The infrared spectrum, measurement and information content

ECMWF/EUMETSAT NWP-SAF Satellite Data Assimilation Training Course

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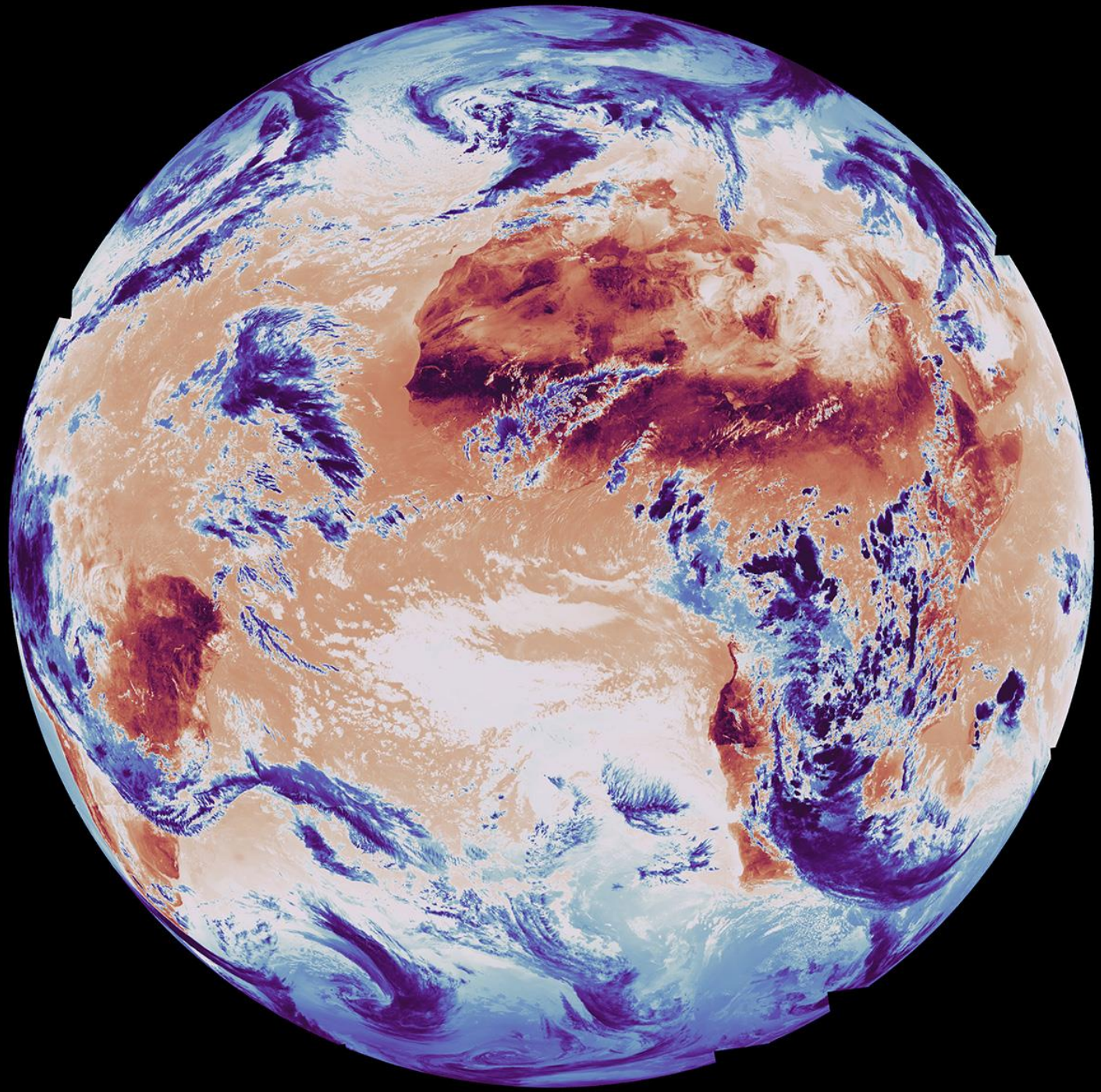
Tony McNally, **Chris Burrows**

chris.burrows@ecmwf.int

First, some images from the IRS sounder on MTG-S1, courtesy of EUMETSAT

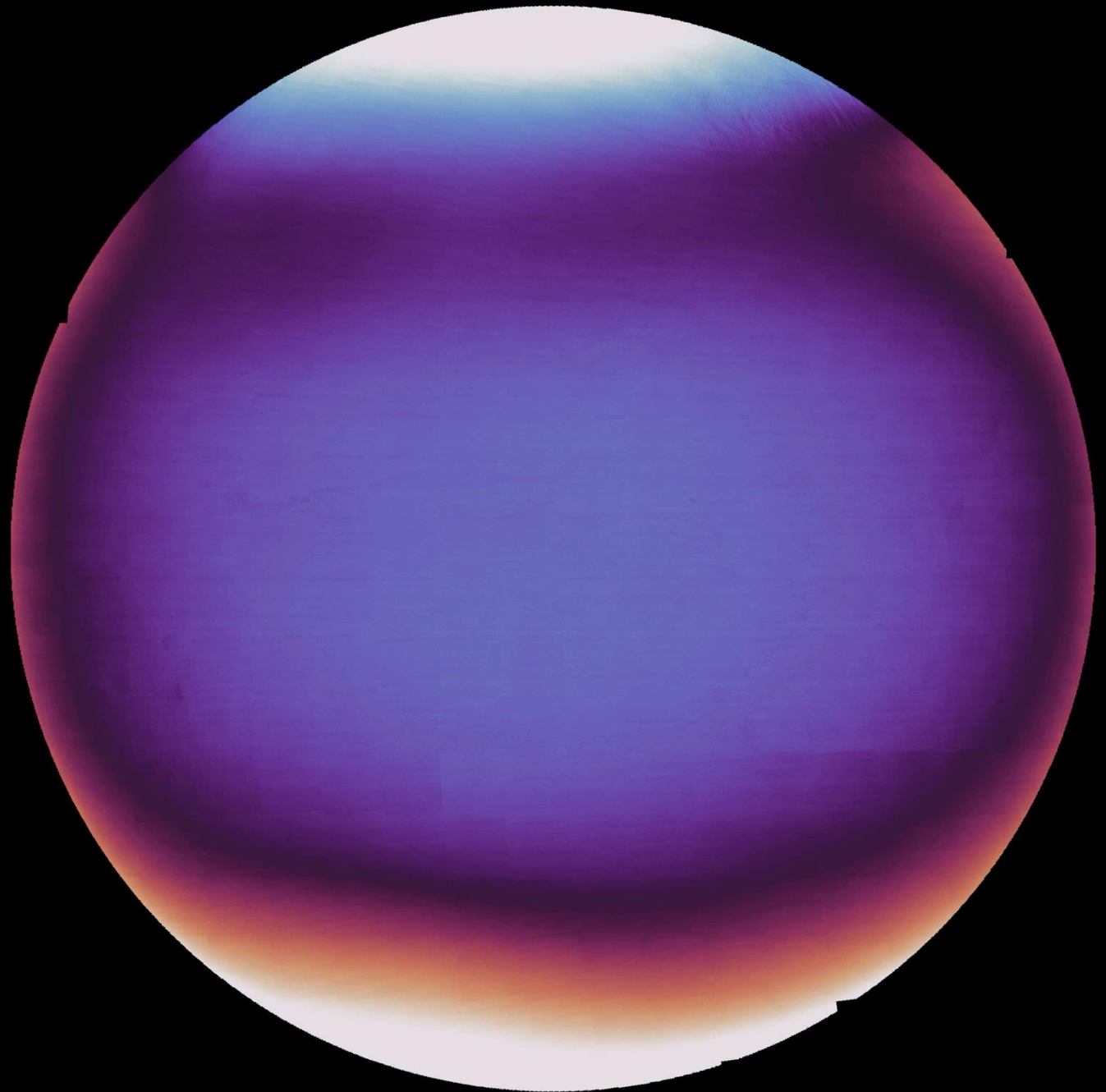
https://www.eumetsat.int/features/see-earths-atmosphere-never

ECMWF

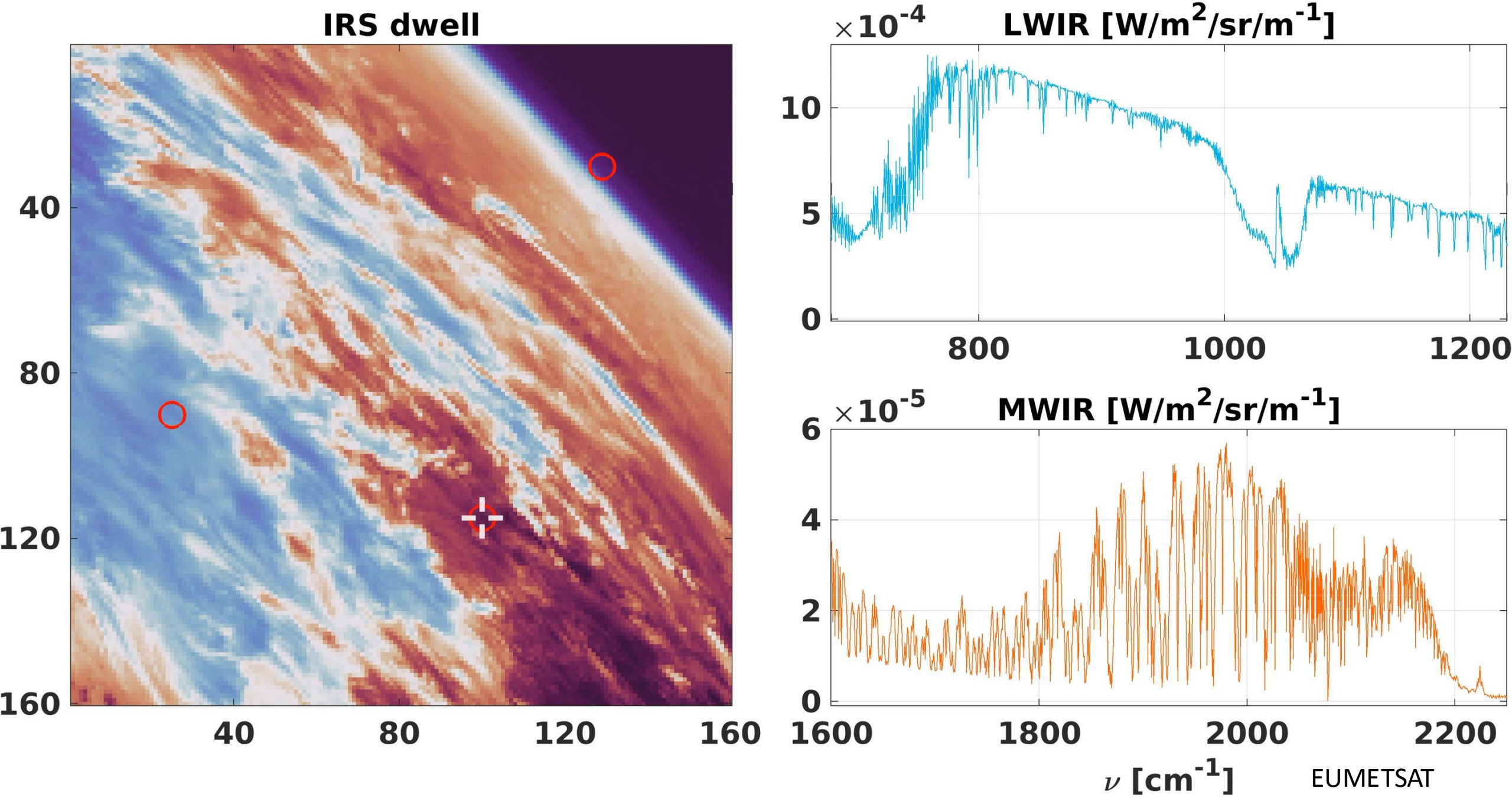


EUMETSAT

690.4 cm^{-1} (14.48 µm)

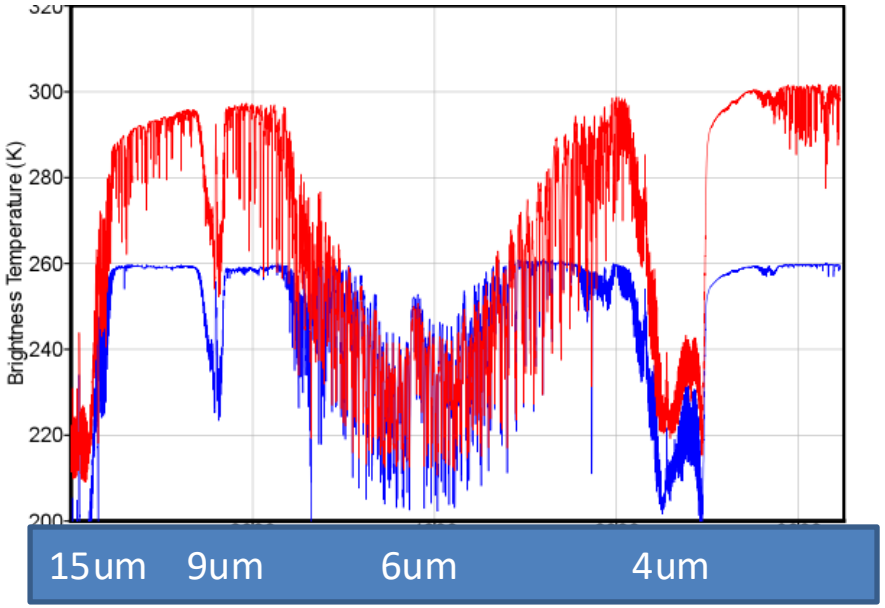


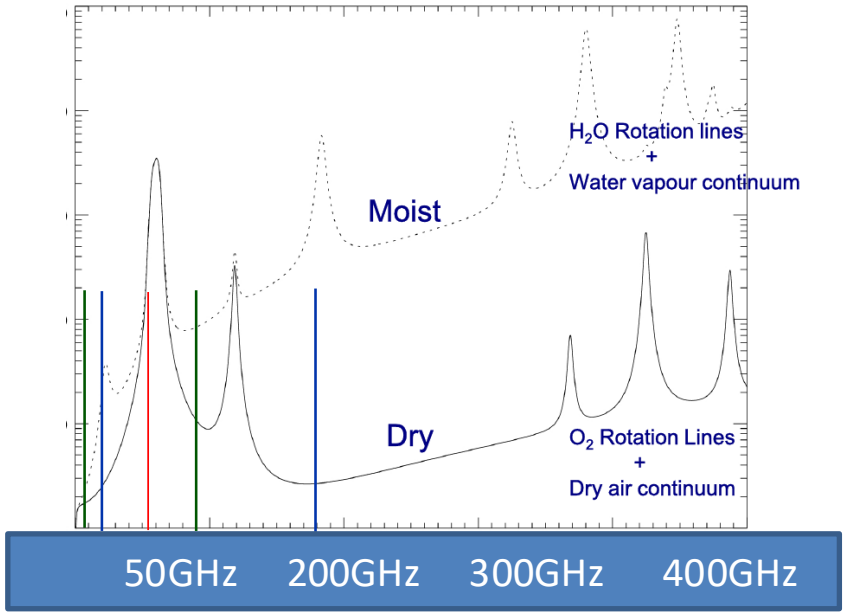
EUMETSAT


IRS dwell
40
80
120
160
40
80
120
160
×10-4
LWIR [W/m2/sr/m-1]
10
5
0
800
1000
1200
×10-5
MWIR [W/m2/sr/m-1]
6
4
2
0
1600
1800
2000
2200
ν [cm-1]

EUMETSAT

Spectral resolution: Infrared vs Microwave



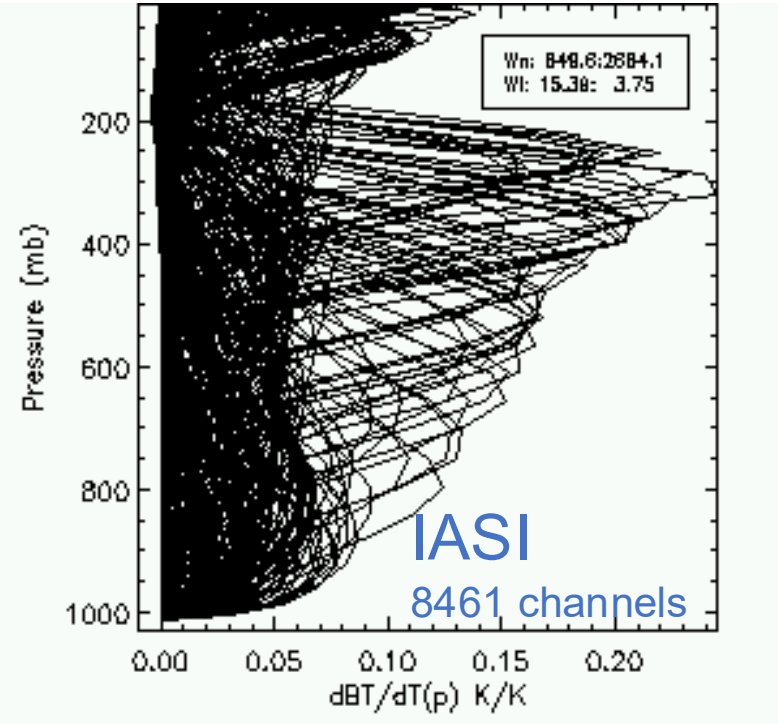


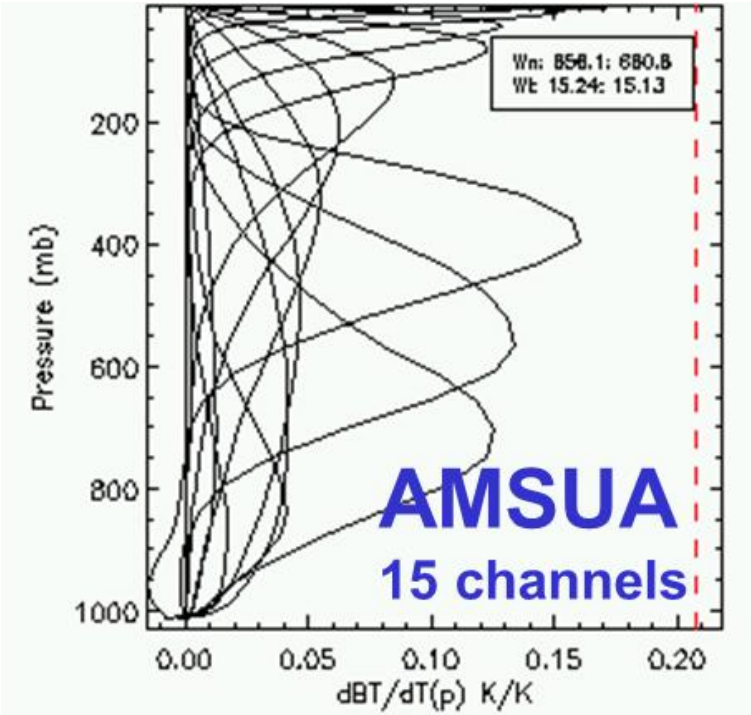
In the infrared, many of the thousands of distinct spectral lines are resolvable – in the microwave there are only a handful of resolved features due to pressure broadening!

Why high spectral resolution..?

…high vertical resolution

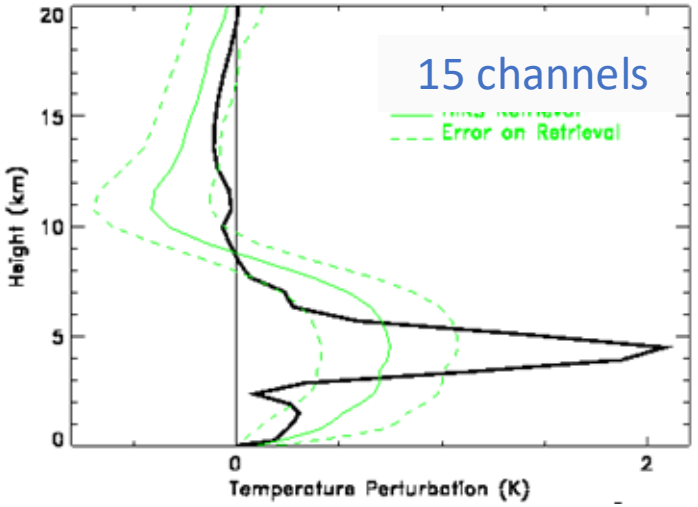
Infrared vs Microwave

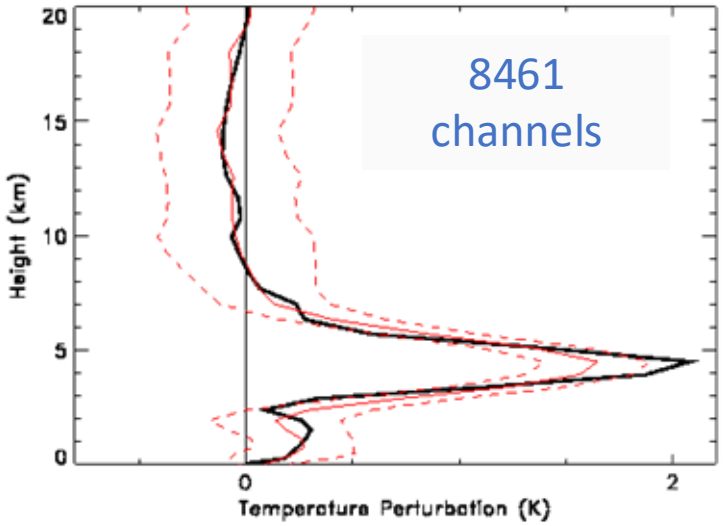




Each channel has a slightly different weighting function – providing information on a slightly different part of the atmosphere.

Infrared vs Microwave

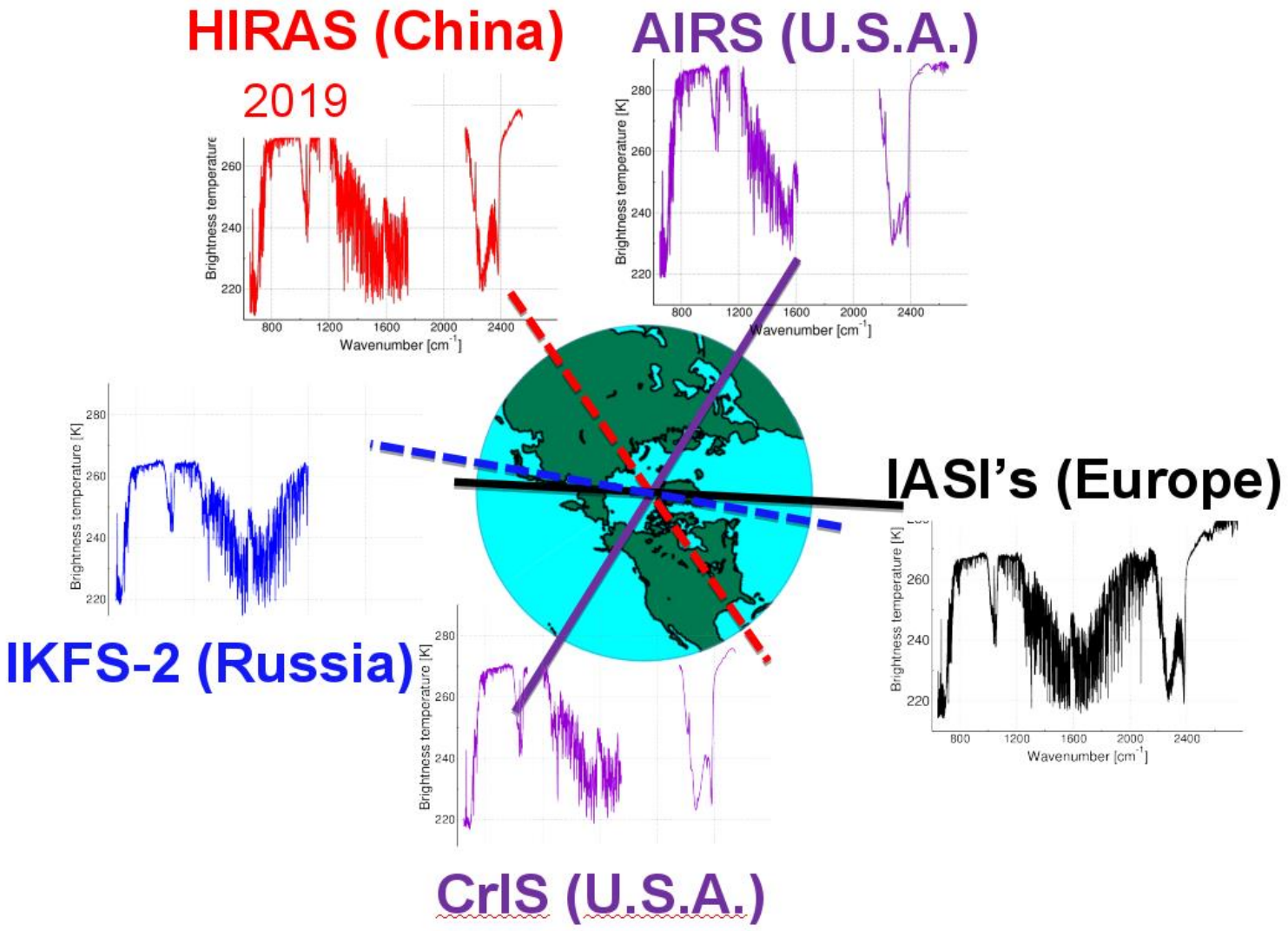




With only a few channels, fine vertical features in the atmosphere are not resolvable – but become better analysed with more channels.

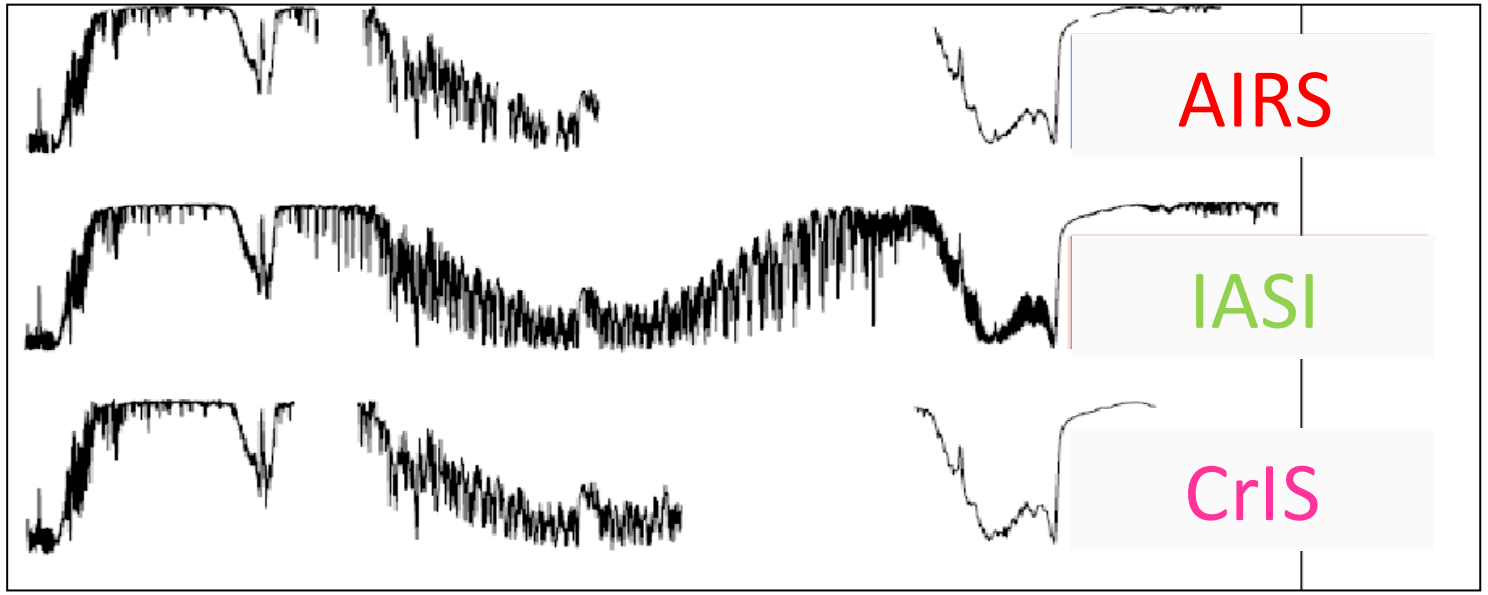
High Spectral Resolution (hyperspectral) IR sounders on Polar-orbiting Spacecraft

High Spectral Resolution IR sounders on Polar-orbiting Spacecraft



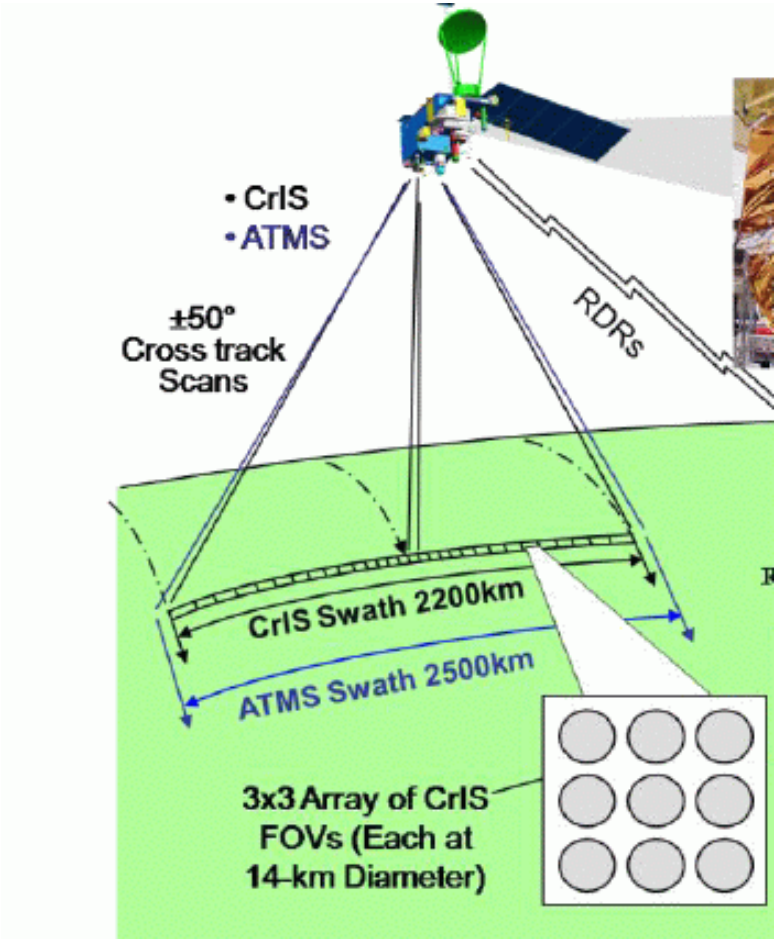
Operationally-used High Spectral Resolution IR sounders

Instrument/ Satellite/	No. of Channel	Spectral Range	Spectral Res.	IFOV	Type/ Orbit
AIRS/ Aqua	2378	650-2550cm^{-1}	~0.25-~1.0cm^{-1}	13.5km	Grating Spectrometer/ Polar
IASI/ Metop	8461	645-2760cm^{-1}	0.25cm^{-1}	12km	Interferometer /Polar
CrIS/ NPP & NOAA	2211	650-2550cm^{-1}	0.625cm^{-1}	14km	Interferometer /Polar

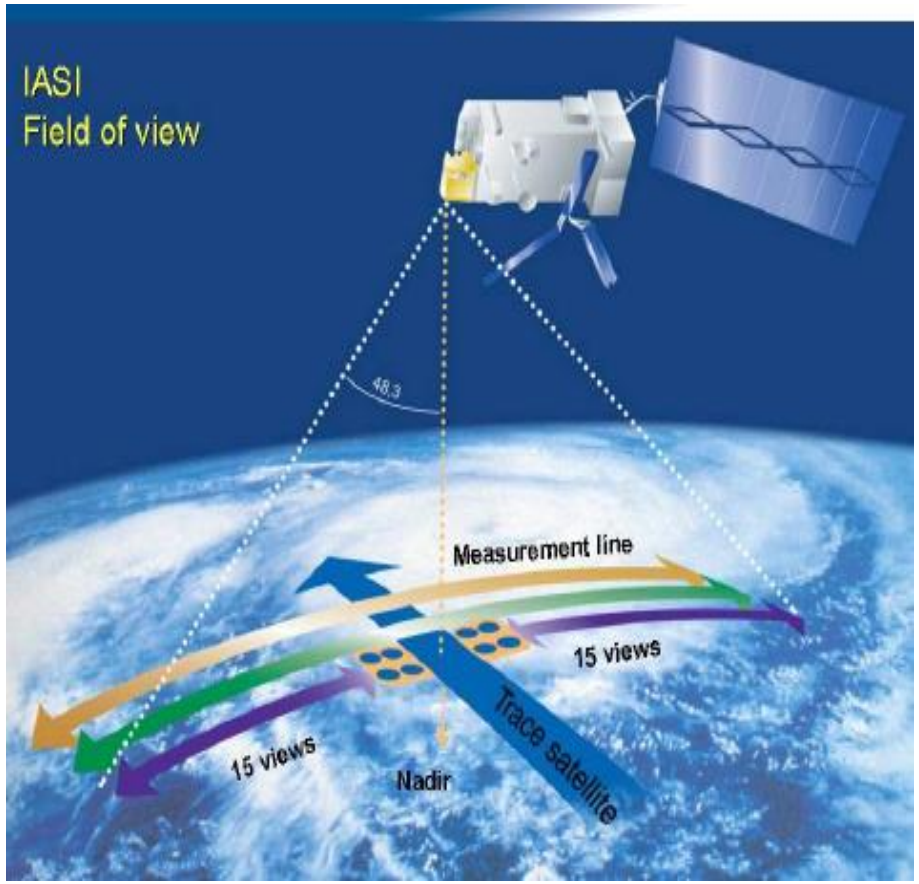


IASI v CrIS

Cross-track Infrared Sounder (CrIS)



Infrared Atmospheric Sounding Interferometer (IASI)



IASI has higher spectral resolution compared to CrIS

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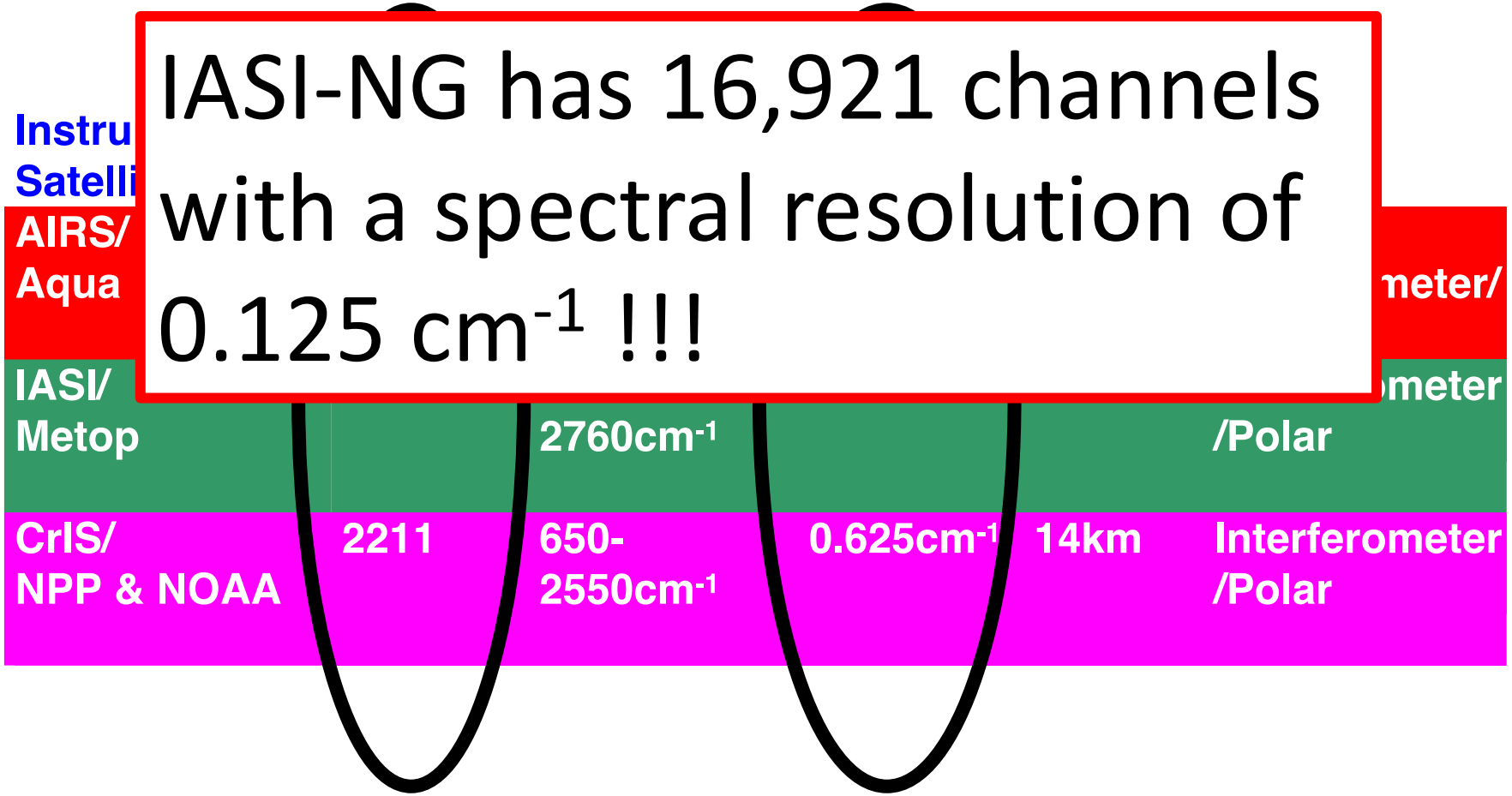
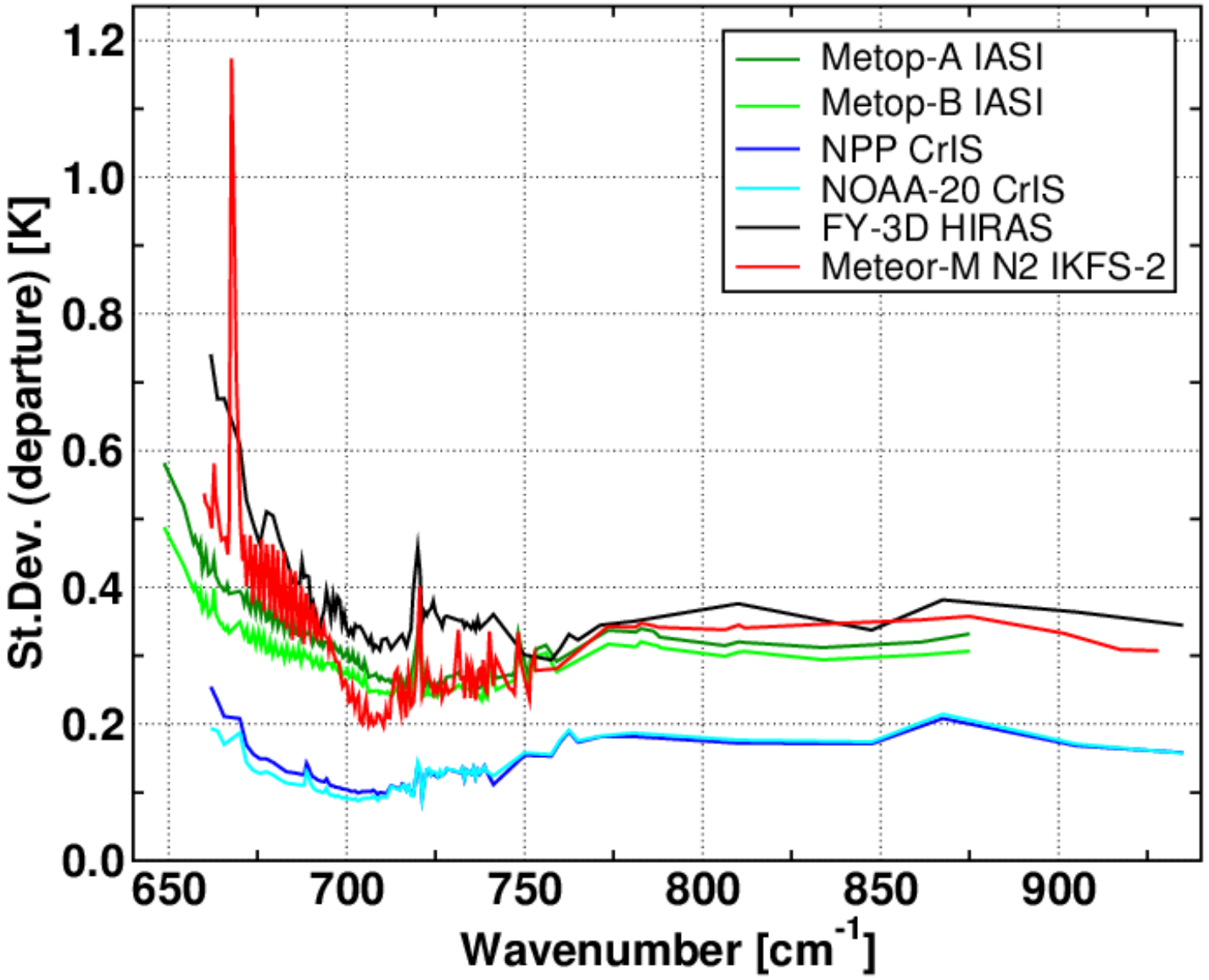
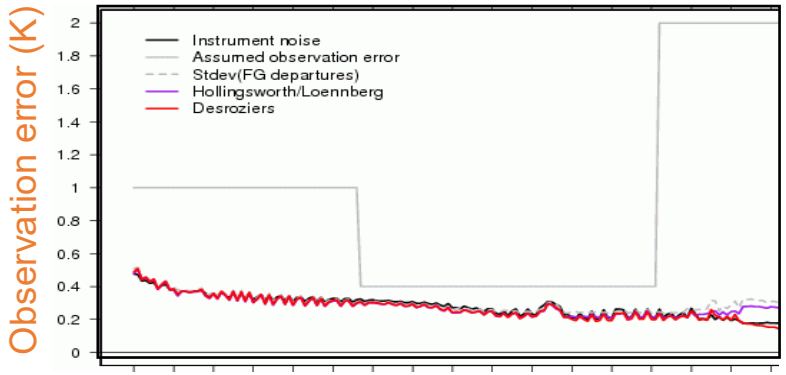
IASI has higher spectral resolution compared to CrIS

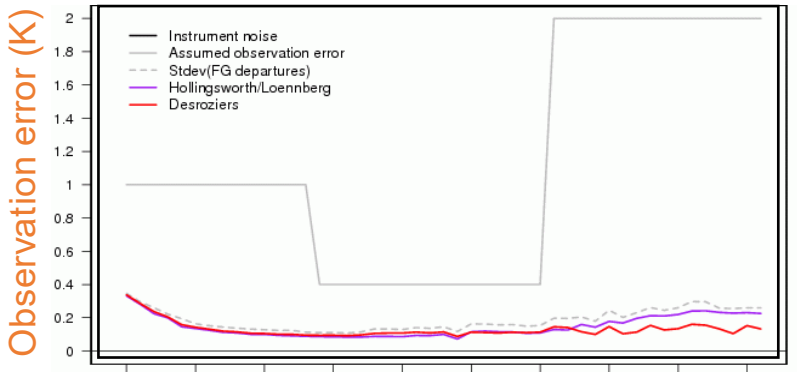


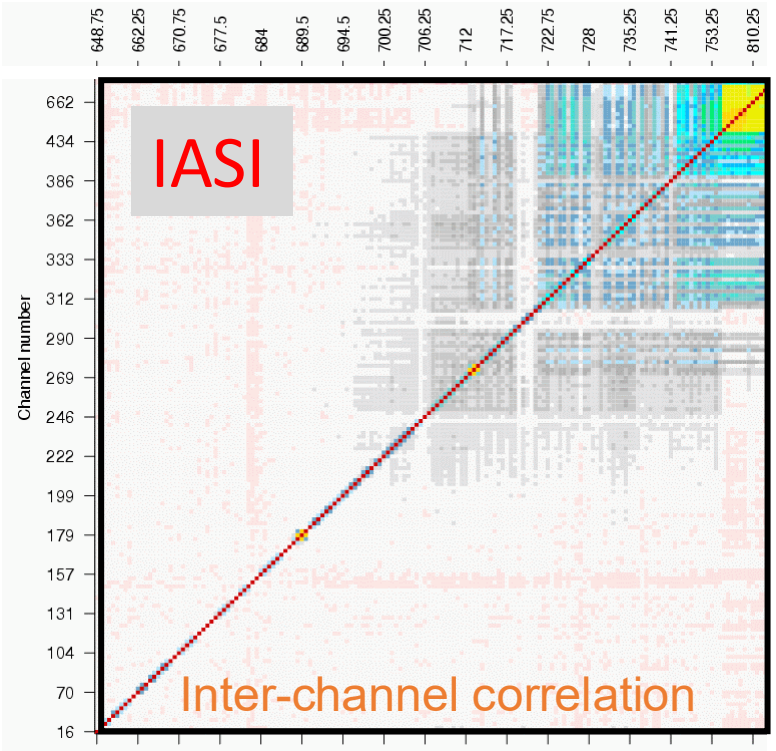
IASI has higher noise compared to CrIS

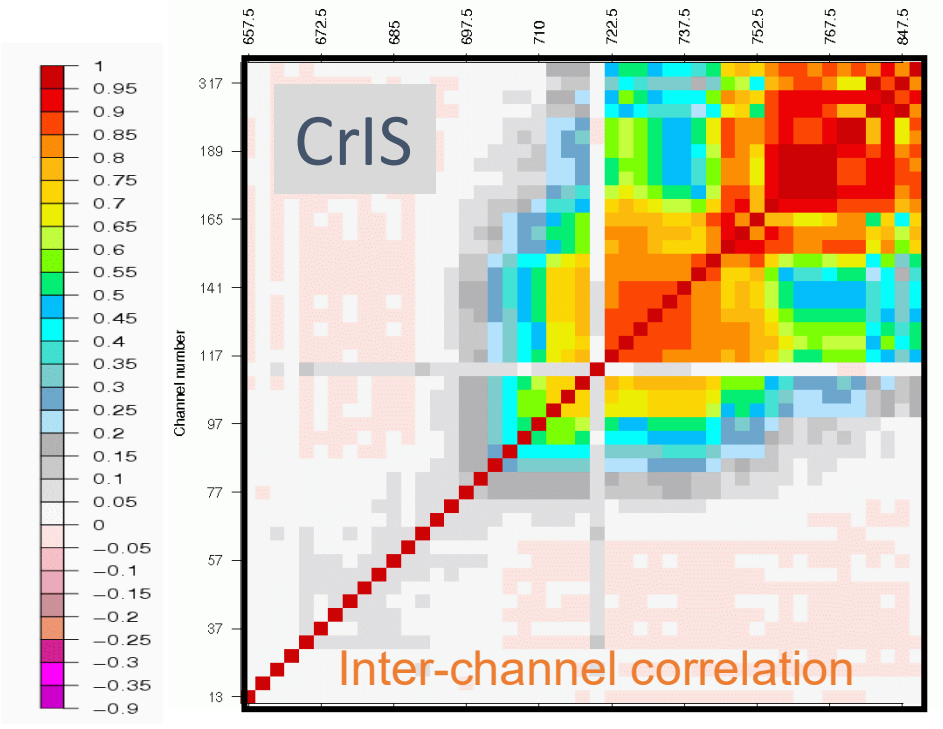


CrIS has stronger inter-channel correlations than IASI







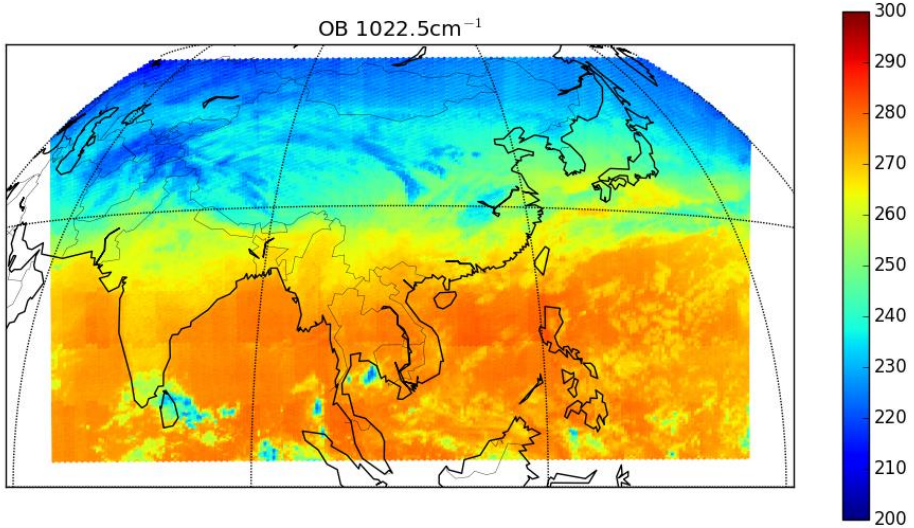


High Spectral Resolution IR sounders on GEO Spacecraft

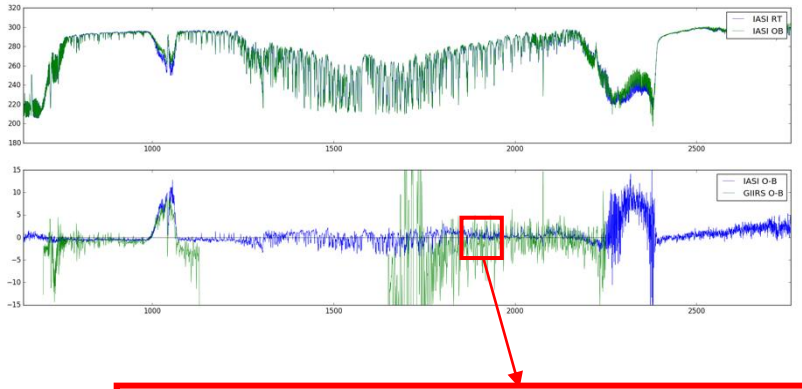
Preparing for MTG-S IRS!

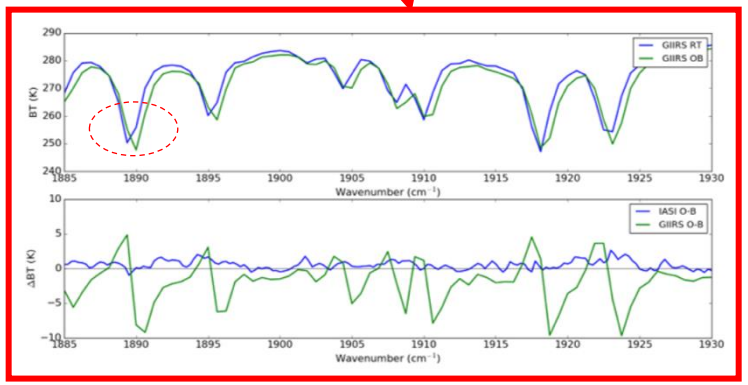
First ever GEO High Spectral Resolution IR sounder

FY- 4A GIIRS radiance observations 20190301



Initial evaluations suggested the GIIRS radiances were significantly more noisy than similar IASI channels





Cross checking with model simulations and IASI suggests much of the noise can be explained (and removed) with a spectral shift

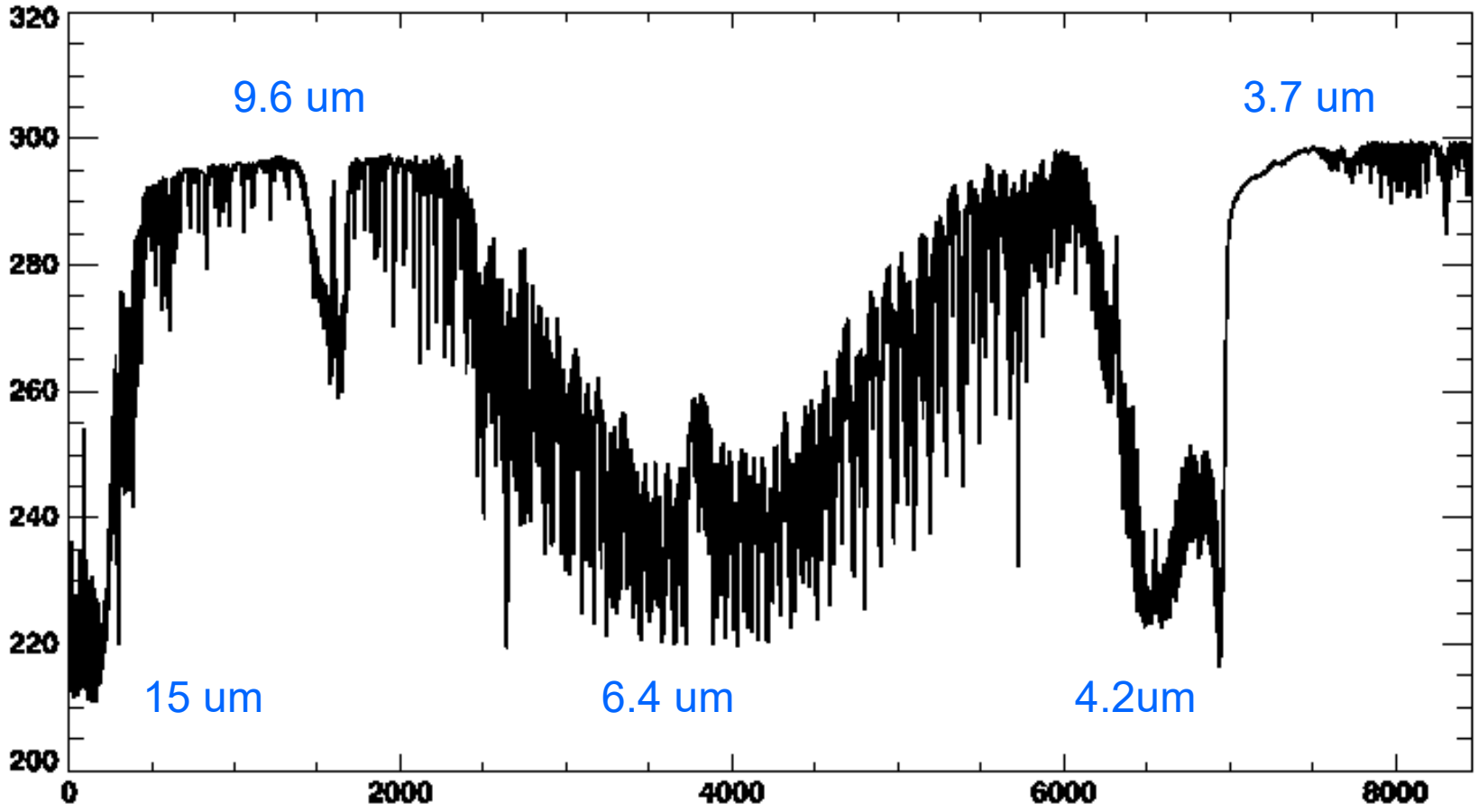
The infrared spectrum

Case study:
The assimilation of IASI

What does IASI measure

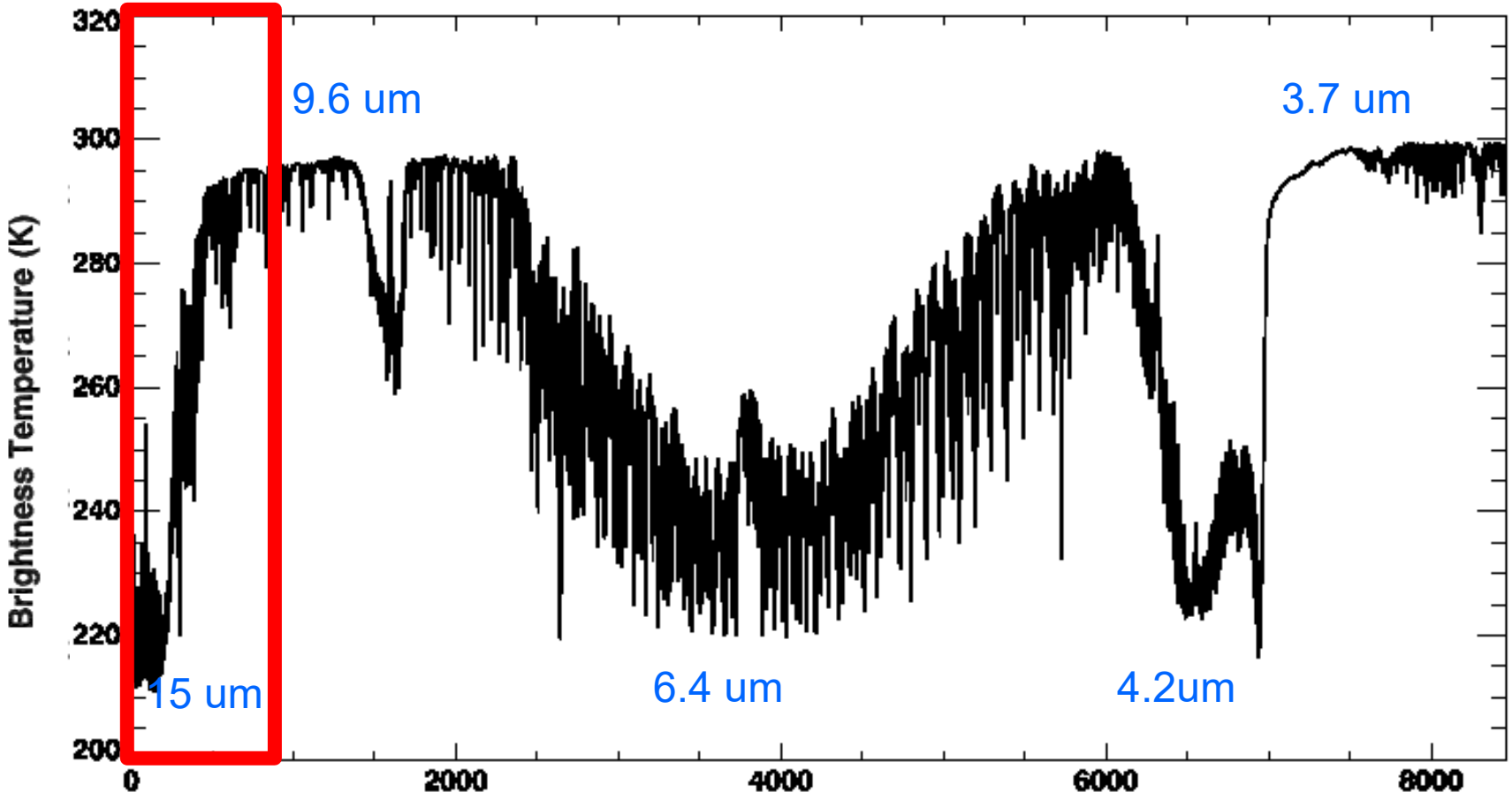
(and what do we assimilate)

The infrared spectrum of atmospheric radiation



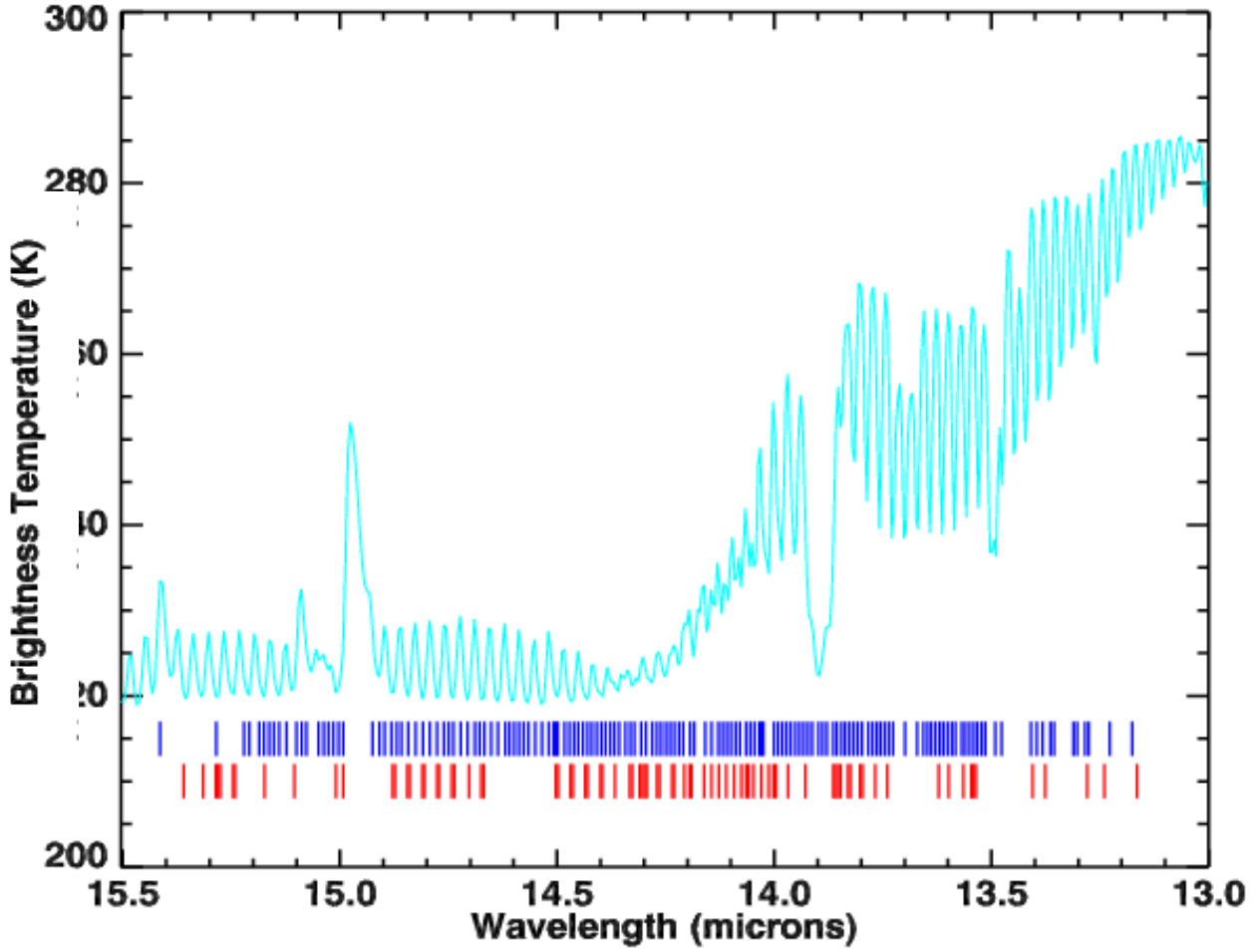
The infrared spectrum of atmospheric radiation

The long-wave temperature sounding band



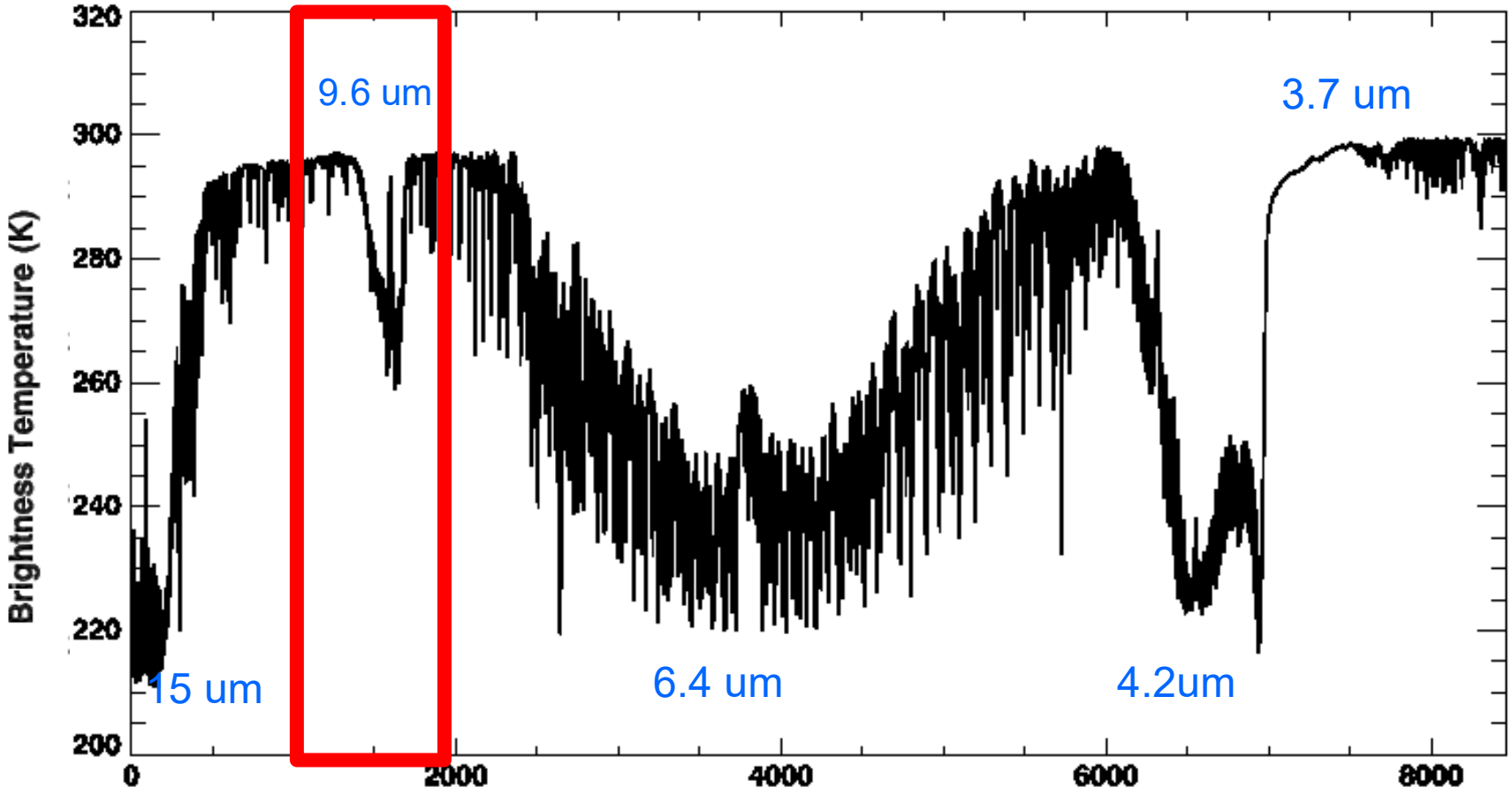
~ 150 channels assimilated

Zoom of long-wave temperature sounding channel usage for IASI



The infrared spectrum of atmospheric radiation

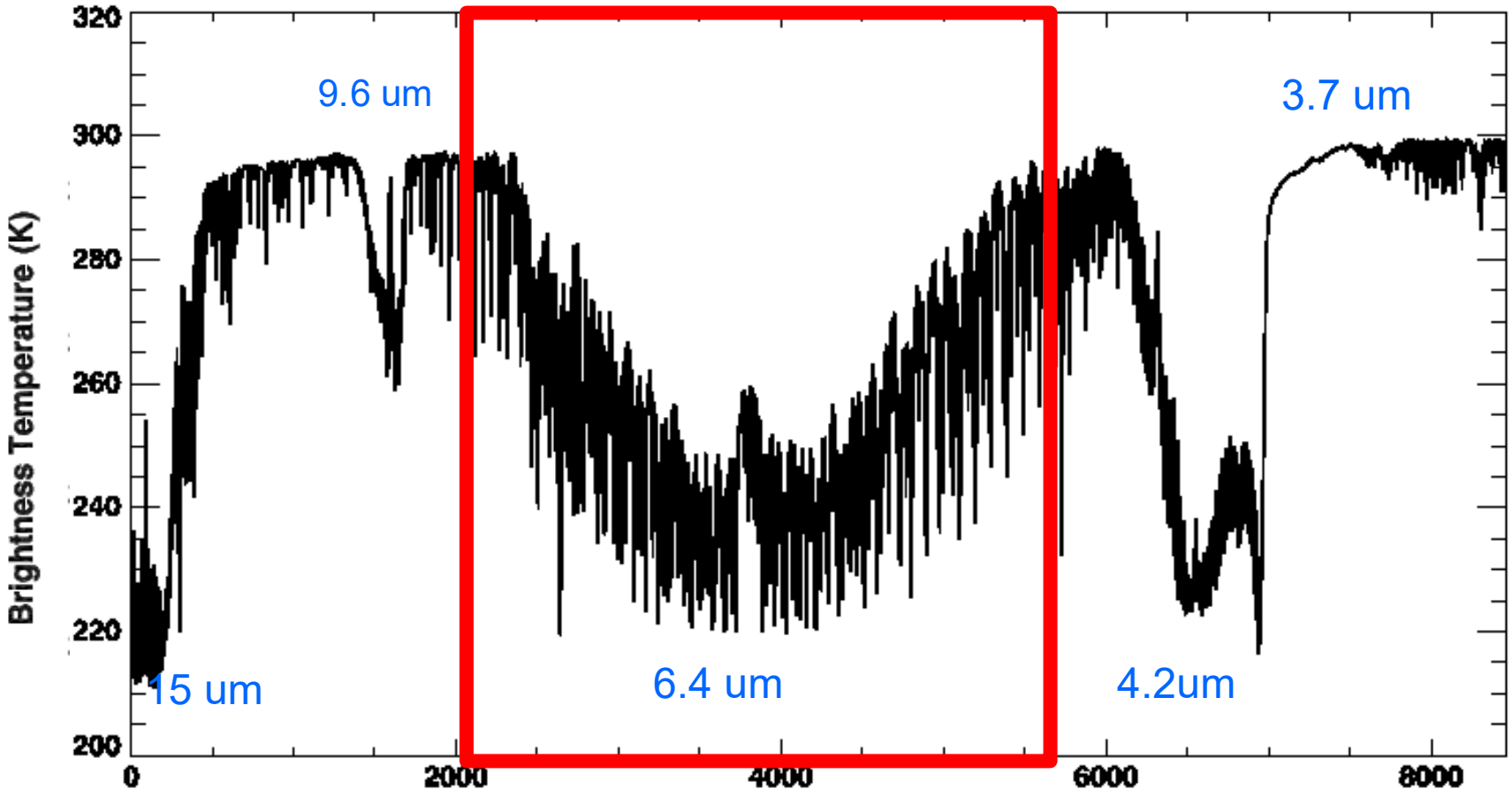
The long-wave ozone sounding band



~ 20 channels assimilated

The infrared spectrum of atmospheric radiation

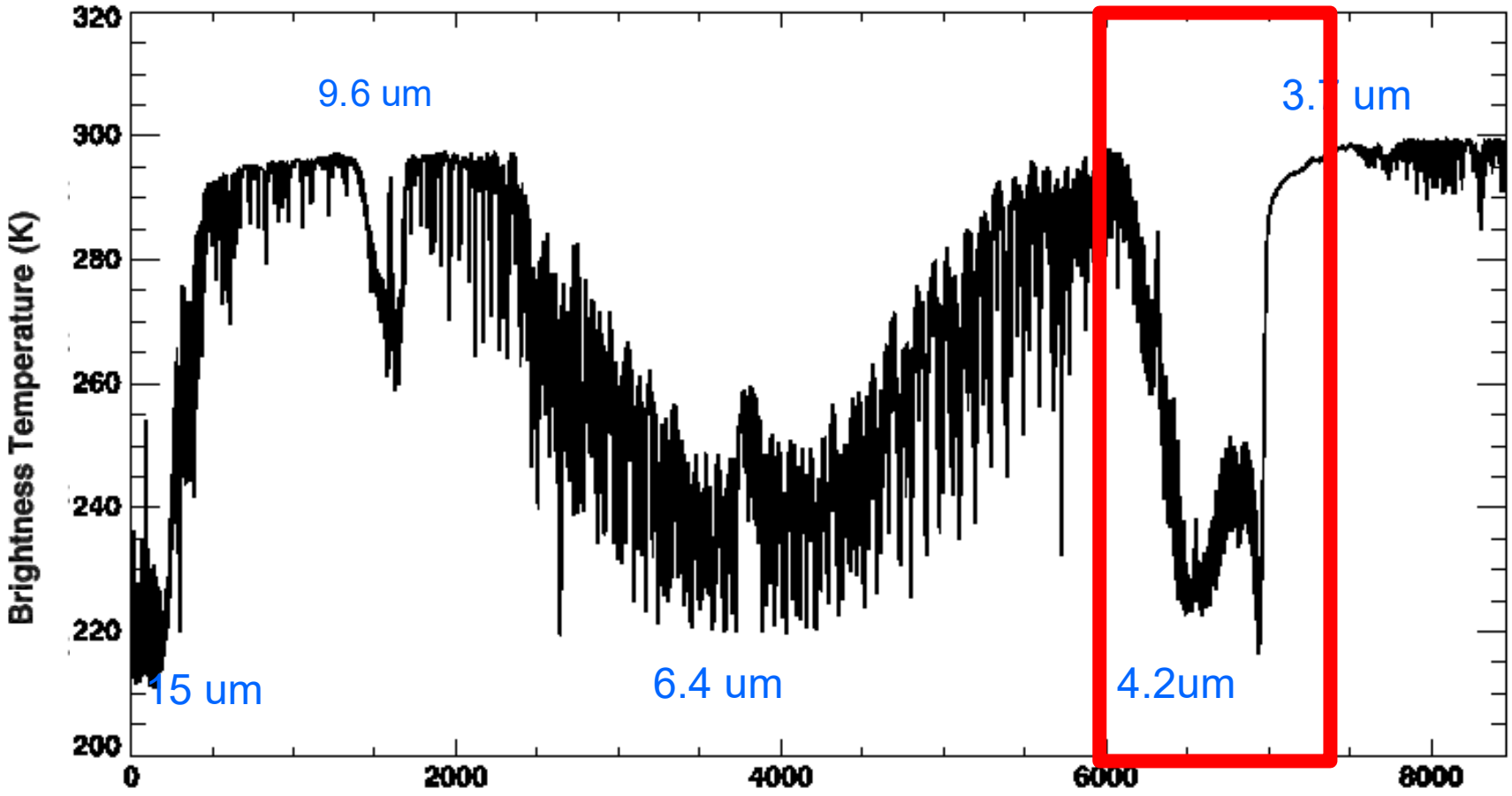
The mid-wave water vapour sounding band



~ 50 channels assimilated

The infrared spectrum of atmospheric radiation

The short-wave temperature sounding band



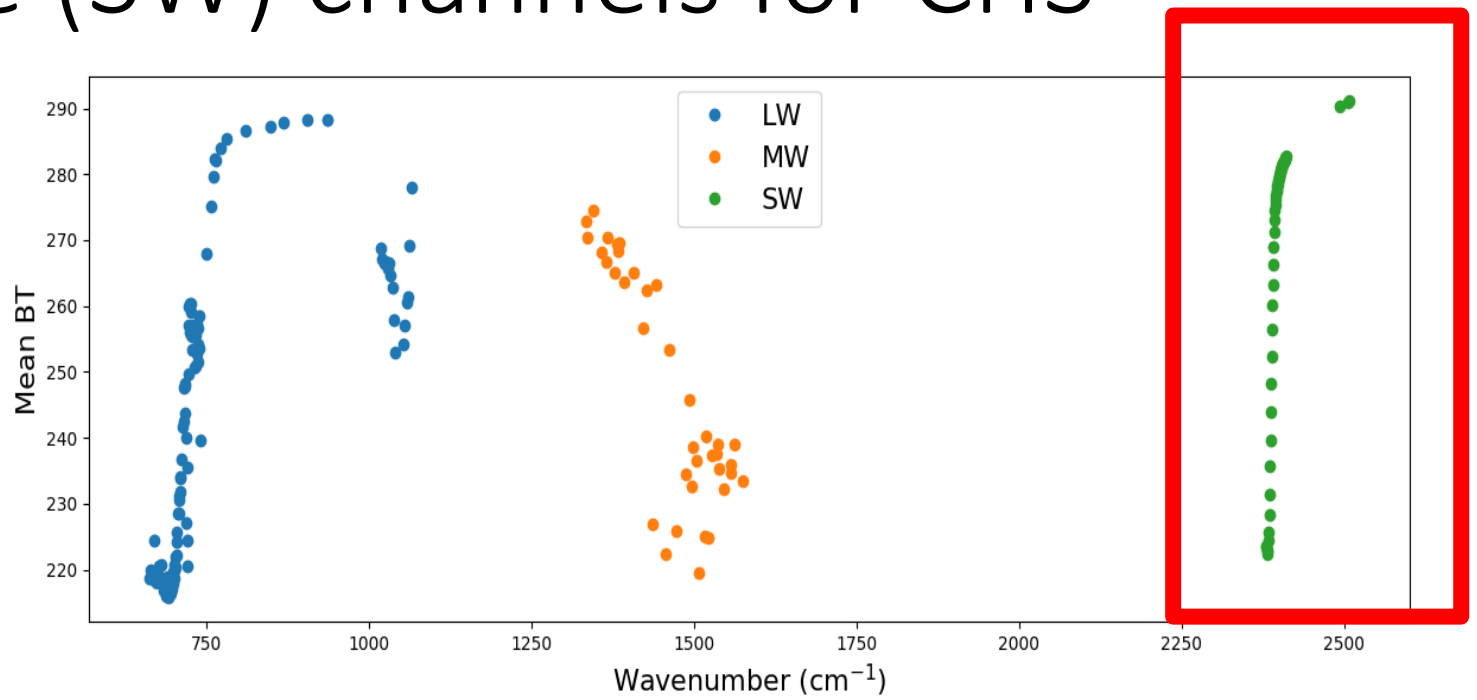
~ 0 channels assimilated – IASI noise high

Aside – short wave (SW) channels for CrIS

Recently, we have made use of the SW channels for CrIS.

This has required:

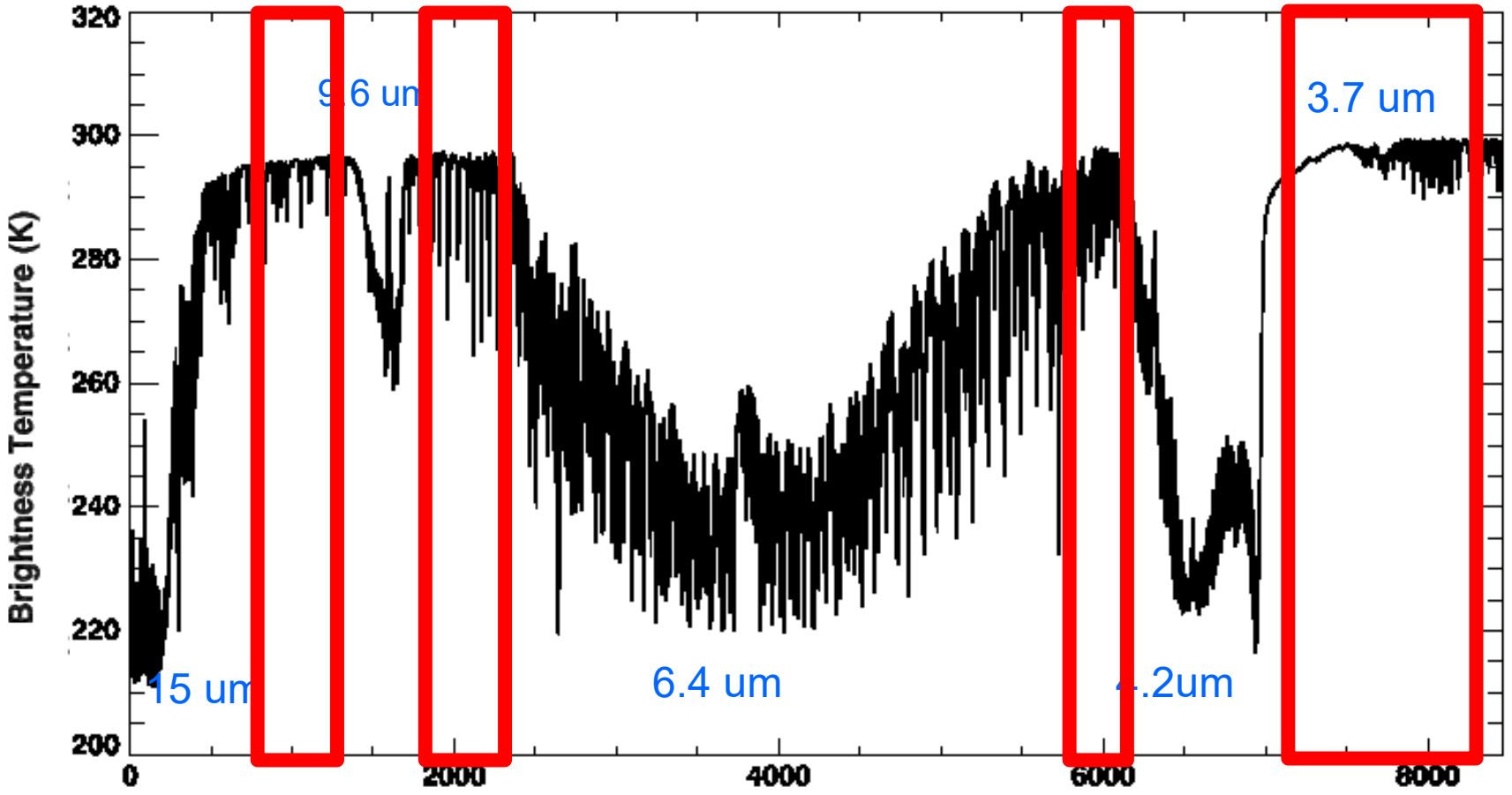
- Non local thermodynamic equilibrium (NLTE) to be accounted for in the radiative transfer.
- Solar term to be included in the RT.
- Scene dependent observation errors.



$$\frac{dB}{dT} = \frac{c_1 c_2 \nu^4 e^{c_2 \nu / T}}{(e^{c_2 \nu / T} - 1)^2}$$

The infrared spectrum of atmospheric radiation

The surface sensing channels (window channels)



channels mostly used for cloud detection

Weighting functions of IASI sounding channels

Atmospheric sounding channels

…selecting channels where there is no contribution from the surface….

$$L(\nu) = \int_0^{\infty} B(\nu, T(z)) \left[\frac{d\tau(\nu)}{dz} \right] dz + \text{Surface emission} + \text{Surface reflection/ scattering} + \text{Cloud/rain contribution} + \ldots$$

IR ATMOSPHERIC TEMPERATURE SOUNDING

If radiation is selected in an atmospheric sounding channel with wavenumber v for which

$$L(\nu) = \int_0^{\infty} B(\nu, T(z)) \left[\frac{d\tau(\nu)}{dz} \right] dz$$

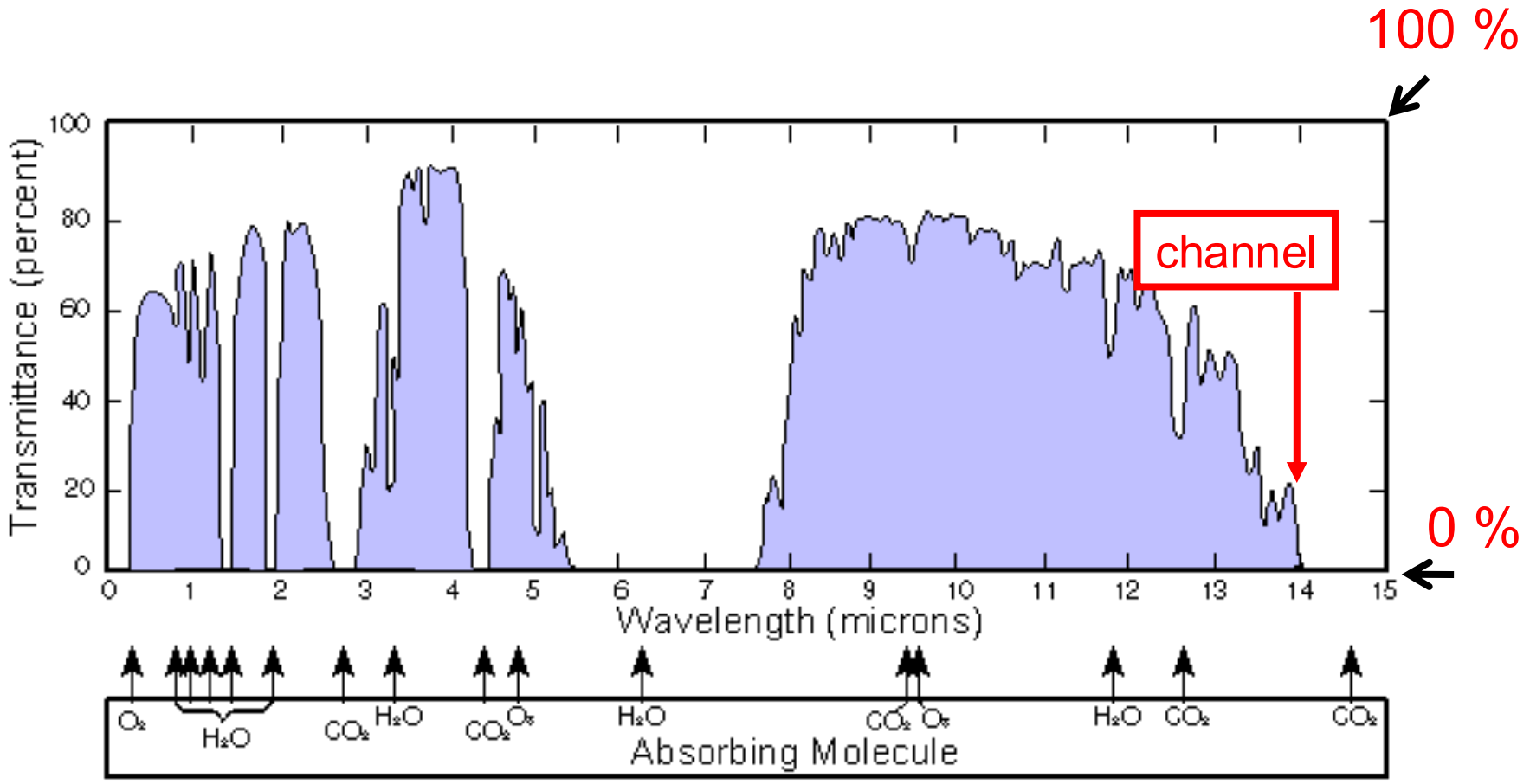
and we define a function $H(z) = \left[\frac{d\tau}{dz} \right]$

When the primary absorber is a well mixed gas (e.g. CO_2) with known concentration it can be seen that the measured radiance is essentially a weighted sum of the atmospheric temperature profile, or

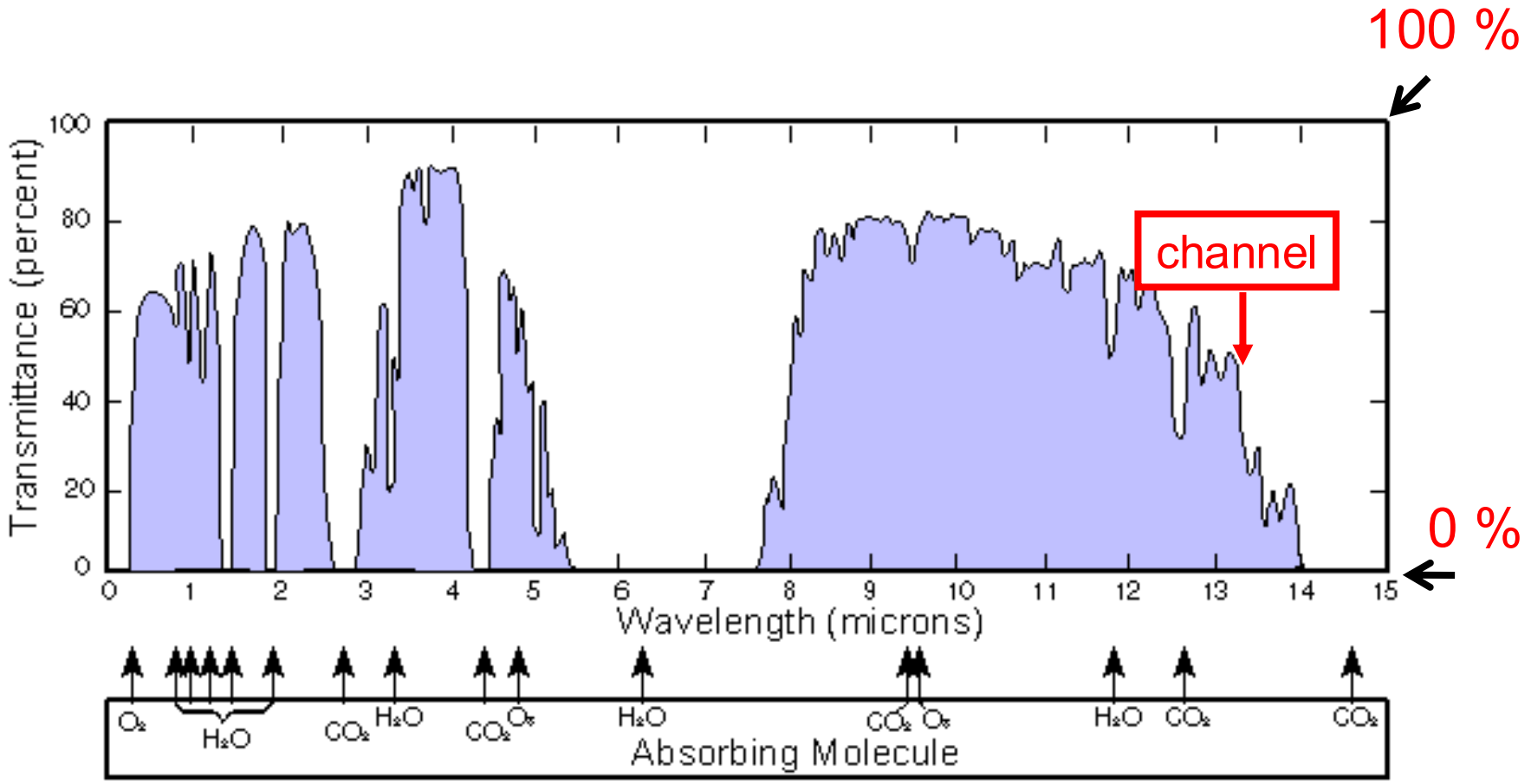
$$L(\nu) = \int_0^{\infty} B(\nu, T(z))\, H(z) dz$$

The function *H(z)* that defines this vertical sum is known as a WEIGHTING FUNCTION

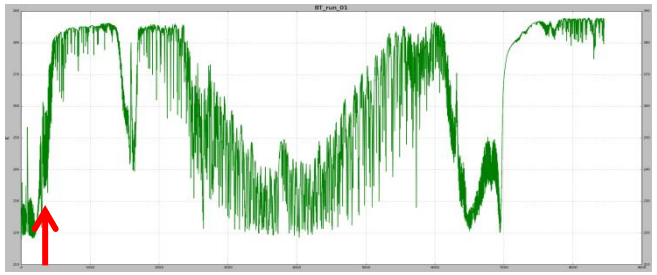
Strong absorbing sounding channels



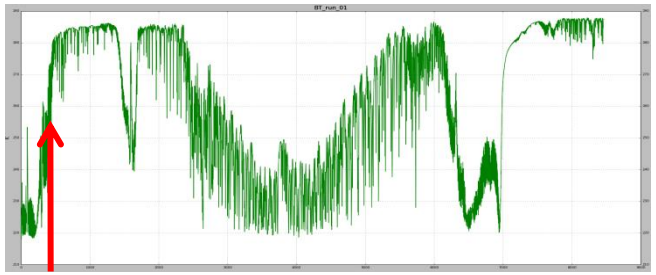
Weaker absorbing sounding channels



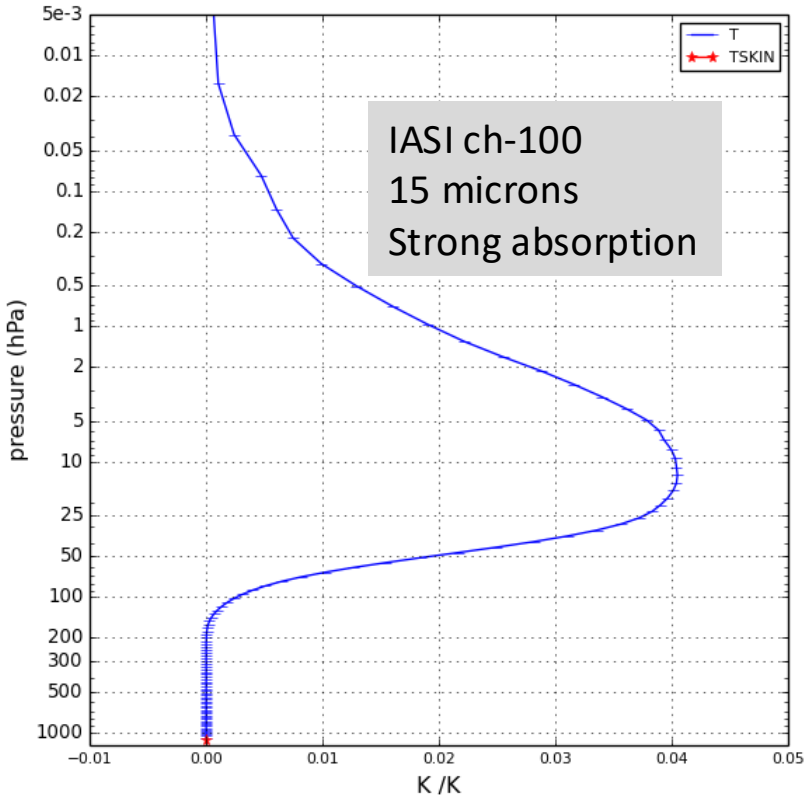
IASI weighting functions for strong and weak absorption channels

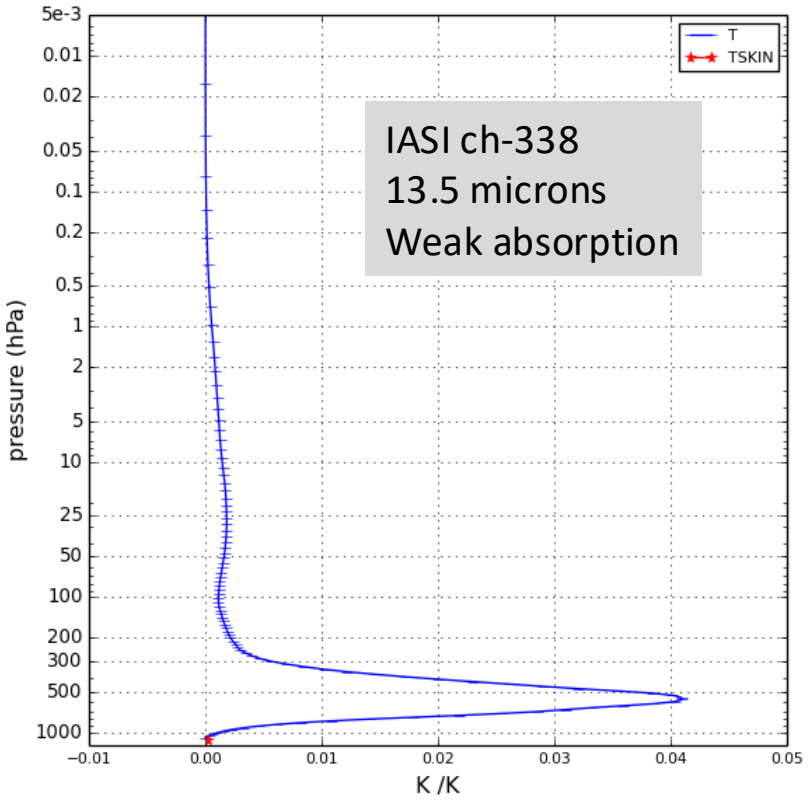


Strong > stratospheric channel



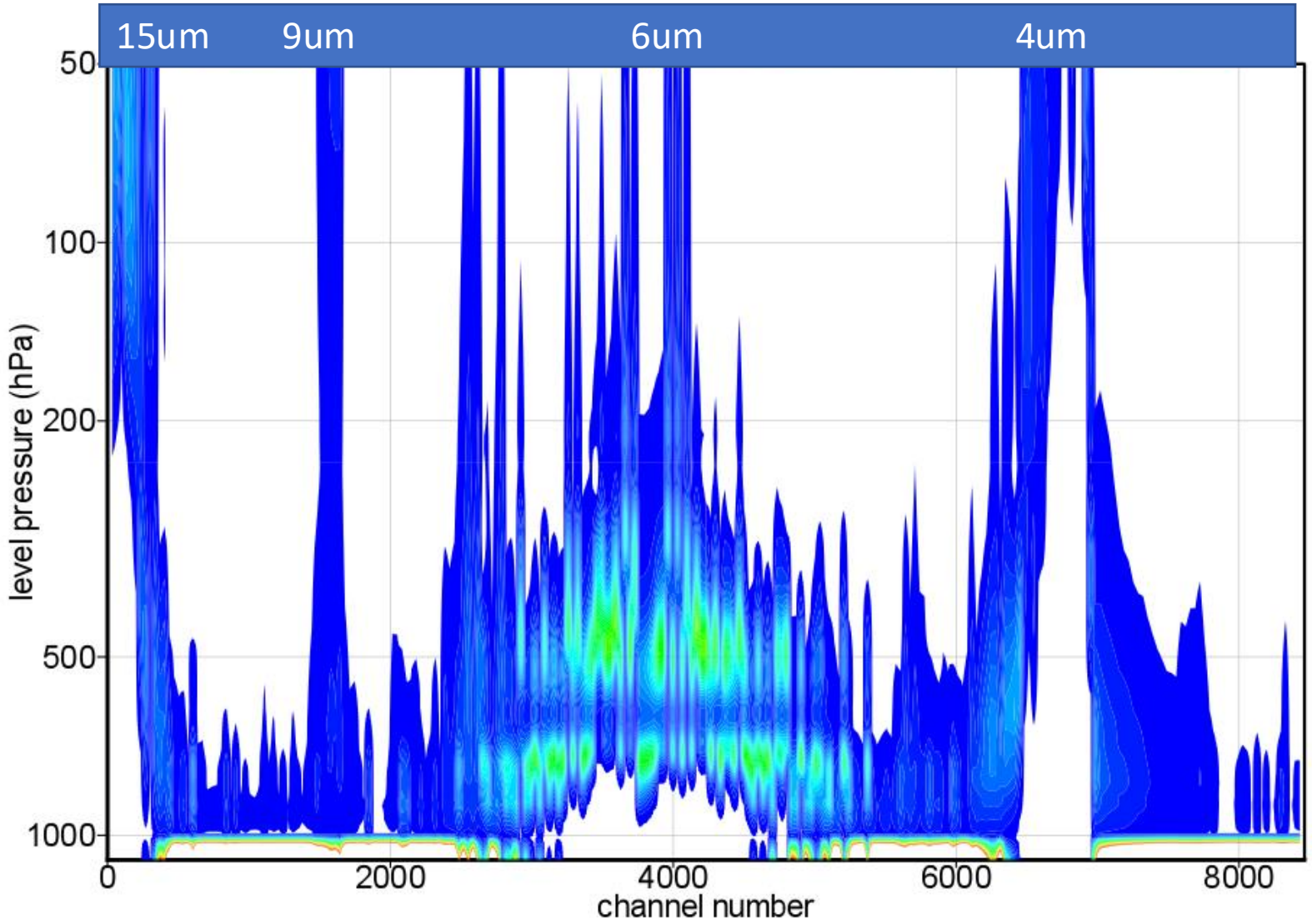
Weak > tropospheric channel





Sampling lines of varying absorption strength IASI provides good vertical coverage of the atmosphere

Peaks altitudes of IASI channel weighting functions



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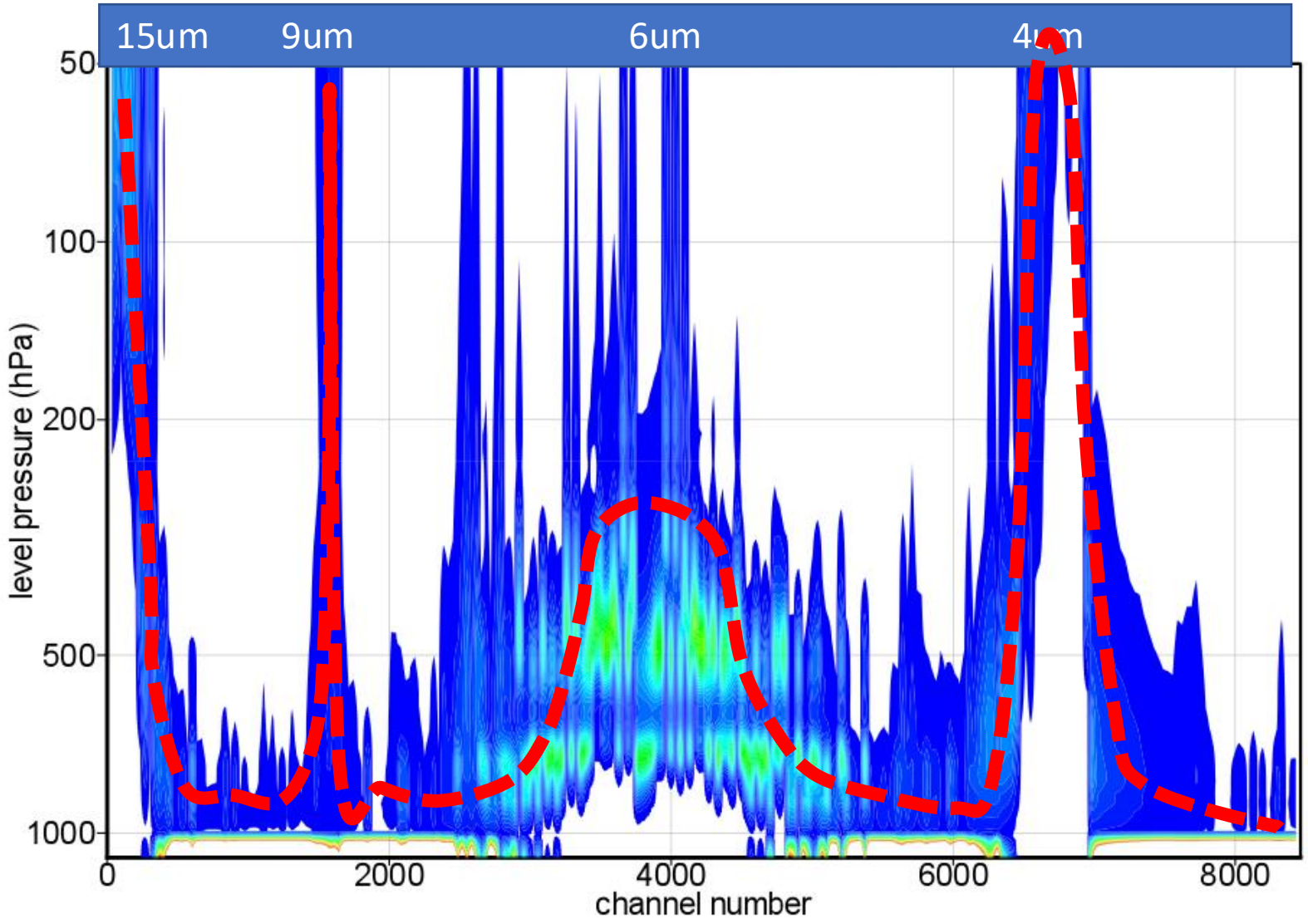


Two challenges to the successful assimilation of infrared radiances:

1) Variable absorbing gases

2) Clouds

Challenge 1:
When the absorbing gas is itself a variable …

When the absorbing gas is itself a variable …

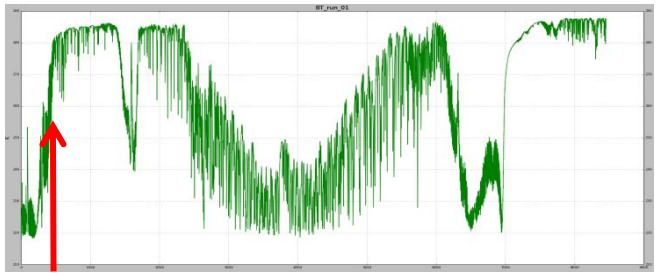
When the primary absorber in a sounding channel is a well mixed gas (e.g. oxygen or carbon dioxide) the radiance essentially gives information about variations in the atmospheric temperature profile only.

$$L(\nu) = \int_0^\infty B(\nu, T(z)) \left[\frac{d\tau(\nu)}{dz} \right] dz$$

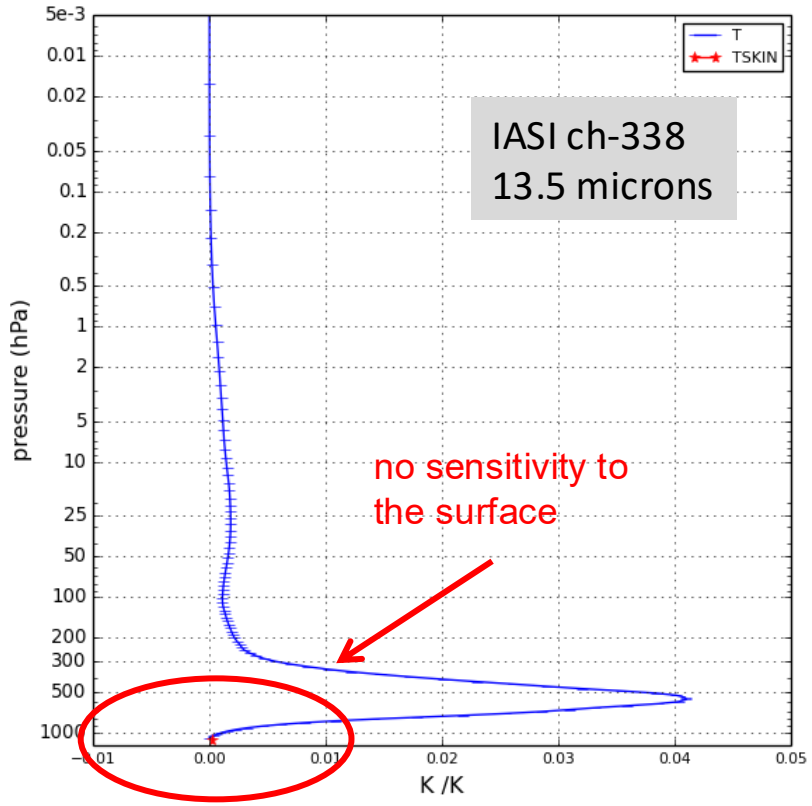
When the primary absorber is not well mixed (e.g. water vapour, ozone) the weighting functions depend on the state of the atmosphere and radiance gives ambiguous information about the temperature profile and the absorber distribution. This ambiguity must be resolved by :

- differential channel sensitivity
- synergistic use of well mixed channels (constraining the temperature)
- the background error covariance (+ physical constraints)

Temperature Channels sensitive to water vapour



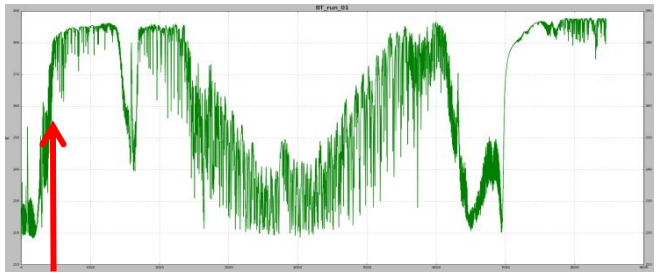
Tropospheric channel



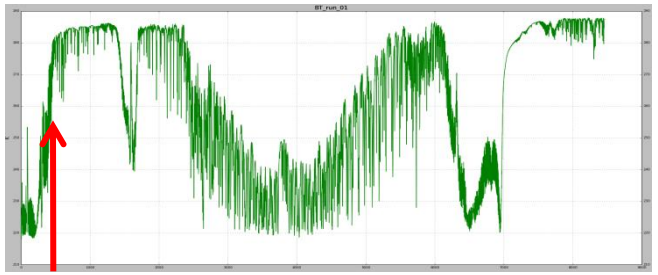
This is in a **moist** atmosphere...

What happens in a very **dry** atmosphere ?

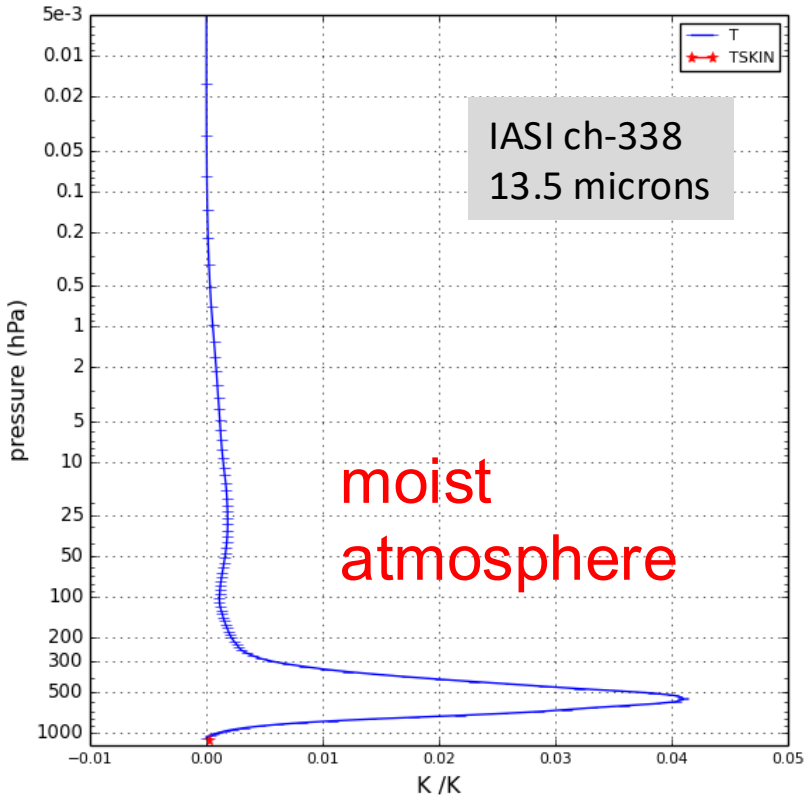
Temperature Channels sensitive to water vapour

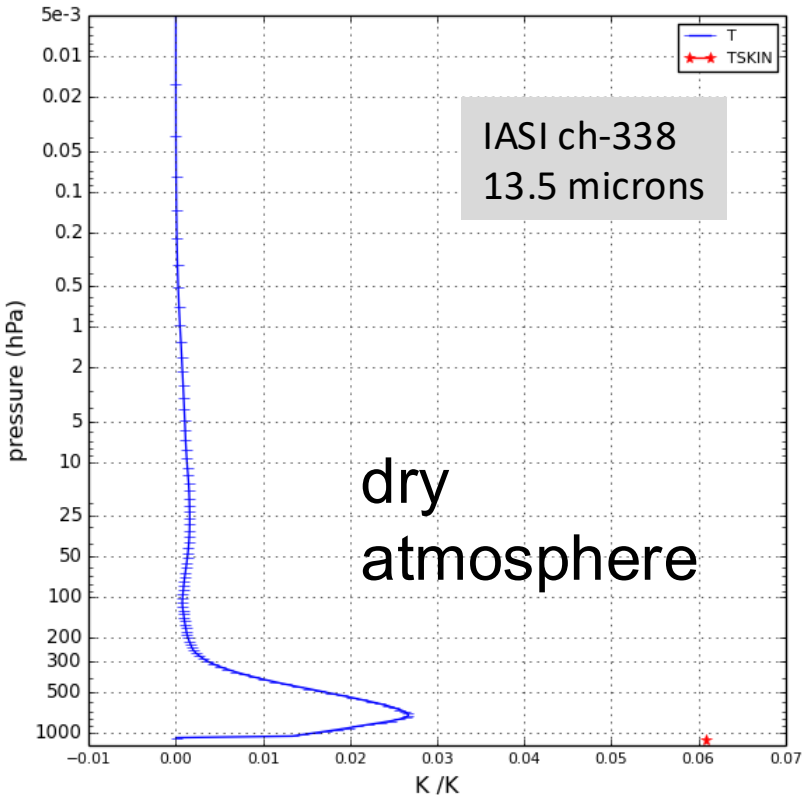


Tropospheric channel

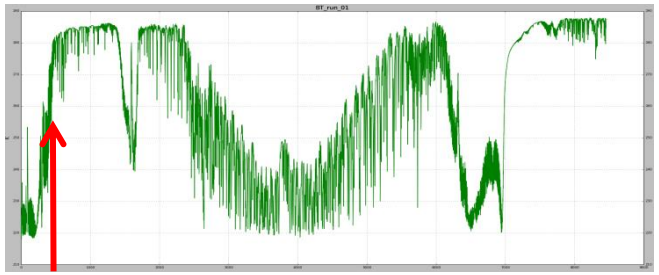


Tropospheric channel

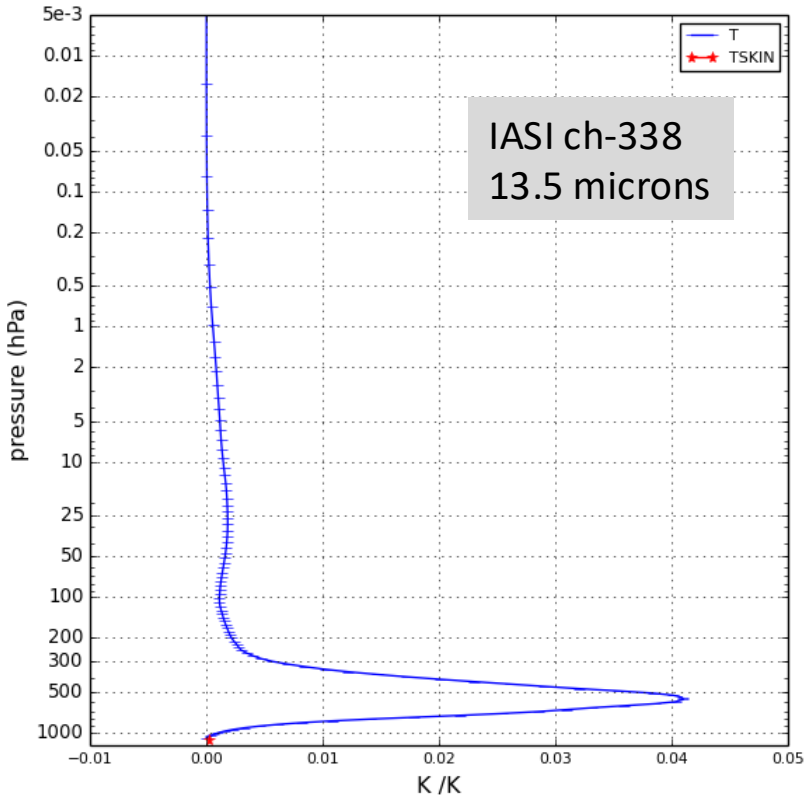


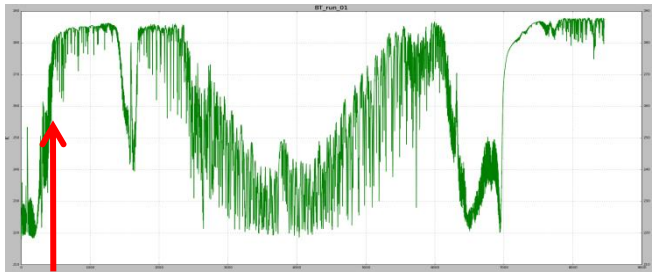


Temperature Channels sensitive to water vapour

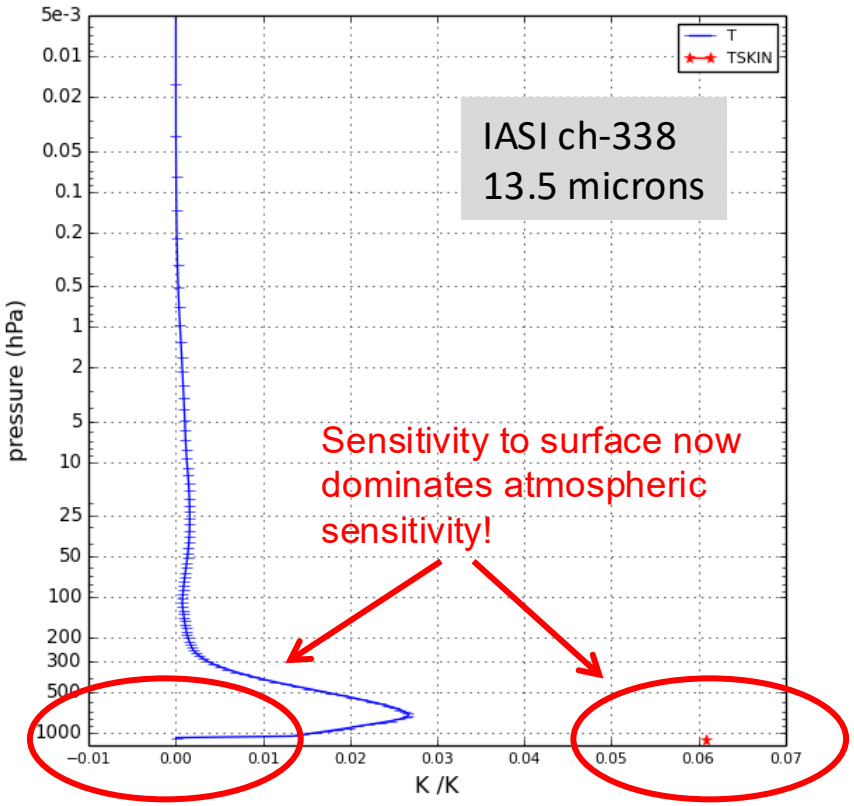


Tropospheric channel



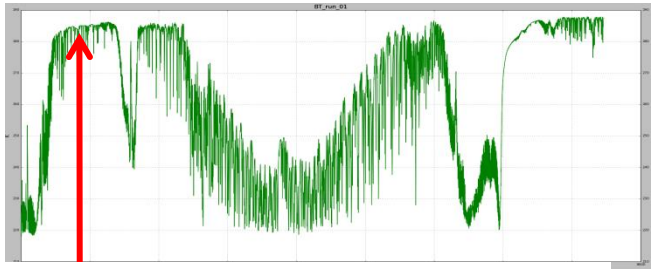


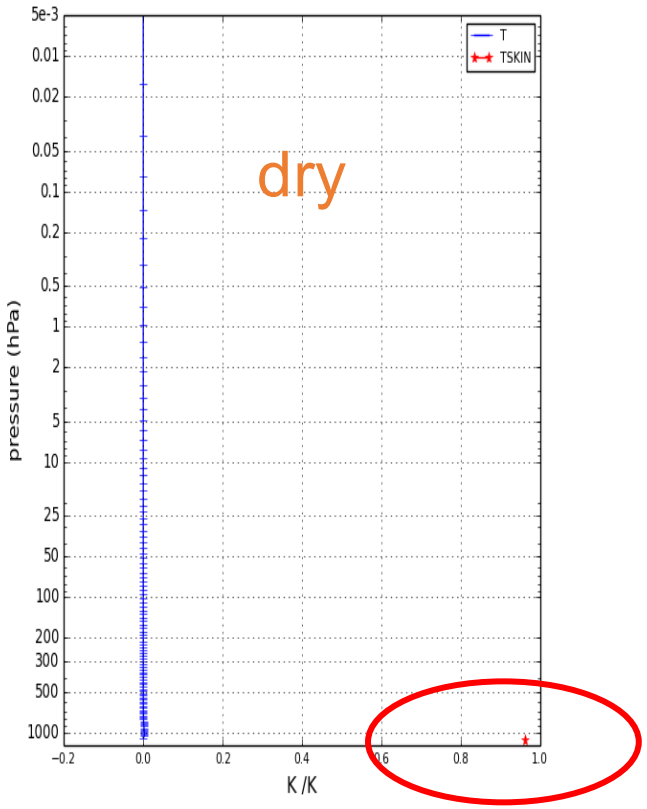
Tropospheric channel

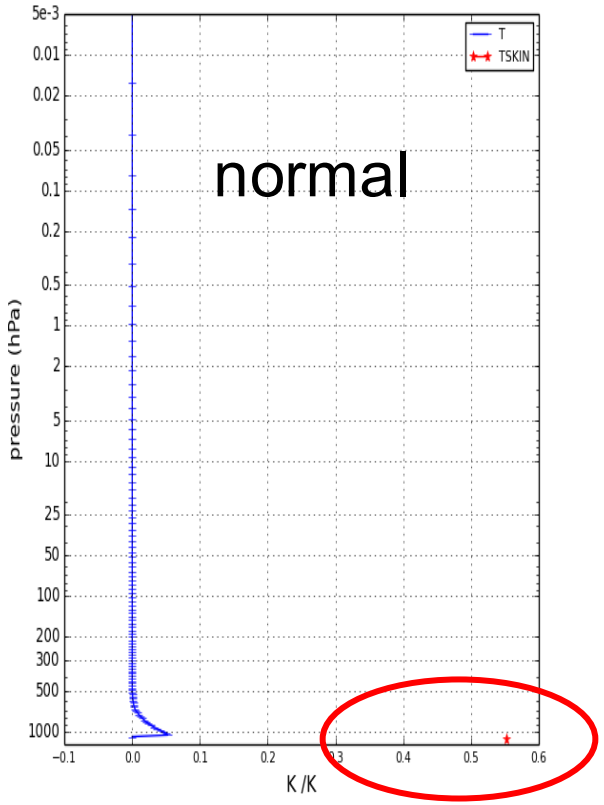


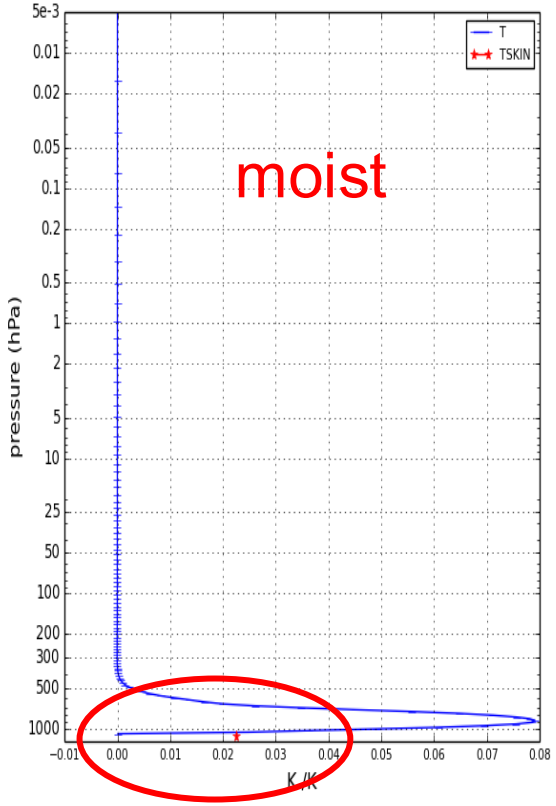
Window Channels sensitive to water vapour

IASI ch-1200
10.5 microns



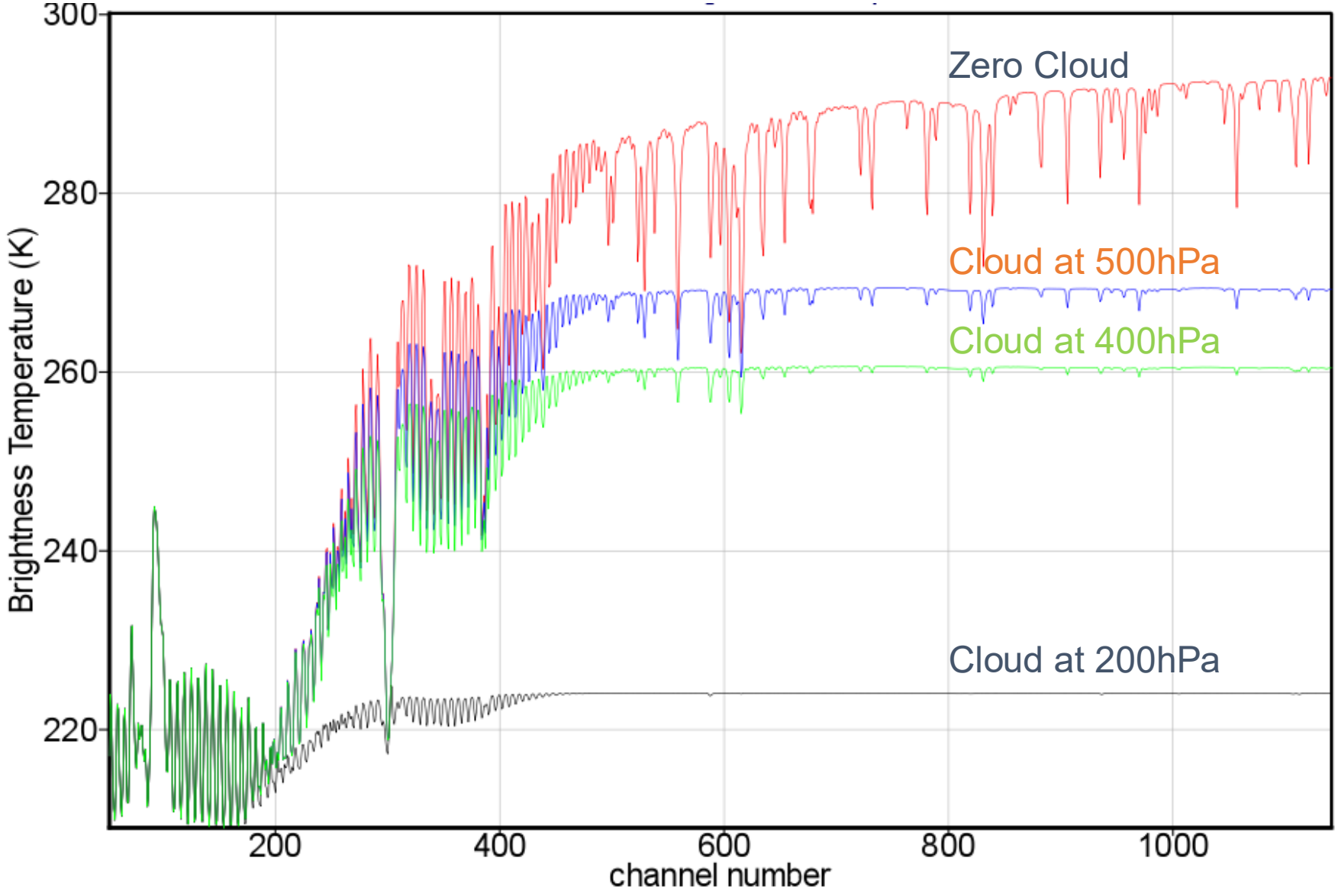




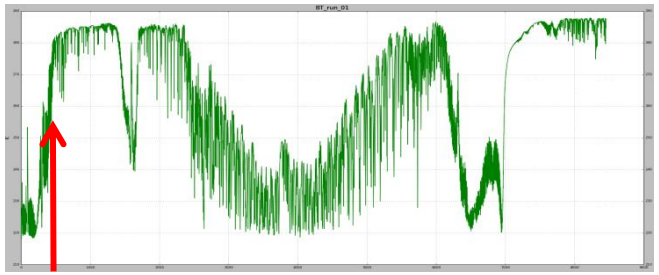


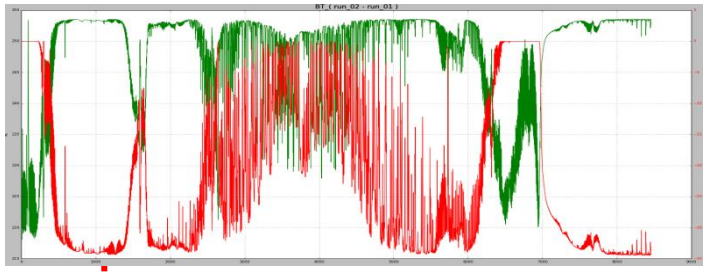
Challenge 2:
Clouds…

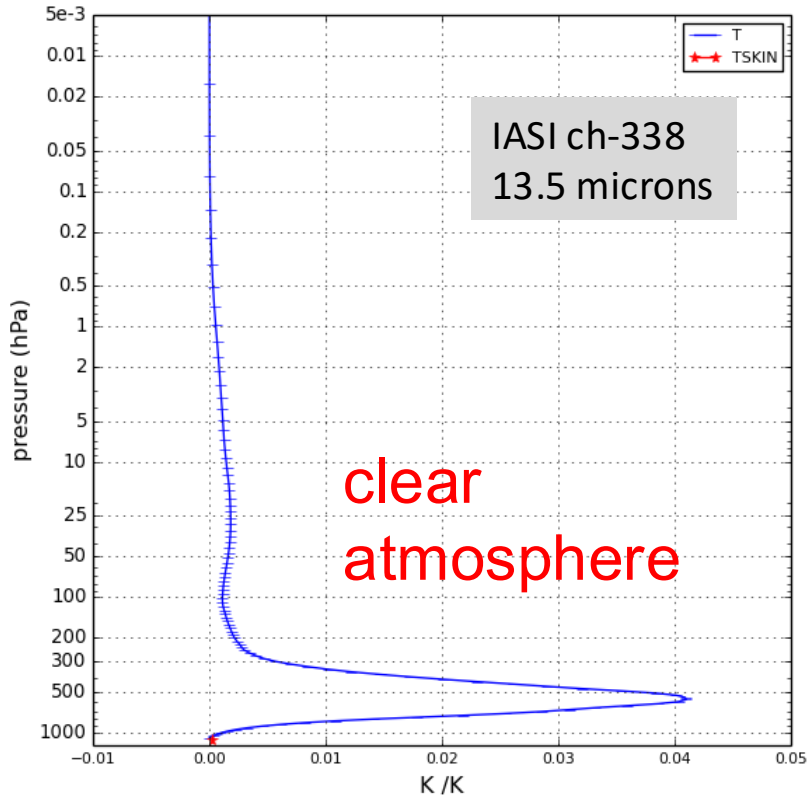
Temperature Channels sensitive to clouds

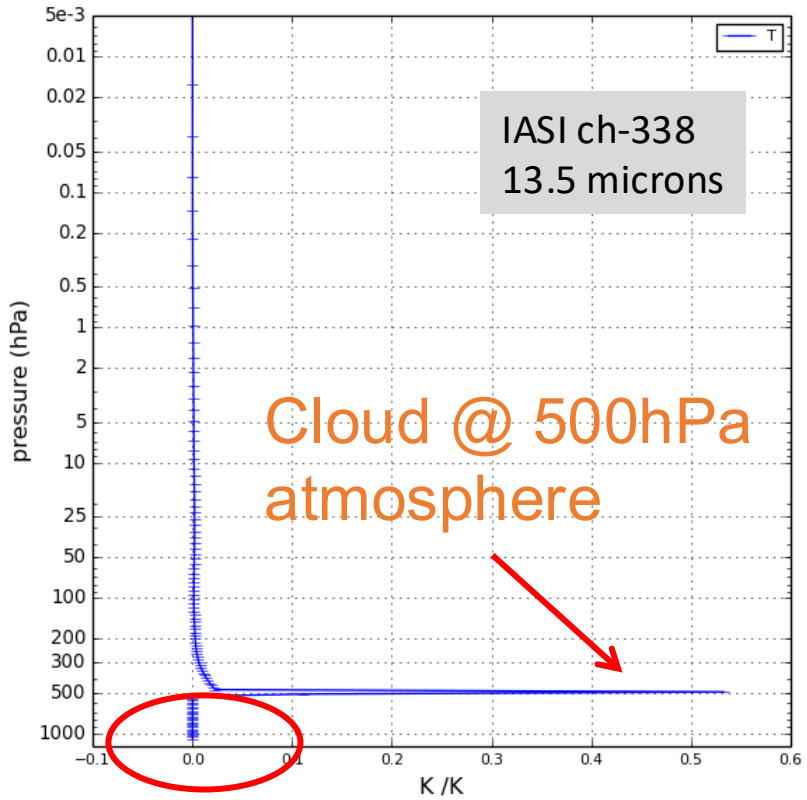


Temperature Channels sensitive to clouds









Challenge 2:
Clouds…

Dedicated lecture on clouds in IR next…..

Summary

We now have excellent high quality (and **high spectral resolution**) measurements of atmospheric infrared radiation.

Instruments such as IASI provide good vertical coverage of the atmosphere by sampling absorption of variable strength. Higher **vertical resolution** is achieved due to the **high number of channels**.

Channels in the **lower troposphere** are also sensitive to the **surface** (and clouds).

Channels affected by absorption by **variable species** (e.g. humidity) provide different information in different atmospheres.

Questions ?