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Sensitivity studies of the 4.8 μm carbon dioxide absorption band for high temperature events

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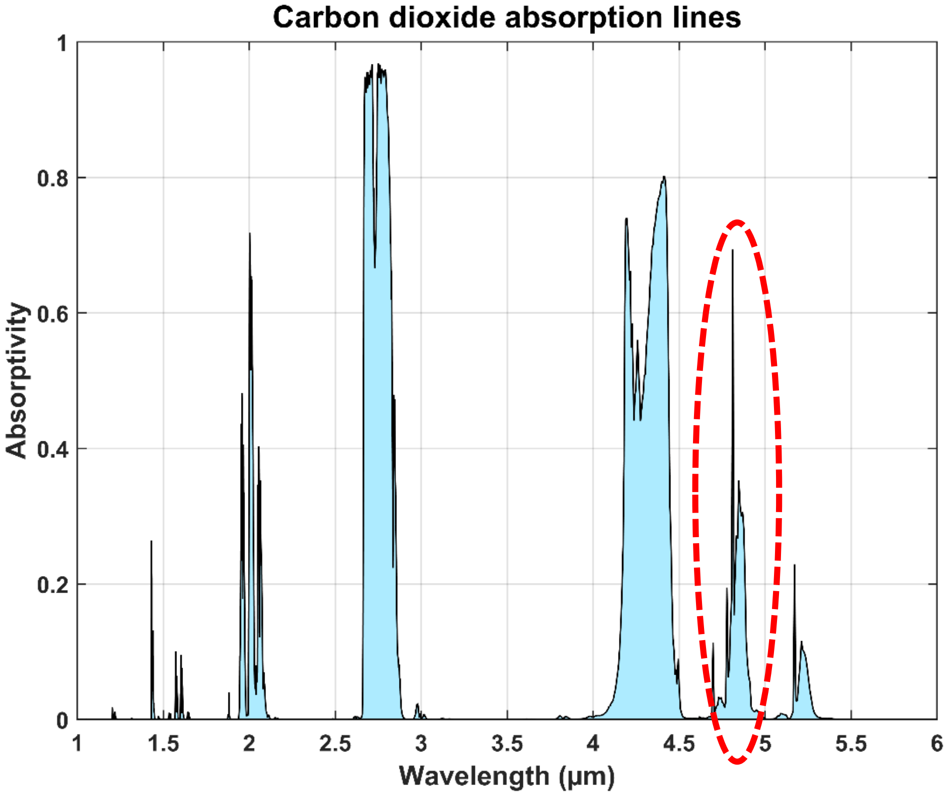
Outline

- Scope of the study
- CO_2 retrieval from satellite: state of the art
- CO_2 absorption band at 4.8 µm and sensitivity studies by the MODTRAN model
- Results of sensitivity studies
- Application example: MASTER multispectral acquisitions on the Kilauea volcano (Hawaii)

Scope of the study

The scope of the present work is to evaluate the possibility of using the absorption band at 4.8 µm to detect/retrieve CO_2 emissions from High Temperature Events (i.e. volcanoes, fires, industrial emissions) from satellite.



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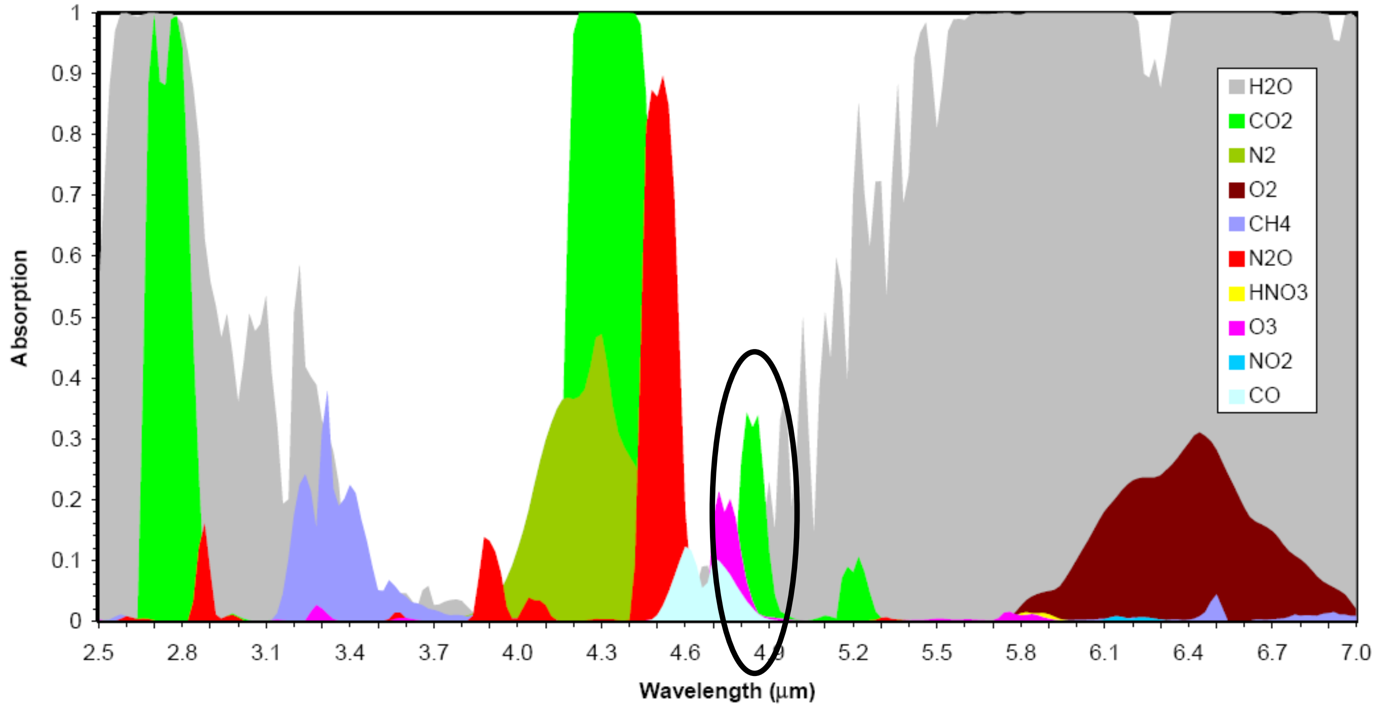
Operative space missions for CO_2 retrieval

Several space missions are able to measure carbon dioxide concentrations with a spatial resolution of some kilometers.
The employed SWIR channels are at 1.61 and 2.06 µm.

Instrument/Mission	Space agency	Satellite/ Launch date	Spatial resolution @nadir	Spectral ranges (µm)	CO_2 bands (µm)
OCO-2 Orbiting Carbon Observatory	NASA	OCO-2 July 2, 2014 (16-day repeat cycle)	3.0 Km^2	0.758 - 0.772 1.594 - 1.619 2.042 - 2.082	1.61 2.06
TANSO-FTS	JAXA	GOSAT January 23, 2009	10.5 Km	0.758 - 0.775 1.562 - 1.724 1.923 - 2.083 5.6 - 14.3	1.61 2.06
IASI Infrared Atmospheric Sounding Interferometer	EUMETSAT	Metop-A October 19, 2006 Metop-B September 17, 2012 Metop-C November 7, 2018	12.0 Km	3.6 - 15.5	4.3 15.0
AIRS Atmospheric InfraRed Sounder	NASA	AQUA May 4, 2002	13.5 Km	3.7 - 15.4	15.0

Advantages of MWIR spectral range 1/3

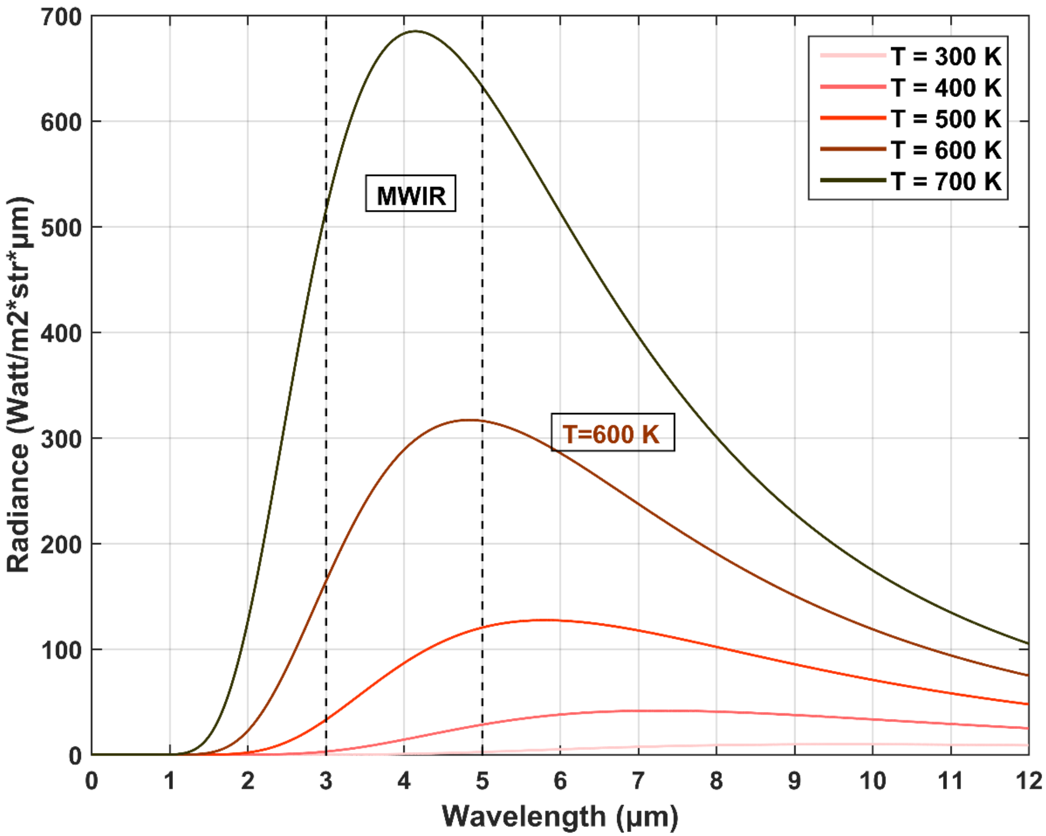
The CO_2 absorption band at 4.8 µm is located in the atmospheric window 3-5 µm



Absorption bands of several gases in the range 2.5-7 µm
(*from Griffin et al., 2004*)

Advantages of MWIR spectral range 2/3

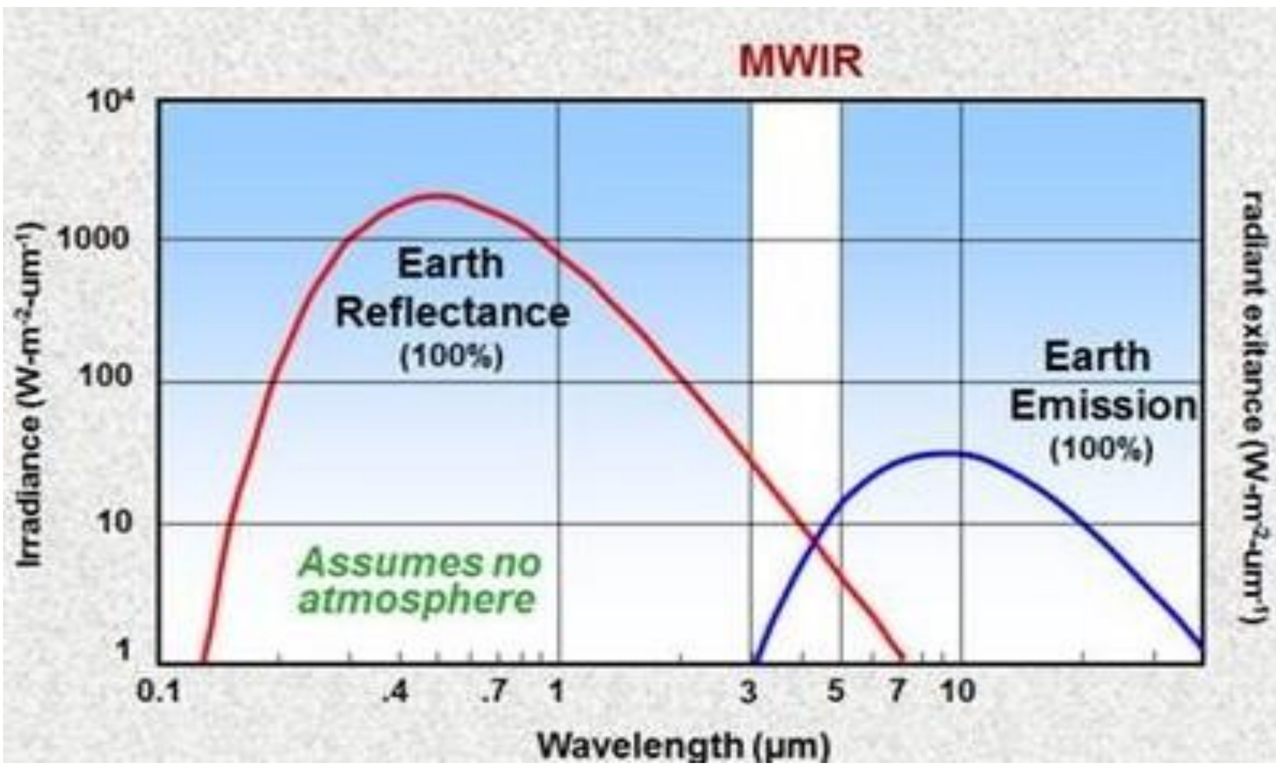
More energy from high temperature events



Blackbody radiation at T=300, 400, 500, 600, 700 K
(Wien's displacement law)

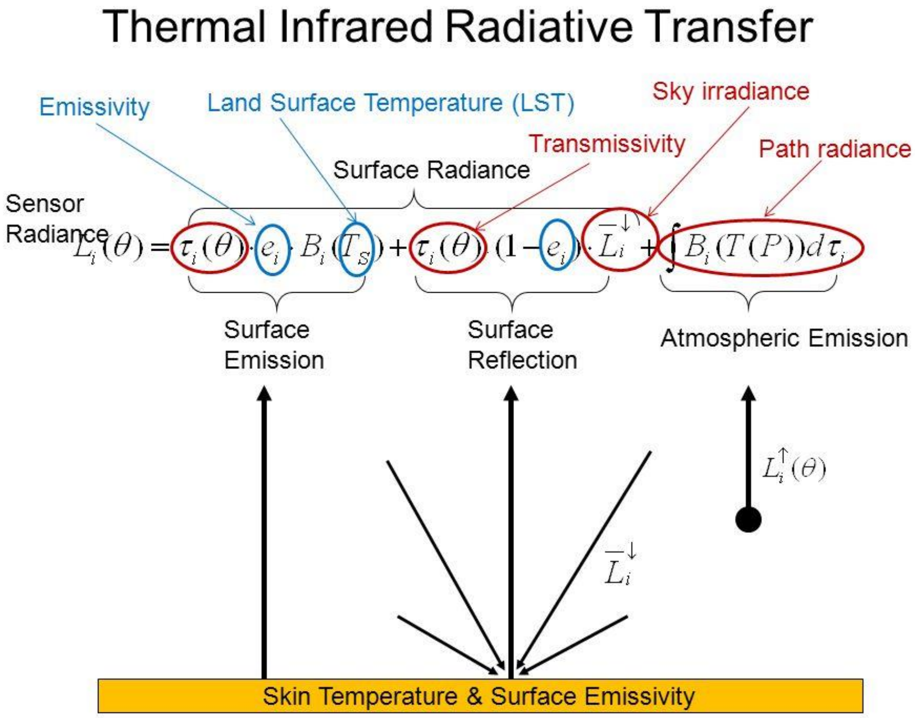
Advantages of MWIR spectral range 3/3

Low backscattering effects
and
possibility of day-night time acquisitions



MODTRAN radiative transfer model

In order to simulate the radiance acquired by a satellite sensor, in the MWIR spectral region, the MODTRAN (MODerate resolution atmospheric TRANsmission) computer code was used (http://modtran.spectral.com/)



Equation and scheme of the radiative transfer in thermal infrared region

Sensitivity experiments

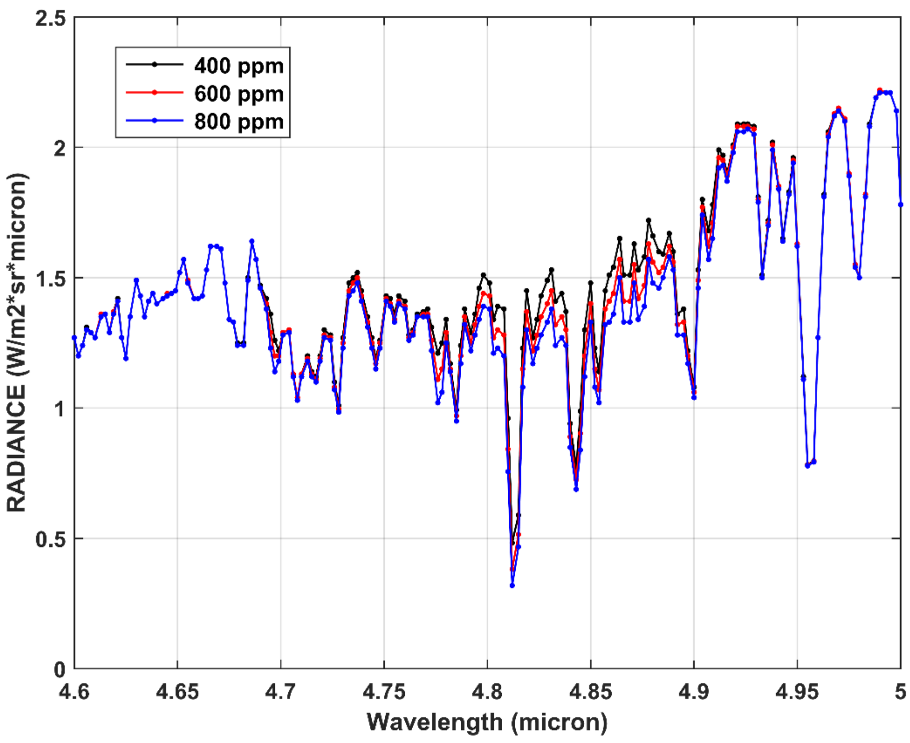
With the aim to analyse the sensitivity of the 4.8 µm absorption band, several model runs were carried out considering different CO_2 concentrations in atmosphere and temperatures at the ground. Surface temperatures range between 300 and 1000 K to consider High Temperatures Events; CO_2 concentrations are in the range 0-1000 ppm.

SIMULATIONS	SURFACE TEMPERATURE (K)	CO_2 CONCENTRATION (PPM)
EXP01 - EXP06	300	0-1000 (step 200)
EXP07 - EXP12	400	0-1000 (step 200)
EXP13 - EXP18	500	0-1000 (step 200)
EXP19 - EXP24	600	0-1000 (step 200)
EXP25 - EXP30	700	0-1000 (step 200)
EXP31 - EXP36	800	0-1000 (step 200)
EXP37 - EXP42	900	0-1000 (step 200)
EXP43 - EXP48	1000	0-1000 (step 200)

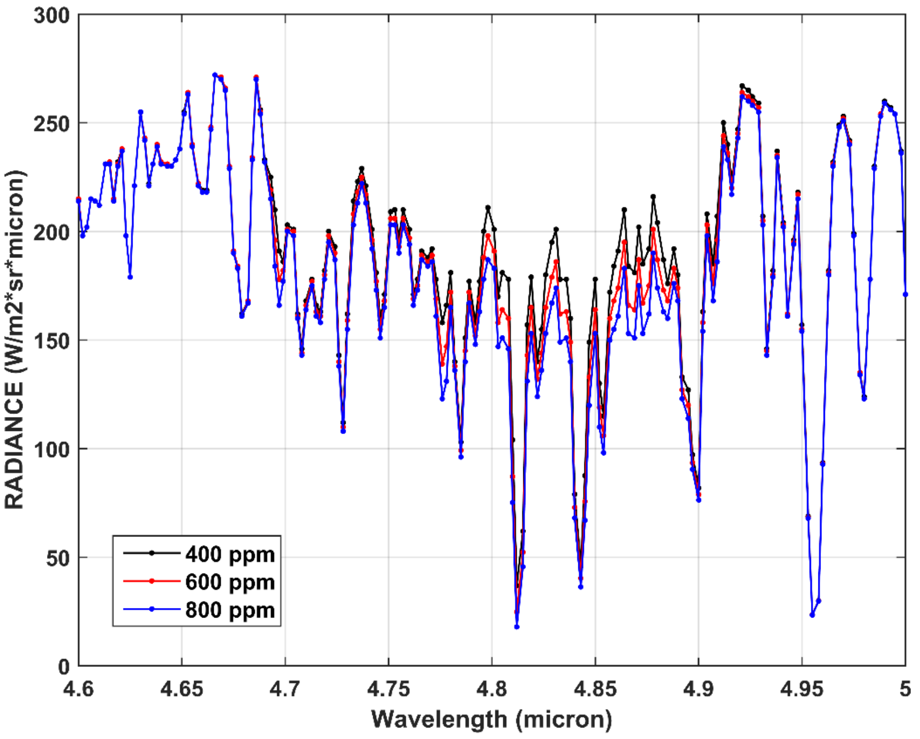
A total number of 48 runs was performed

Sensitivity experiments: results

Simulated radiances are reported for T=300 K and T=600 K, considering [CO_2] equal to 400, 600, 800 ppm



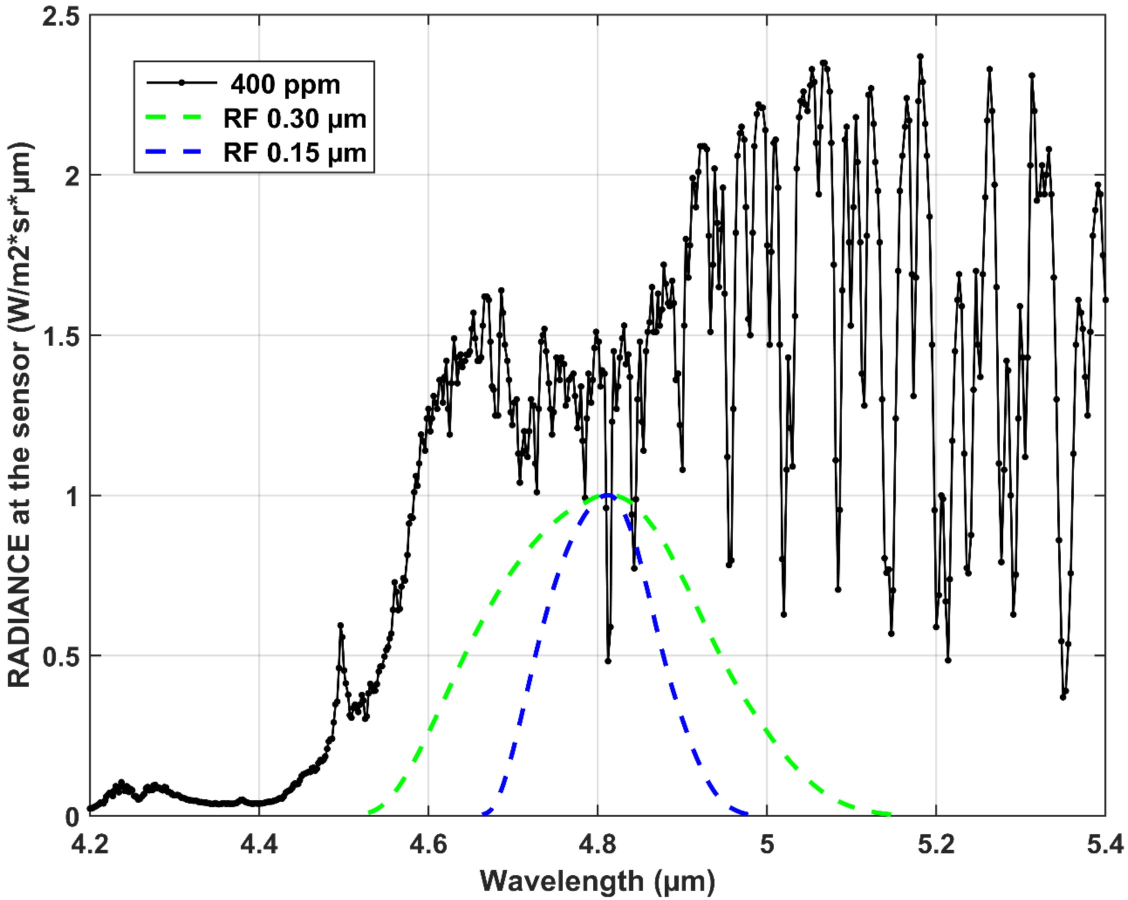
Simulated TOA radiances for T=300K



Simulated TOA radiances for T=600K

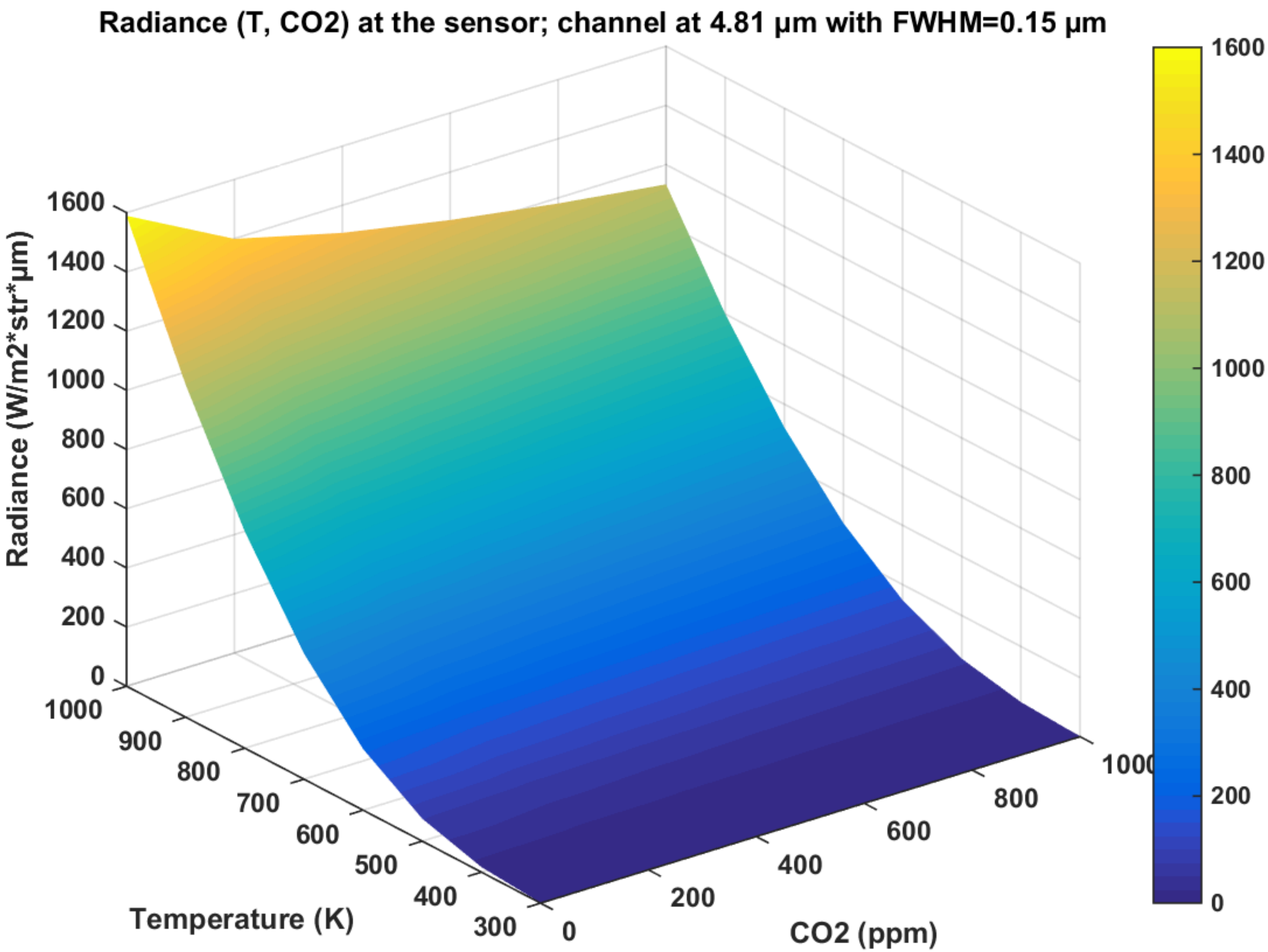
Convolution of radiances

With the aim to obtain radiances at the satellite sensor, simulated radiances are convolved on typical response functions with FWHM equal to 0.15 and 0.30 µm



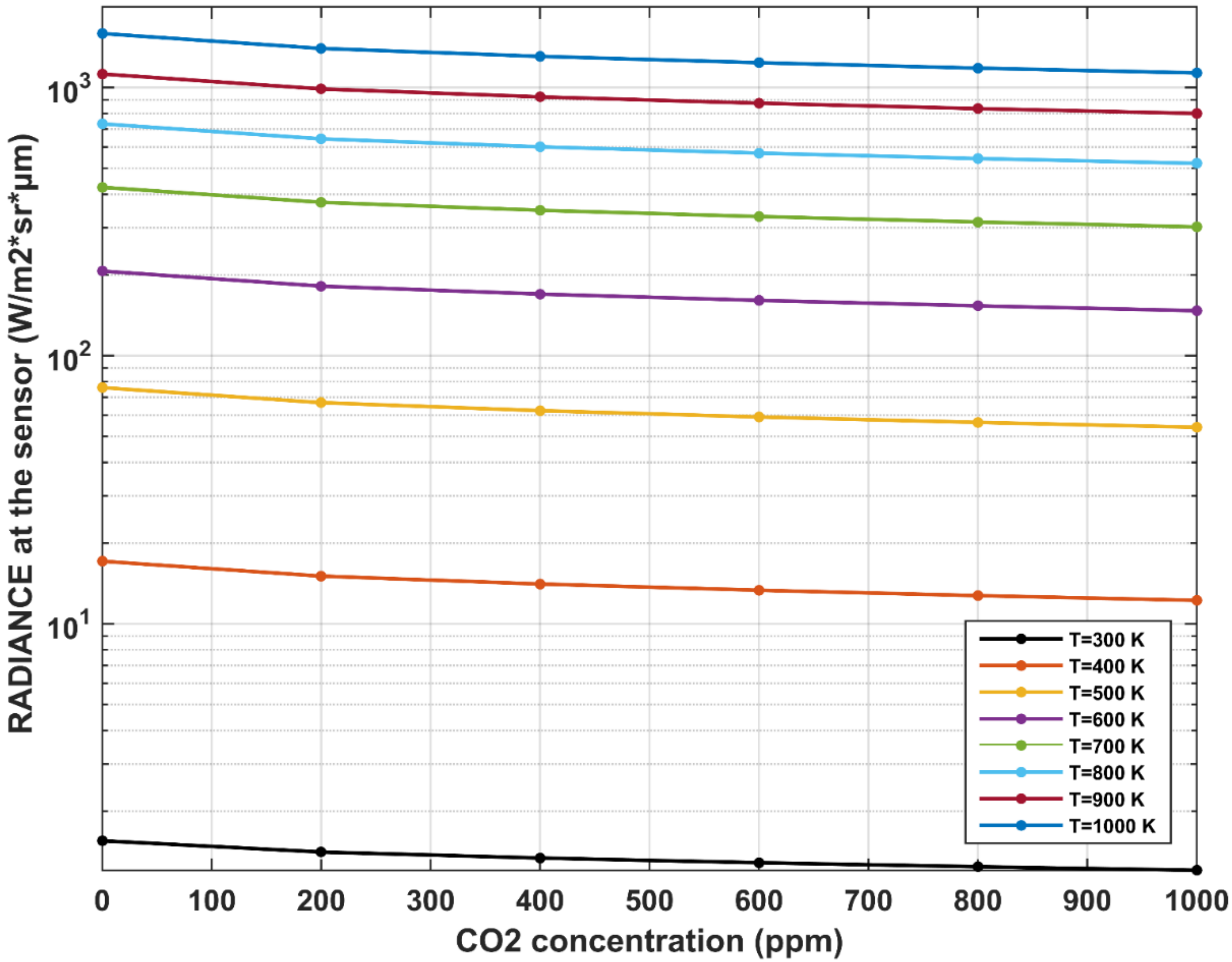
Simulated TOA radiances for T=300 K and [CO2]=400 ppm; typical response functions from MASTER instrument (dot green line: FWHM=0.30 µm; dot blue line: FWHM=0.15 µm)

Channel sensitivity to CO_2 and surface temperature



Simulated at-sensor radiances (interpolated), after the convolution considering FWHM=0.15 µm, as function of CO_2 concentration and surface temperature

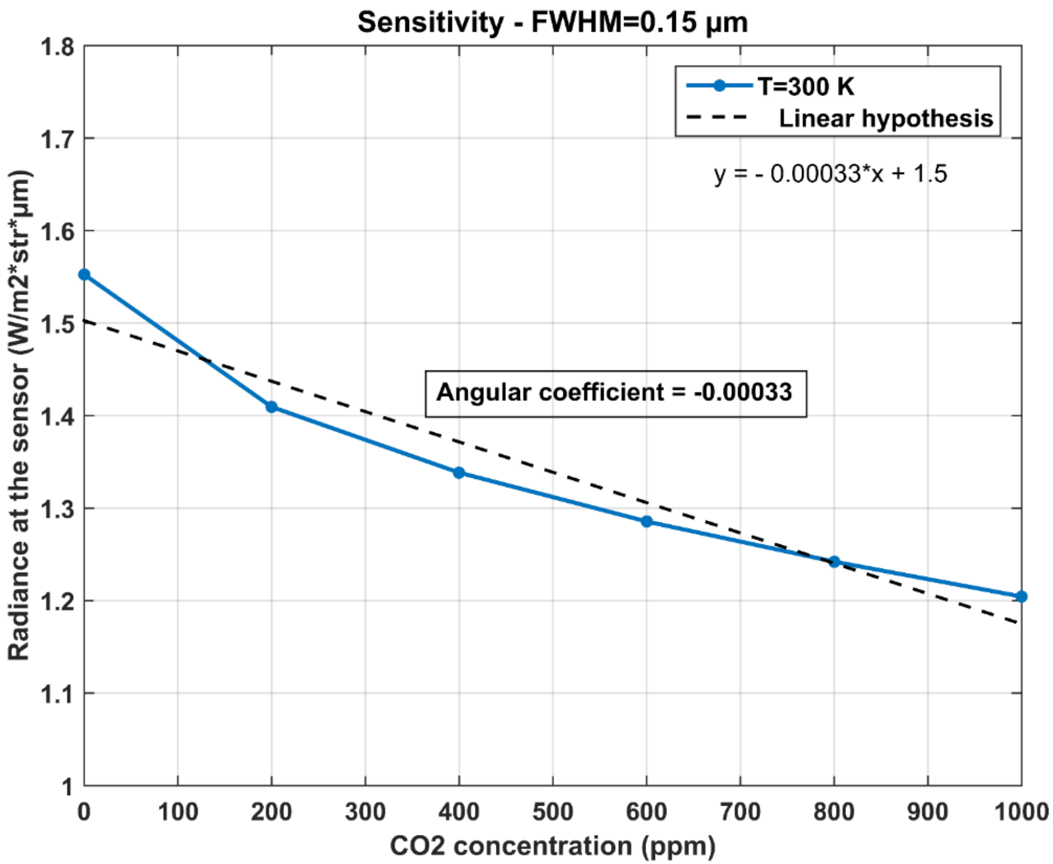
Channel sensitivity to CO_2 and surface temperature



Simulated TOA radiances (in logarithmic scale), after the convolution considering FWHM=0.15 µm, as function of CO_2 concentrations for the 8 different surface temperatures

Computation of the NEDT

By using descent curves we can calculate the NEDT for the 8 considered surface temperatures



Convolved radiances vs CO_2 concentration for T=300 K (example in 'standard condition')

Angular coefficient

↓

$NedR$

↓

$NEDT$

where:
$NedR$ = *Noise equivalent delta Radiance*
$NEDT$ = *Noise Equivalent Delta Temperature*

Computation of the NEDT: results

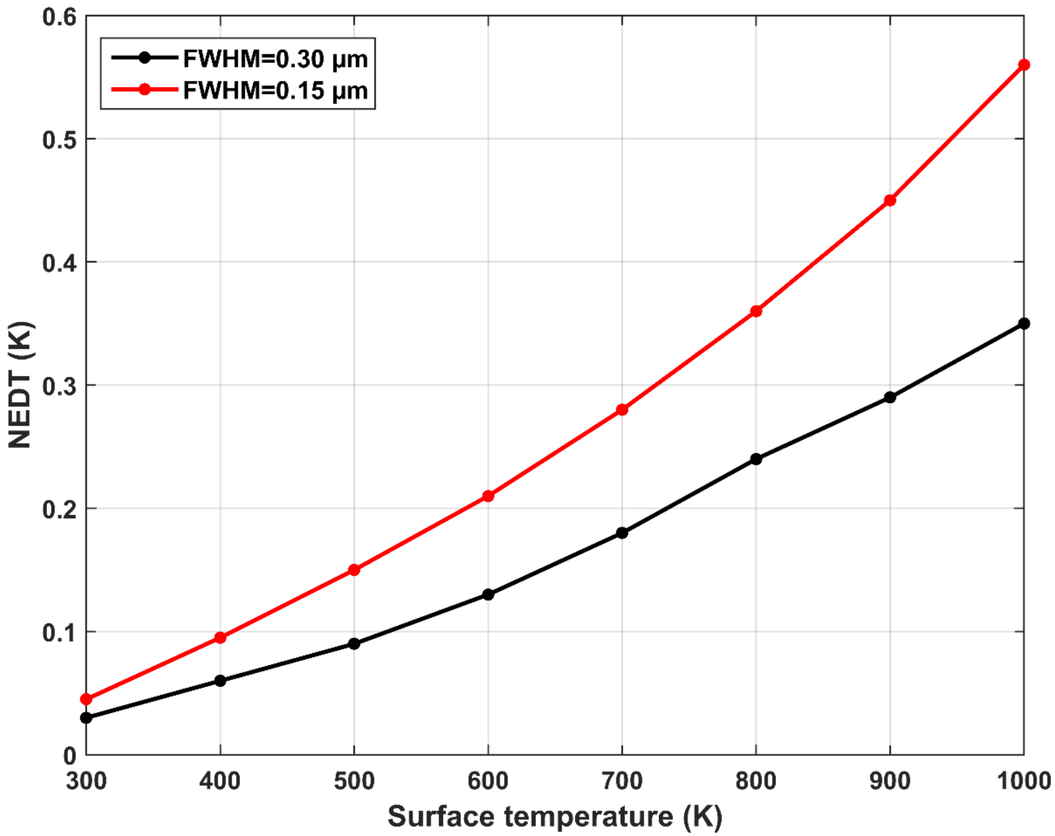
Parameters	**T=300 K**	**T=400 K**	**T=500 K**	**T=600 K**	**T=700 K**	**T=800 K**	**T=900 K**	**T=1000 K**
Angular coeff. to detect 1 ppm change	-0.00033	-0.0046	-0.021	-0.056	-0.115	-0.198	-0.303	-0.429
Angular coeff. to detect **10 ppm** change	-0.0033	-0.046	-0.21	-0.56	-1.15	-1.98	-3.03	-4.29
NedR (mW/m2*str*µm)	3.3	46	210	560	1150	1980	3030	4290
NEDT (K)	0.045	0.095	0.15	0.21	0.28	0.36	0.45	0.56

Sensitivity parameters for the considered surface temperatures assuming a response function with FWHM=0.15 µm

The target is a [CO_2] increase of **10 ppm** in the entire atmospheric column

Computation of the NEDT: results

NEDT are also calculated considering a response function with FWHM=0.30 μm to analyse the role of satellite sensor characteristics



NEDT as function of surface temperature considering a response function with FWHM=0.15 μm (red line) and FWHM=0.30 μm (black line)

Application example: MASTER instrument

The MASTER (Modis/ASTER) experiment is an airborne simulator having 50 spectral channels and a spatial resolution of 25-50 m

The primary objective of the MASTER activity is to support the ASTER and MODIS instrument teams in the areas of algorithm development, calibration and validation

Further information at:
https://master.jpl.nasa.gov/

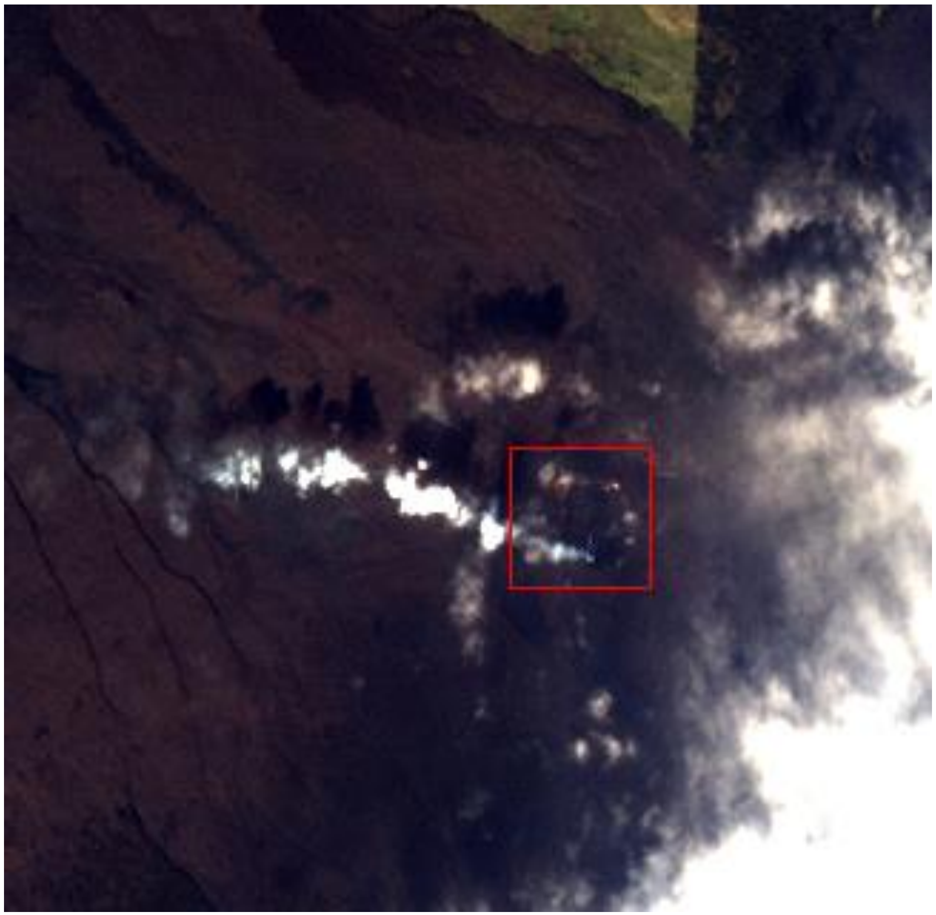
MASTER
Jet Propulsion Laboratory
California Institute of Technology

Channel	Full width half maximum	Channel center	Channel peak
26	0.1559	3.1477	3.142
27	0.1459	3.2992	3.292
28	0.1478	3.4538	3.452
29	0.1544	3.6088	3.607
30	0.1345	3.7507	3.757
31	0.1524	3.9134	3.912
32	0.1548	4.0677	4.067
33	0.153	4.2286	4.224
34	0.153	4.3786	4.374
35	0.1446	4.5202	4.522
36	0.1608	4.6684	4.667
37	0.1521	4.8233	4.822
38	0.1487	4.9672	4.962
39	0.1495	5.116	5.117
40	0.1578	5.2629	5.272
41	0.3645	7.7599	7.815
42	0.4333	8.1677	8.185
43	0.3543	8.6324	8.665
44	0.4253	9.0944	9.104
45	0.4083	9.7004	9.706
46	0.3963	10.116	10.115
47	0.5903	10.6331	10.554
48	0.6518	11.3293	11.365
49	0.4929	12.117	12.097
50	0.4618	12.8779	12.876

Spectral characteristics of MWIR-LWIR channels

Application example: MASTER data on Kilauea volcano

In order to test the channel at 4.8 micron for detecting CO_2 emissions, MASTER acquisitions on Kilauea volcano (Hawaii) were considered



MASTER acquisition on
January 18, 2018 (18:49 UTC)

MASTER images	
January 18, 2018	18:49 UTC
January 18, 2018	19:47 UTC
January 18, 2018	21:01 UTC
January 18, 2018	21:13 UTC
January 30, 2018	19:39 UTC
January 30, 2018	20:53 UTC
February 8, 2018	07:50 UTC
February 8, 2018	08:06 UTC

Application example: CIBR parameter

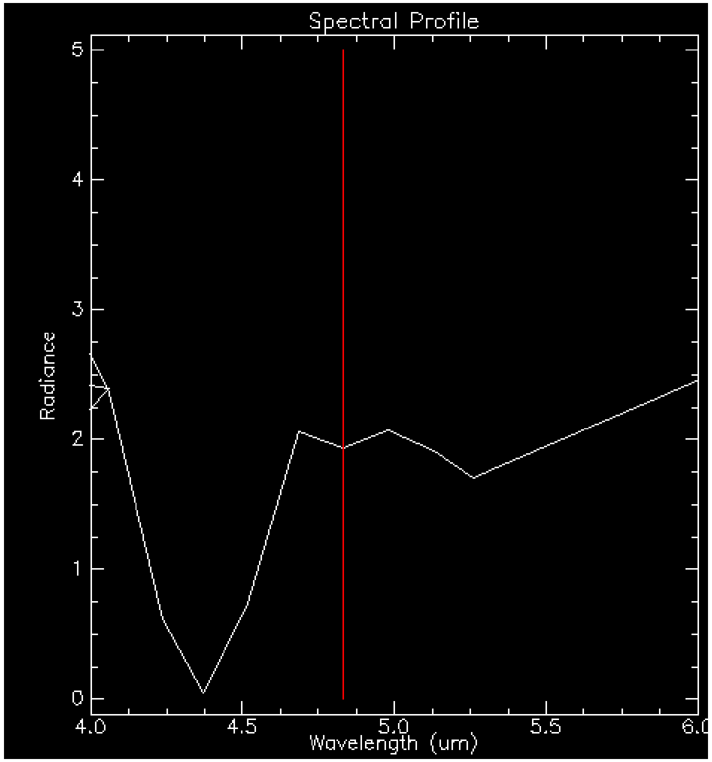
Generally, inversion algorithms to calculate CO_2 concentrations are based on a differential absorption technique, which assumes that the absorption deep in the atmospheric spectrum curve is related to the CO_2 concentration in the column.

The CIBR (Continuum Interpolated Band Ratio) parameter is considered to detect the CO_2 emissions:

$$CIBR = \frac{L}{a \cdot L_1 + b \cdot L_2}$$

where:

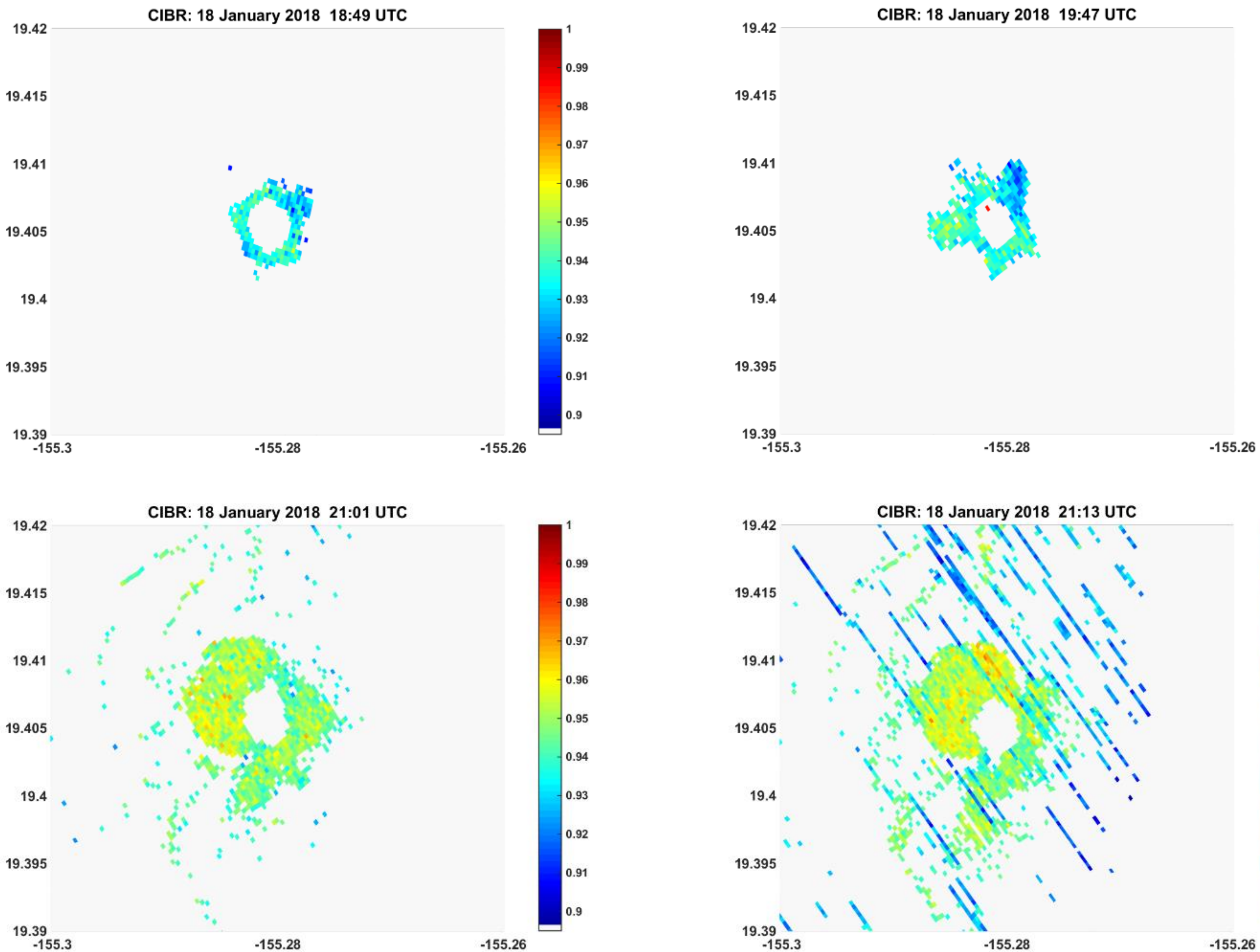
L = Radiance at the channel 37 (4.8 µm)
L_1 = Radiance at the channel 36
L_2 = Radiance at the channel 38
a,b = weighing coefficients (a+b=1)



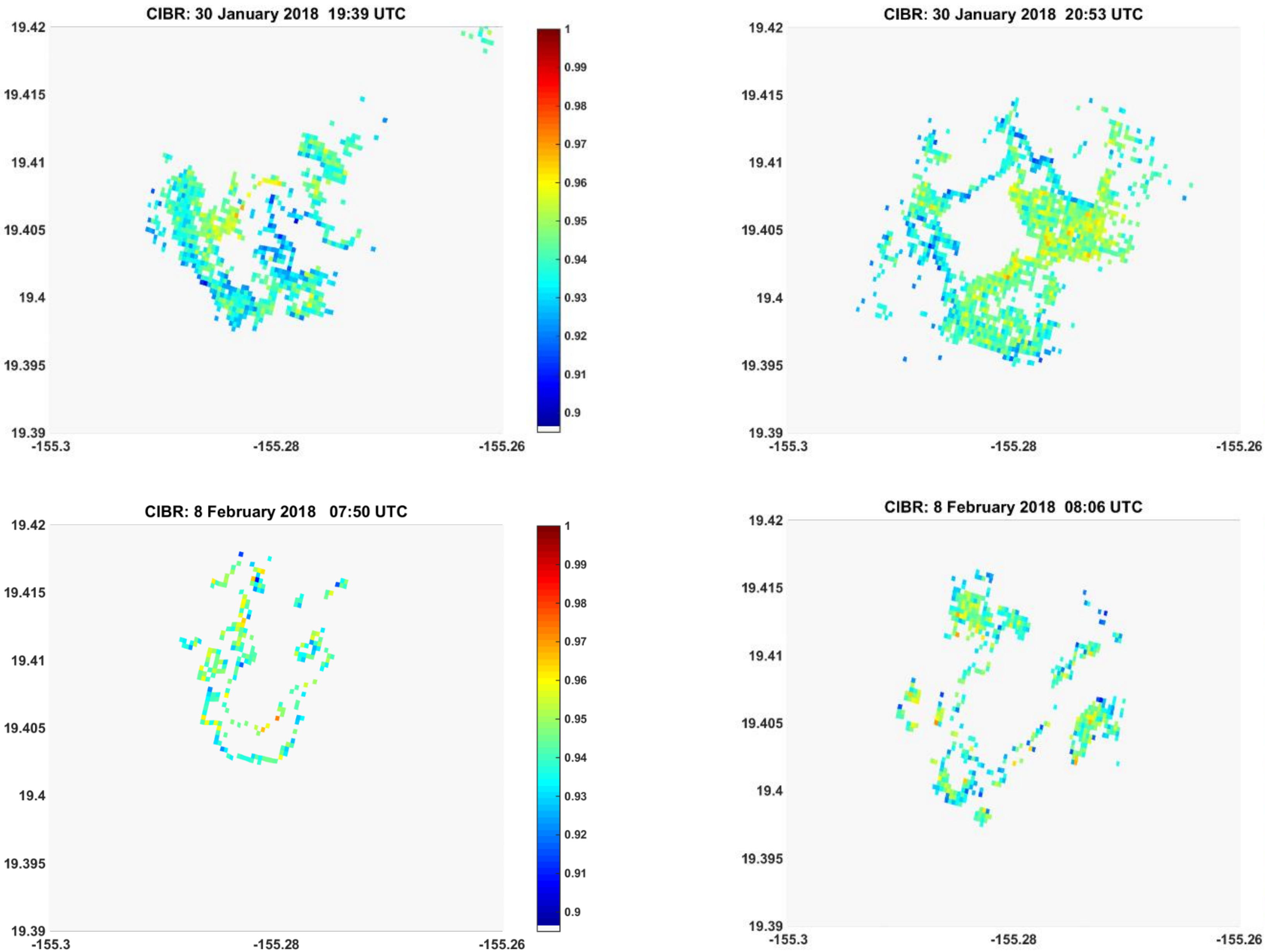
Example of MASTER spectral profile in the range 4-6 µm

REF: Spinetti C., Carrère V., Buongiorno M. F., Sutton A. J., Elias T., *Carbon dioxide of Pu`u`O`o volcanic plume at Kilauea retrieved by AVIRIS hyperspectral data*, RSE, 2008, 112, 6.

Application example: CIBR on the Kilauea crater



Application example: CIBR on the Kilauea crater



Paper on *Remote Sensing* journal

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Letter

A Sensitivity Study of the 4.8 μm Carbon Dioxide Absorption Band in the MWIR Spectral Range

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Abstract: The measurements of gas concentrations in the atmosphere are recently developed thanks to the availability of gases absorbing spectral channels in space sensors and strictly depending on the instrument performances. In particular, measuring the sources of carbon dioxide is of high interest to know the distribution, both spatial and vertical, of this greenhouse gas and quantify the natural/anthropogenic sources. The present study aims to understand the sensitivity of the CO_2 absorption band at 4.8 μm to possibly detect and measure the spatial distribution of emissions from point sources (i.e., degassing volcanic plumes, fires, and industrial emissions). With the aim to define the characteristics of future multispectral imaging space radiometers, the performance of the CO_2 4.8 μm absorption band was investigated. Simulations of the "Top of Atmosphere" (TOA) radiance have been performed by using real input data to reproduce realistic scenarios on a

Romaniello, V.; Spinetti, C.; Silvestri, M.; Buongiorno, M.F. *A Sensitivity Study of the 4.8 μm Carbon Dioxide Absorption Band in the MWIR Spectral Range*. Remote Sens. 2020, 12, 172.

Conclusions and remarks

- The model simulations supply preliminary indications about the sensitivity necessary to appreciate carbon dioxide variations and then retrieving its concentration from a space sensor.
- The at-sensor radiance sharply increases for increasing temperatures, ranging from 1 $W/m^2*sr*\mu m$ (in the "standard condition") to more than 1200 $W/m^2*sr*\mu m$ (in the warmest case).
- The NEDT strongly depends on the ground temperature and the FWHM of the response function. Higher temperatures under emitting point sources induce NEDT higher values allowing the possibility to retrieve CO_2 changes.
- Best values of NEDT are obtained considering the FWHM equal to 0.15 µm; in this case, the parameter ranges from 0.045 to 0.56 K depending on the ground temperature (a variation of 10 ppm in gas concentration was considered as target).
- Operative spaceborne sensors have not the channel at 4.8 µm; however, other TIR channels generally have a NEDT less than 0.2 K. Considering our results, we can say that current space technology could be able to detect changes of tens ppm in CO_2 concentration on HTEs emitting the greenhouse gas.

If you need more information please do not hesitate to contact:

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Thank you!

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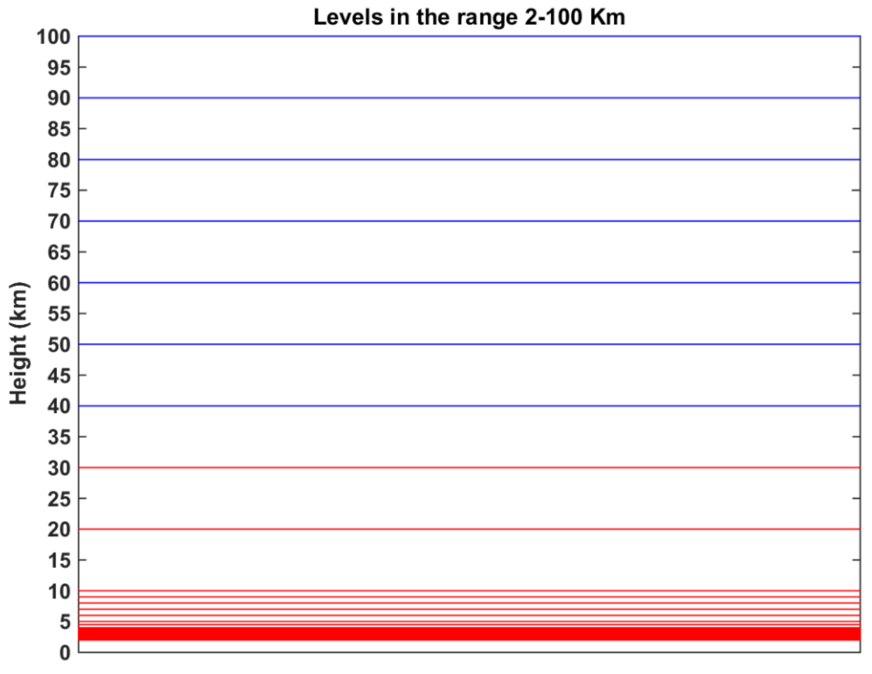
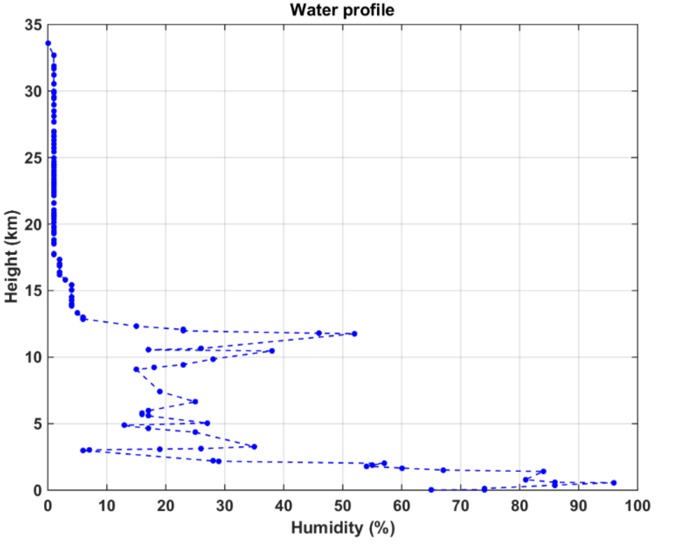
Appendix: MODTRAN model setup

The model setup considers 37 vertical levels from 2 to 600 Km (altitude of the sensor) not equispaced but more thickened in the lower layers



MODTRAN setup: vertical levels in the range 2-100 Km

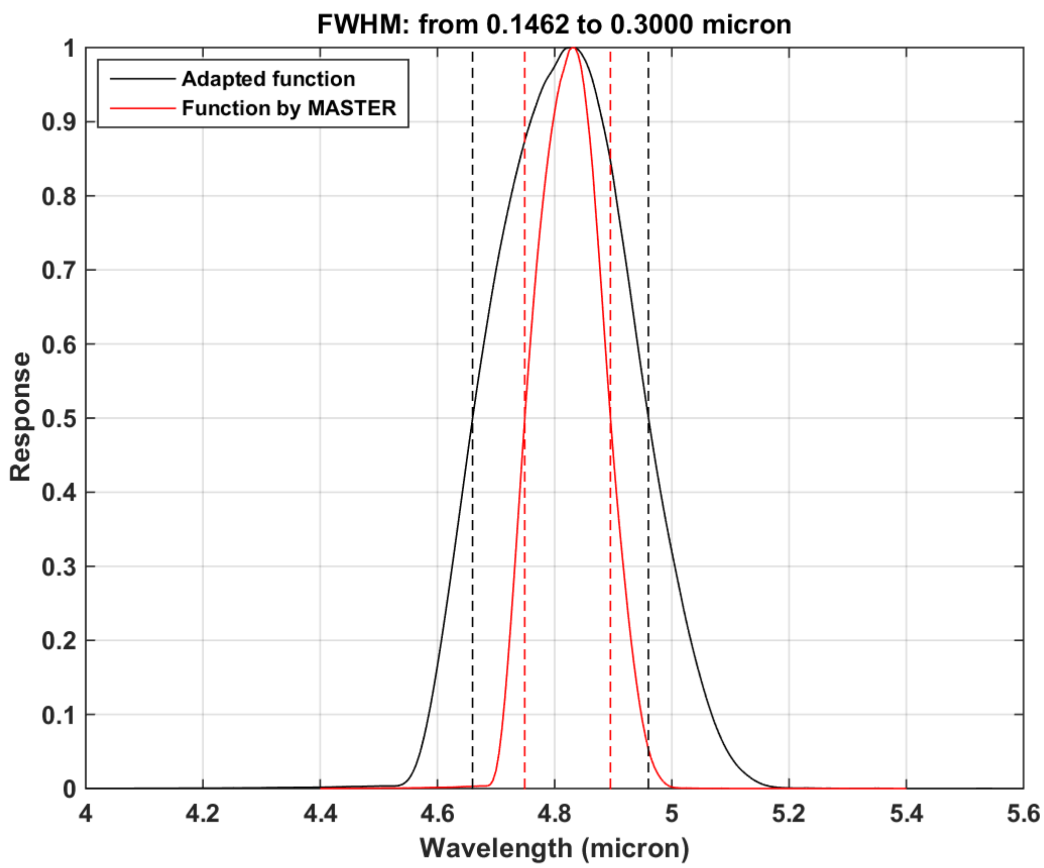
For the lowest levels (0-30 Km), measurements of pressure, temperature and humidity by probe ballons were used as input



Water profile from Trapani (Italy)

Appendix: response functions

The MASTER response function at 4.8 µm is adapted, maintaining the same shape and enlarging the FMHW



Adapting of MASTER response function for the CO_2 band at 4.81 µm (red native - black adapted)