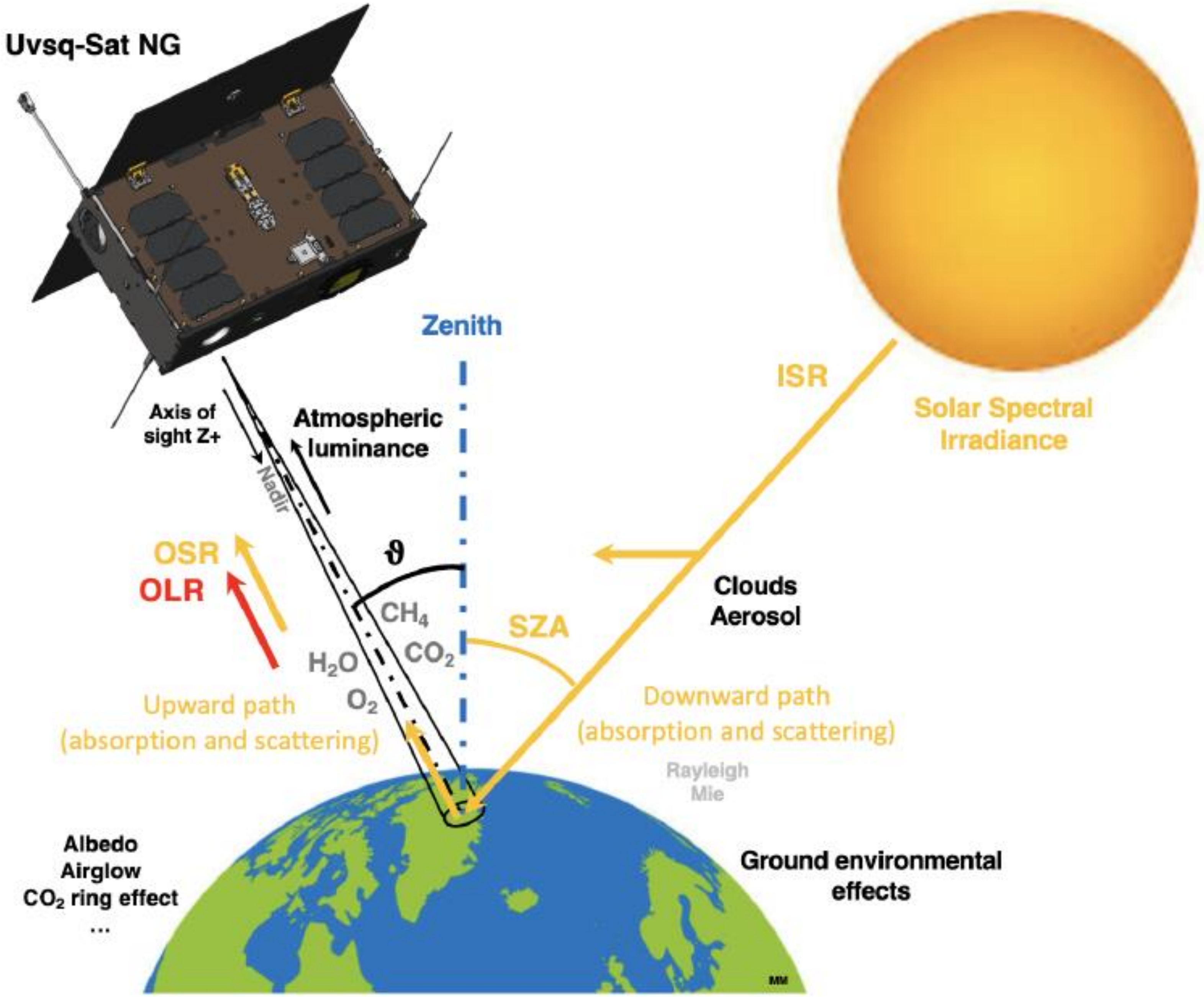
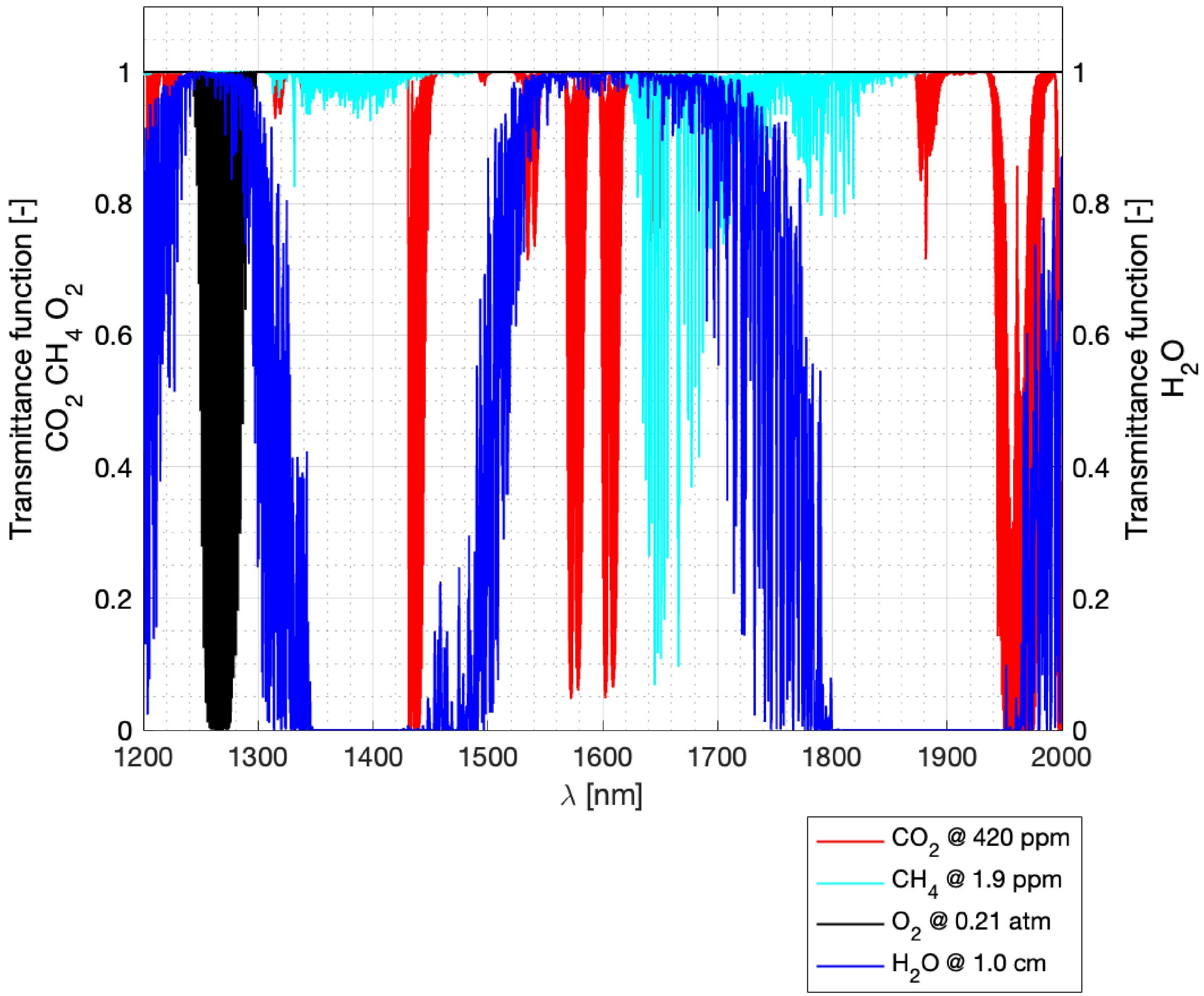




Outline

I. Introduction

II. Description of the Uvsq-Sat NG space-based mission

III. Methods for Evaluating the performances of GHG Instruments using SolAtmos

IV. Results – Application to the Uvsq-Sat NG mission

V. Conclusions & Perspectives

III. Methods for evaluating GHGs observations

SolAtmos is an end-to-end simulator developed to assess performances of space-based instruments designed to monitor greenhouse gases.

SolAtmos is based on 3 numerical tools:

Tool	Objectives
IRIS	Simulation of spectral radiances at instrument level
OptiSpectra	Simulation of the optical and radiometric performances of the instrument
GHGRetrieval	Determination of the GHG concentrations according to IRIS and OptiSpectra results

Inputs:
Solar Spectrum, Atmospheric, Surface and Instrument parameters

Tool 1:
IRIS

Spectral Radiance at TOA

Tool 2:
OptiSpectra

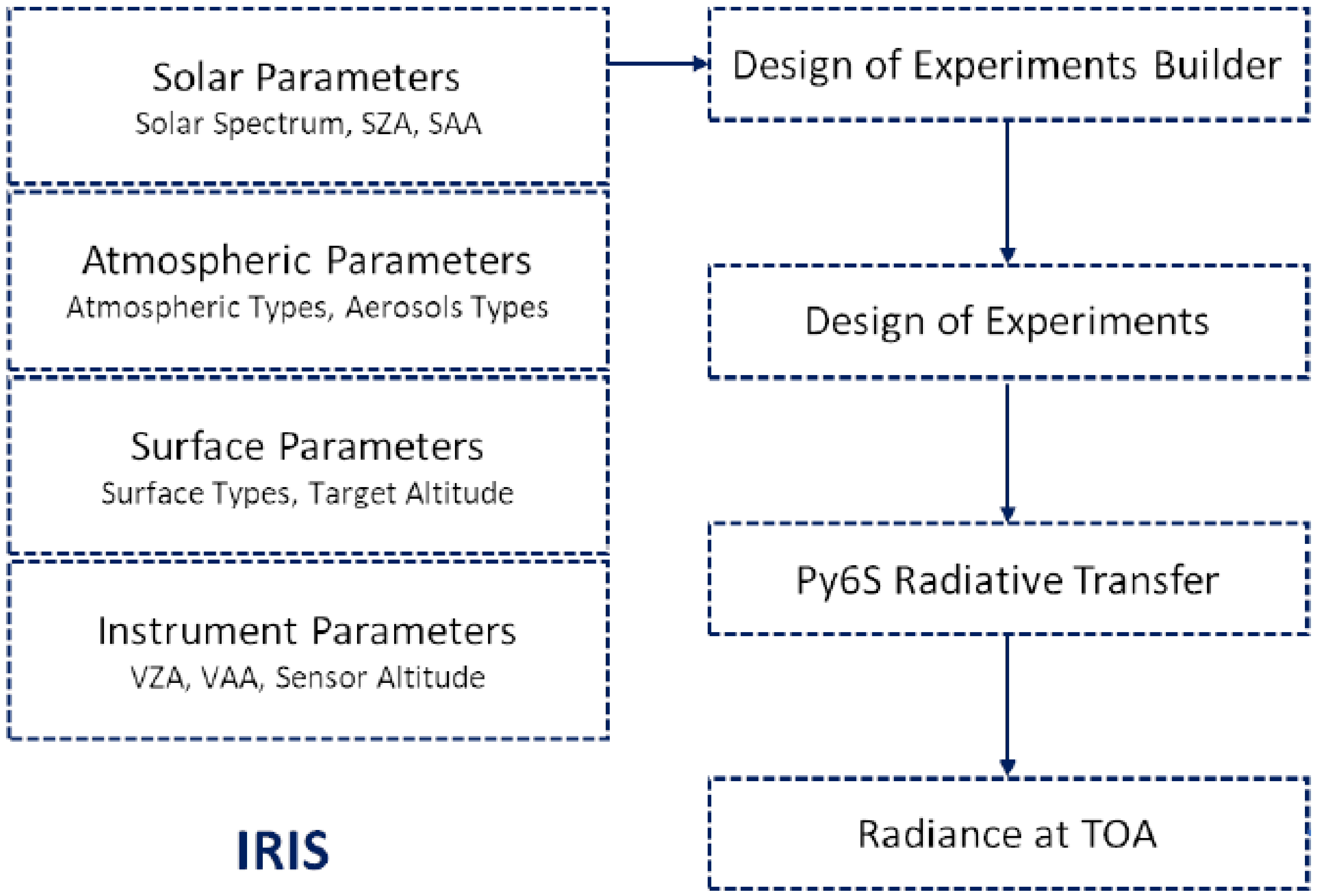
Optical and Radiometric analysis

Tool 3:
GHGRetrieval

Outputs:
GHG (CO_2, CH_4, H_2O) and O_2 concentrations and uncertainties

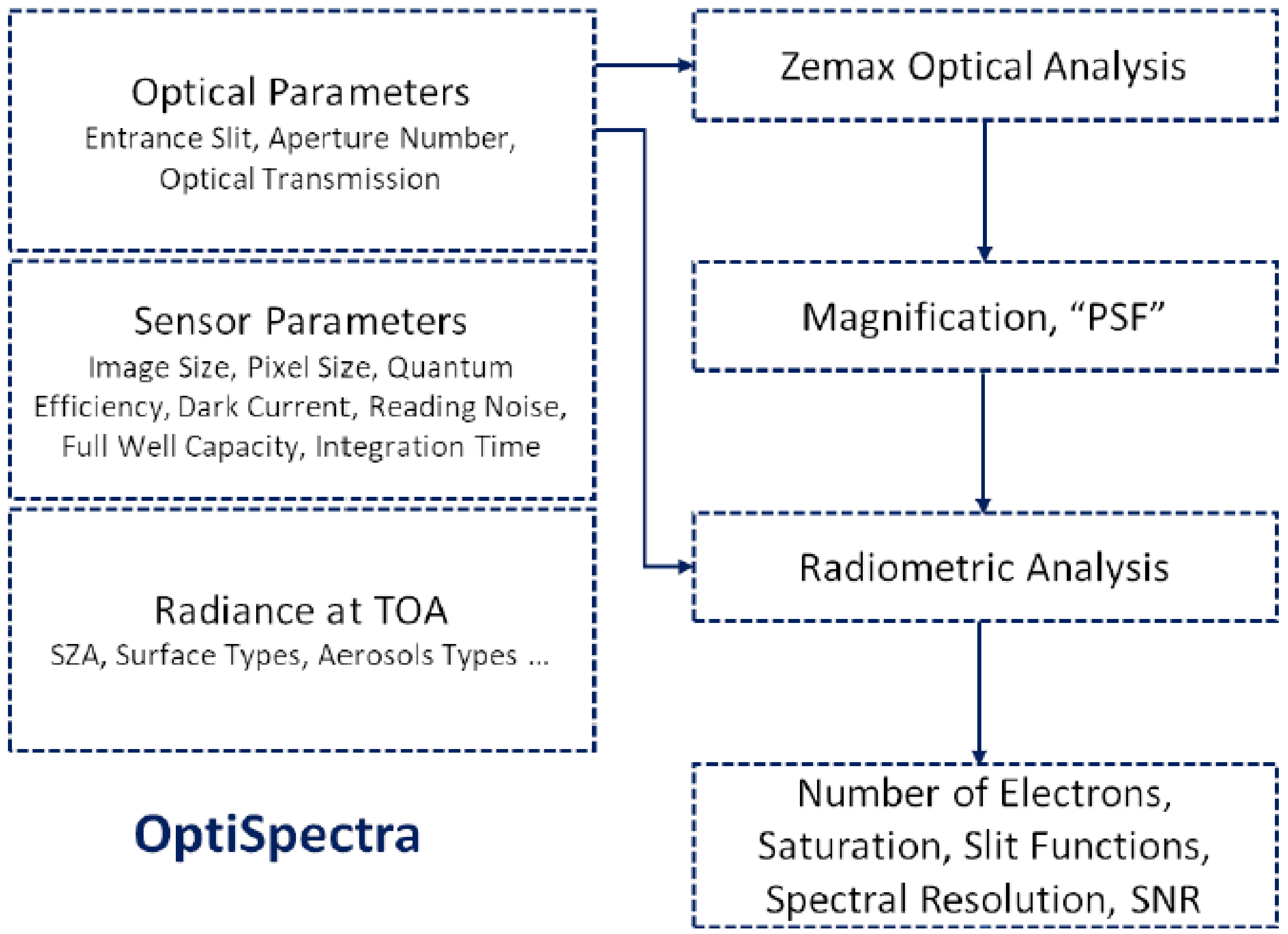
III. Evaluation of the performances of GHG Instruments

- ❑ Tool 1 – IRIS → Simulation of spectral radiances at instrument level



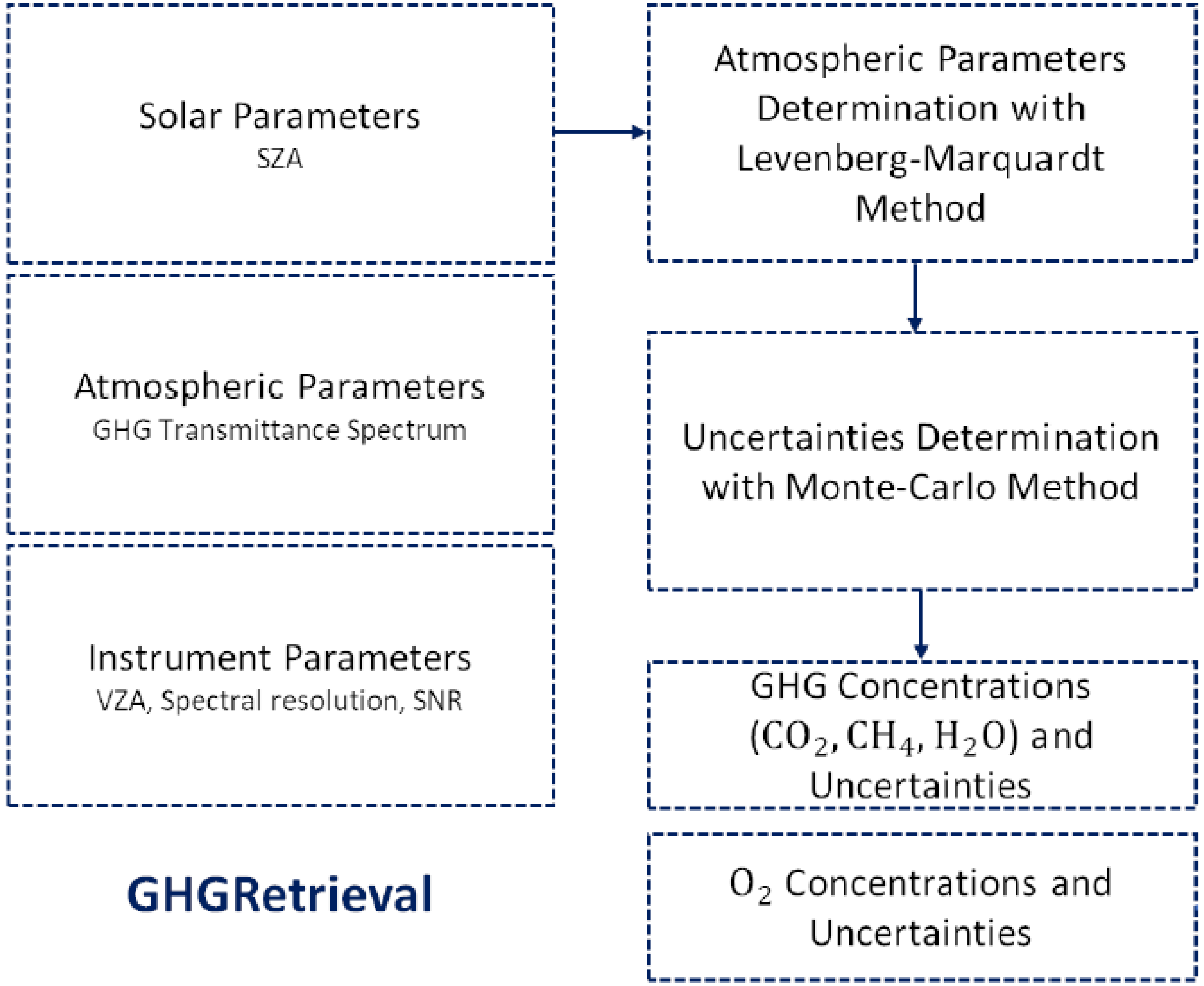
III. Evaluation of the performances of GHG Instruments

- ❑ Tool 2 – OptiSpectra → Simulation of the optical and radiometric performances of the instrument



III. Evaluation of the performances of GHG Instruments

- Tool 3 – GHGretrieval → Determination of the GHG concentrations according to IRIS and OptiSpectra results



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II. Description of the Uvsq-Sat NG space-based mission

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IV. Results – Application to Uvsq-Sat NG

The SolAtmos end-to-end simulator has been developed to evaluate the performances of space-based instruments that are designed for the monitoring of GHG such as CO_2 and CH_4.

Various cases have been studied:

'Surface' / 'Aerosols'	Pine forest (a)	Deciduous forest (b)	Ocean (c)	Homogeneous snow (d)
Continental	X	X	X	X
Desert	X	X	X	X
Maritime	X	X	X	X
Urban	X	X	X	X

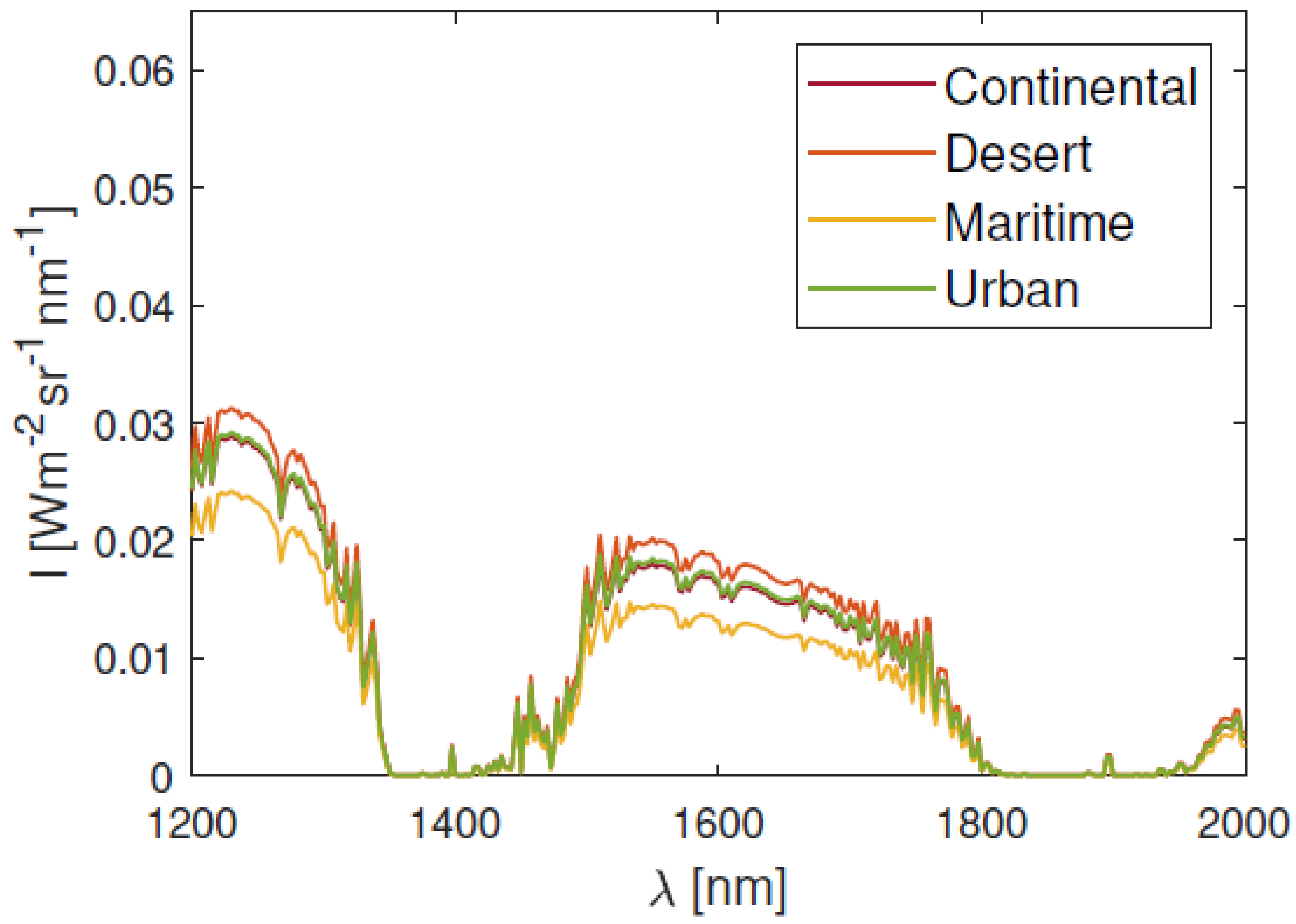
16 scenarios studied for different 'Aerosols' types and targeted 'Surface' – SZA of 20°.

'Aerosols' / 'SZA'	Continental (a)	Desert (b)	Maritime (c)	Urban (d)
0°	X	X	X	X
20°	X	X	X	X
50°	X	X	X	X
70°	X	X	X	X

16 scenarios studied for different SZA and 'Aerosols' types – Pine forest targeted 'Surface'.

IV. Results – Application to Uvsq-Sat NG

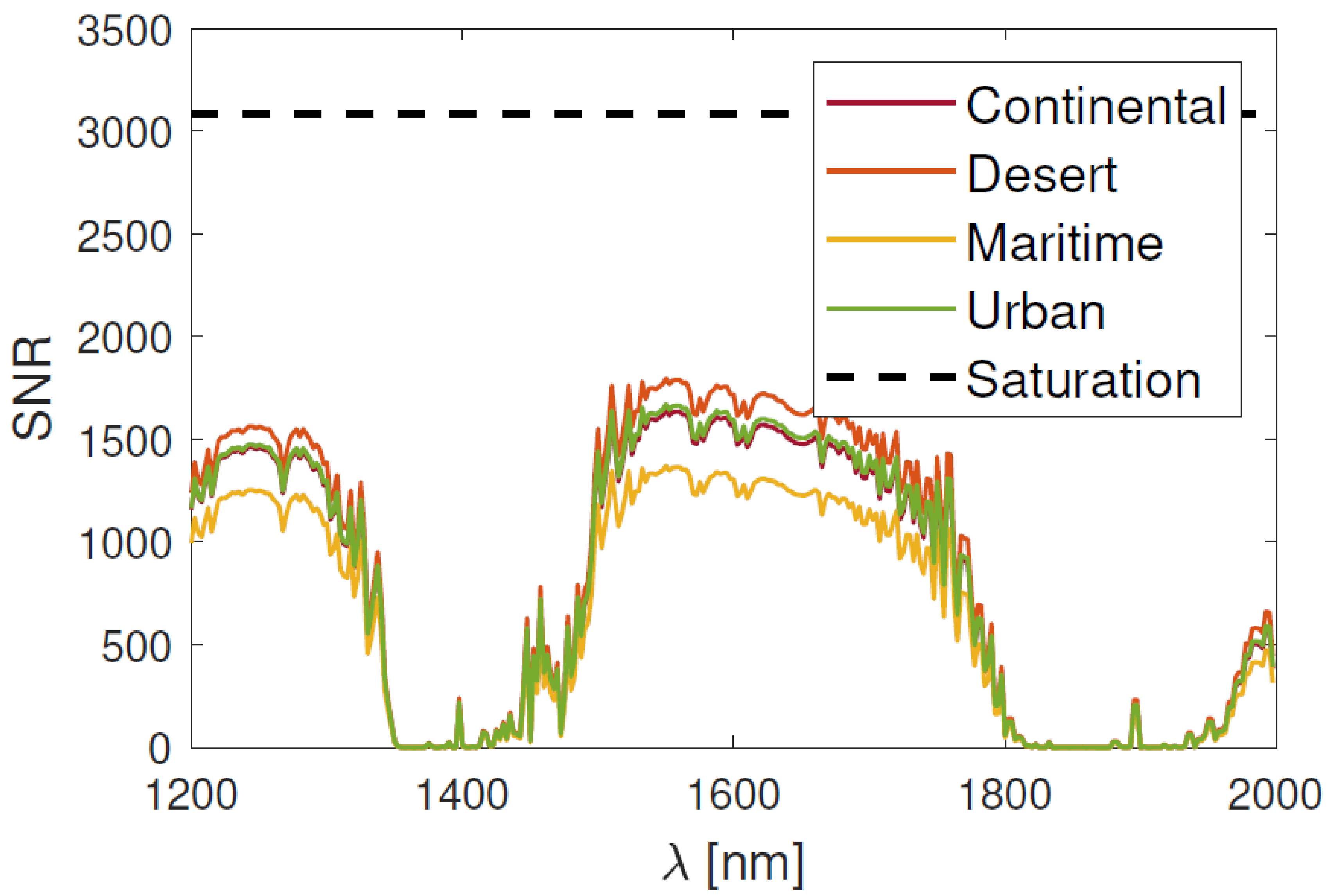
- ❑ Tool 1 – IRIS → Simulation of spectral radiances at instrument level



Example of an IRIS simulation studying the impact of the different aerosols above a pine forest scene for a 20° SZA on the TOA radiance.

IV. Results – Application to Uvsq-Sat NG

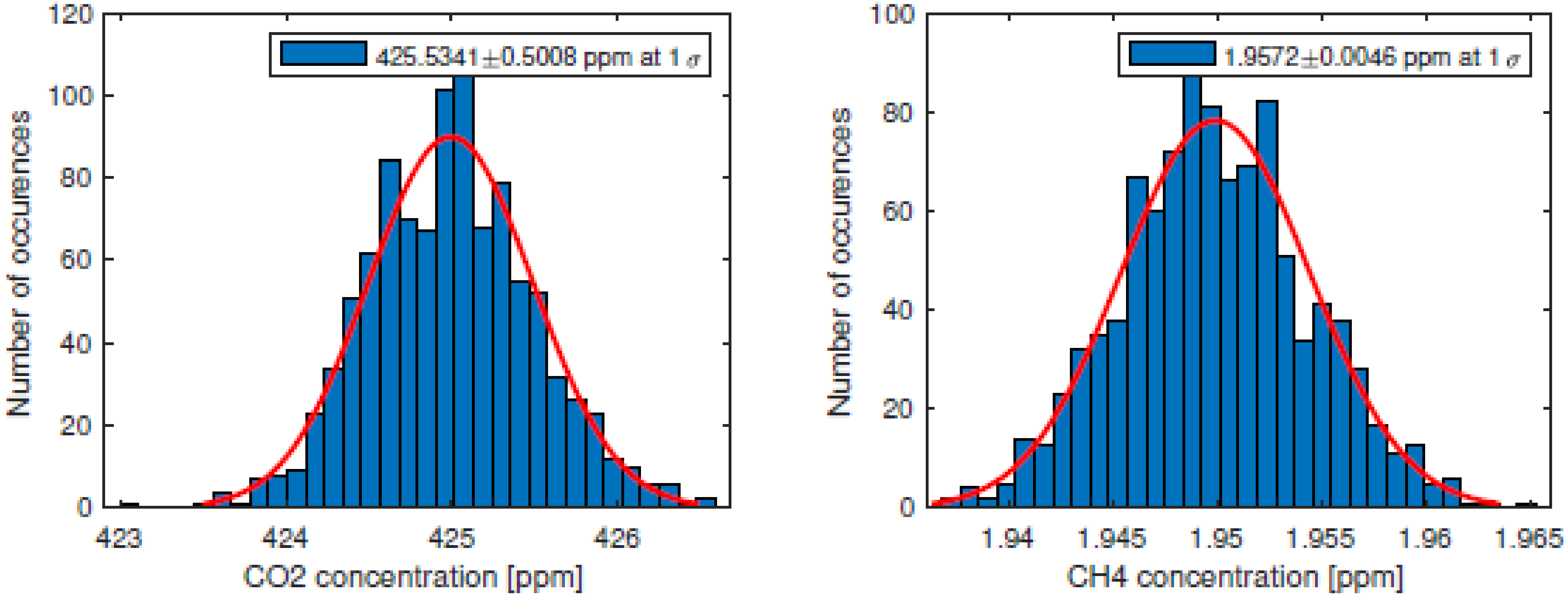
❑ Tool 2 – OptiSpectra → Simulation of the optical and radiometric performances of the instrument



Example of an OptiSpectra simulation studying the impact of the different aerosols above a pine forest scene for a 20° SZA on the spectral SNR.

IV. Results – Application to Uvsq-Sat NG

- ❑ Tool 3 – GHGretrieval → Determination of the GHG concentrations according to IRIS and OptiSpectra results



Example of a GHGRetrieval results for continental aerosols above a pine forest scene for a 20° SZA. The Uvsq-Sat NG spectrometer is supposed to have an 1 nm spectral resolution.

IV. Results – Application to Uvsq-Sat NG

- Results of the SolAtmos global toolchain applied to the Uvsq-Sat NG mission for CO_2 determination

Uvsq-Sat NG instrument spectral resolution: 1 nm				
Aerosols \ Surface	Pine forest (a)	Deciduous forest (b)	Ocean (c)	Homogeneous snow (d)
Continental	0.5 ppm	0.4 ppm	77.6 ppm	0.3 ppm
Desert	0.5 ppm	0.3 ppm	82.8 ppm	0.3 ppm
Maritime	0.6 ppm	0.4 ppm	81.4 ppm	0.3 ppm
Urban	0.5 ppm	0.4 ppm	78.4 ppm	0.3 ppm
Uvsq-Sat NG instrument spectral resolution: 5 nm				
Aerosols \ Surface	Pine forest (a)	Deciduous forest (b)	Ocean (c)	Homogeneous snow (d)
Continental	1.3 ppm	0.9 ppm	234.5 ppm	0.7 ppm
Desert	1.7 ppm	0.8 ppm	225.8 ppm	0.6 ppm
Maritime	1.4 ppm	1.1 ppm	228.6 ppm	0.8 ppm
Urban	1.3 ppm	0.9 ppm	233.2 ppm	0.7 ppm

Uvsq-Sat NG instrument spectral resolution: 1 nm				
SZA \ Aerosols	Continental (a)	Desert (b)	Maritime (c)	Urban (d)
0°	0.5 ppm	0.4 ppm	0.6 ppm	0.5 ppm
20°	0.5 ppm	0.5 ppm	0.6 ppm	0.5 ppm
50°	0.8 ppm	0.8 ppm	1.0 ppm	0.9 ppm
70°	2.2 ppm	1.7 ppm	2.9 ppm	2.2 ppm
Uvsq-Sat NG instrument spectral resolution: 5 nm				
SZA \ Aerosols	Continental (a)	Desert (b)	Maritime (c)	Urban (d)
0°	1.2 ppm	1.0 ppm	1.3 ppm	1.1 ppm
20°	1.3 ppm	1.1 ppm	1.5 ppm	1.1 ppm
50°	2.0 ppm	1.7 ppm	2.4 ppm	2.0 ppm
70°	5.6 ppm	4.3 ppm	6.5 ppm	5.2 ppm

CO_2 uncertainties (at 1σ) determination according to the various simulation cases (requirements: 1 ppm).

IV. Results – Application to Uvsq-Sat NG

- Results of the SolAtmos global toolchain applied to the Uvsq-Sat NG mission for CO_4 determination

Uvsq-Sat NG instrument spectral resolution: 1 nm				
Surface / Aerosols	Pine forest (a)	Deciduous forest (b)	Ocean (c)	Homogeneous snow (d)
Continental	4.9 ppb	3.7 ppb	194.1 ppb	2.5 ppb
Desert	4.4 ppb	3.2 ppb	184.8 ppb	2.4 ppb
Maritime	5.8 ppb	4.2 ppb	202.2 ppb	3.2 ppb
Urban	4.7 ppb	3.4 ppb	193.4 ppb	2.8 ppb
Uvsq-Sat NG instrument spectral resolution: 5 nm				
Surface / Aerosols	Pine forest (a)	Deciduous forest (b)	Ocean (c)	Homogeneous snow (d)
Continental	12.2 ppb	10.2 ppb	735.6 ppb	7.8 ppb
Desert	10.5 ppb	8.5 ppb	710.8 ppb	7.0 ppb
Maritime	15.5 ppb	12.7 ppb	763.2 ppb	8.8 ppb
Urban	12.2 ppb	10.3 ppb	730.5 ppb	7.1 ppb

Uvsq-Sat NG instrument spectral resolution: 1 nm				
Aerosols / SZA	Continental (a)	Desert (b)	Maritime (c)	Urban (d)
0°	4.2 ppb	3.8 ppb	5.0 ppb	4.1 ppb
20°	4.5 ppb	4.3 ppb	5.6 ppb	4.3 ppb
50°	7.3 ppb	5.8 ppb	8.9 ppb	6.6 ppb
70°	14.7 ppb	12.6 ppb	19.4 ppb	14.7 ppb
Uvsq-Sat NG instrument spectral resolution: 5 nm				
Aerosols / SZA	Continental (a)	Desert (b)	Maritime (c)	Urban (d)
0°	12.7 ppb	11.2 ppb	14.3 ppb	11.4 ppb
20°	13.1 ppb	12.5 ppb	15.2 ppb	12.8 ppb
50°	19.9 ppb	16.7 ppb	23.4 ppb	19.9 ppb
70°	41.0 ppb	37.8 ppb	53.1 ppb	39.8 ppb

CH_4 uncertainties (at 1σ) determination according to the various simulation cases (requirements: 10 ppb).

Outline

V. Conclusions & Perspectives

- The SolAtmos end-to-end simulator, along with its tools IRIS, OptiSpectra, and GHGRetrieval, has been implemented to evaluate the capabilities of monitoring greenhouse gases, particularly carbon dioxide and methane, from a space-based instrument.

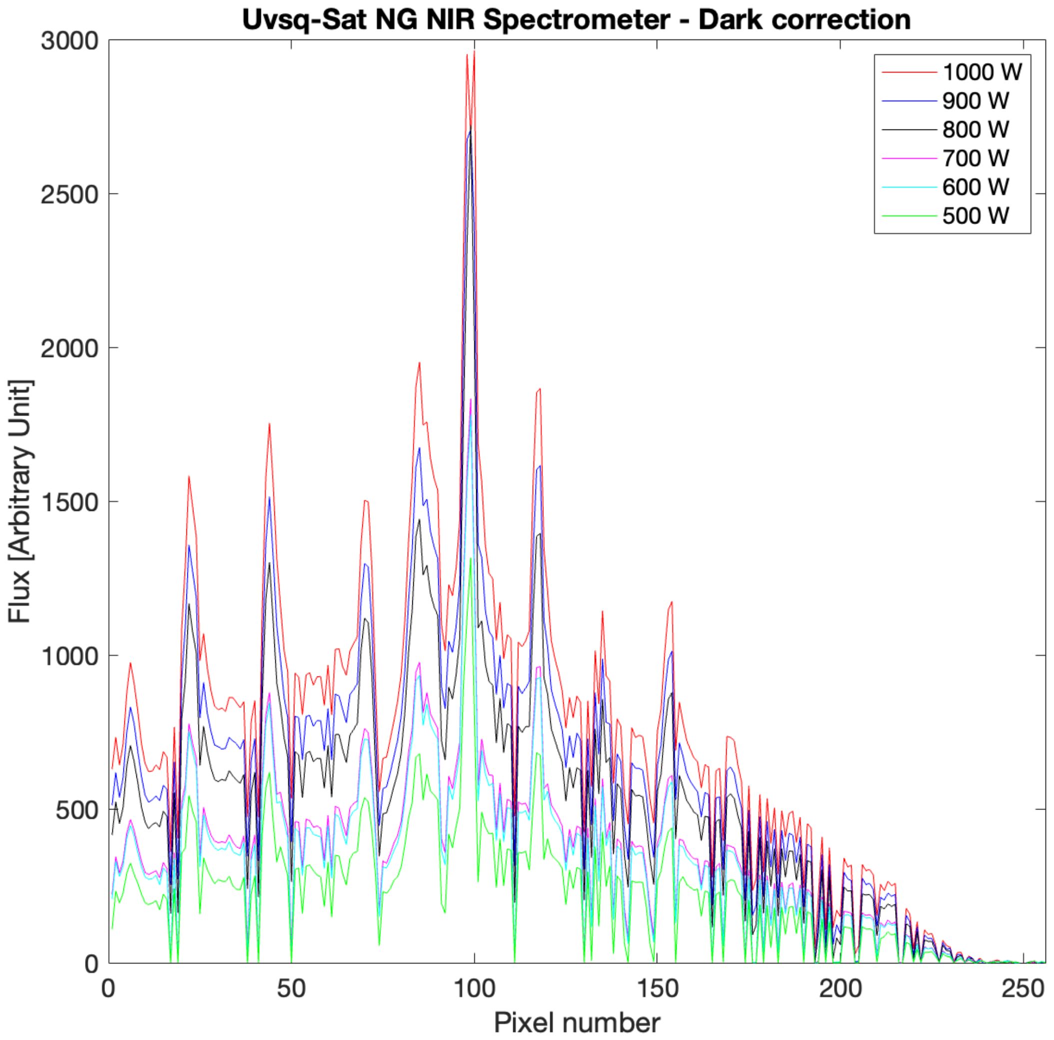
- This simulator is especially used to assess the scientific performance of the Uvsq-Sat NG mission. This simulator is implemented to be applicable to other observation missions as well.

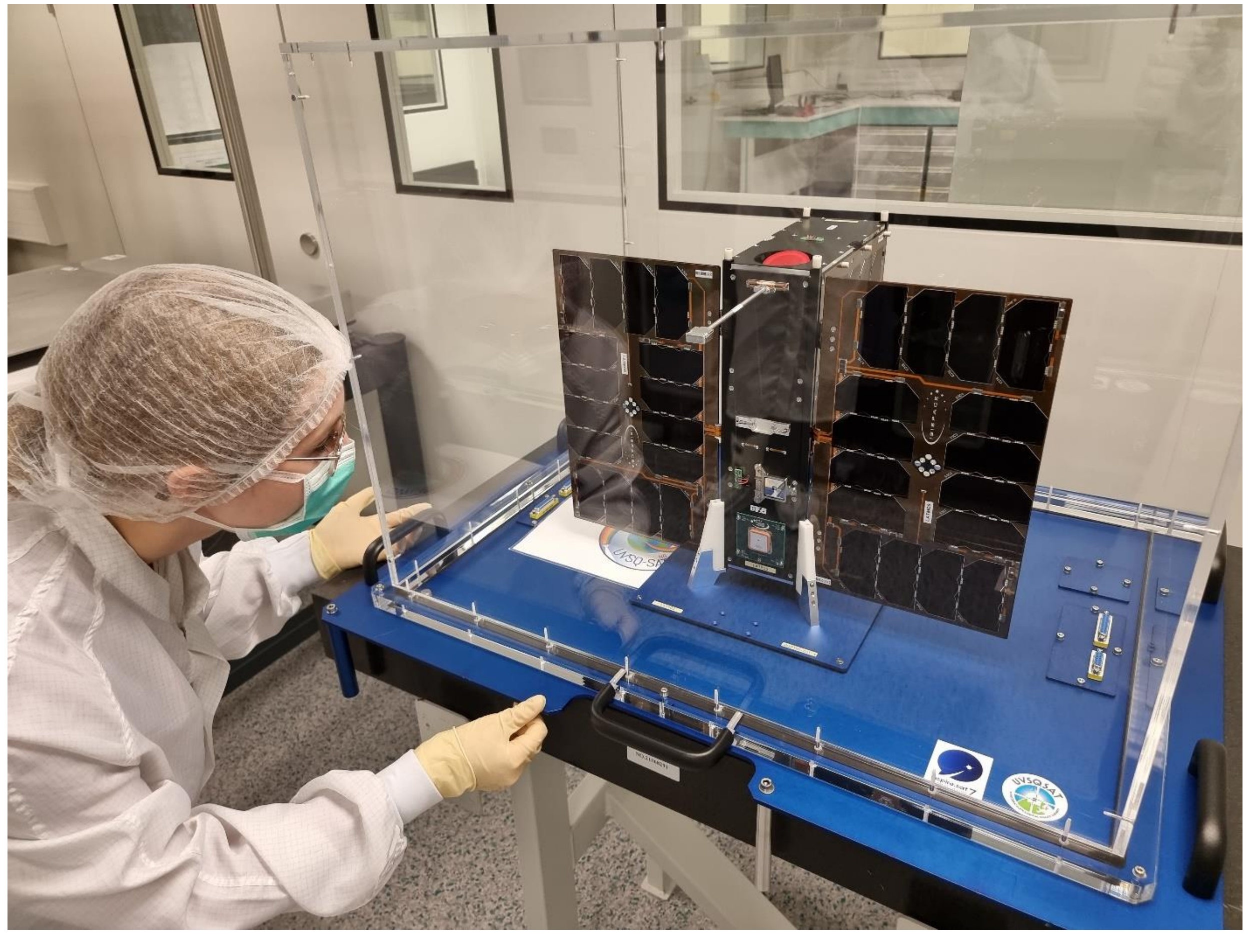
- To be even more efficient, the SolAtmos end-to-end simulator will need to fully integrate the SCIATRAN and 4A/OP radiative transfer models.

- Based on the SolAtmos simulator, the miniaturized spectrometer seems to have the potential to reach excellent accuracies above continental scene, especially in polar regions. These results seem to confirm the value of a constellation of small satellites for GHG monitoring.

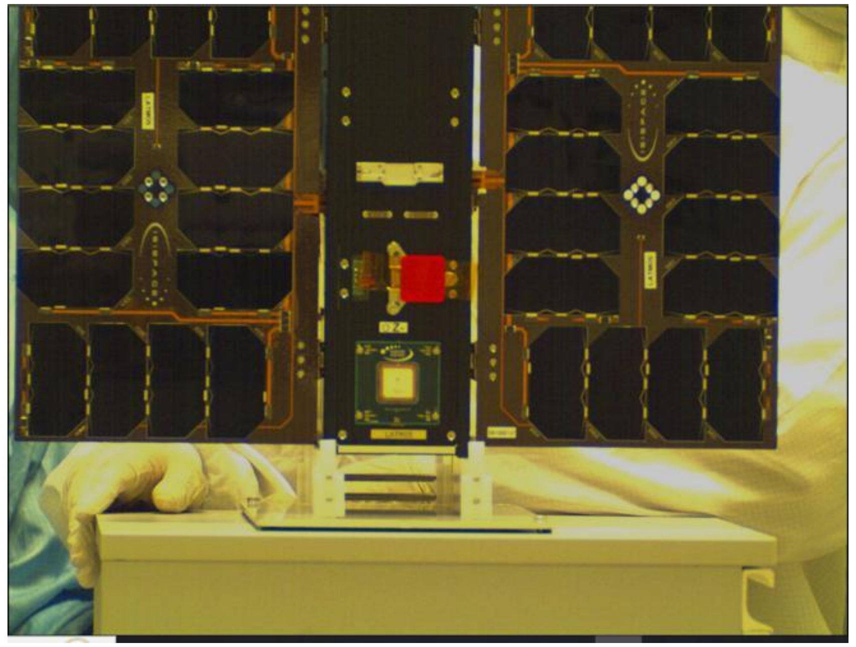
- The method highlight the limits of such a miniaturized spectrometer: above oceans the signal seems too low to reach good accuracies with a nadir pointing. The idea is to optimize the integration time and to use the Sun’s glint to increase the signal.

V. Conclusions & Perspectives





LATMOS credits

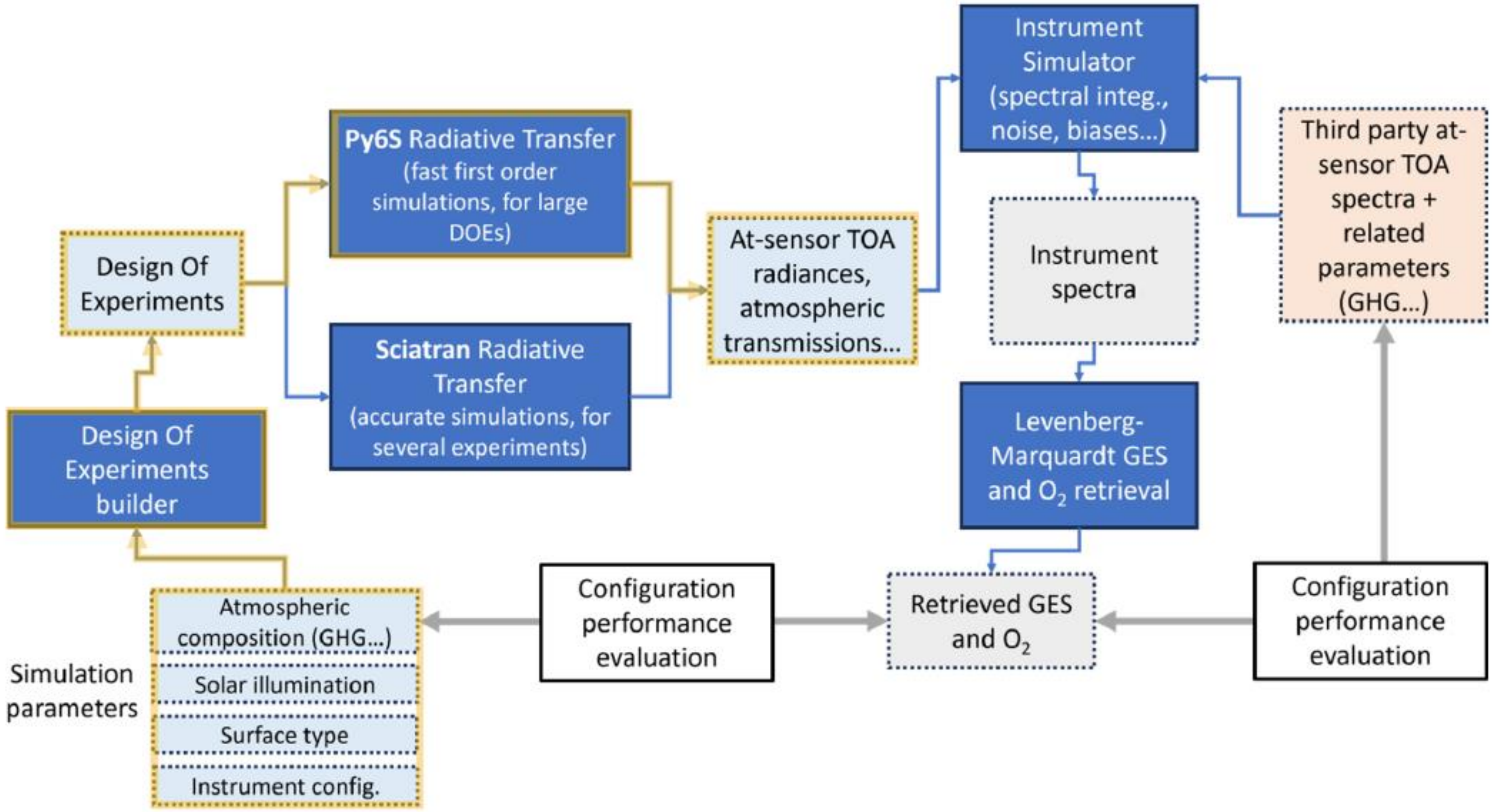


Thank you for your attention.

Radiative transfer models

RTM	SR[1]	Spectral Accuracy	Atmosphere Geometry	References
6S/6SV	VIS – NIR	2.5 nm	PP	Vermote et al. (1997) [18]
SCIATRAN	UV – FIR	$<$ 0.2 nm on VIS and NIR	PP / PS / S	Rozanov et al. (2014) [19]
4A/OP	NIR – FIR	$0.005\,cm^{-1}$	/	Scott and Chedin (1981) [20]
DART	VIS – FIR	$1\,cm^{-1}$	S	Wang and Gastellu-Etchegorry (2020) [21]
LBLRTM	VIS – LWIR	Line-by-line	S	Clough et al. (1981) [22]
MODTRAN6	UV – LWIR	$0.2\,cm^{-1}$	PP	Berk et al. (1998) [23]
Eradiate	VIS – NIR	Line-by-line, 1 nm, 10 nm	PP / S	https://www.eradiate.eu/
LibRadTran	UV – FIR	0.05 to 1 nm (MWIR)	PP / S	Mayer and Kylling (2005) [24]

IRIS tool



Instrument Simulator (spectral integ., noise, biases...)
Py6S Radiative Transfer (fast first order simulations, for large DOEs)
At-sensor TOA radiances, atmospheric transmissions...
Third party at-sensor TOA spectra + related parameters (GHG...)
Design Of Experiments
Instrument spectra
Sciatran Radiative Transfer (accurate simulations, for several experiments)
Design Of Experiments builder
Levenberg-Marquardt GES and O2 retrieval
Configuration performance evaluation
Retrieved GES and O2
Configuration performance evaluation
Atmospheric composition (GHG...)
Simulation parameters
Solar illumination
Surface type
Instrument config.