Spectroscopy for space remote sensing: Status and challenges

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Plan

1. Earth observation from space

2. Atmospheric sounding

3. Needs for current and future space missions

- Improving well-known spectral regions
- Towards the use of new spectral bands
- Specific needs for active missions

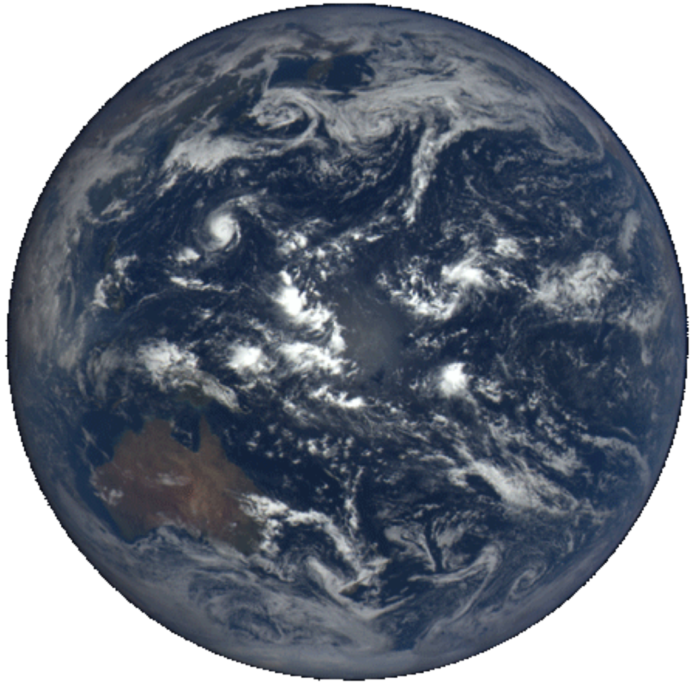
4. Concluding thoughts

Earth observation

Scientific and societal challenges are strongly linked to global change and environmental questions

Knowing and understanding the Earth

- Understanding The Earth structure and the processes that control it.
- Predicting its evolution
- Understanding human impact



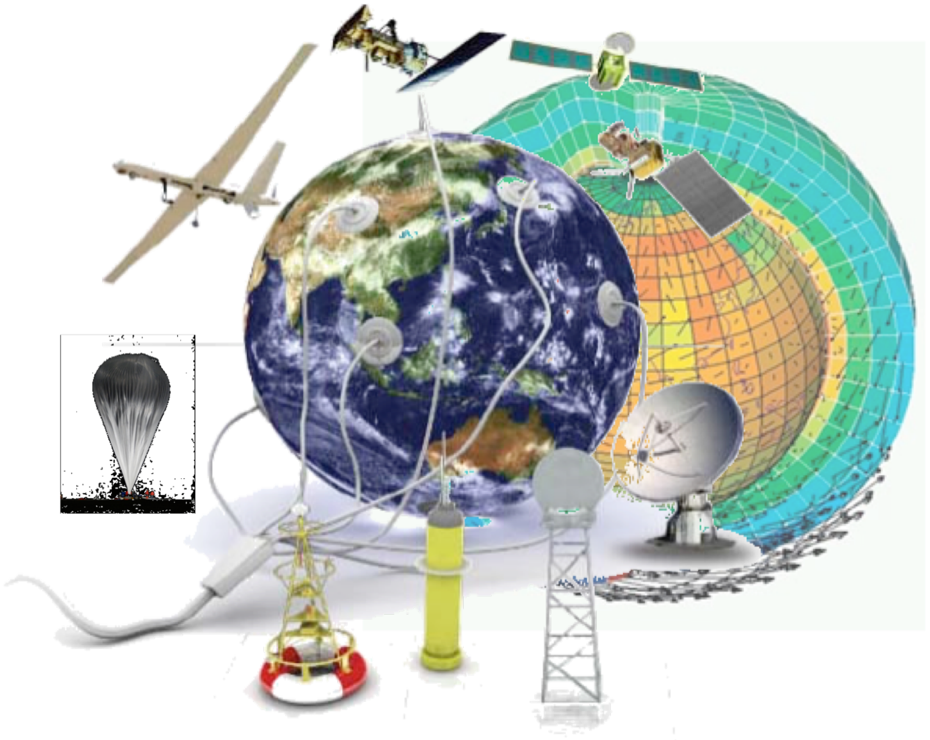
Live better

- Forecasting our environment in the next days/weeks
- Predicting and dealing with extreme events
- Addressing our needs (water, food)

A common need: to study and understand processes over large spatio-temporal scales, by combining all Earth sub-systems.

Observations

Earth study are highly dependent on observing capabilities.



An integrated Earth system observation for a global and homogeneous coverage of key parameters ("Essential Variables")

- in-situ observations and campaigns
- Space observation: Sentinels, contributing missions

  → **Need for high quality, well validated data.**

Wide range of spatio-temporal scales:

- Long-term follow-up, high need for revisits.
- Global observation but an increasing need to move towards high/very high spatial resolution.
- Study of specific objects (e.g. cloud formation).

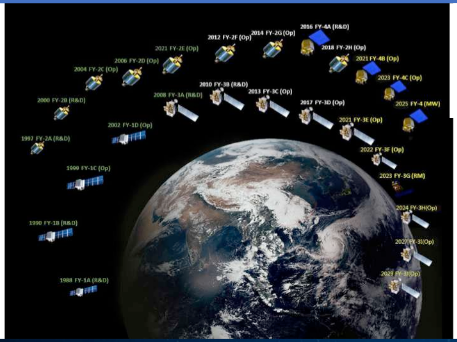
Challenges:

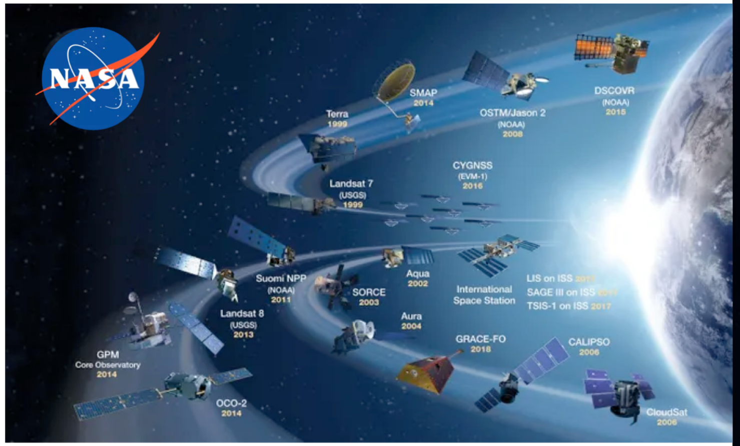
- Taking into account the indirect nature of the measurement – observable – scientific question link.
- Joint use of variables and/or missions.

  → Numerical models and data assimilation

New scientific questions and new services means new needs in observables, in measurement techniques… but also to ensure continuity!

Current and foreseen EO missions



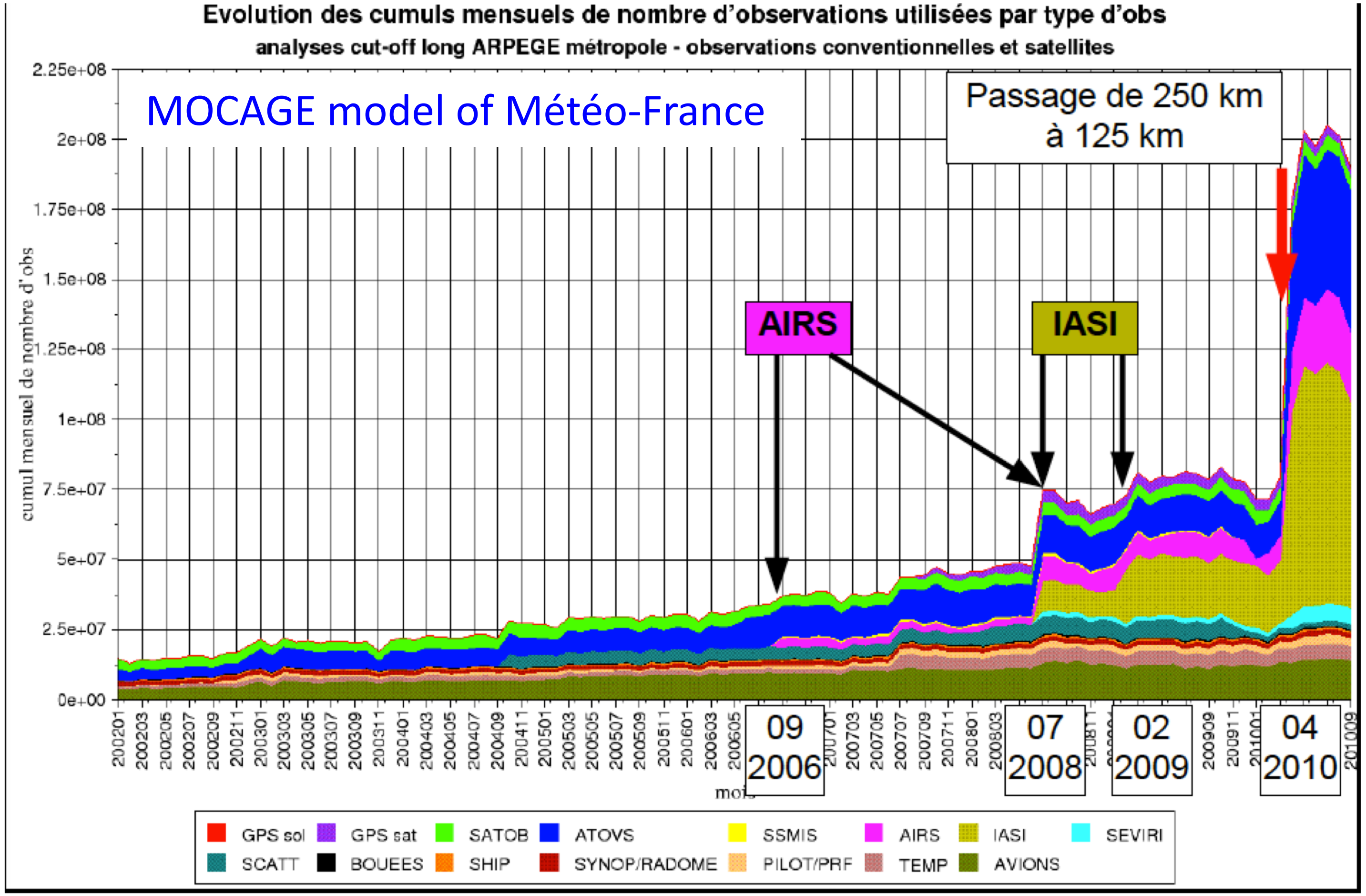


- A wide variety of EO missions
- A bright future (especially EU/ESA Copernicus/Sentinel)
- About half for the atmosphere

Numerical Weather Prediction

-First operational application in Earth observation from space.

-Measurement of vertical profiles of temperature, water vapour, wind, surface, etc.



V. Guidard, pers. comm.

Studying Earth atmosphere

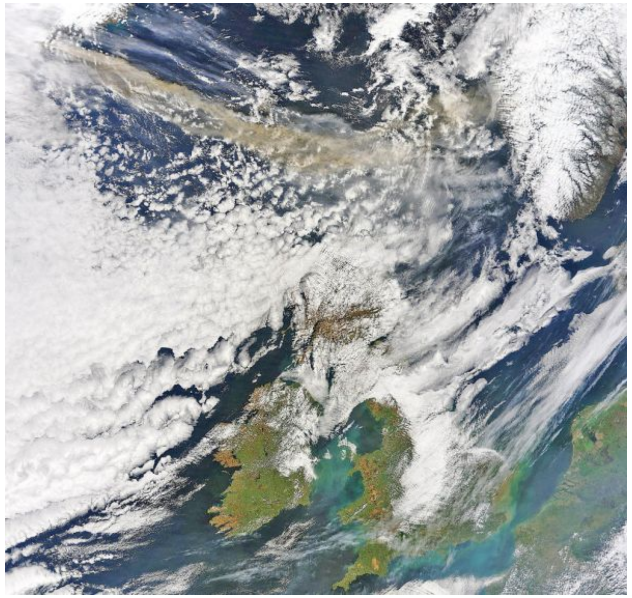
Numerical Weather Prediction

Atmospheric composition

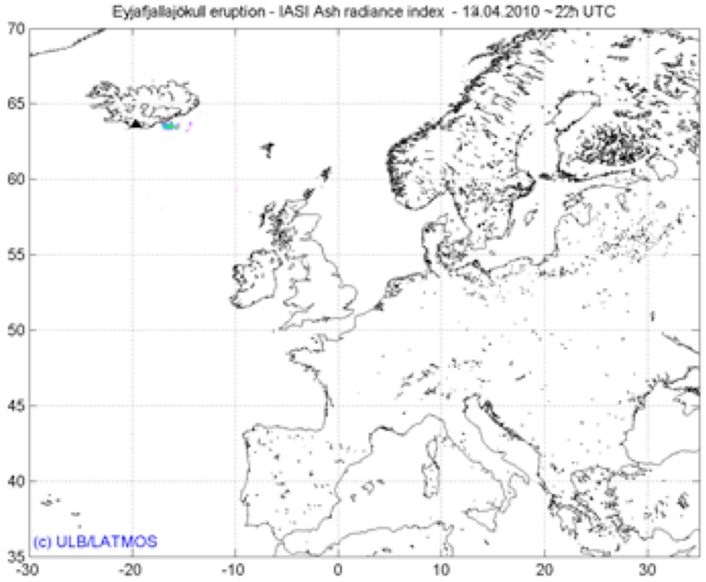
- Monitoring of stratospheric ozone.
- Air quality and tropospheric pollution: CO, SO_2, ash, etc.
- Impact of extreme events

Volcanic eruption of Eyjafjöll as seen by…

Envisat/MISR



MetOp-A/IASI



Studying Earth atmosphere

Numerical Weather Prediction | **Atmospheric composition** | **Climate studies**

Two main objectives:

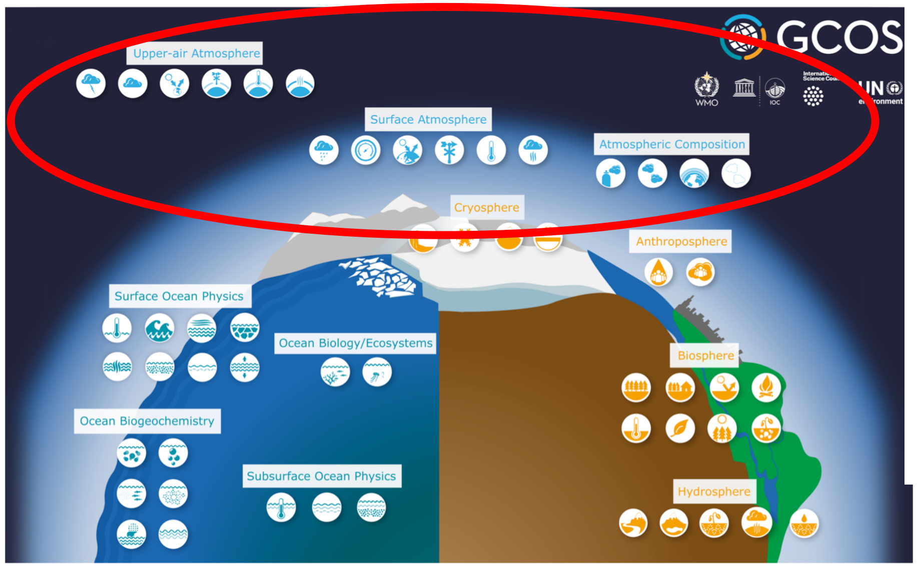
- Understanding **processes** that drive climate evolution and climate change.
- Monitoring over the long term and homogeneously the climate system.

GCOS (Global Climate Observing System) international program :

Definition of 54 **Essential Climate Variables** (ECVs), with 23 that can only be observed from space.

→ ECV = physical, chemical, bio. variables that critically contributes to the characterization of Earth's climate.

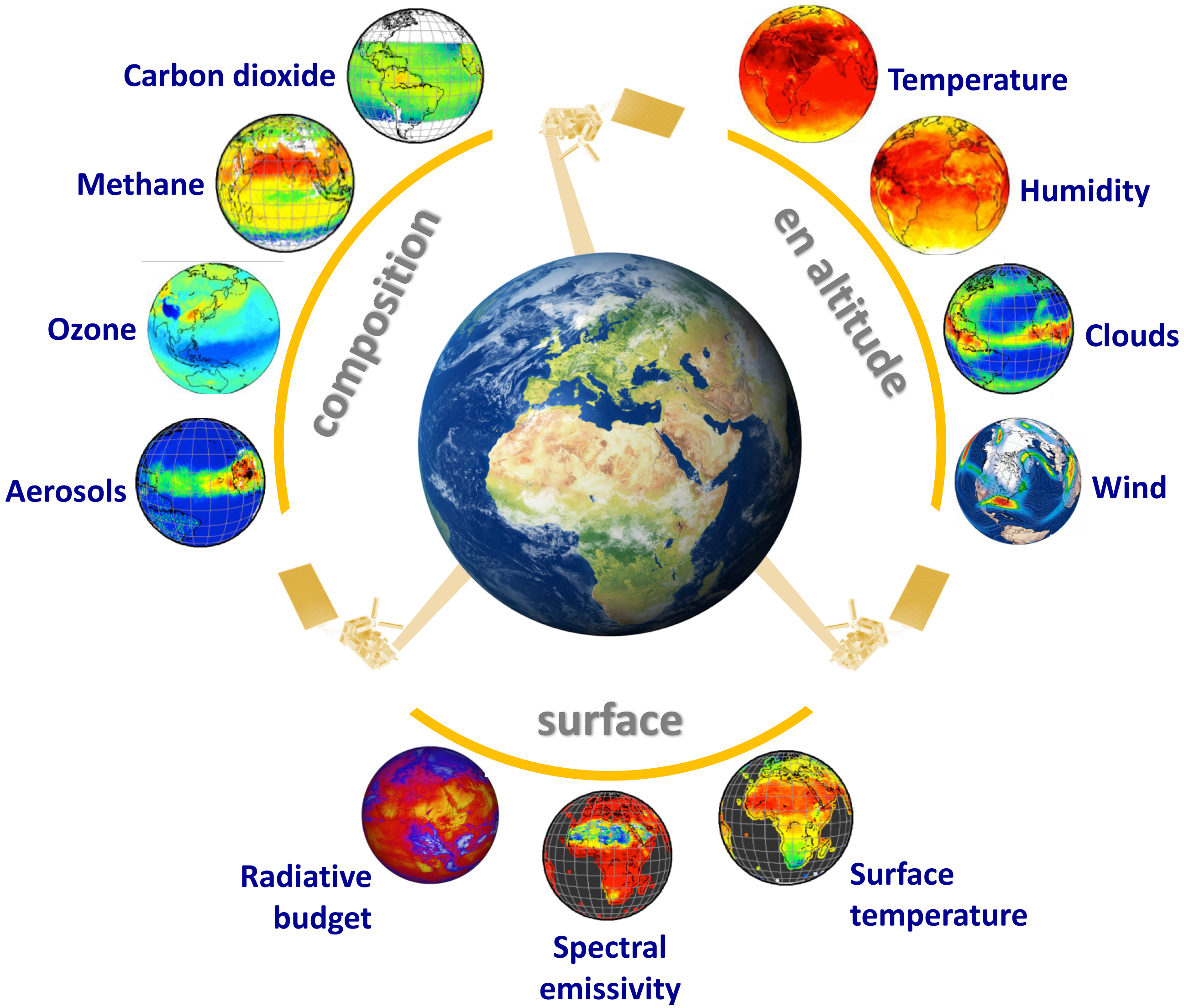
→ 16 ECVs for the **atmosphere**



The Essential Climate Variables

Domain	Essential Climate Variables	
Atmospheric (over land, sea and ice)	Surface:	Air temperature, **precipitation**, air pressure, surface radiation budget, wind speed and direction, water vapour.
	Upper air:	**Earth radiation budget (including solar irradiance), upper air temperature (including MSU radiances), wind speed and direction, water vapour, cloud properties.**
	Composition:	**Carbon dioxide**, methane, **ozone**, other long-lived greenhouse gases, **aerosol properties.**

Essential Climate Variables for Earth's **atmosphere** seen by IASI-A/B/C



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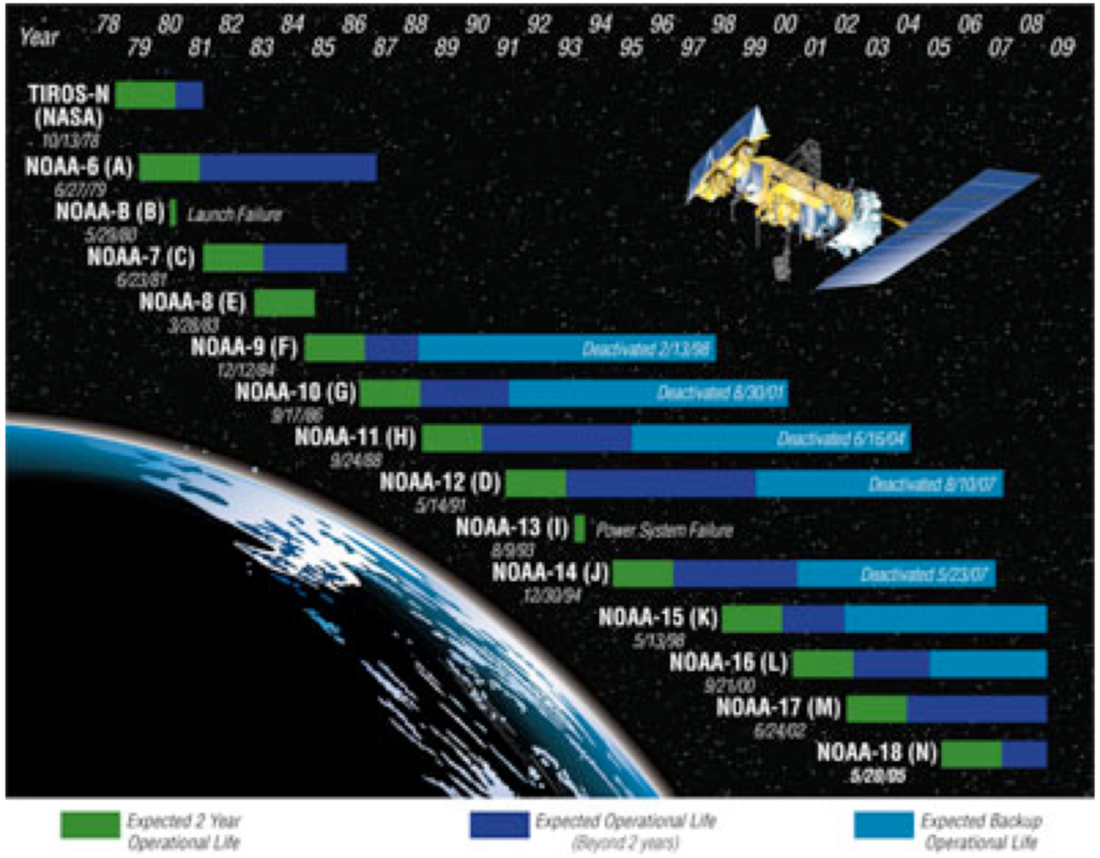
Spectroscopic measurements: from the beginning of Earth Observation

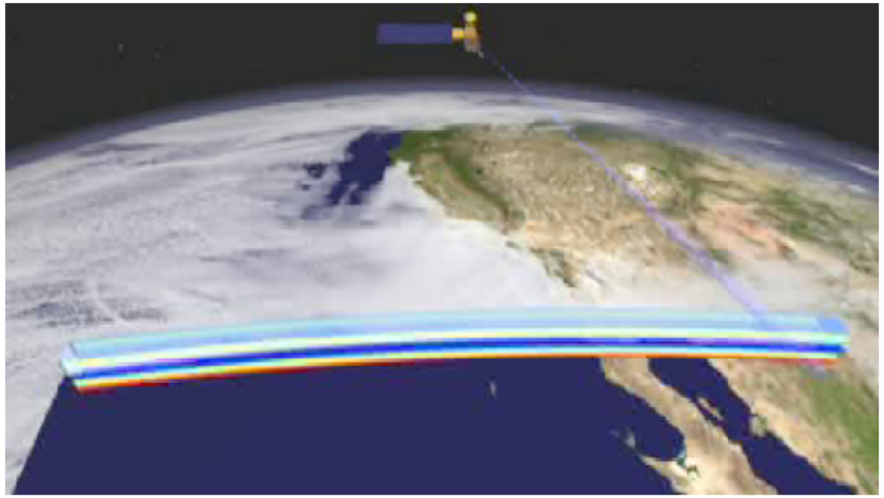
NWP started the need for Earth Observation from space… and the need for accurate and accessible spectroscopic data and radiative transfer models

→ **April 1st ,1960**: 1st weather satellite Television Infrared Observation Satellites (TIROS).

→ **First weather satellite series in 1978**: TIROS-N/NOAA program.



Main component: **infrared** and **microwave** **sounders** that measure the radiation field emitted by Earth system at various frequencies with a scan angle close to the vertical.



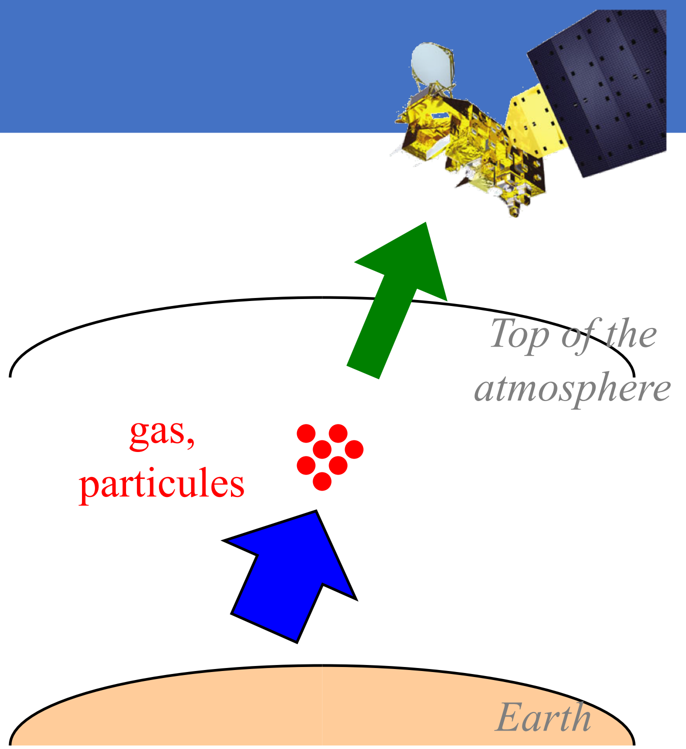
Remote sensing measurement

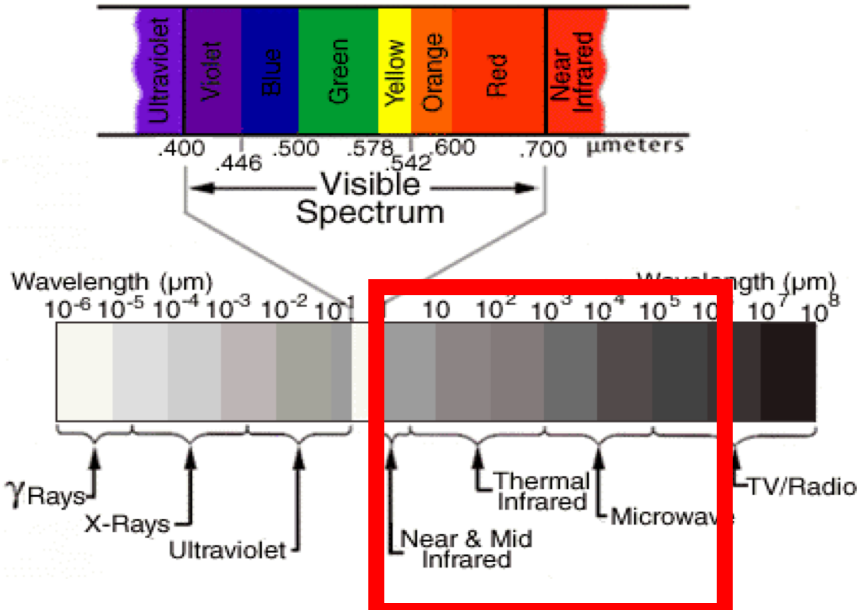
The principle of the measurement is always the same:

1. A radiation goes through the amosphere.

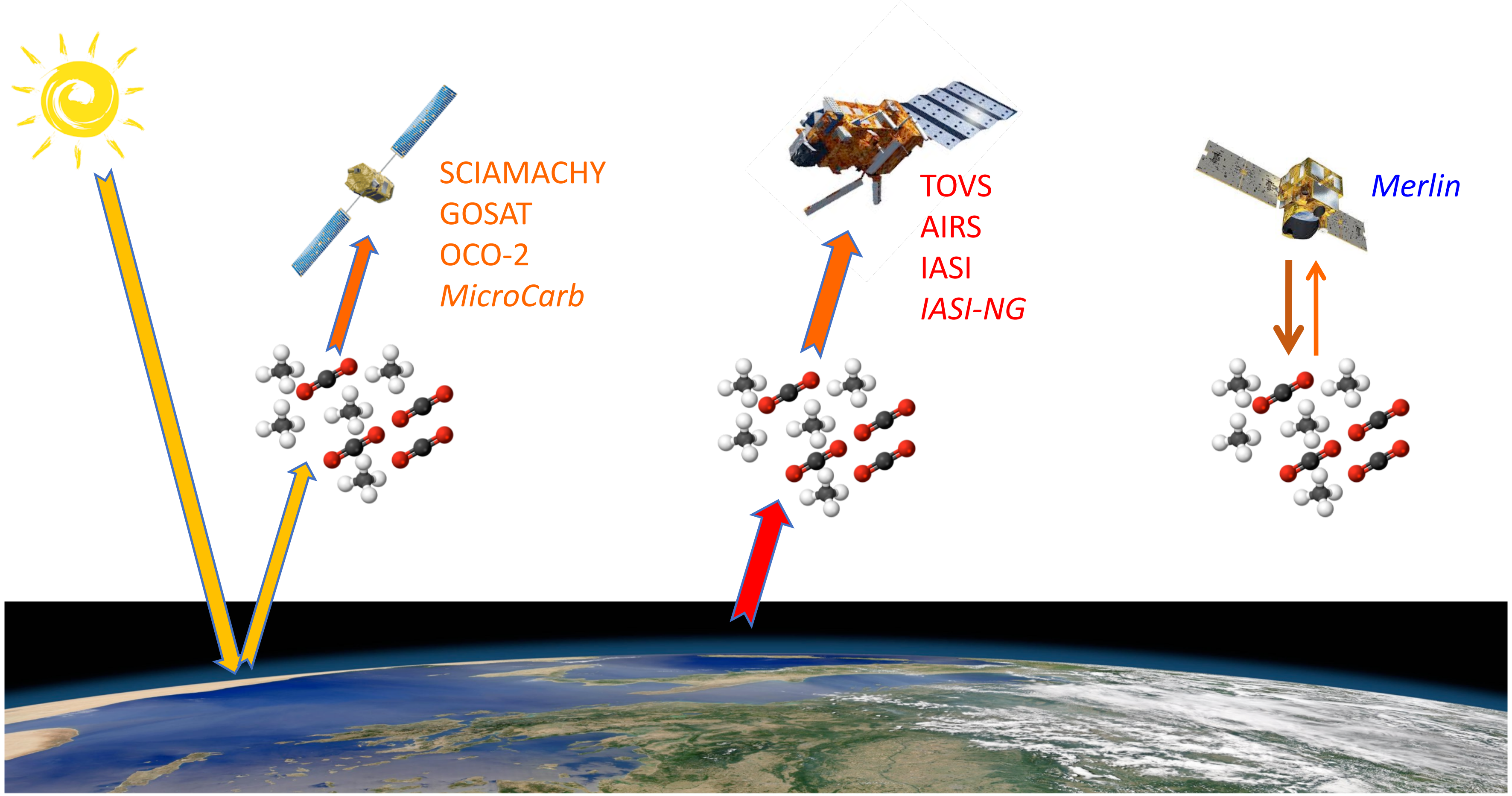
2. It is absorbed/reemiited/scattered by gas molecules/particules in a proportion driven by their concentration and altitude (T, P).

3. The modified radiation is measured by an instrument (outside of the atmosphere for a satellite).

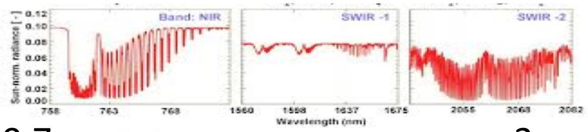




Atmospheric sounding in the Infrared (IR)

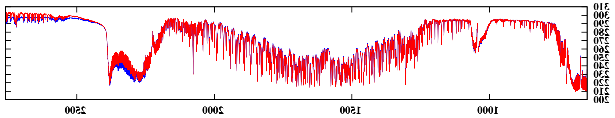


Shortwave infrared (0.7-3µm)



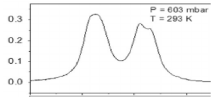
0.7µm — 3 µm

Thermal infrared (4-15µm)



4 µm — 15 µm

Lidar (2µm)



2 µm

Processing remote sensing data

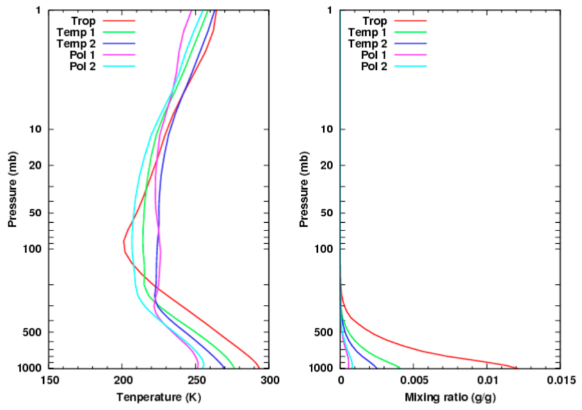
Spectroscopic data

Foward modeling (RT code)

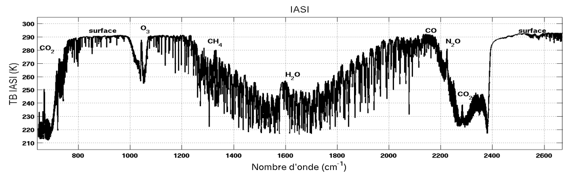
Instrument characteristics

Atmospheric state

Radiances



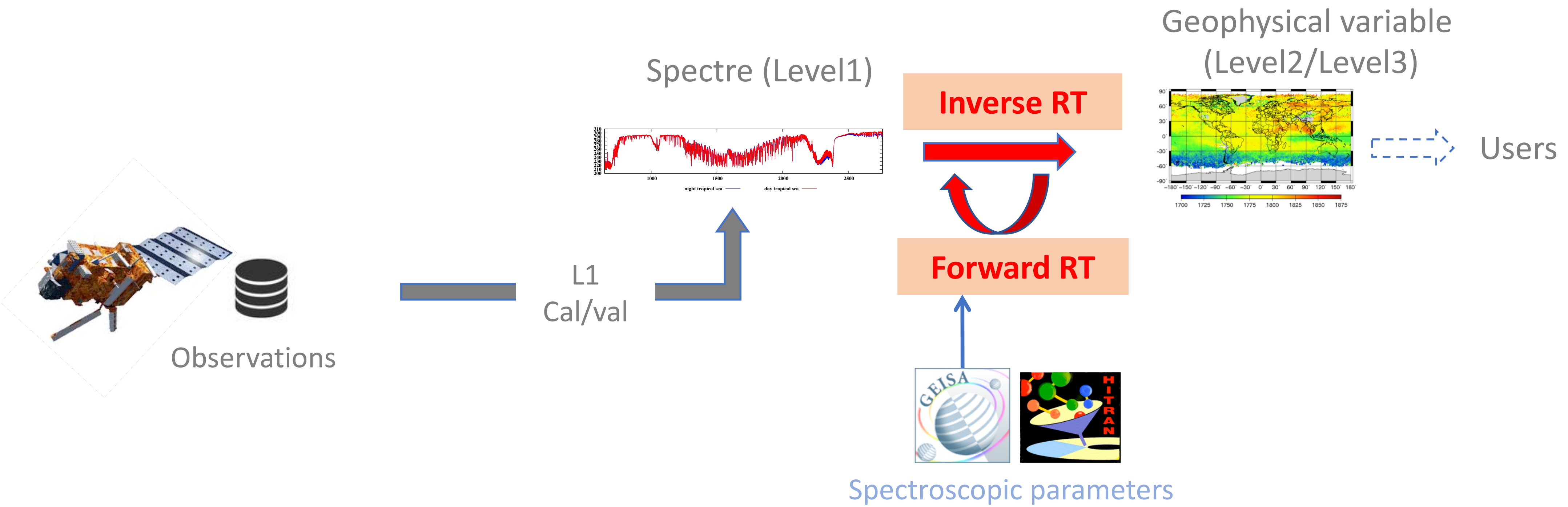
Radiative transfer equation



Inverse modeling

a priori data on the atmospheric state

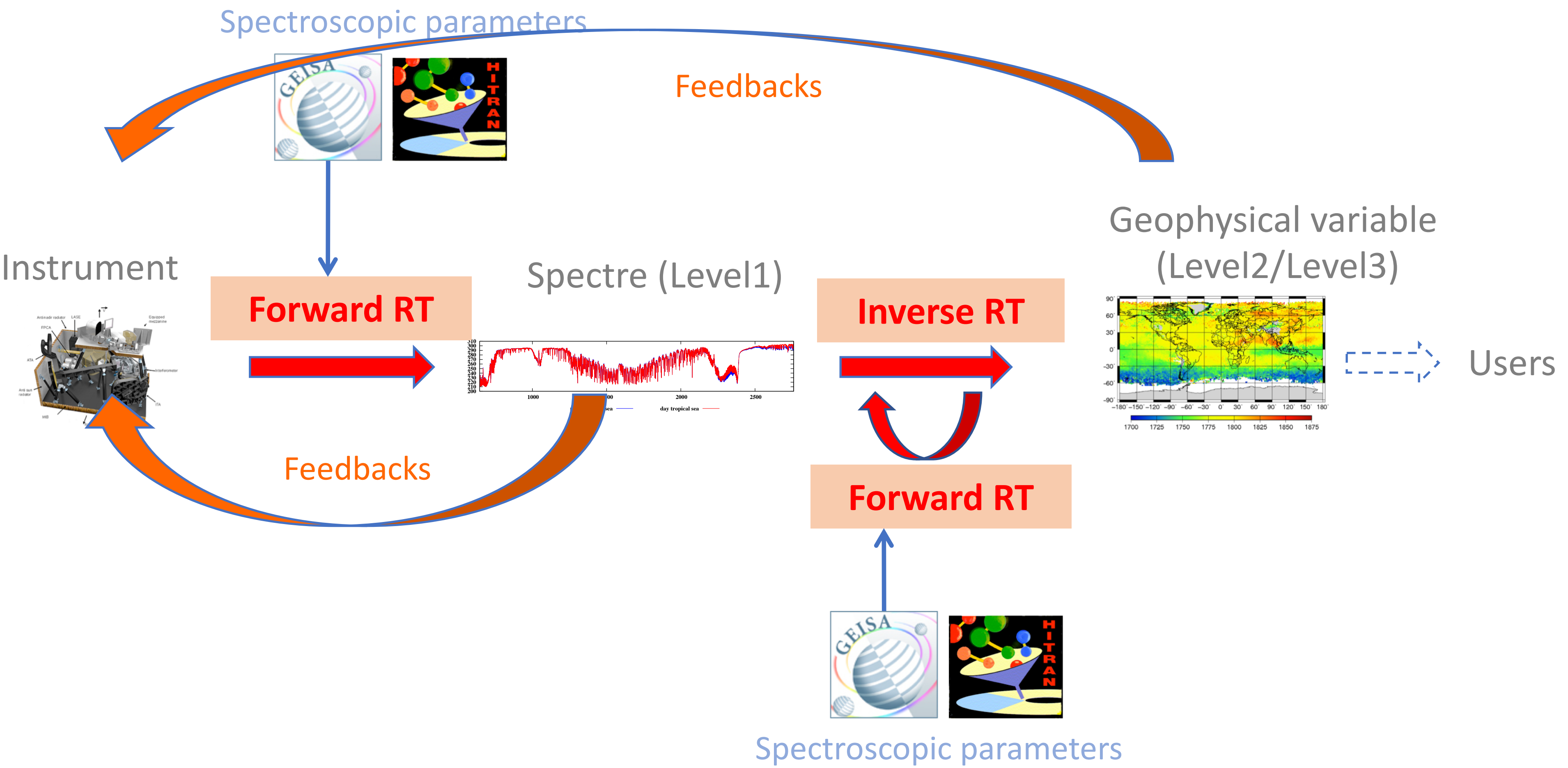
Applications



Objectives:

- **Processing data from current missions**

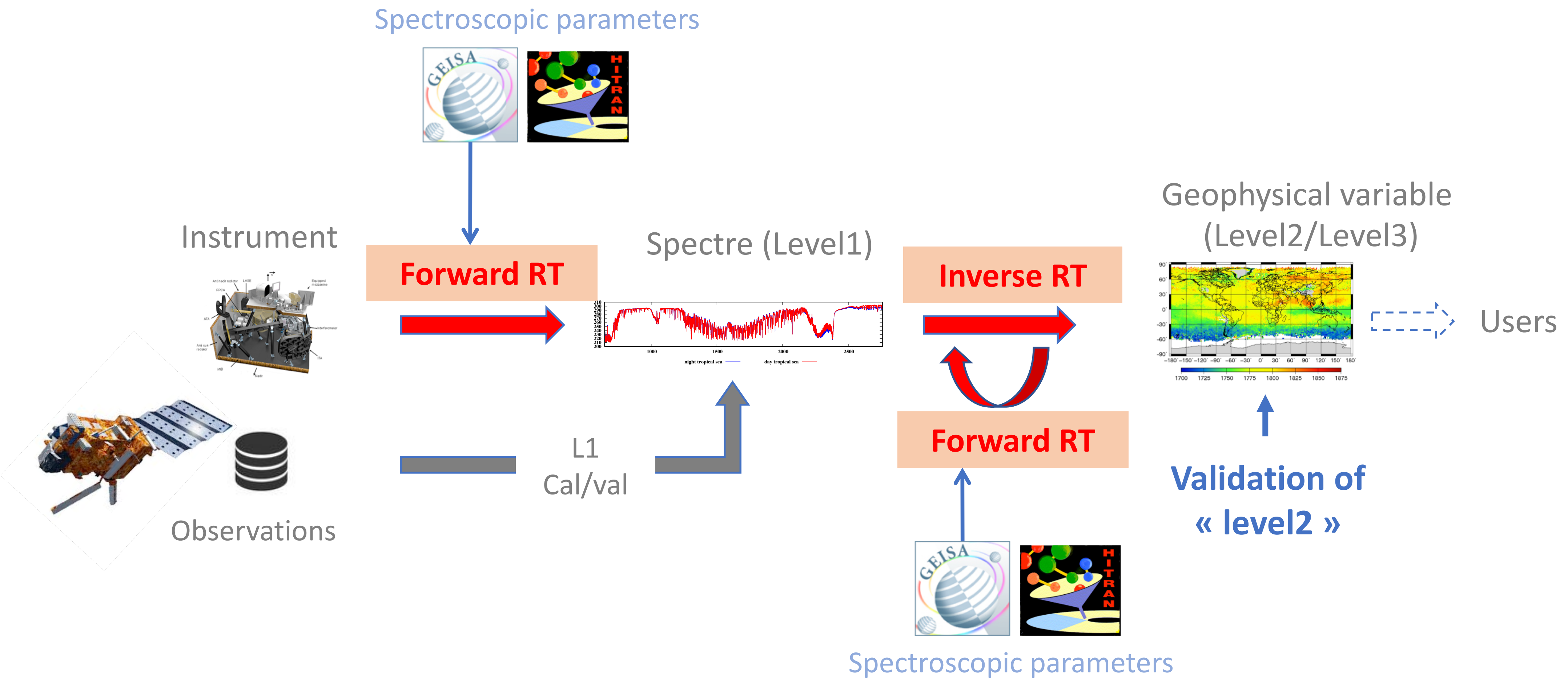
Applications



Objectives:

- *Processing data from current missions*
- **Preparing future instruments**

Applications



Objectives:

- *Processing data from current missions*
- *Preparing future instruments*
- **Validation, based on ground-based or airborne remote sensing**

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Pending questions for the exploitation of past and current missions

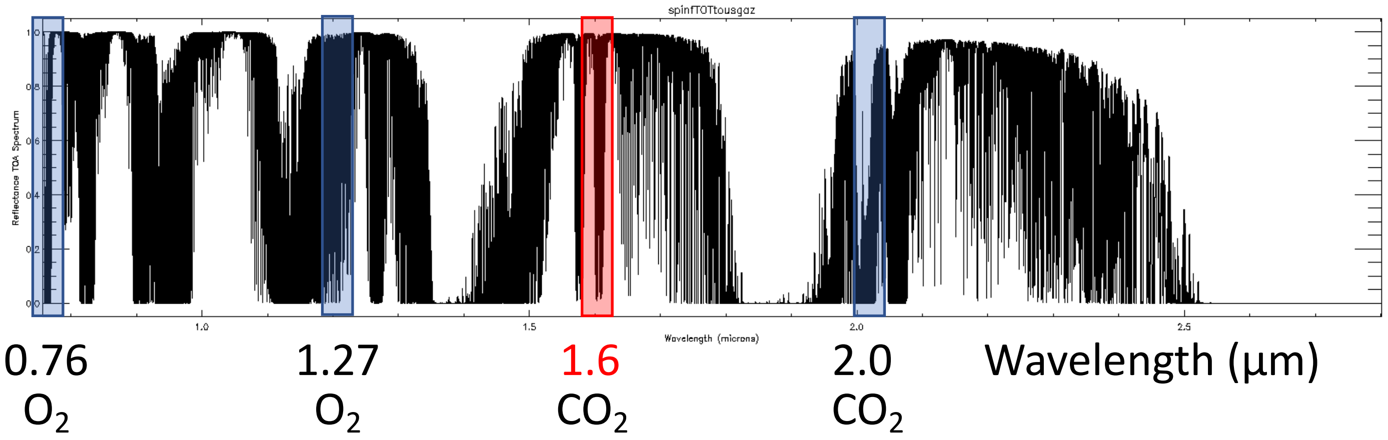
Short-Wave Infrared (SWIR)

SWIR domain is mostly use to derive total columns of greenhouse and trace gases : CO_2, CH_4, CO.

Goal: to monitor and characterize surface fluxes.

Observation Method: passive spectrometers operating in 3/4 wavelengths (0.76 and 1.27 µm O_2 bands, and 1.6 and 2 µm CO_2 bands)

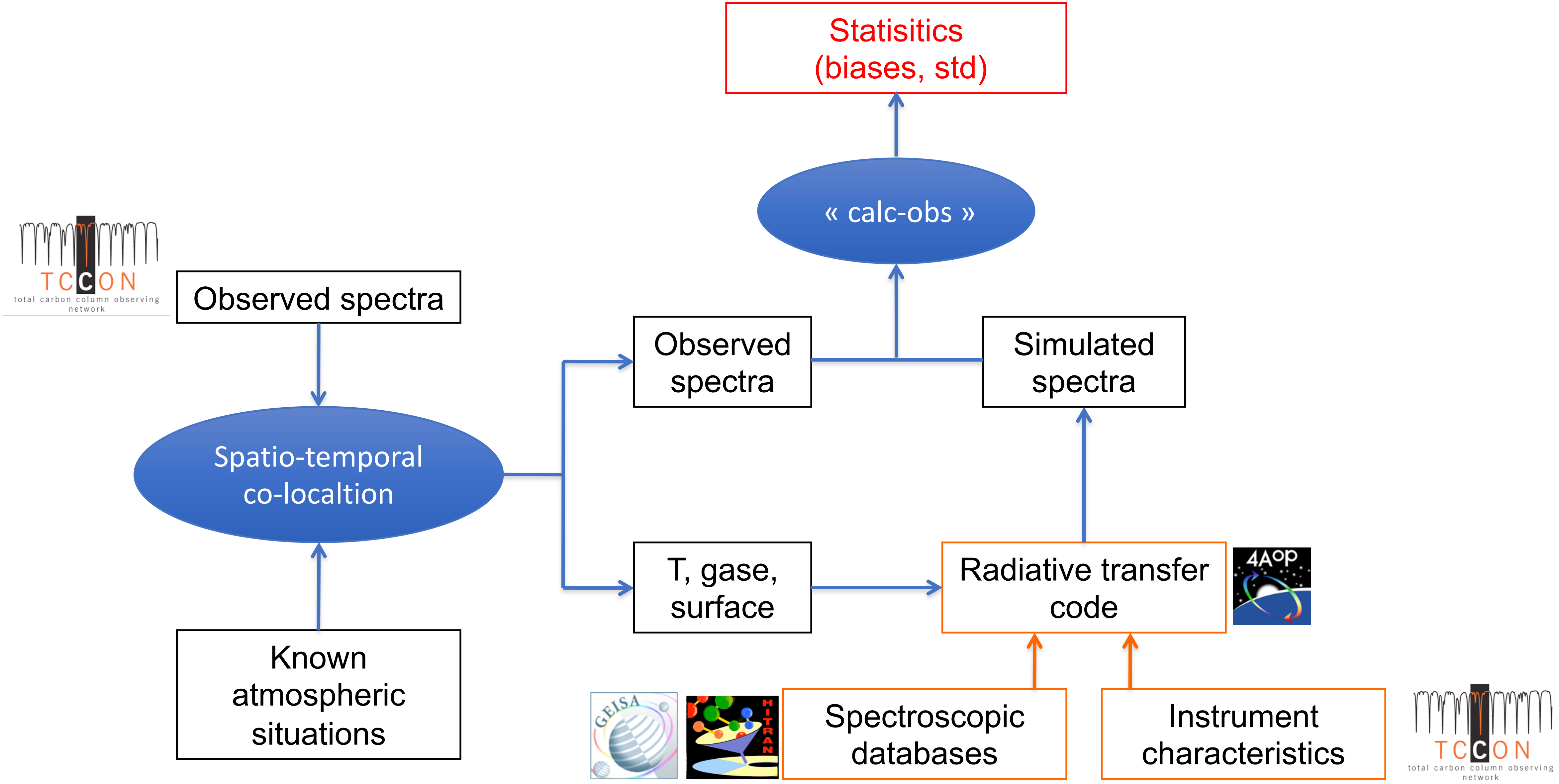
Atmospheric transmission in the SWIR



Instrument	Type	Launch date	Spectral coverage
TCCON	Ground-based FTS network	2004	Whole spectrum
OCO-2 (NASA)	Grated spectrometer	2014	3 bands
MicroCarb (CNES/UKSA)	FTS	2024	4 bands (new: 1.27µm)

→ Comparison between TCCON observations and simulations (spectro+RT code) helps identify spectrosocpic issues.

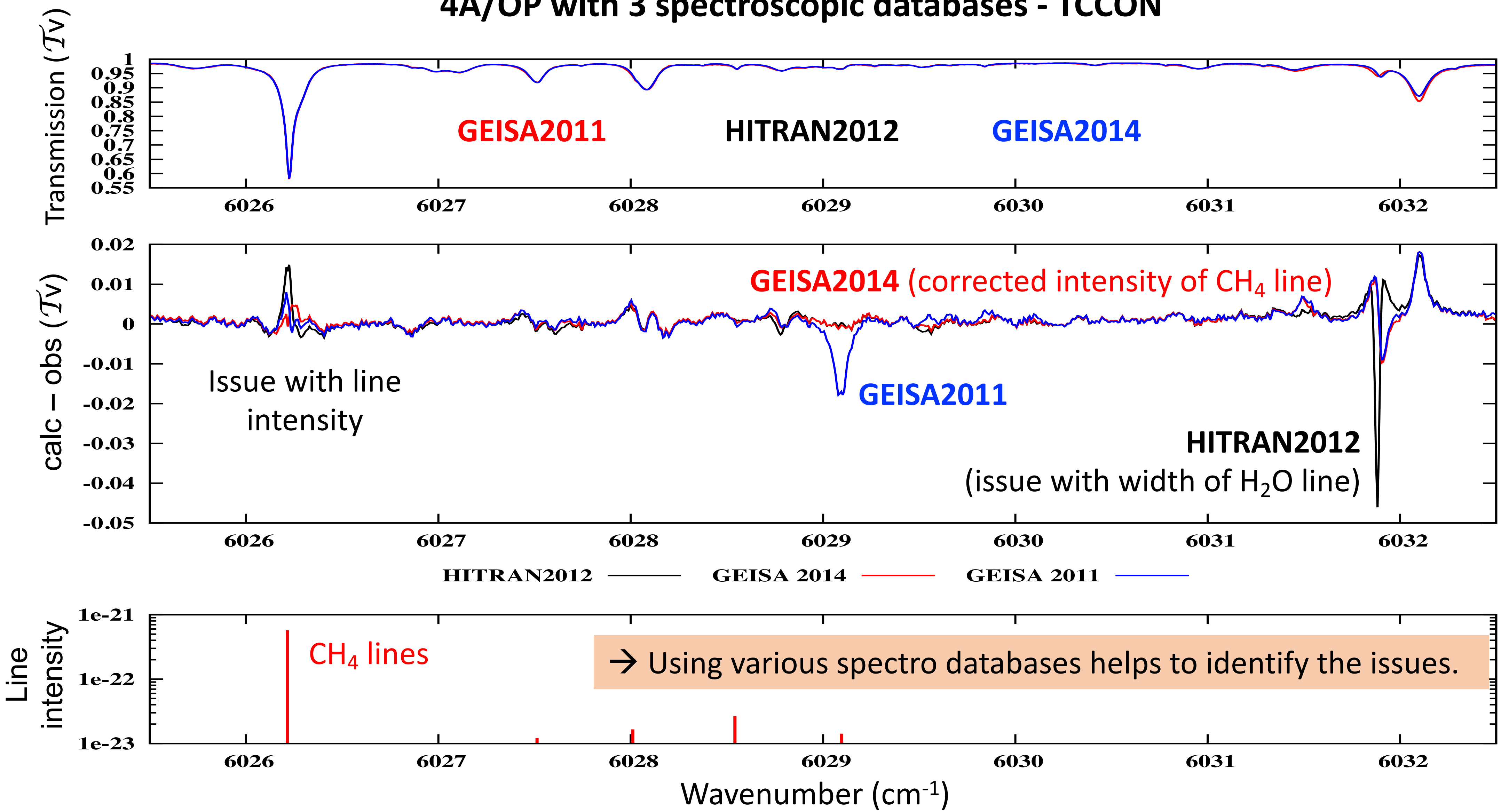
Evaluation of spectroscopic databases and radiative transfer codes



Evaluation of spectroscopic databases

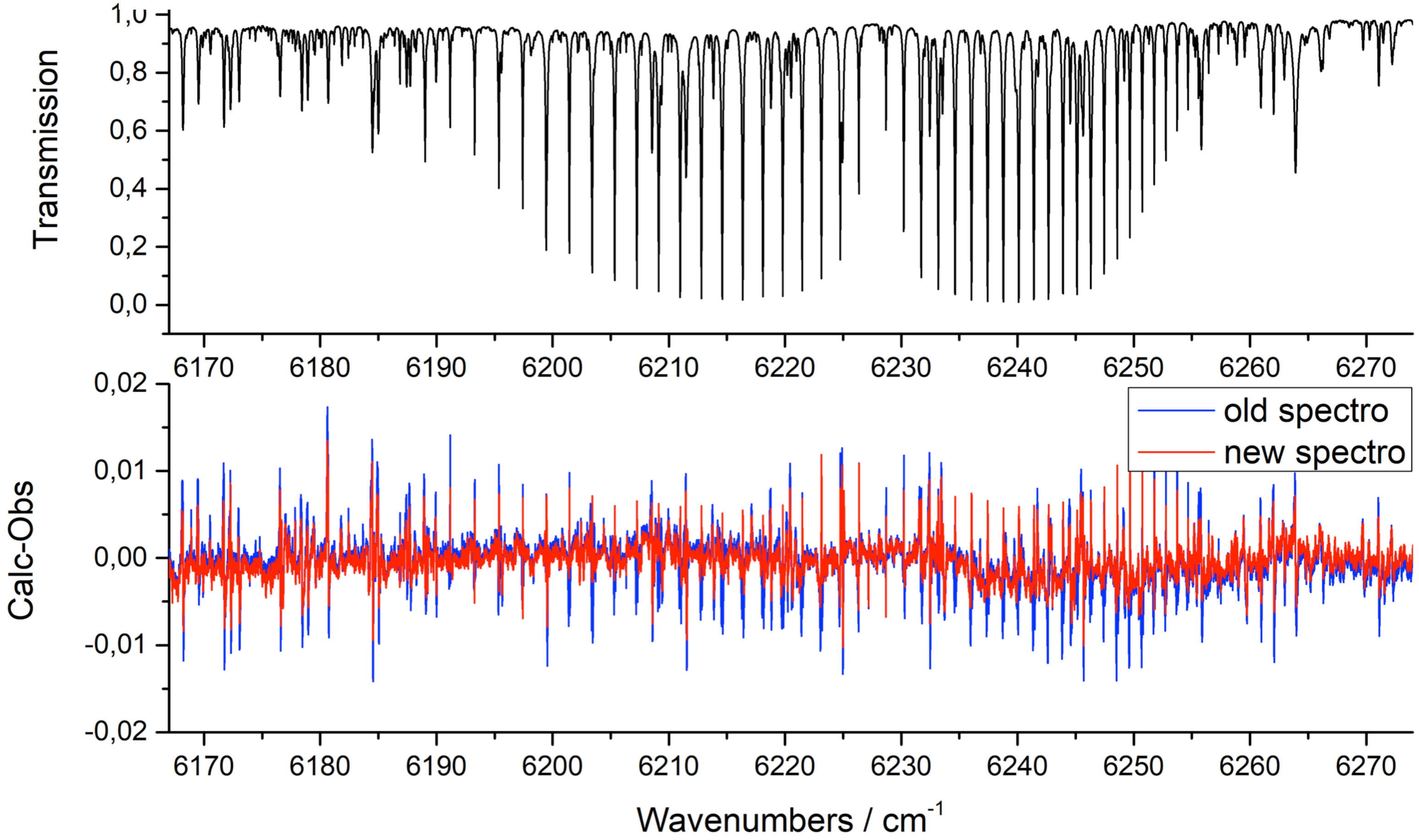
Short-Wave Infrared (SWIR)

'calc-obs' residual spectrum @ 1.65 µm
4A/OP with 3 spectroscopic databases - TCCON



Impact of a change in spectroscopy at Level 1 (spectra)

calculated-observed spectral residuals evalutated on 300 TCCON spectra (CO_2 weak 1.6 µm)



Two different spectroscopic parameter sets are tested:

old spectro:

- O_2: Tran Hartmann 08 collision-induced absorption (CIA) model
- CO_2: HITRAN08 + Lamouroux 2010 line mixing

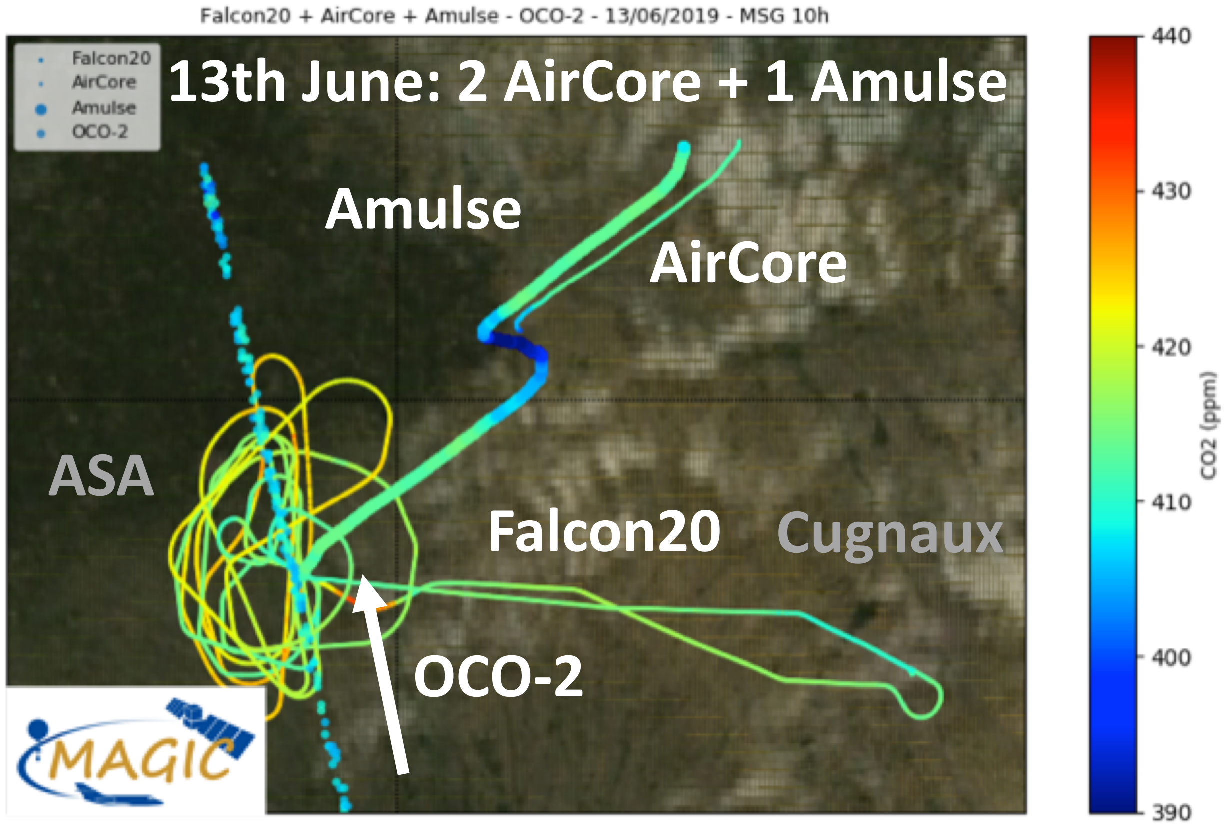
new spectro:

- O_2: **empirically correction** on Tran and Hartmann 2008 CIA model
- CO_2: Lamouroux 2015 model, adapted for **Speed-Dependent Y (1st order) line mixing approach** fueled with HITRAN 2012 line parameters
- Improved sampling strategy of spectrocopic parameters

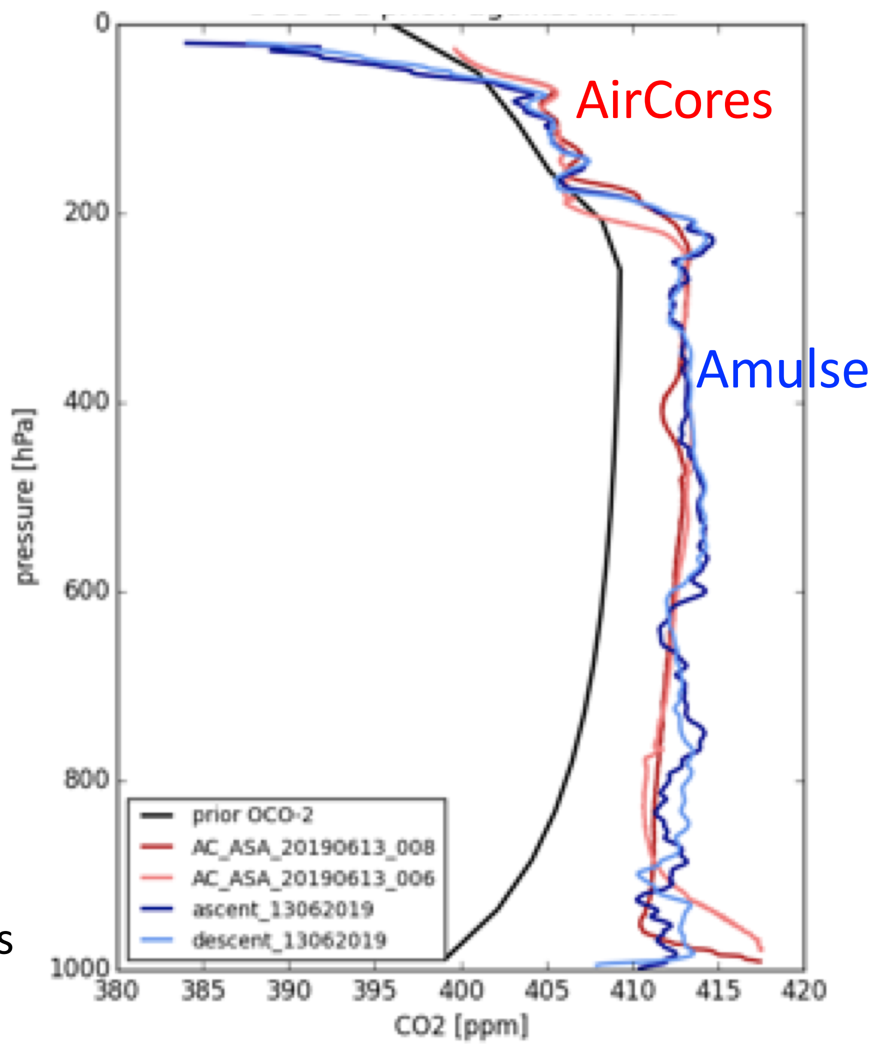
Less than 1% transmission difference between **old** and **new** on forward computations.
What is the impact on retrievals ?

Impact of a change in spectroscopy at Level 2 (CO_2)

Colocation between OCO-2 and balloon-borne instruments



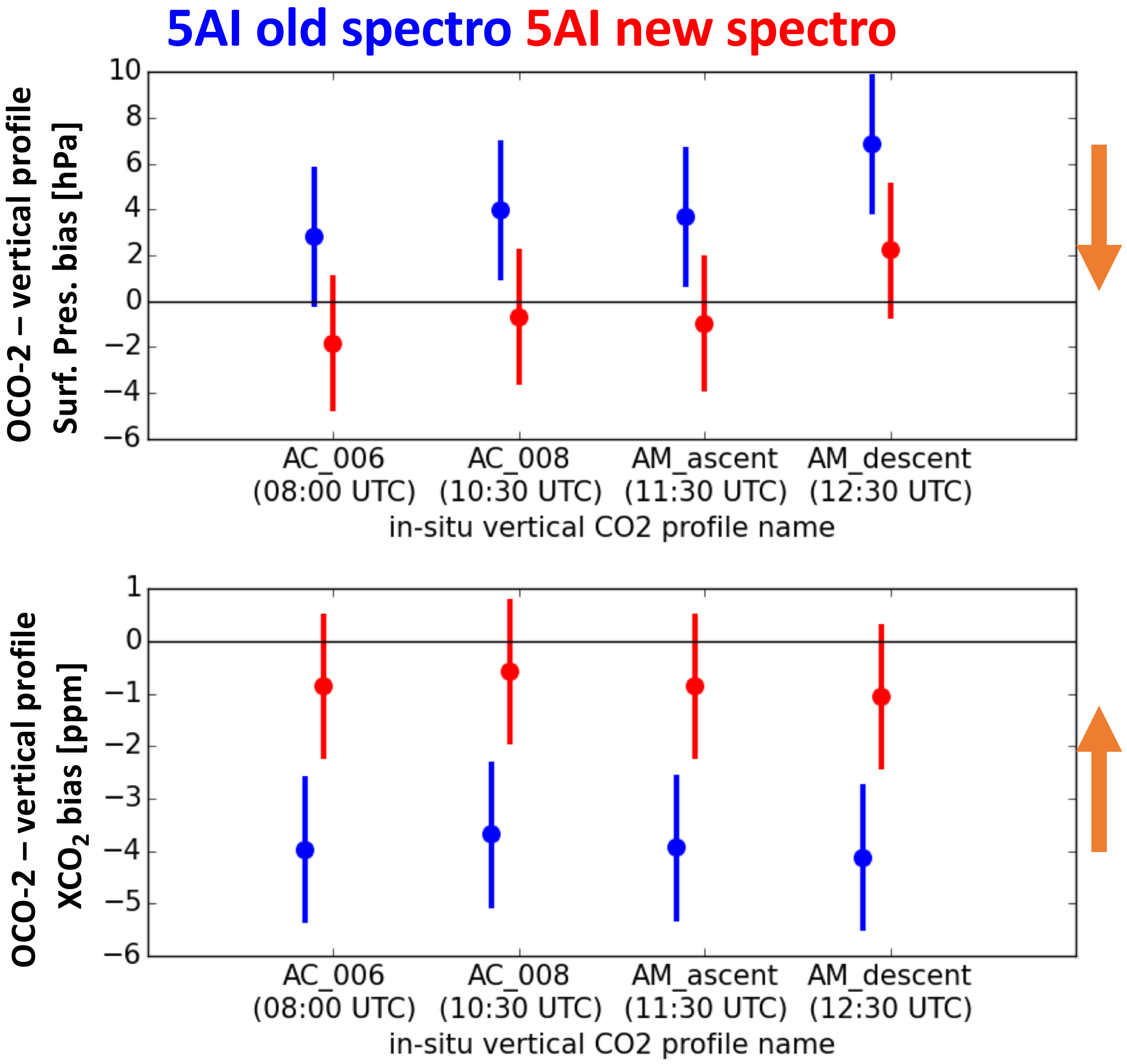
4 CO_2 in-situ vertical profiles



- Use of 4 co-located in-situ measurements with OCO-2 observations
- MAGIC2019 field campaign (13th June).
- OCO-2 spectra are inversed with the 5AI retrieval code, based on 2 spectroscopies.

Impact of a change in spectroscopy at Level 2 (CO_2)

SWIR: Impact on the retrieved surface pressure and CO_2 column from OCO-2



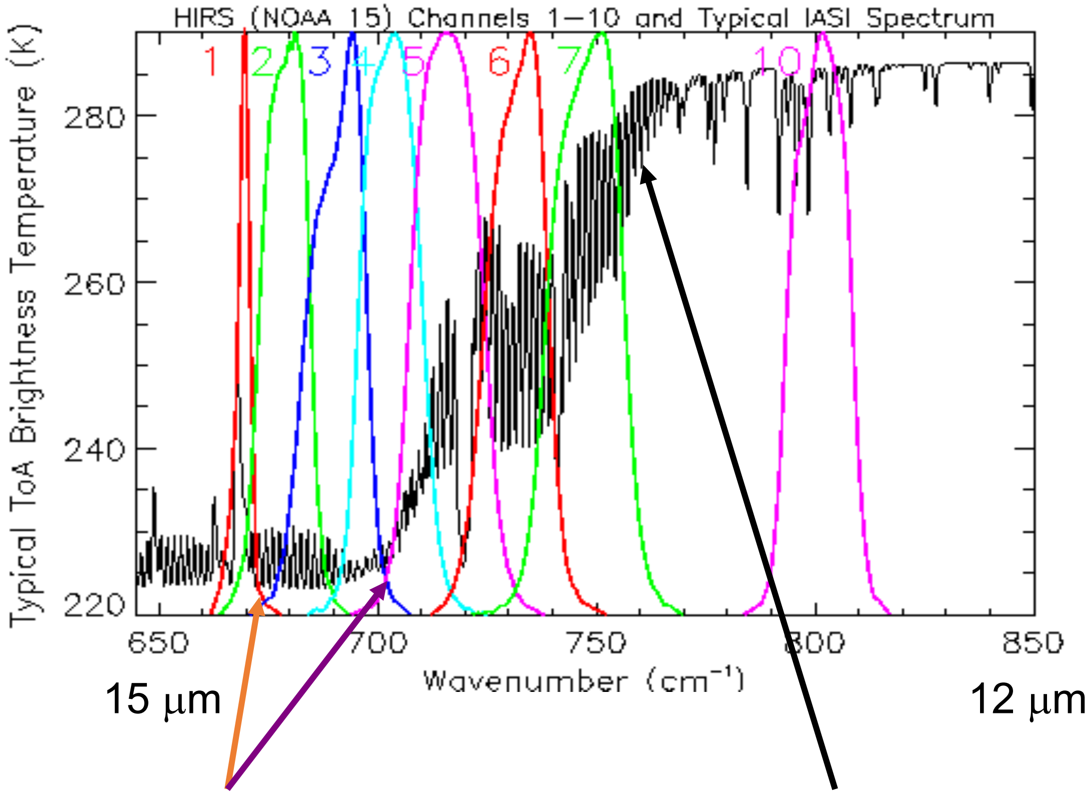
The **empirical CIA correction** reduces the surface pressure bias.

It contributes to reducing XCO_2 bias along with **SDY line mixing + HITRAN 2012 model** for CO_2, compared to **previous spectroscopic parameters**.

Improving the spectroscopy helps reducing biases on level 2 ☺

From the first to the current and future generations of infrared sounders

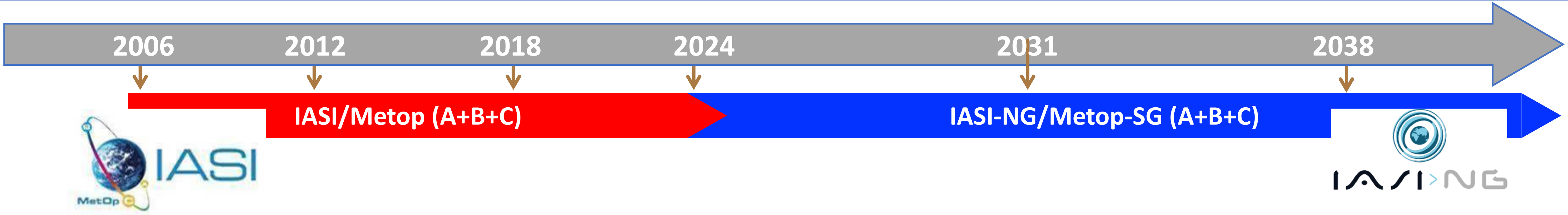
Thermal Infrared (TIR)

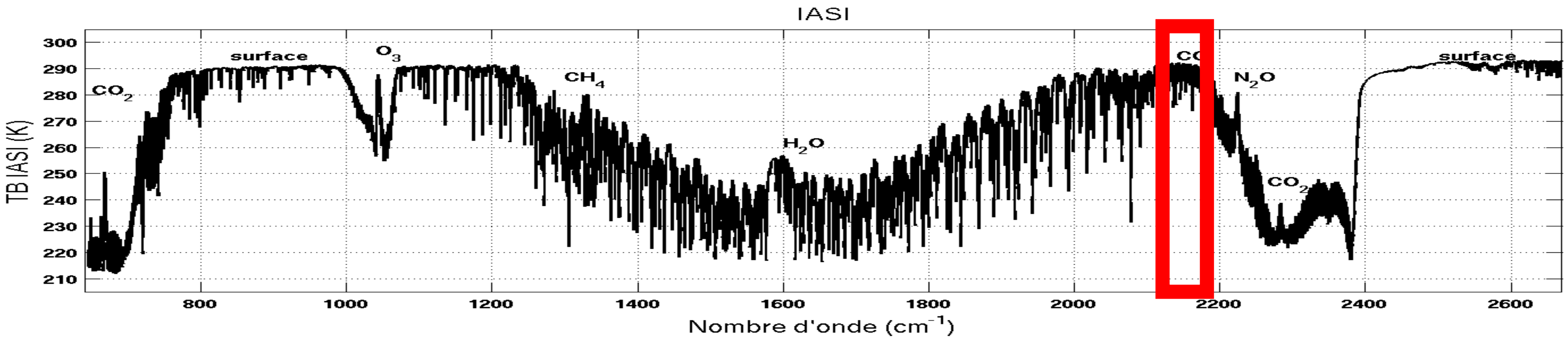


Improvement on spectral and radiometric characteristics call for improved spectroscopy and radiative transfer modeling

- First generation instruments:
  - 1978 : HIRS
    - -19 channels
    - -resolution ~15cm^{-1}
- Second generation instruments:
  - 2002 : AIRS -2378 channels
    - -resolution ~0.5-2 cm^{-1}
  - 2006 : IASI -8461 channels
    - -resolution ~0.25 cm^{-1}
- Next generation instruments:
  - 2024 : IASI-NG
    - -16921 channels
    - -resolution ~0.125cm^{-1}

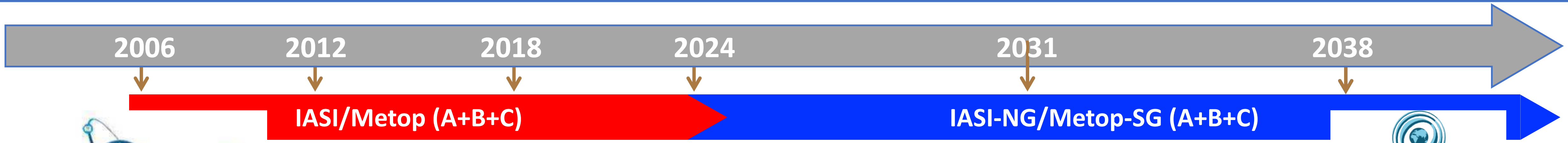
From current to future generations of infrared sounders

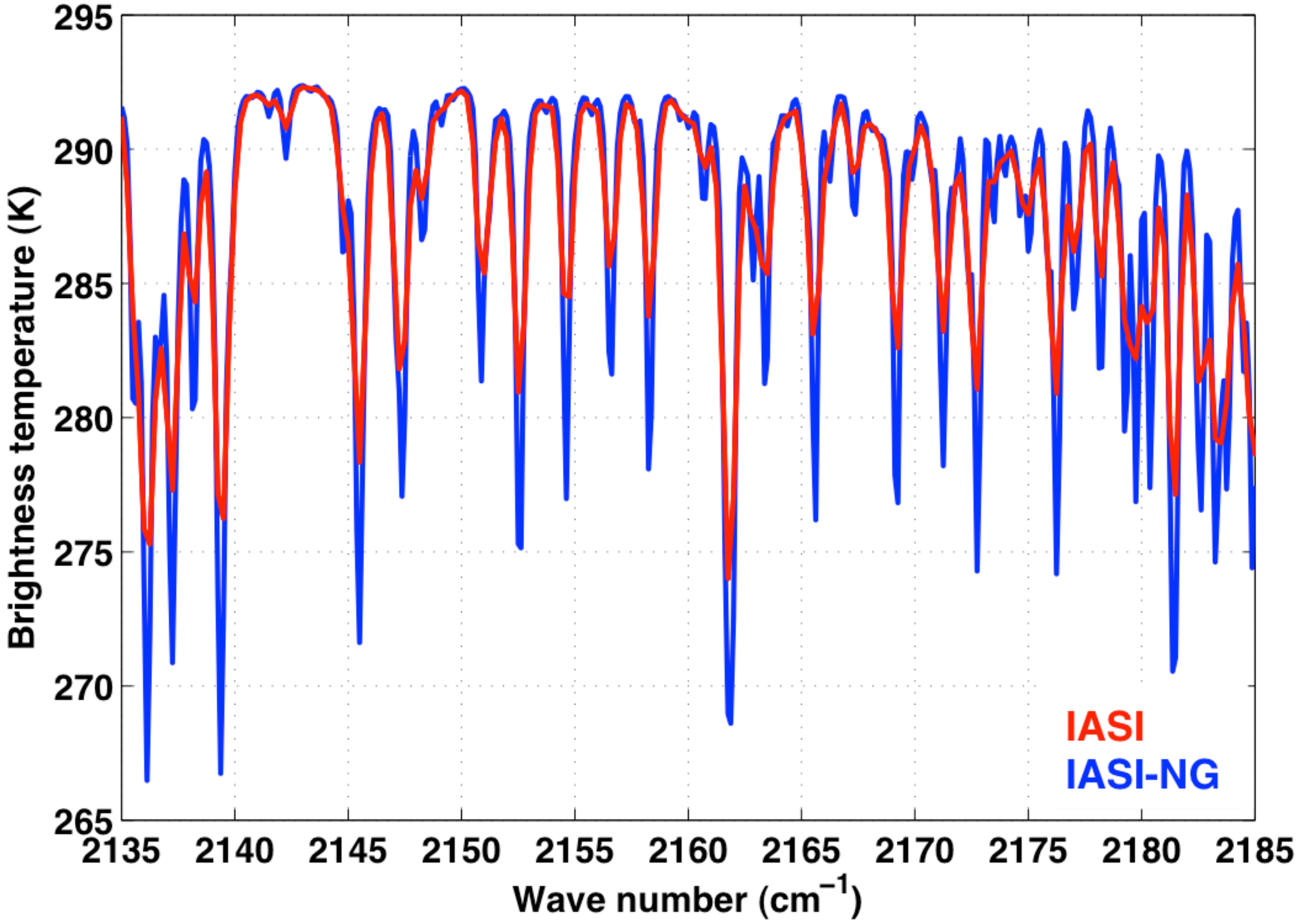




Spectral resolution x2
Spectral sampling x2
Radiometric resolution 2.

From current to future generations of infrared sounders



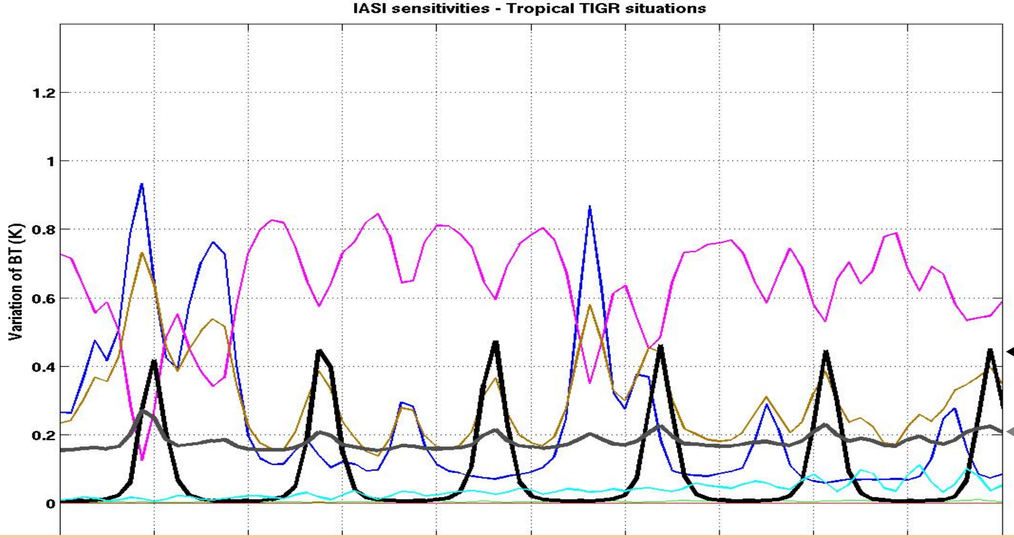


Spectral resolution x2
Spectral sampling x2
Radiometric resolution 2.

From current to future generations of infrared sounders

IASI

0.5 cm^{-1}



For a 10ppbv CO perturbation:

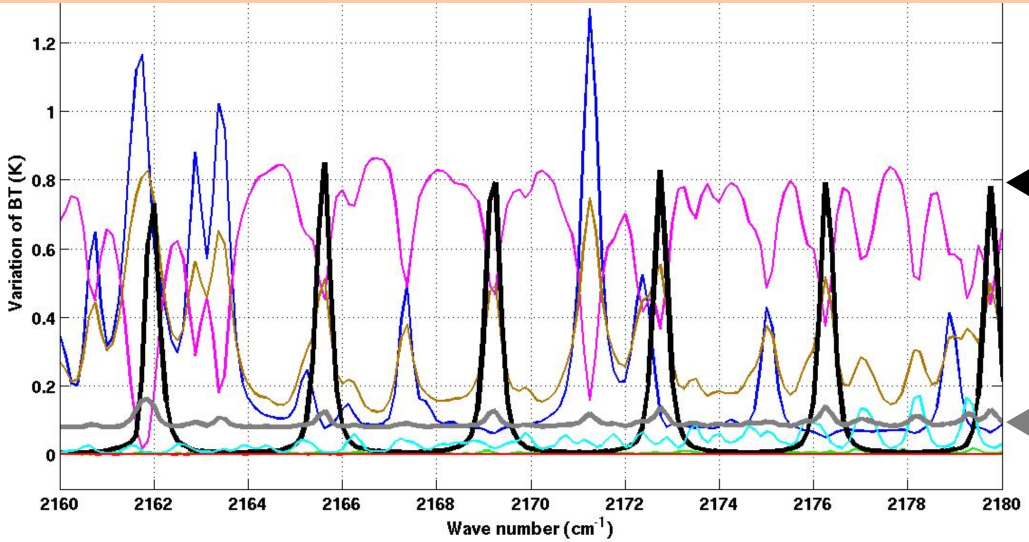
CO ~0.4K

Noise: ~0.2K

- An improvement by a factor of 4 at Level 2 is expected from IASI-NG.
  - Is there still something to improve in the Thermal IR ? YES!

IASI-NG

0.25 cm^{-1}



CO ~0.8K

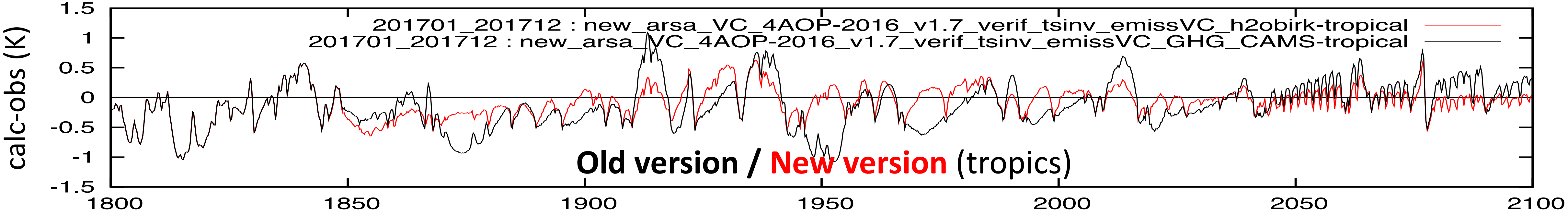
Noise: ~0.1K

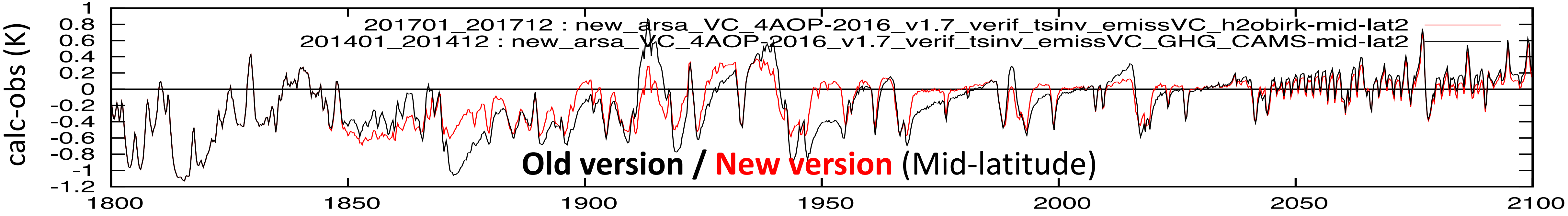
T (1K) H_2O (20%) CO_2 (1%) O_3 (10%) N_2O (2%) CO (10%) CH_4 (10%) Tsurf (1 K)

Focus on H_2O

Towards the use of a new line shape in RT modeling (from Voigt to HTP profile)

Birk: H2O **(1850 → 4439 cm-1)**, HDO (**2478 → 4439 cm-1**) Speed Dependent Voigt (SDV) line profile



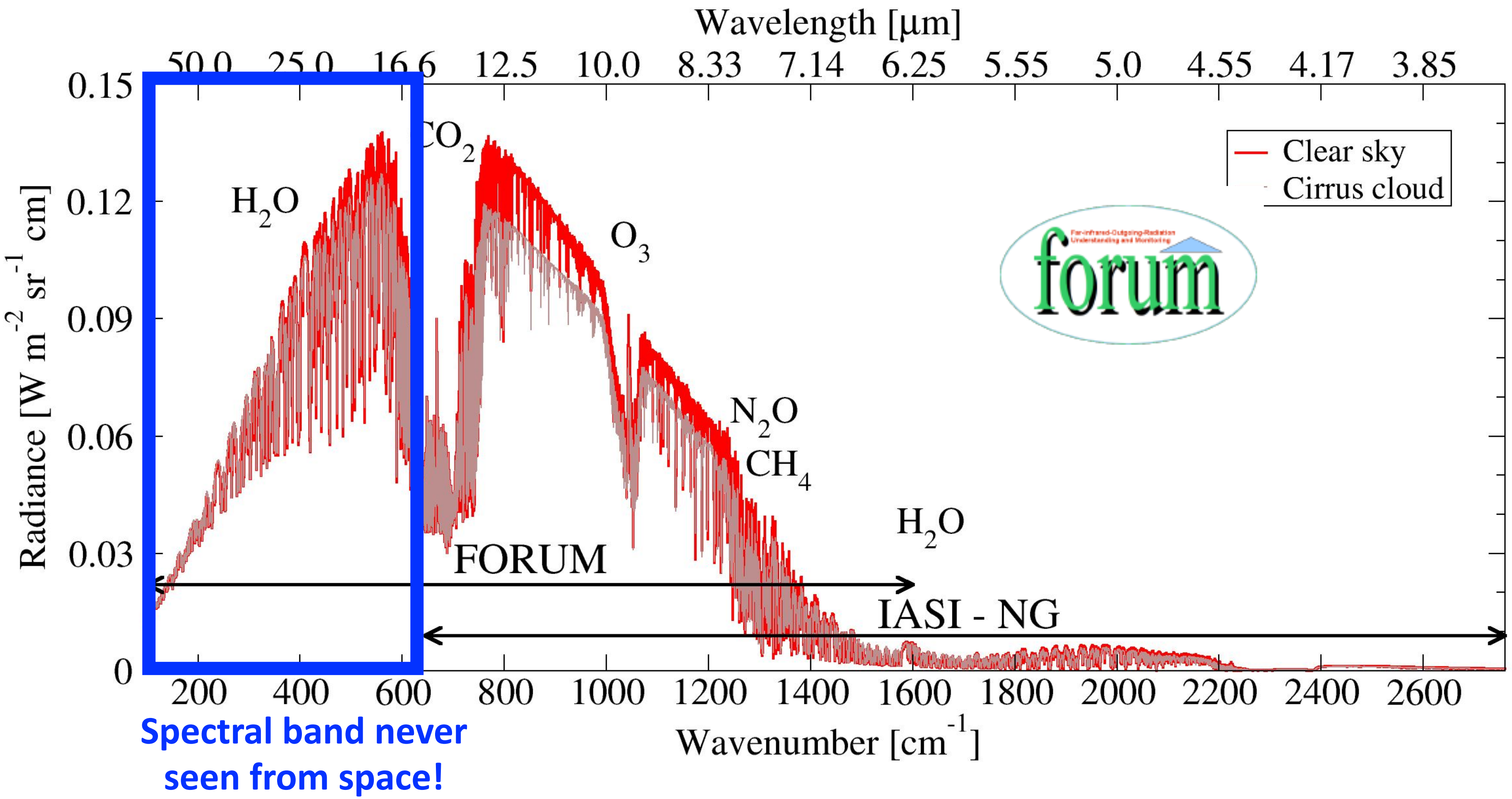


Even in the well-known TIR range, there is still room for improvements!

Needs for future missions

New spectral bands: FORUM (FIR)

- **The new EE9 mission selected by ESA**
- **Goals** : Earth radiative budget and 1st measurement in the Far IR.
- **Launch date**: 2026. In a train with IASI-NG



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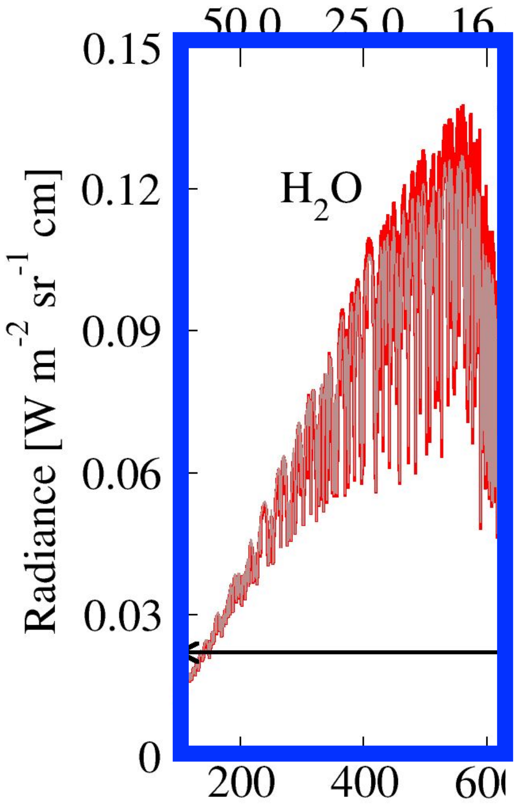
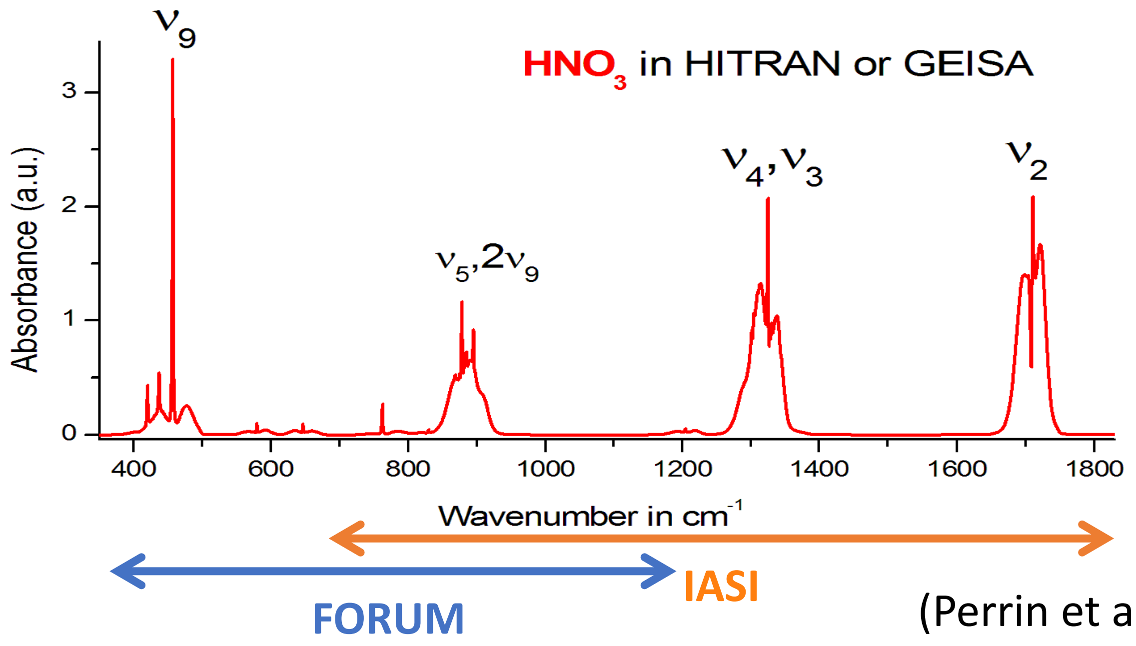


Spectral band never seen from space!



(Perrin et al.)

- Need for new or improved spectroscopy: methane, NO_2, N_2O, NH_3, O_3, methanol (CH3OH), abs coefficients (PAN etc).
- Work on continua of absorption.

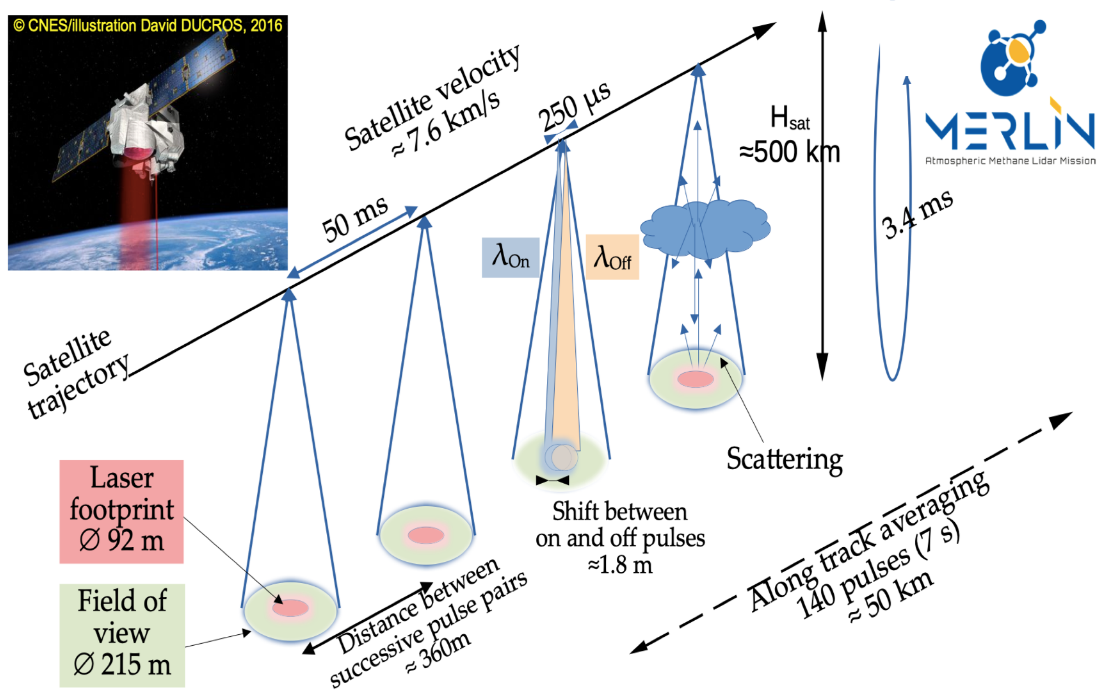
Specific questions: Active missions

The joint CNES/DLR MERLIN: MEthane Remote sensing LIdar missioN

Goal: to improve the understanding of the global methane cycle and the processes, which govern the exchange of methane between atmosphere and biosphere.

Observation Method: Differential absorption of gaseous methane at two laser wavelengths reflected from Earth surface or dense clouds.

Launch date: 2027.



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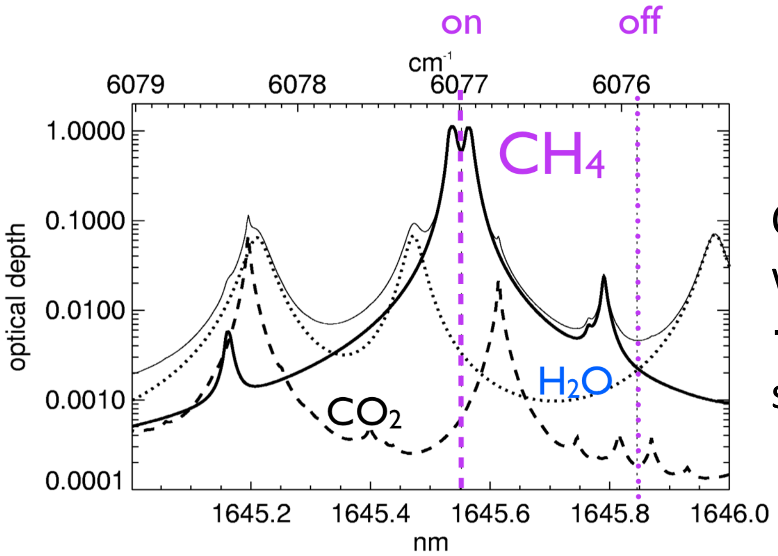
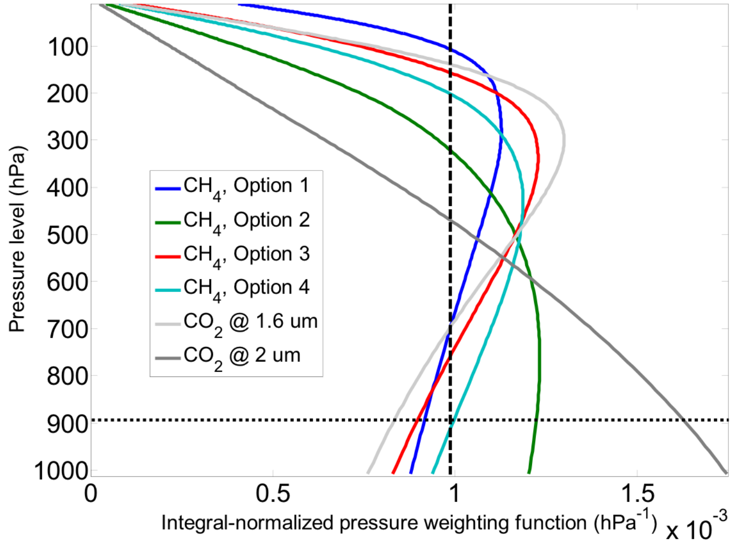


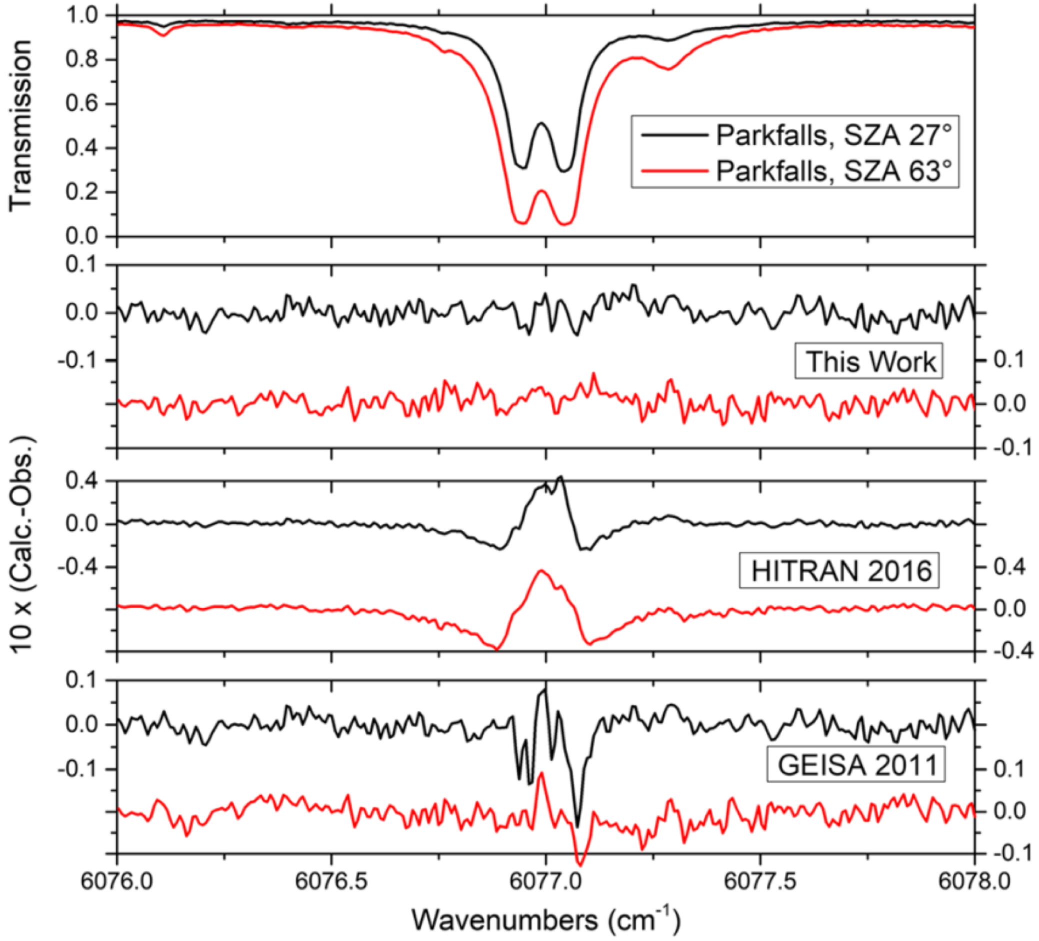
Choice of the two wavelengths on and off
→ Strong requirement on spectrosocpic knowledge



(Kiemle et al., AMT, 2011)

Impact on vertical sensitivity of the instrument …and on the retrieved column of CH_4

Evaluation of various spectroscopy



Delahaye et al.

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Concluding thoughts

Recent and foreseen evolutions

- **Instruments with increased characteristics** (IASI, GOME-2, SAPHIR, TCCON, etc) **:**
  - Detection/retrieval of new species (ex : more than 30 now "seen" by IASI).
  - Improved spectral resolution and radiometric noise.
  - A renewed interest (and funding…) for spectroscopy and radiative transfer for calibration/validation activities at both Level1 and Level2, even for well-known spectral regions
- **Intense work around the line at 183 GHz**
- **Heavy developments in the SWIR:** GHG missions (OCO-2, GOSAT, MicroCarb, CO2M, etc.)
- **New coupling between spectral bands:**
  - IR-MW: a classic coupling (NWP, thermodynamics, clouds)
  - IR-UV/Vis: Ozone and aerosols
  - IR-SWIR: GHG, aerosols
  - Vis/SWIR : surface, aerosols.
- **New spectral bands to start exploring:** SWIR (O_2 1.27µm for MicroCarb), Far IR (FORUM), etc.

Concluding thoughts

A programmatic point of view

- **Future Satellite Observing System will combine:**
  - High demanding reference missions for Earth Observation.
  - Research oriented missions, that can then be integrated in an operational program like Copernicus/Sentinel.
  - Constellation of small satellites
  - State vs. NewSpace missions

- **To insure the success all these missions and their corresponding applications (science, societal needs), it is required to have:**
  - Up-to-date and validated spectroscopy.
  - Up-to-date and validated forward and inverse RT codes.
  - Cal/Val activities, including field campaigns and innovative instrumentation.
  - Improved Earth System models.