# Radiative transfer modeling in the far-infrared with emphasis on the estimation of $H_2O$ continuum absorption coefficients

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# Outline

- ***Consistency***
  - Using data from ECOWAR-COBRA campaign (March 2007)
    - I-BEST
    - REFIR-PAD
      - LBLRTM 11.3
      - LBLRTM 11.3+ECOWAR
      - LBLRTM 12.0
- ***Closure experiment***
  - σ-IASI updates
  - Results
- ***Conclusions***

# ECOWAR/COBRA

**ECOWAR: Earth COoling by WAter vapour Radiation**

**COBRA: Campagna di Osservazioni della Banda Rotazionale del vapor d'Acqua**

**A research contribution to spectrally resolved observations of the Earth emission spectrum in the water vapour rotational band (17-50 μm) to test models of atmospheric radiative transfer.**

***(Italian Ministry of University and Research, DM n. 287 23 feb. 2005, project # 2005025202)***


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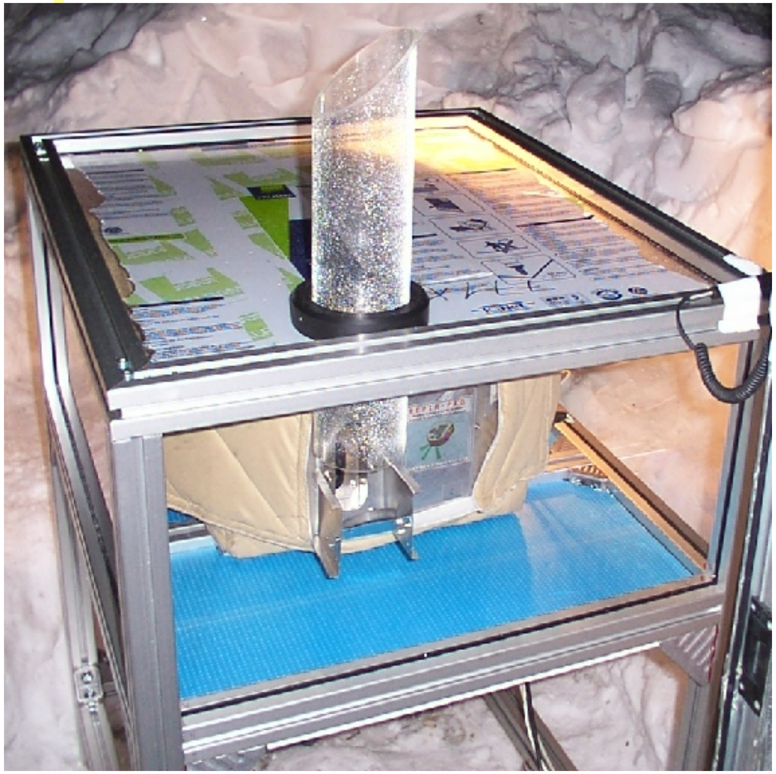
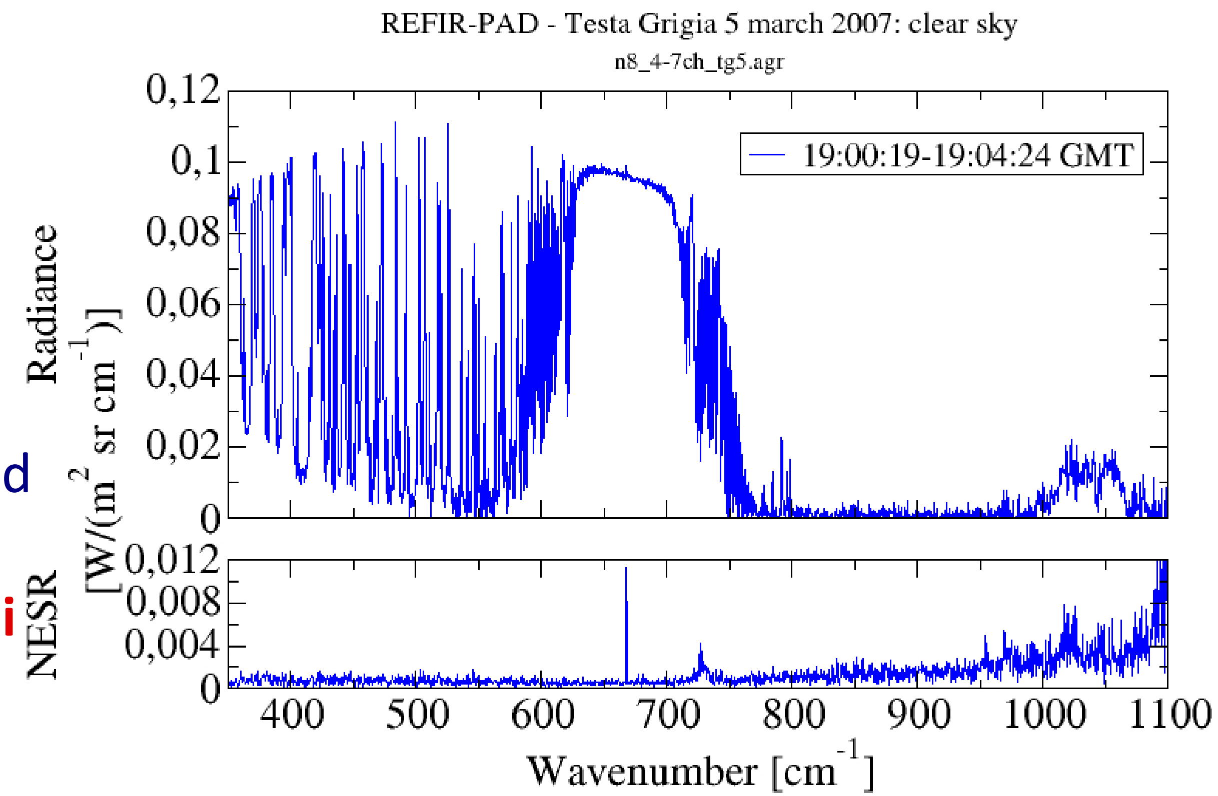
- The key instruments
  - REFIR and I-BEST, FTS instruments developed in our laboratories in order to sense properly the Far Infrared portion of atmospheric radiance
  - 10-100 **μm with a sampling rate finer than 0.5 cm$^{-1}$**

# REFIR (Radiation Explorer in the Far InfraRed)



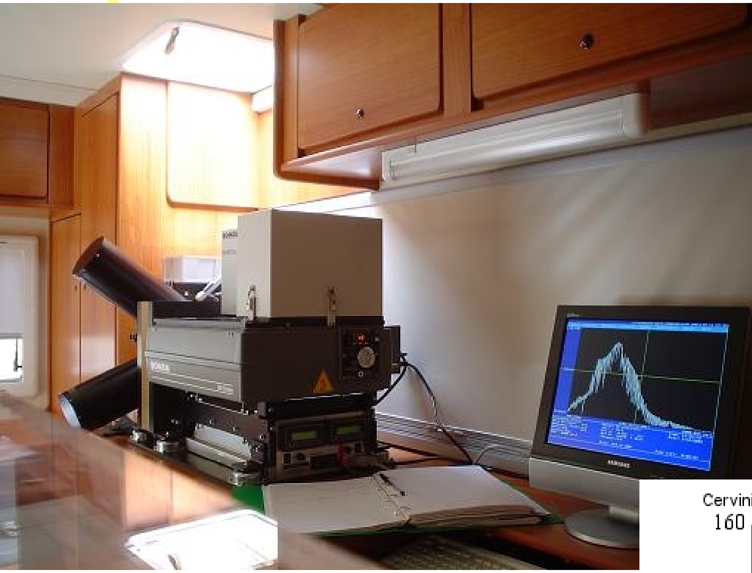
REFIR/PAD developed at IFAC/CNR in Florence

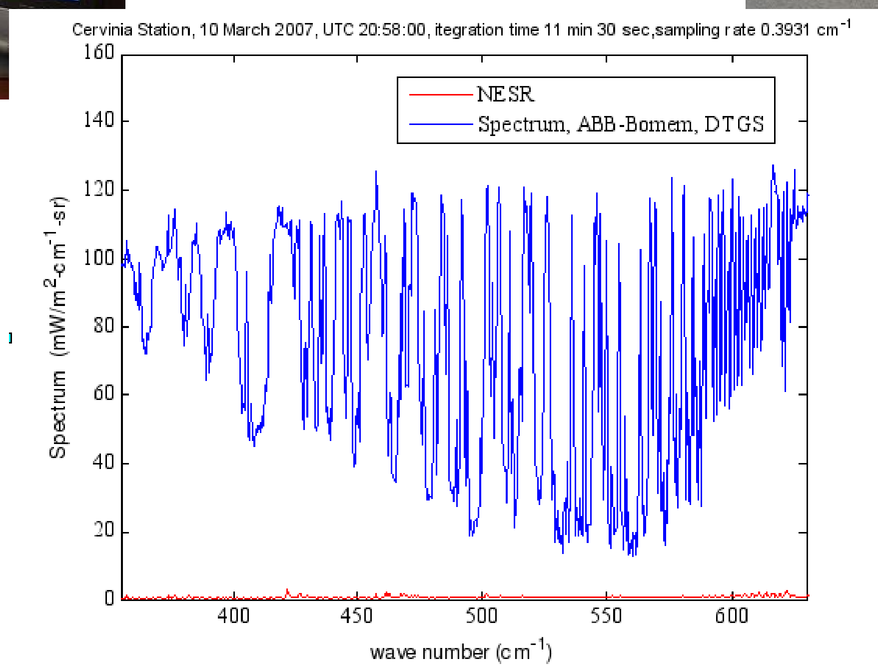


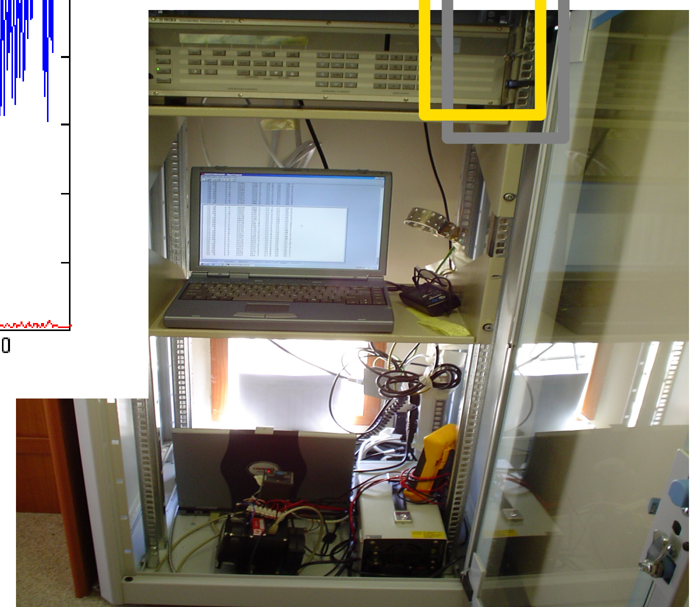

- REFIR-PAD clear sky spectrum and related NESR
- **Details in Palchetti and Bianchini presentations.**

# I-BEST

## Interferometer for Basic observation of Emitted Spectral Radiance of the Troposphere





**I-BEST FTS**

**ABB-BOMEM MR104**

Spectral Range 5-40 µm,
Sampling rate 0.393 $cm^{-1}$

Detectors:

- Uncooled Pyroelectric
- Cooled MCT

Operated at Difa/Unibas Laboratory since 2001

***More details in***

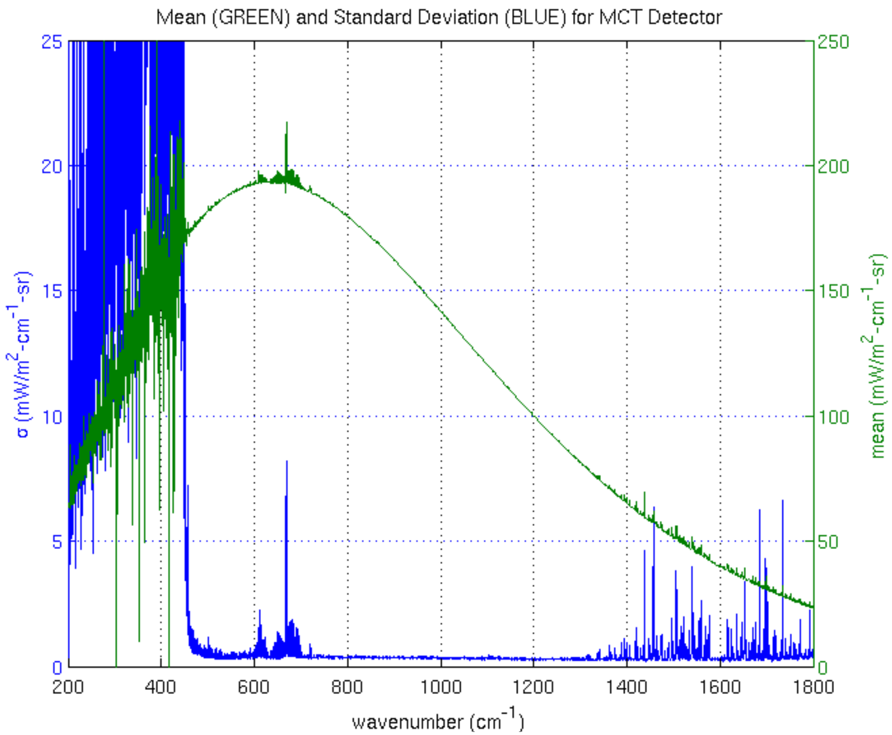
Serio C., et al. Appl. Opt., 2008

doi:10.1364/AO.47.003909

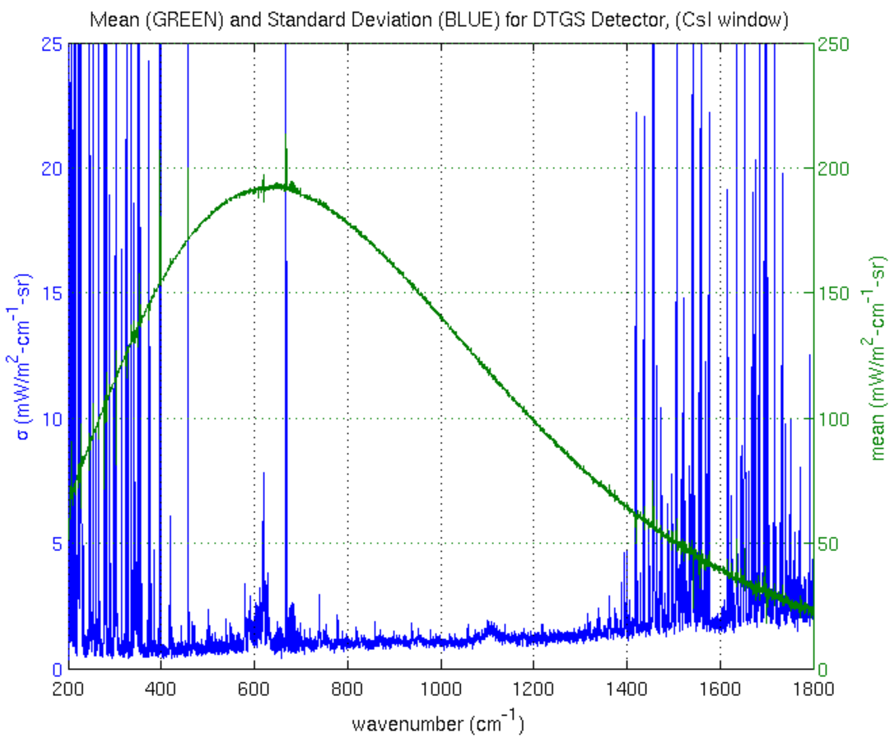
**VAISALA RS-92K**

Radio-sounding Unit

# I-BEST Radiometric Noise




- Detector MCT




- Detector DTGS
  - HBB T= 50°C,
  - Meas. time 2'18''
  - 60 Spectra
  - sigma scale is 10 time smaller than mean scale

# Methodology

***Spectral radiance*** ***Forward model***

$$\mathbf{r} = F(\mathbf{s};\mathbf{v})$$

***spectral parameters*** ***atmospheric state vector T,W***

**$H_2O$ Foreign Continuum** coefficients vector c is part of the set of spectroscopic parameters.

After Taylor expansion with respect to a initial guess (denoted with 0 pedix)

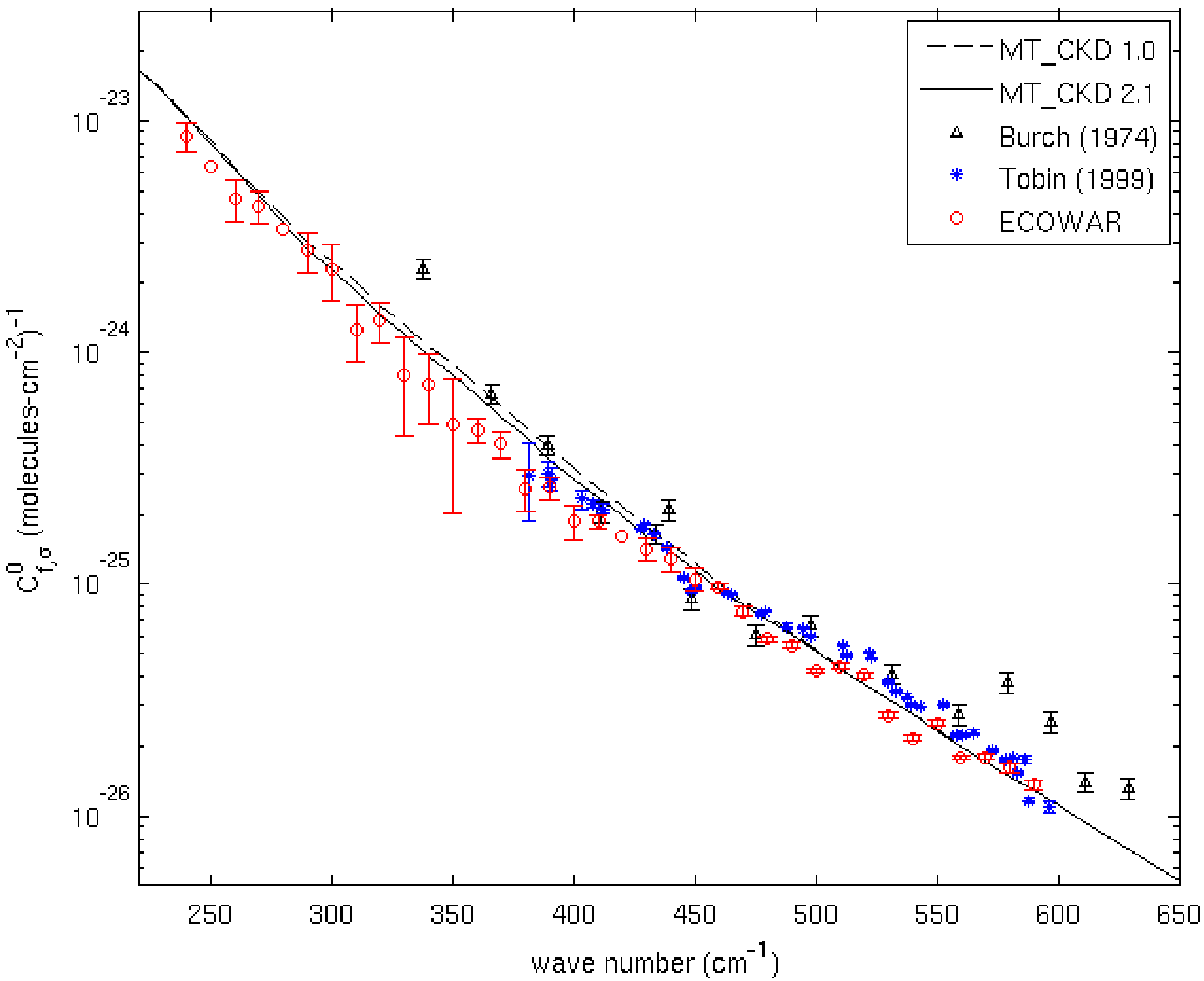
***continuum coeff. Jacobian*** ***T and W Jacobians***

$$\mathbf{r} = \mathbf{r}_0 + \mathbf{K}_c(\mathbf{c} - \mathbf{c}_0) + \mathbf{K}_T(\mathbf{T} - \mathbf{T}_0) + \mathbf{K}_q(\mathbf{q} - \mathbf{q}_0) + \text{higher order terms}$$

$$\mathbf{K}_c = \left( \frac{\partial F}{\partial c_1(\sigma_i)}, \cdots, \frac{\partial F}{\partial c_L(\sigma_i)} \right)$$

Inverted using least square method

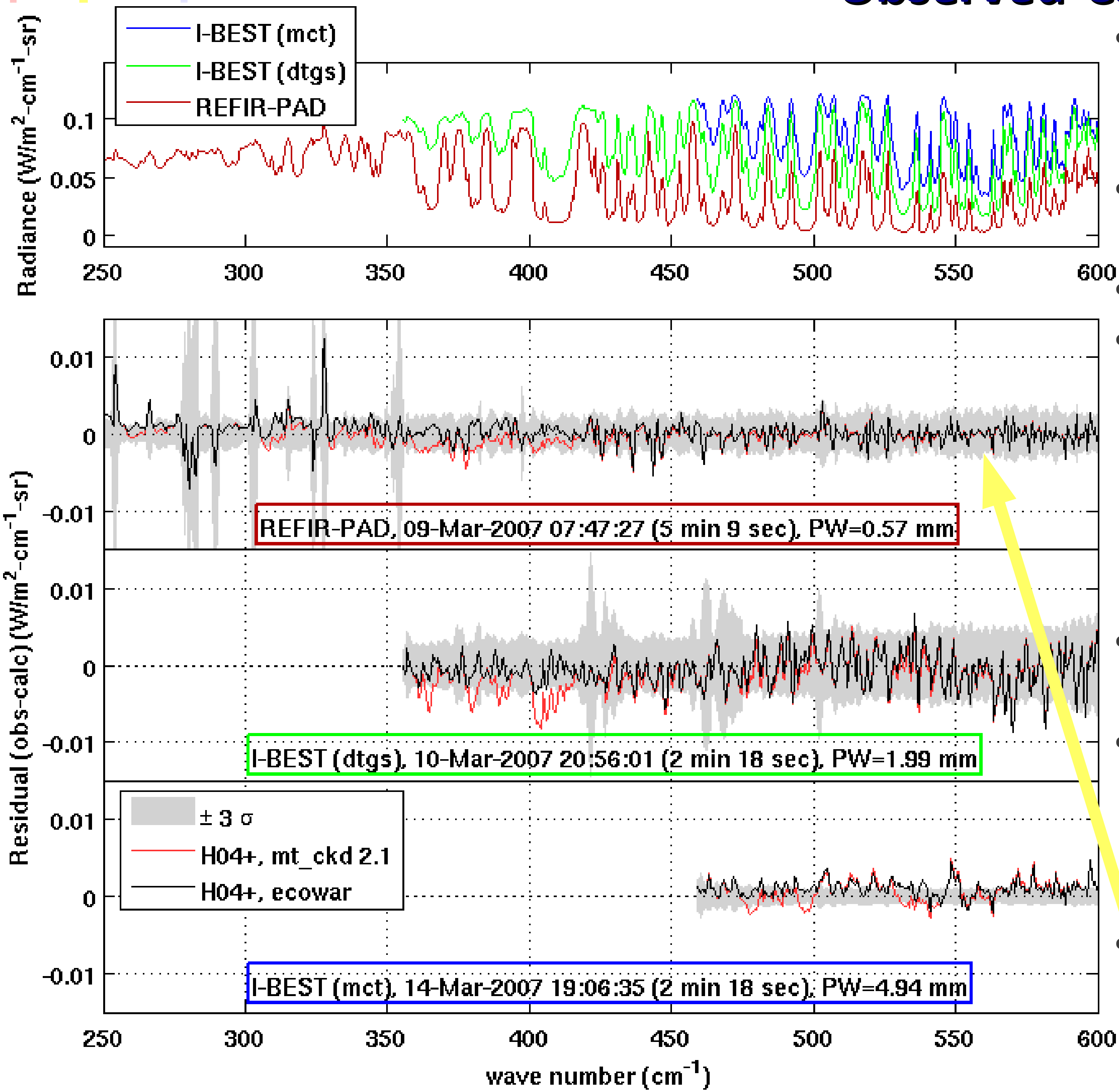
# New water vapor continuum absorption coefficients




- REFIR and I-BEST have provided basic contributions to the science of water vapour spectroscopy: $H_2O$ rotation band
- ***The Atmosphere is less opaque than model***
- More details in Serio C.,et al., Opt.Ex., 2008, doi:10.1364/OE.16.015816.

- Water vapor foreign-broadened continuum coefficients for the range 240 to 590 cm-1 as derived from our analysis and comparison with two versions of MT_CKD model, Burch's (1974) and Tobin data (1999)

# Observed-Calculated Residual

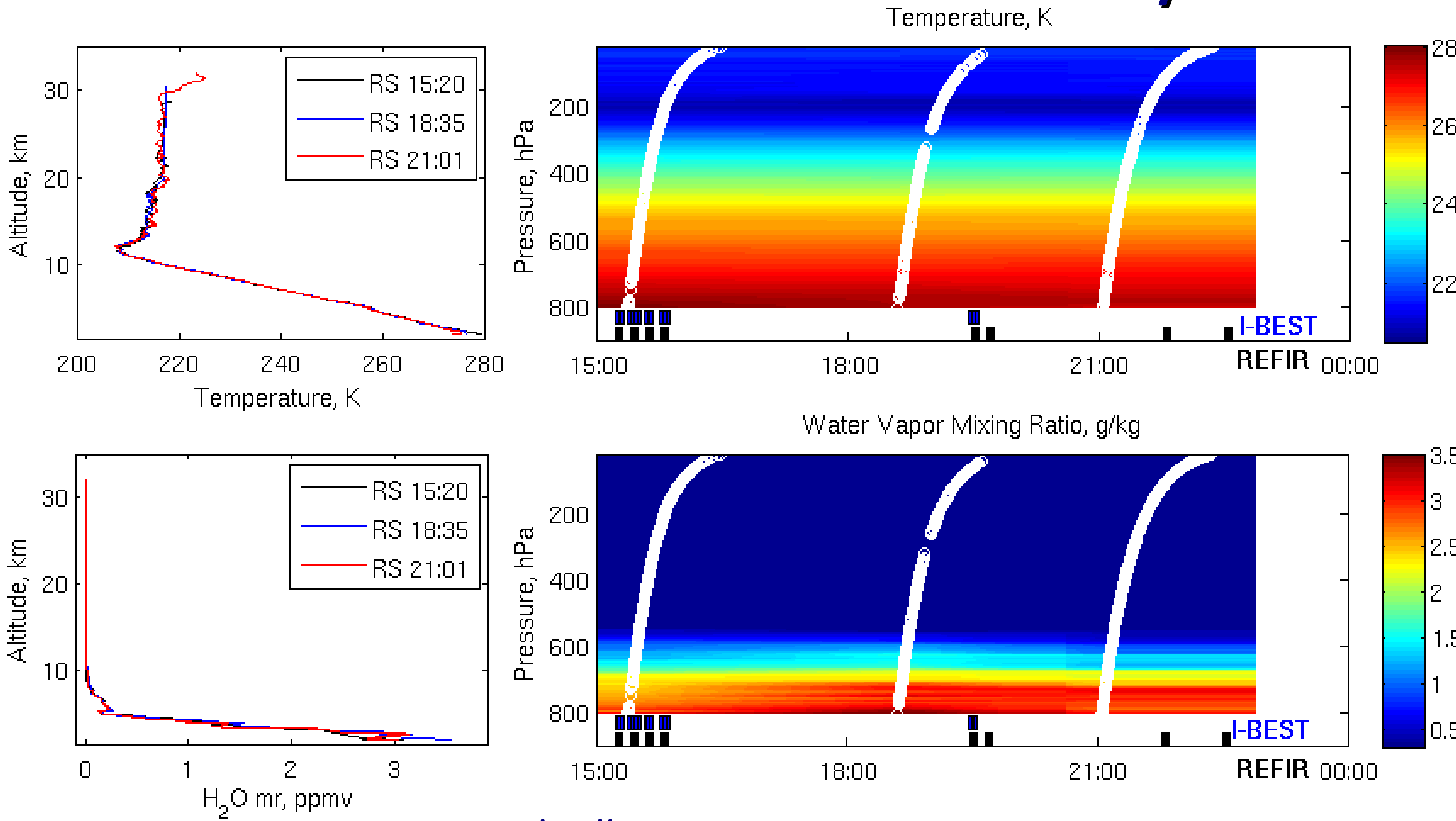



- Observed radiance (upper panel) and observed minus calculated (lower panel).
- Calculations are shown using
- H04+, mt_ckd 2.1
- H04+, ecowar, i.e. continuum coeff. determined from the 3 case studies analyzed in the ECOWAR/COBRA campaign.
- Light gray area indicated 3 sigma interval.
- This consistency sensitively improves using new continuum coefficients
- *Maestri Presentation for this day, but in cloudy condition.*

# ECOWAR/COBRA 15 March 2007, Cervinia

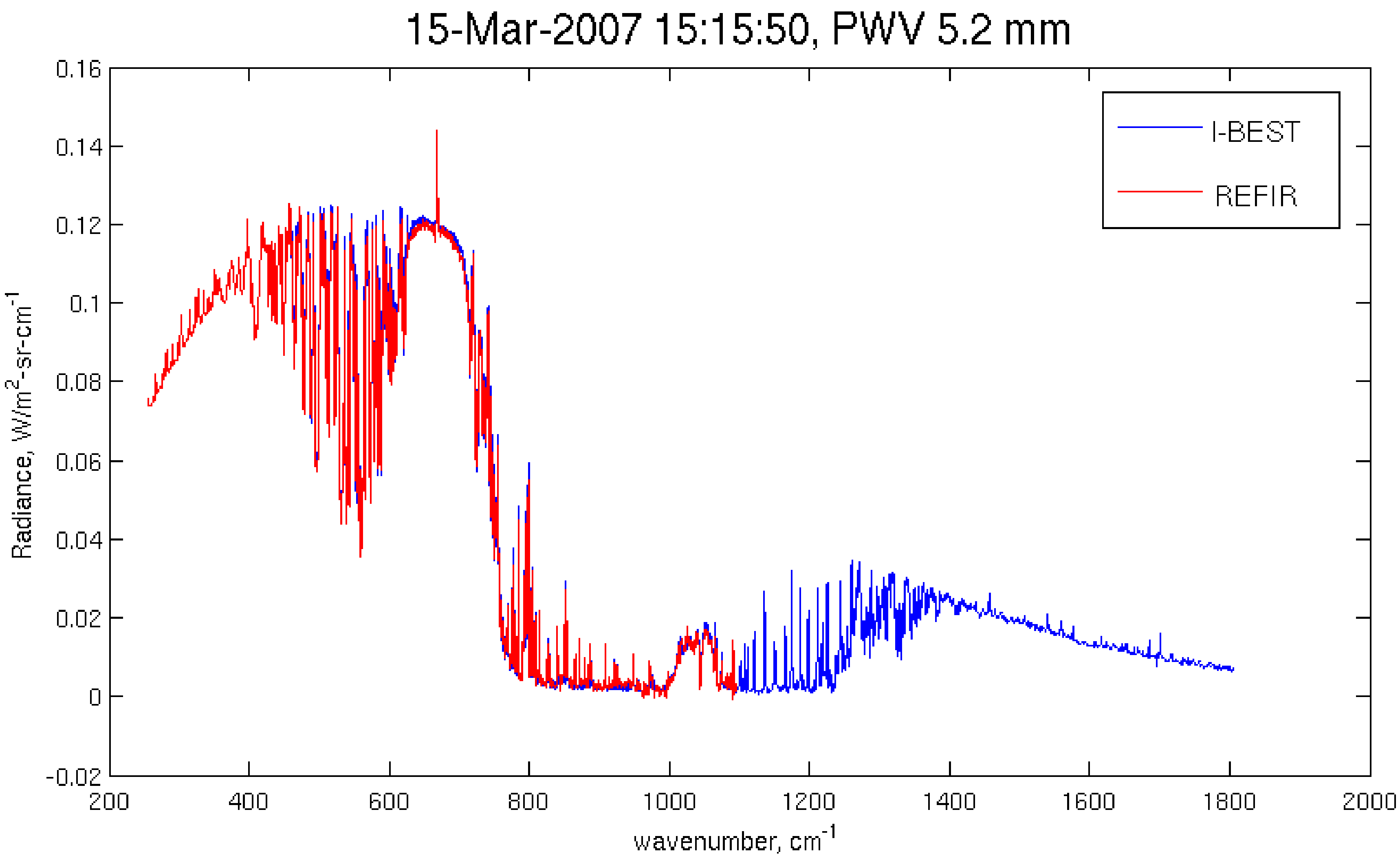

- The 15 of March 2007, I-BEST and REFIR were at Cervinia station 2000 m a.s.l.
- REFIR was hosted in the lidar container.

# Ancillary Information



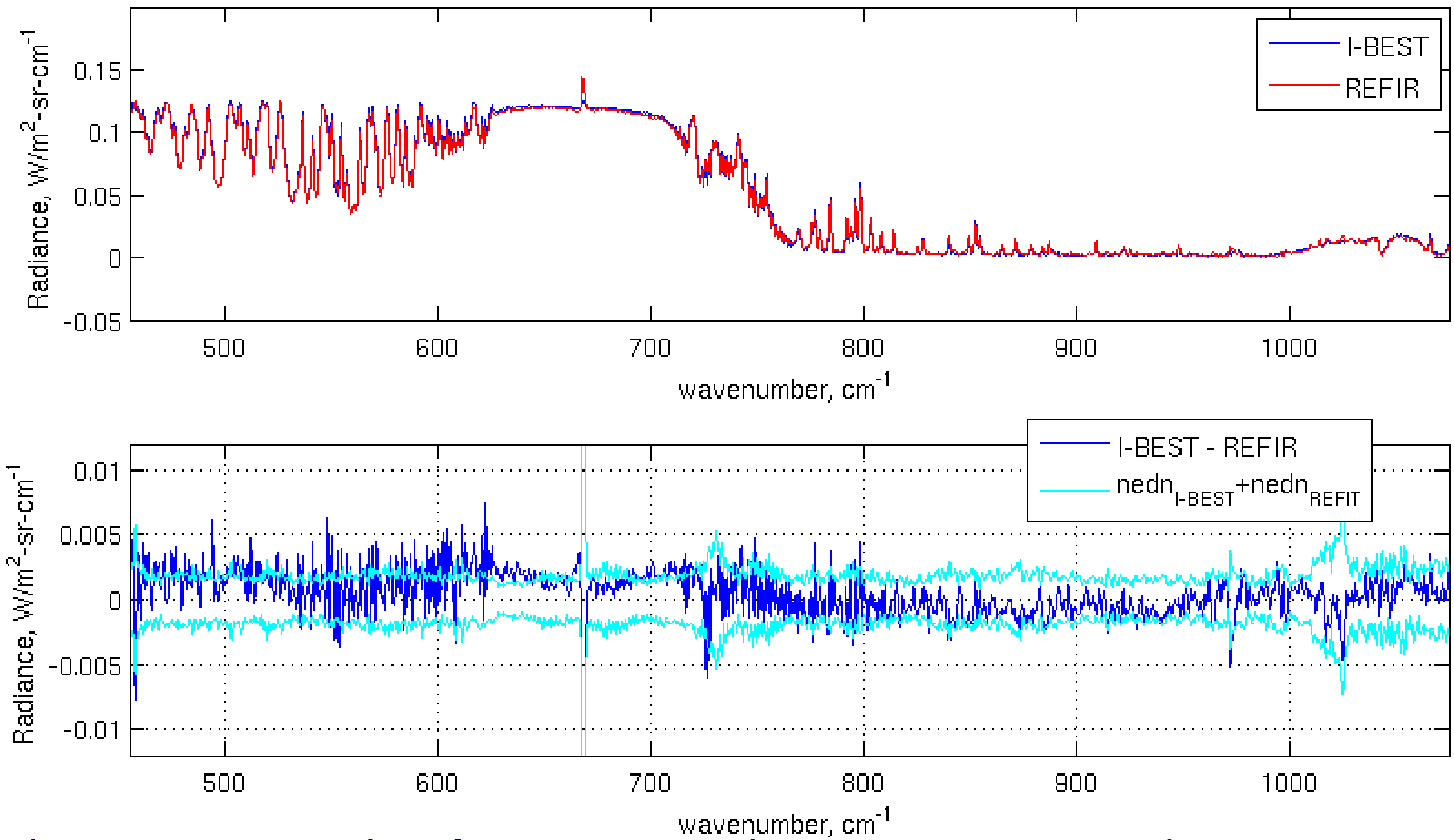

- 16 I-BEST spectra 2'16'' Long
- 8 REFIR Spectra 5'10''long
- Recorded the 15 of March 2007, between 15:00 and 23:00 GMT
- Three Radiosondes, RS92k (started @ 15:20, 18:35, 21:01)
- ***These data have never been used in the previous study***

# Colocated i-BEST and REFIR observations




- An example of REFIR and I-BEST simultaneous spectra,
- The spectral coverage extends from 260 to 1800 $cm^{-1}$

# Colocated i-BEST and REFIR observations




- This is an example of comparison between REFIR and I-BEST simultaneous observations.
- I-BEST was operated in MCT mode
- The bottom panels shows the difference between spectra (blue) compared with the sum of the radiometric noises.

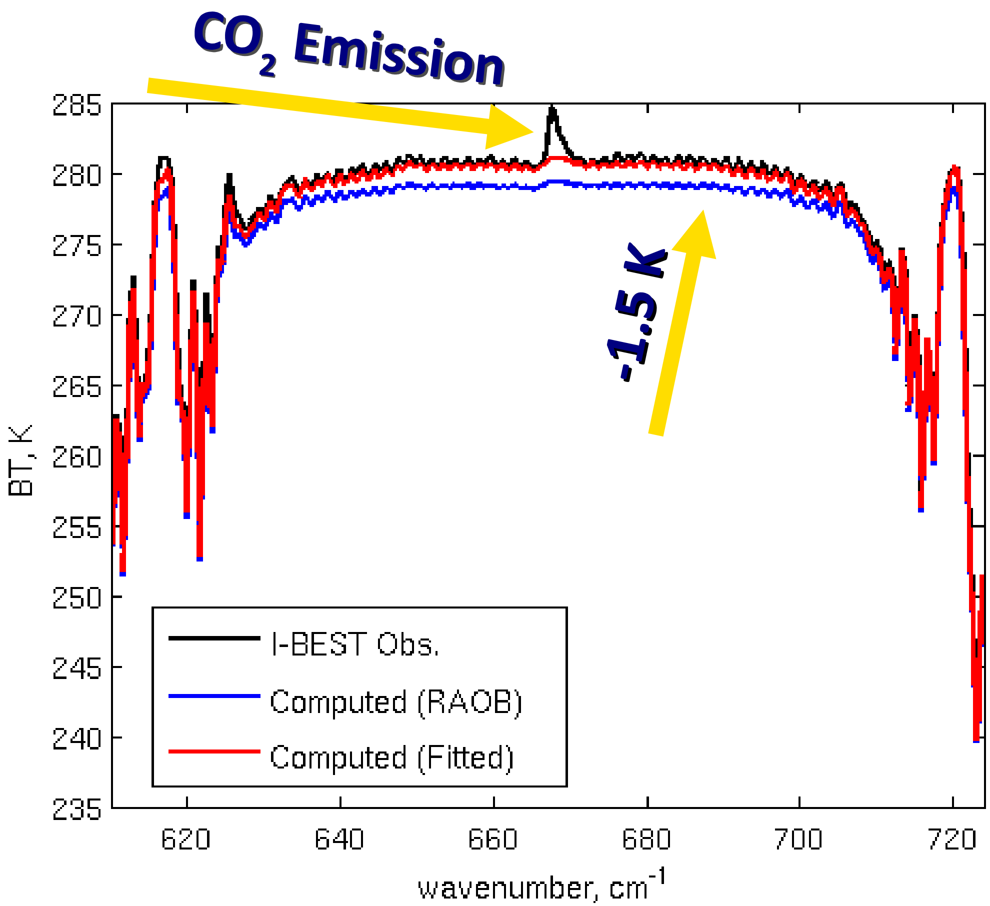
# Synoptic table of spectral parameter used

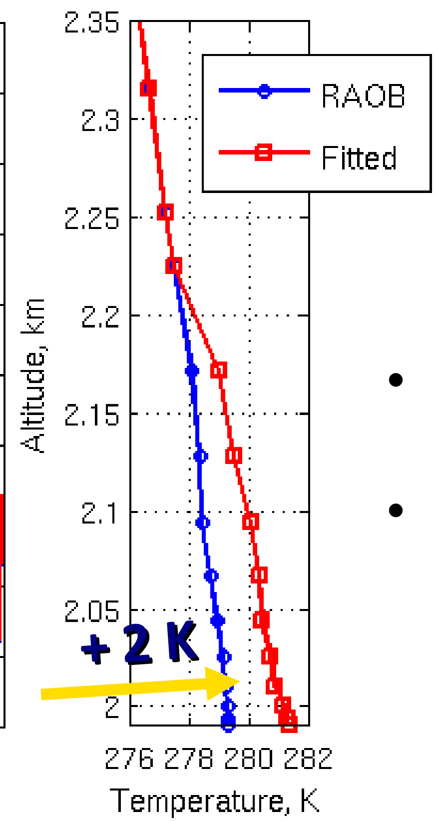
| Name | LBLRTM Version | Continua MT_CKD | Released | Changes | Line File | Based on | Changes |
|---|---|---|---|---|---|---|---|
| **11.3** | V11.3 | V 2.1 | Nov 2007 | | aer_v2.1 | HIT04+ [1] | |
| **EC** | V11.3 | V 2.1 modified [2] | Jun 2008 | Foreign in [240-590] $cm^{-1}$ | aer_v2.1 | HIT04+ [1] | |
| **12.0** | V12.0 | V 2.5.2 | Dec 2010 | Self and Foreign [4] | aer_v3.0 | HIT08, [3] Not for $H_2O$&$CO_2$ | $H_2O$ Half-widths in [350-667] $cm^{-1}$ [4] |


1. Gordon et al. (2007), JQSRT, doi:10.1016/j.jqsrt.2007.06.0092007.
2. Serio et al. (2008), Opt.Ex., doi:10.1364/OE.16.015816.
3. Rothman et al. (2009), JQSRT, doi:10.1016/j.jqsrt.2009.02.01
4. Delamere et al. (2010), JGR, doi:10.1029/2009JD012968

# Fitting Local Environment: Temperature

- Using the raw radiosonde profile, in the $CO_2$ Q-branch at 15 μm, the computed spectrum shows a “cold” bias of 1.5 K.
- In this range the atmosphere is very opaque(τ ~ 0)
  - → downwelling radiance is sensitive to the temperature of atmospheric layers very close to the instrument.
- The instruments are in the van and it may heats the air close to it.




- The structure of temperature in the firsts 15 hPa with a regression scheme described in Esposito et al. QJ, 2007 doi: 10.1002/qj.131.
- The cold bias is sensitively reduced
- The intense spike at 667 $cm^{-1}$ is due to the emission of $CO_2$ inside the instruments

# Water Vapor: Methodology

*Spectral radiance* — *Forward model*

$$\mathbf{r} = F(\mathbf{s};\mathbf{v})$$

*spectral parameters* — *atmospheric state vector T,W*

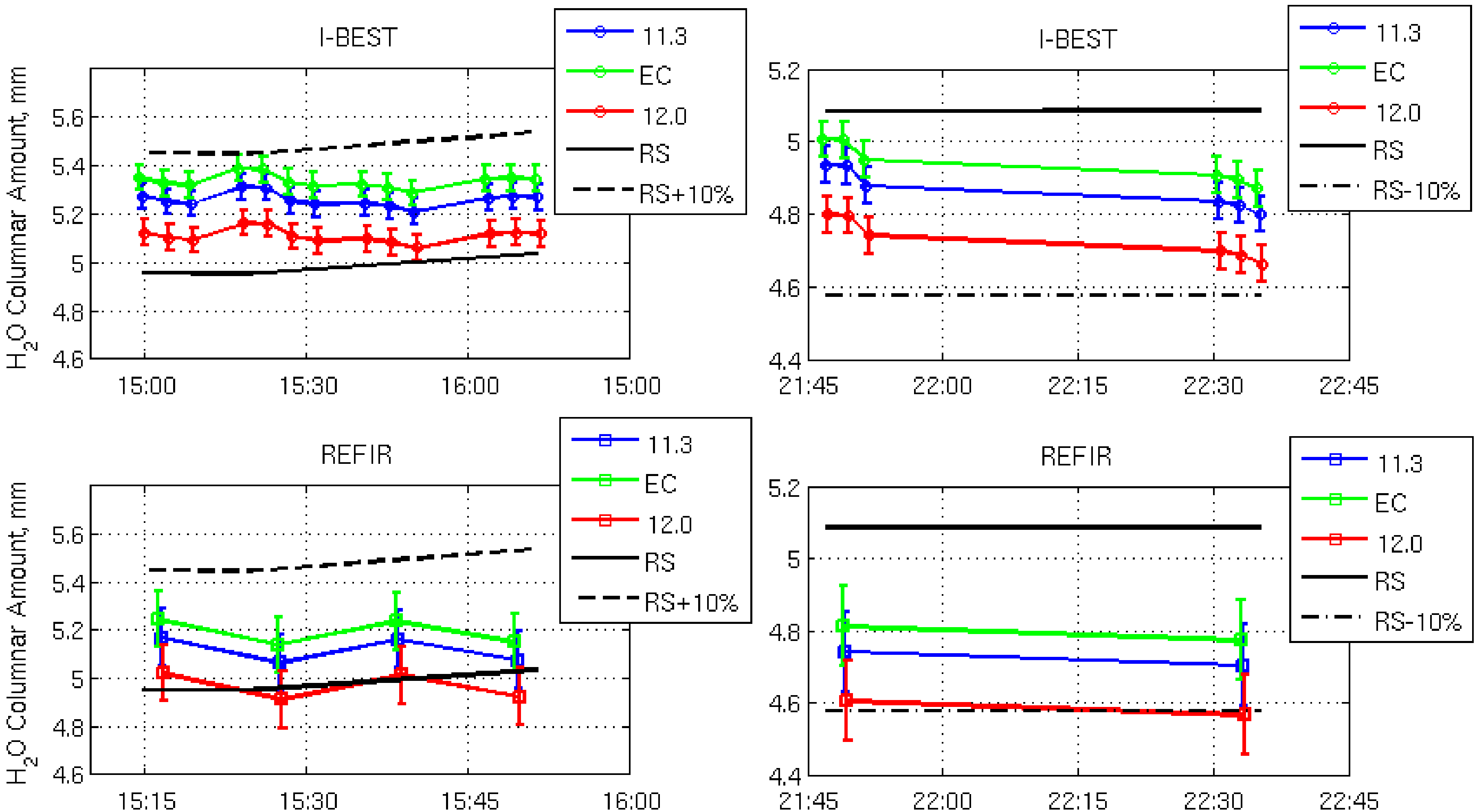
- To take into account both local environment and eventual bias introduced by Radiosonde (and/or) Interpolation we tuned PWVs for each spectrum and for each spectroscopic issues.
- In this case we assume fixed spectral parameter and we move only water vapor PWV.

- Taylor expansion with respect to a initial guess (denoted with 0 pedix)

$$\mathbf{r} = \mathbf{r}_0 + \mathbf{K}_q(\mathbf{q} - \mathbf{q}_0) + \text{higher order terms}$$

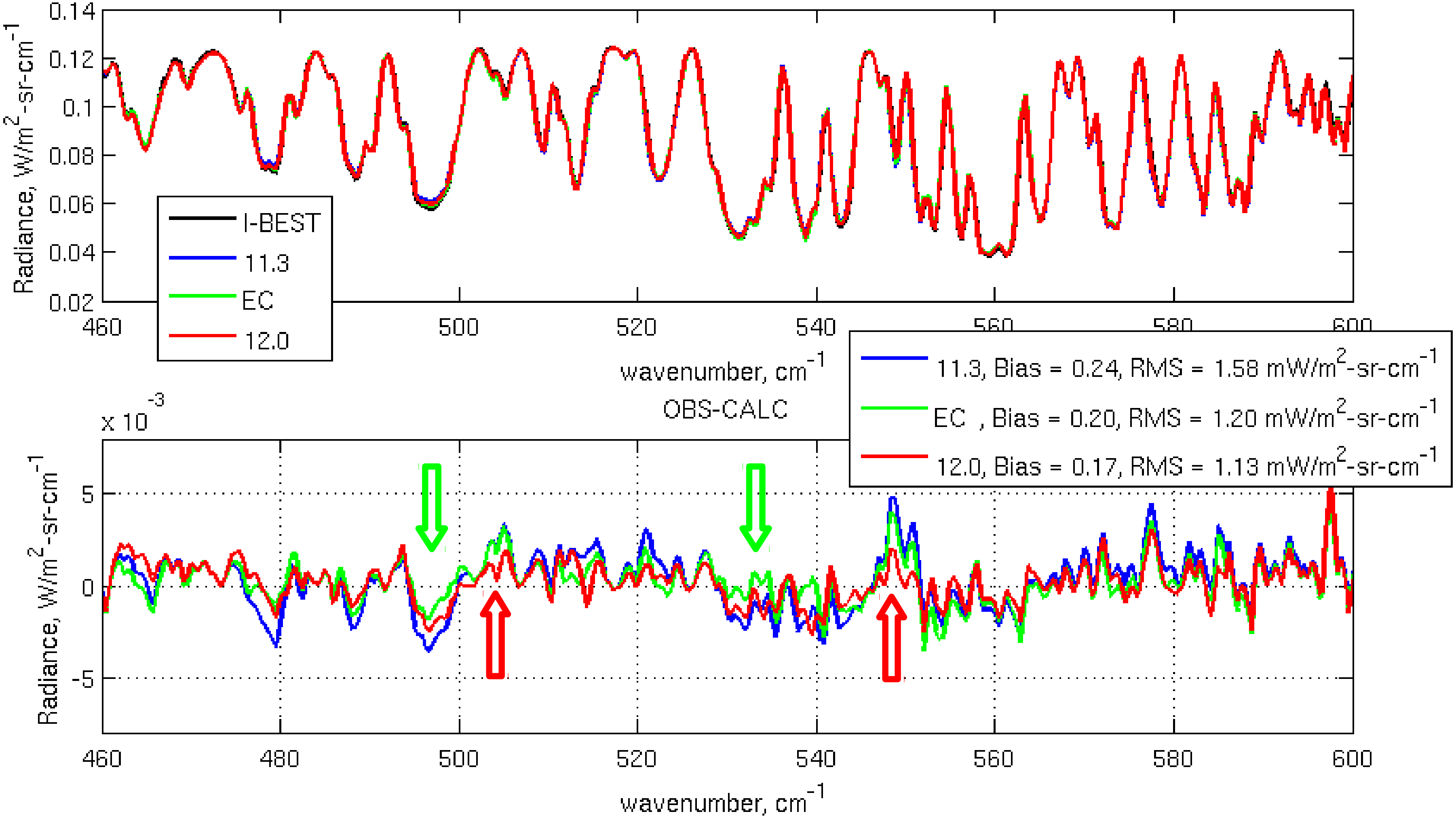
- Inverted using least square method using the spectral range **[360-600] $cm^{-1}$**

# Fitting Local Environment: Water Vapor




- The Columnar Amount retrieved for the two Instruments and for the three spectral parameter choices.
- The Retrieved PWVs are in +/- 10 % with respect to the Raodiosonde.
- 12.0 Sees less water vapor than others
  - 12.0 says that the atmosphere is more opaque!

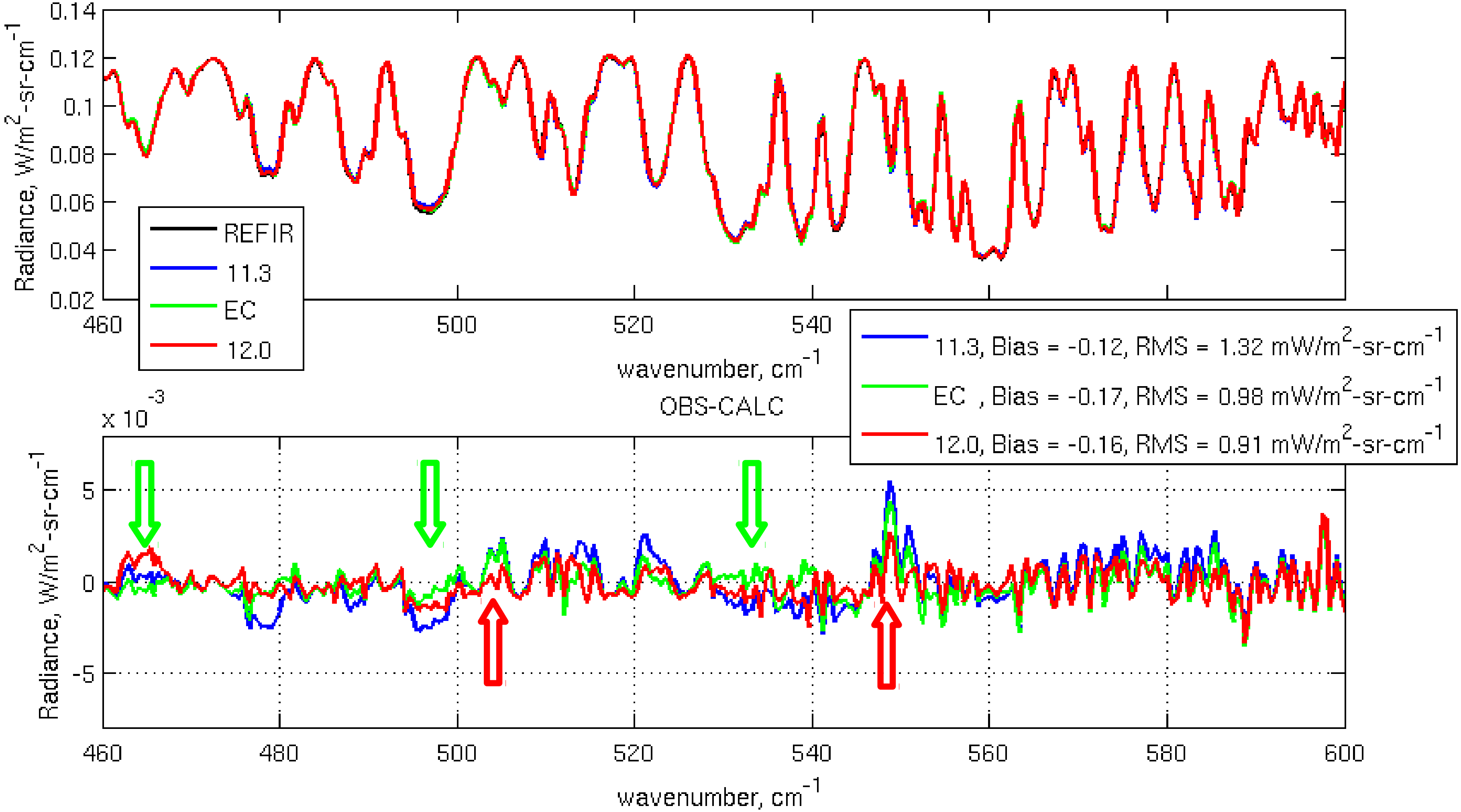
# Consistency with I-BEST @ 20 micron




- Both EC and 12.0 outperform the 11.3 one,
- There are regions where EC fits better than 12.0 the spectra (495 & 530) cm$^{-1}$ and regions where 12.0 fits better EC (505 & 550) cm$^{-1}$

| Name | Bias (R.U.) | RMS (R.U.) |
|---|---|---|
| 11.3 | 0.24 | 1.58 |
| EC | 0.20 | 1.20 |
| 12.0 | 0.17 | 1.13 |

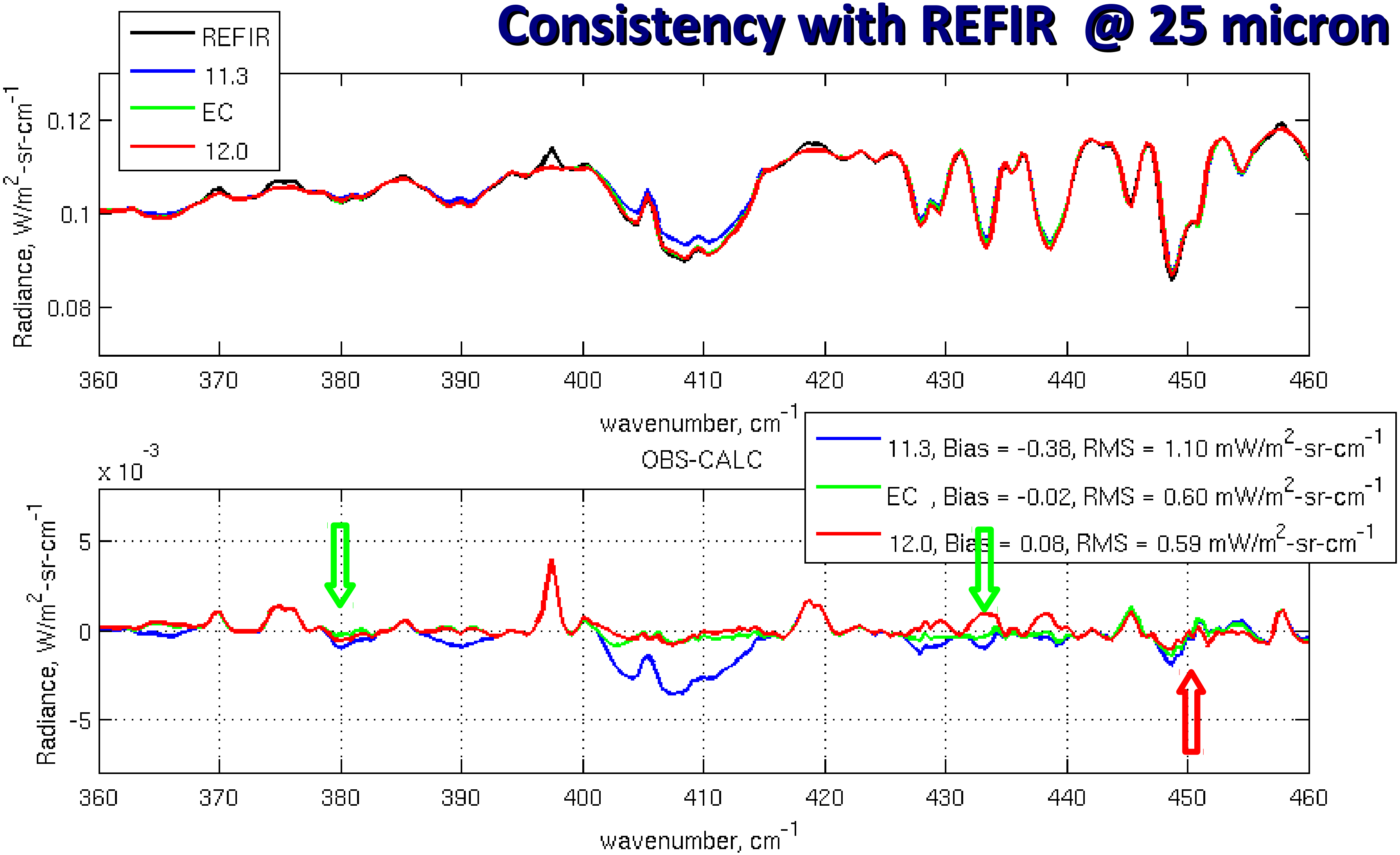
# Consistency with REFIR @ 20 micron




- Both EC and 12.0 outperform the 11.3 one,
- There are regions where EC fits better than 12.0 the spectra (465, 495 & 530) $cm^{-1}$ and regions where 12.0 fits better than EC (505 & 550) $cm^{-1}$

| Name | Bias (R.U.) | RMS (R.U.) |
|---|---|---|
| 11.3 | -0.12 | 1.32 |
| EC | -0.17 | 0.98 |
| 12.0 | -0.16 | 0.91 |

# Consistency with REFIR @ 25 micron

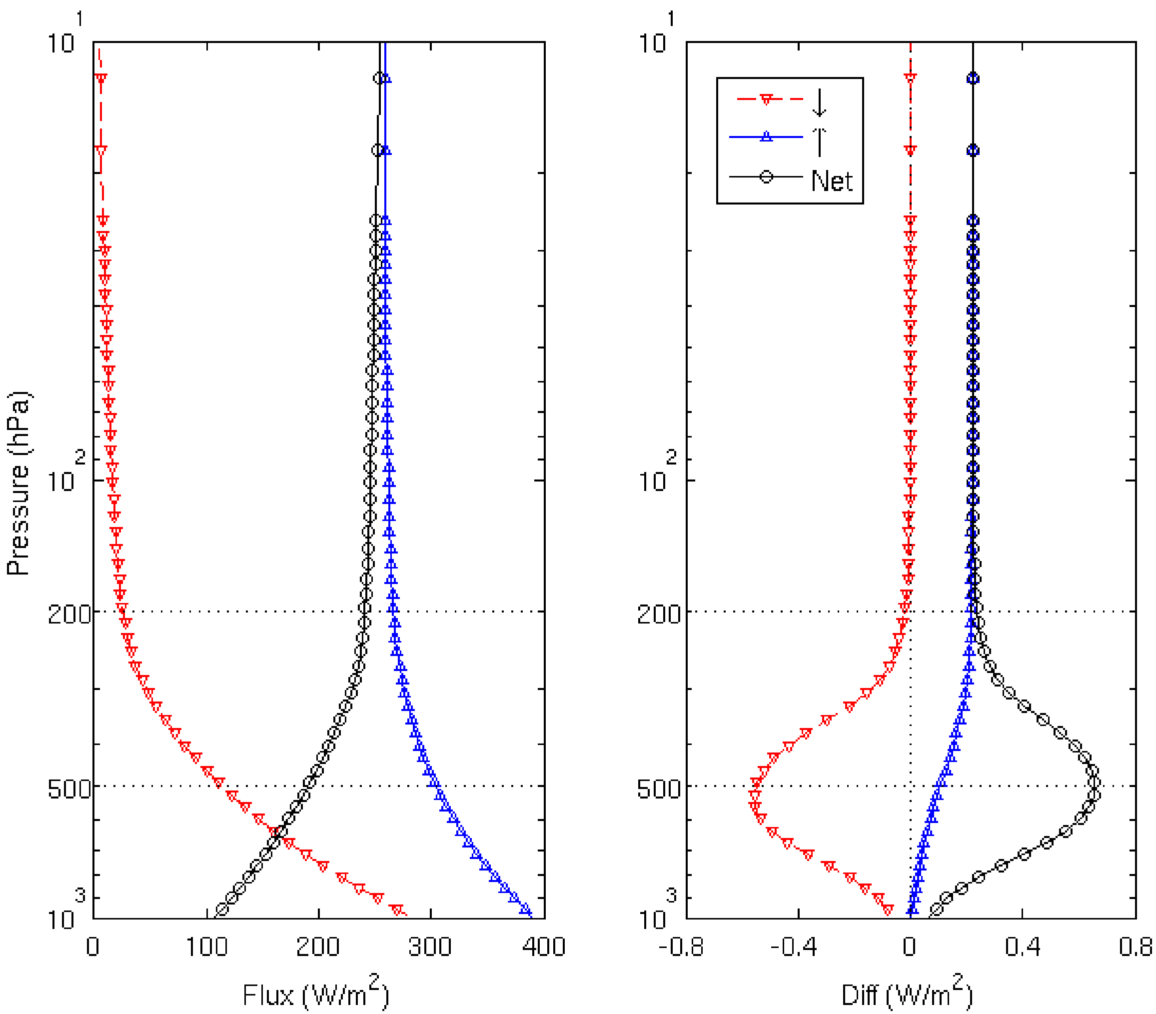



- Both EC and 12.0 outperform the 11.3 one,
- EC fits better than 12.0 the spectra @ 380 & 435 $cm^{-1}$ while 12.0 fits better than EC around 450 $cm^{-1}$

| Name | Bias (R.U.) | RMS (R.U.) |
|---|---|---|
| 11.3 | -0.38 | 1.10 |
| EC | -0.02 | 0.60 |
| 12.0 | 0.08 | 0.59 |

# Radiative Fluxes

- EC and 12.0 show the same consistency with observed data.
- But the atmosphere modeled by 12.0 is more opaque than EC model.
- This fact has climatological implication.




- Radiative fluxes (**Down**, **Up** and **Net**) computed for U.S.Std. atmosphere (left)
- Difference introduced by new coefficients (right)
  - ***The new coefficients produce a net flux 0.65 W/m² higher @500 hPa.***
  - This change is equivalent to that of subtracting ≈ 30 ppmv of $CO_2$ into the atmosphere.
- More Details in Masiello et al. 2009, IRS08 Proc., doi:10.1063/1.3116933

# While from lblrtm upadates...

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 115, D17106, doi:10.1029/2009JD012968, 2010

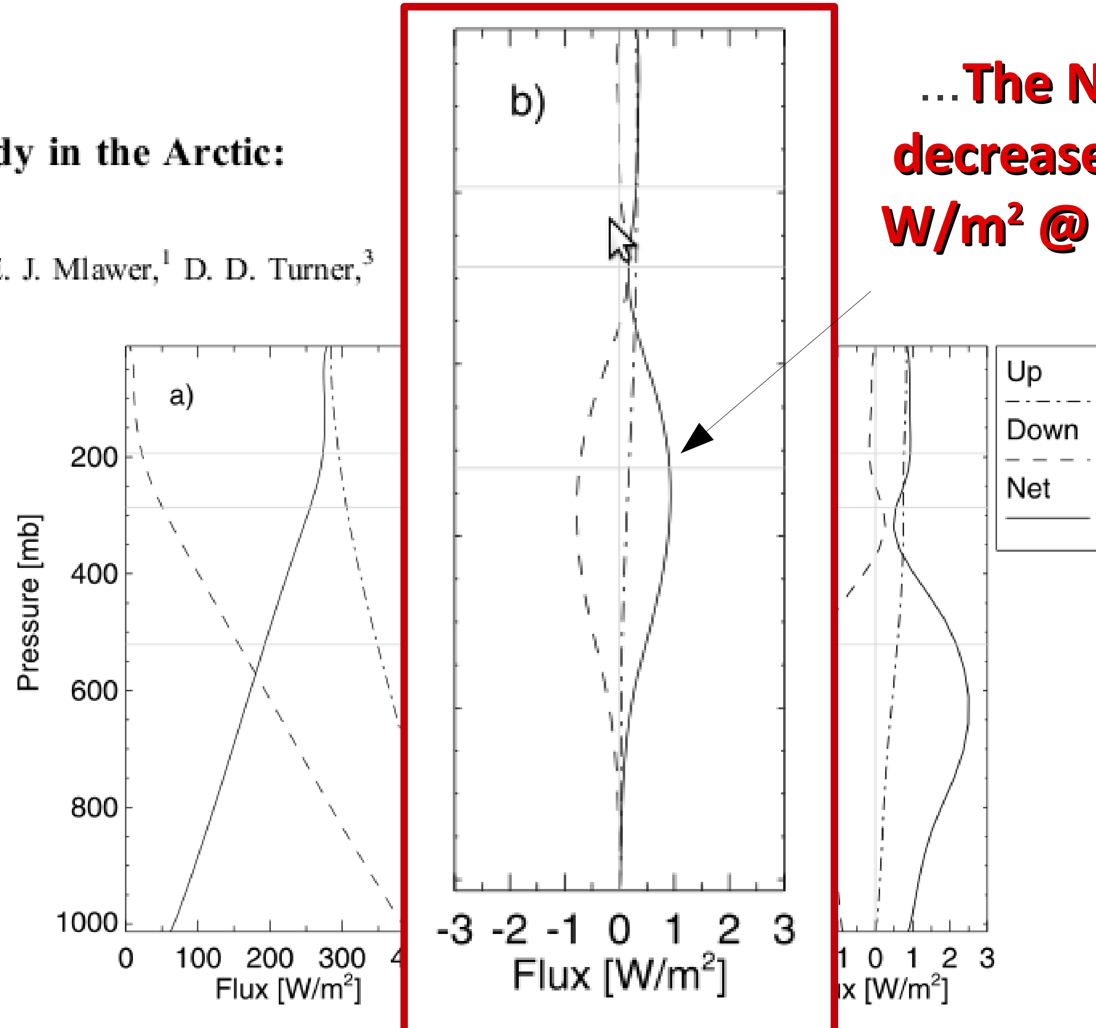
## A far-infrared radiative closure study in the Arctic: Application to water vapor

J. S. Delamere,[1] S. A. Clough,[2] V. H. Payne,[1] E. J. Mlawer,[1] D. D. Turner,[3] and R. R. Gamache[4]

Received 12 August 2009; revised 16 Febru

[1] Far-infrared (λ > 15.0 μm) (
Earth's outgoing longwave radia
Water vapor, because of its abun
spectral range, is the primary sou
of spectrally resolved radiometri
have precluded extensive studies
Department of Energy Atmosphe
organized a series of field experi
Campaigns (RHUBC), to address
2007 at the ARM North Slope o
before and during this campaign
closure study aimed at reducing l
models. Extended-range Atmosp
observations taken in clear sky c
Line-By-Line Radiative Transfe
calculations were retrieved from
these integrated water vapor retri
over past studies. This far-IR rad
Mlawer-Tobin Clough-Kneizys-l
and updates to numerous, far-IR
2006 version of the HITRAN m

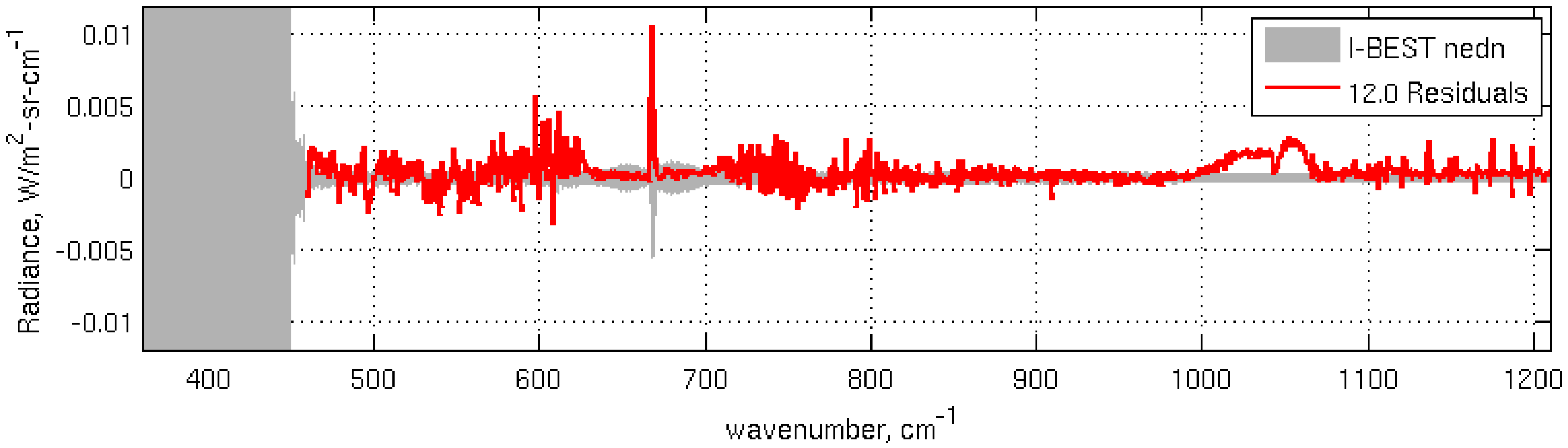
Citation: Delamere, J. S., S. A. Cloug
radiative closure study in the Arctic: Ap

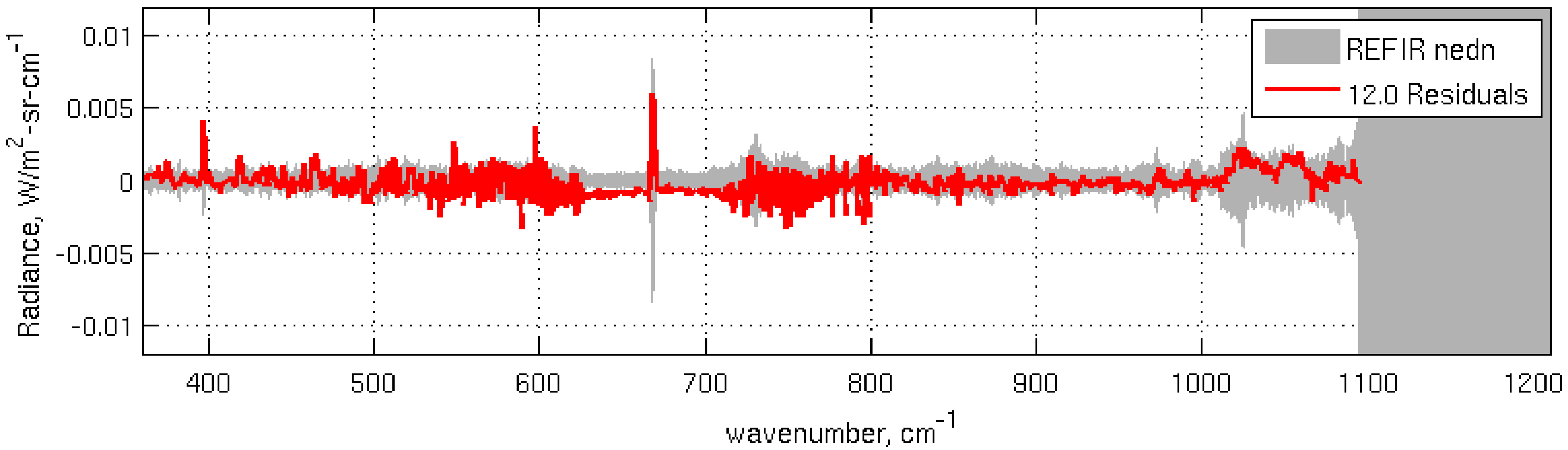



...The Net flux decreases of 0.7 W/m² @ 500 hPa

**Figure 16.** Impact of model revisions on clear-sky longwave fluxes (10–2000 cm$^{-1}$) for a standard tropical atmosphere. (a) Downwelling, upwelling, and net (up minus down) fluxes computed using LBL09. (b) Differences in computed fluxes (LBL06 minus LBL09). (c) Differences in computed fluxes (LBL99 minus LBL09). Grey lines are reference pressures used in spectral net flux calculations presented in Figure 17.

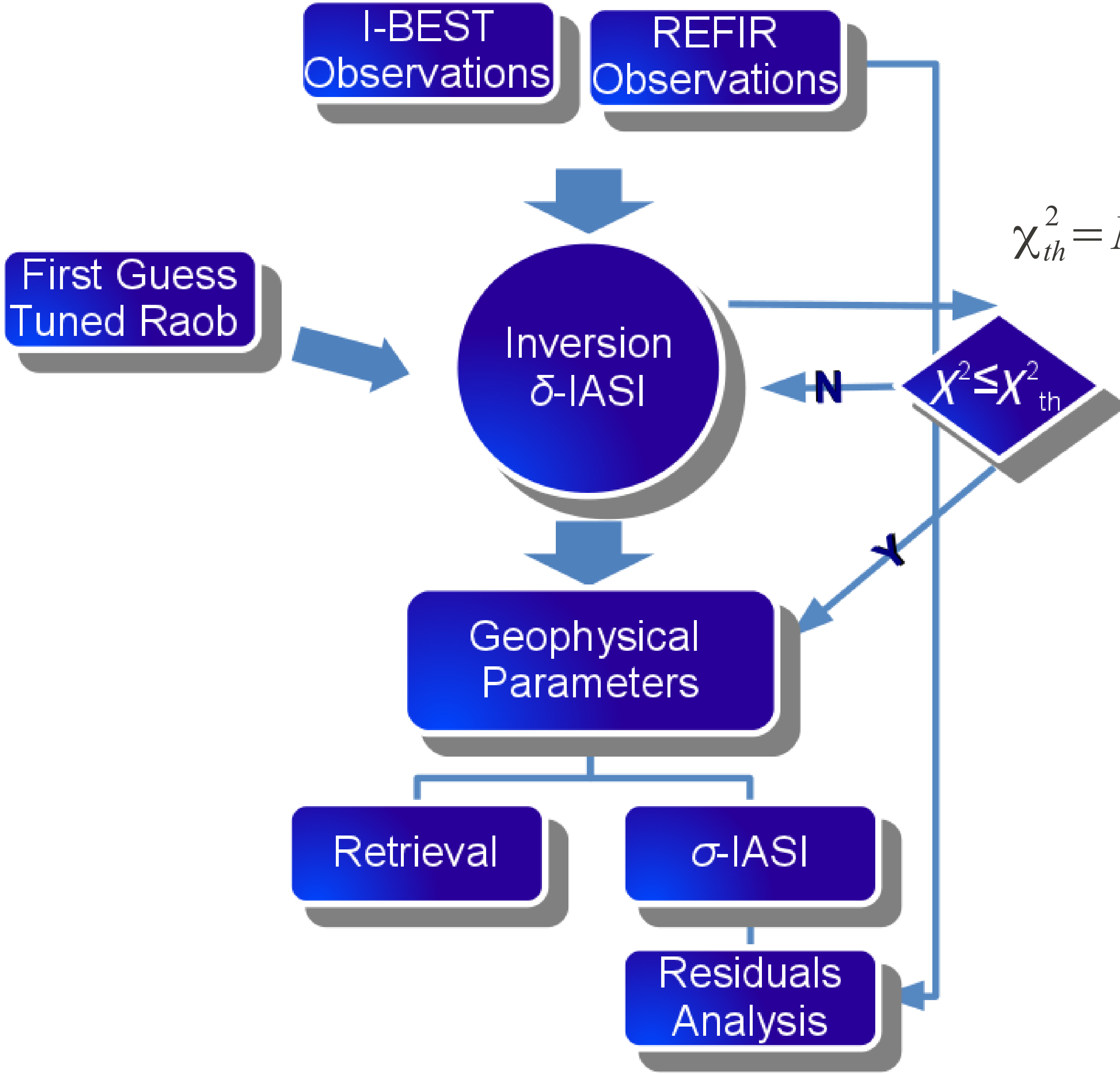
# Comparing residuals with radiometric noise




- The mean residuals  are larger than the radiometric noise.
  - In the CO2 band (Temperature profile)
  - In the Ozone band (Ozone Profile)
  - In H2O rotational band (Water Vapour profile)
- It is crucial to perform a closure experiment.

# Flow charts




$$\chi^2_{th} = N_{ch} + 2\sqrt{2N_{ch}}$$

# σ-IASI

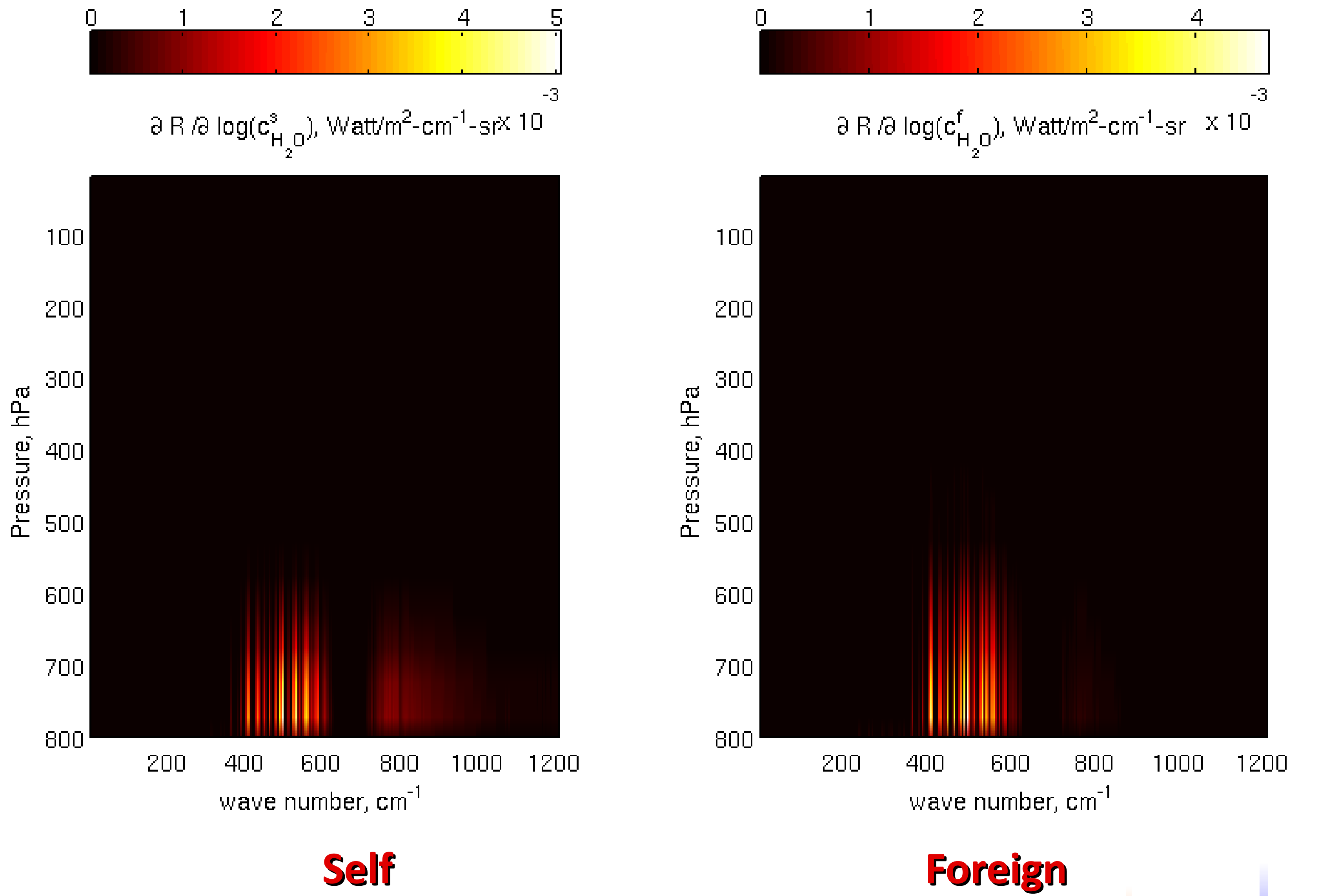
- σ-IASI is a line-by-line radiative transfer model designed for fast computation of spectral radiance and its derivatives (Jacobian) with respect to a given set of geophysical parameters
- It adopts a grid of 63 pressure levels [1050.00-0.005 hPa].
- It is Based on look-up table of monochromatic optical depth + an interpolation procedure.
- The OD look-up-table has been built starting from LBLRTM 12.0 (HITRAN08 spectral database, aer_v3.0)
- Continuum MT_CDK 2.5.2

- It is a FORTRAN90 Code running on LINUX and Windows platform with Intel Compiler.

# New Features of σ-IASI

- σ-IASI has been up-graded and now allows us for the computation of analytical Jacobians with respect to:
  - Foreign component of the $H_2O$ continuum
  - Self-broadened component of $H_2O$ continuum
  - $CO_2$ continuum
- It works for Satellite, Airplane and Ground-Based Measurements
- New parameterization for the clouds

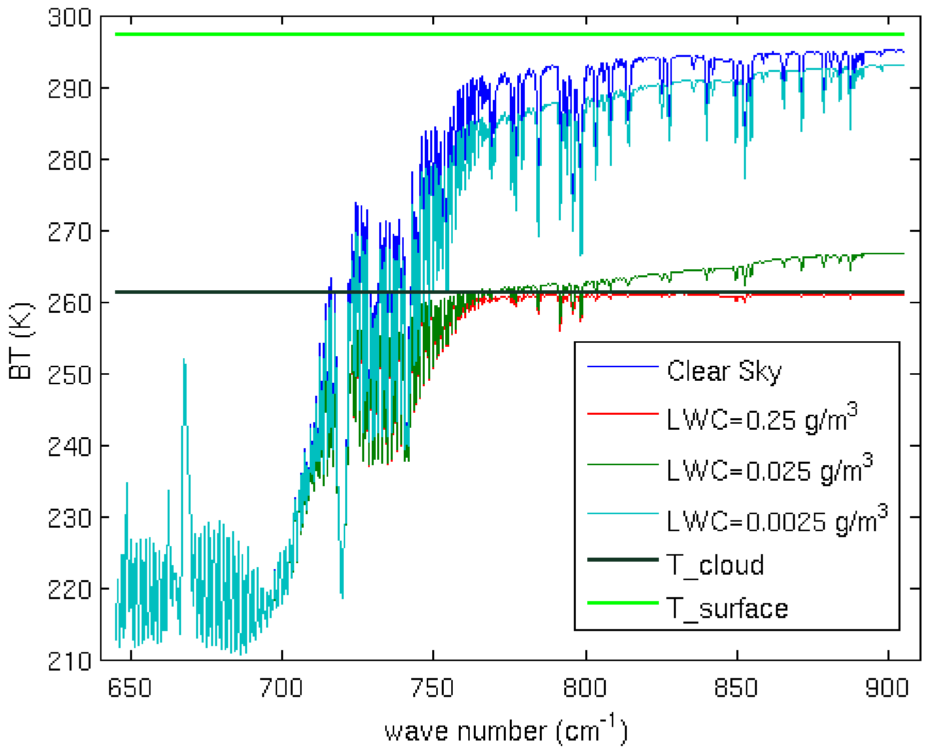
# Water Vapour Continua Jacobians



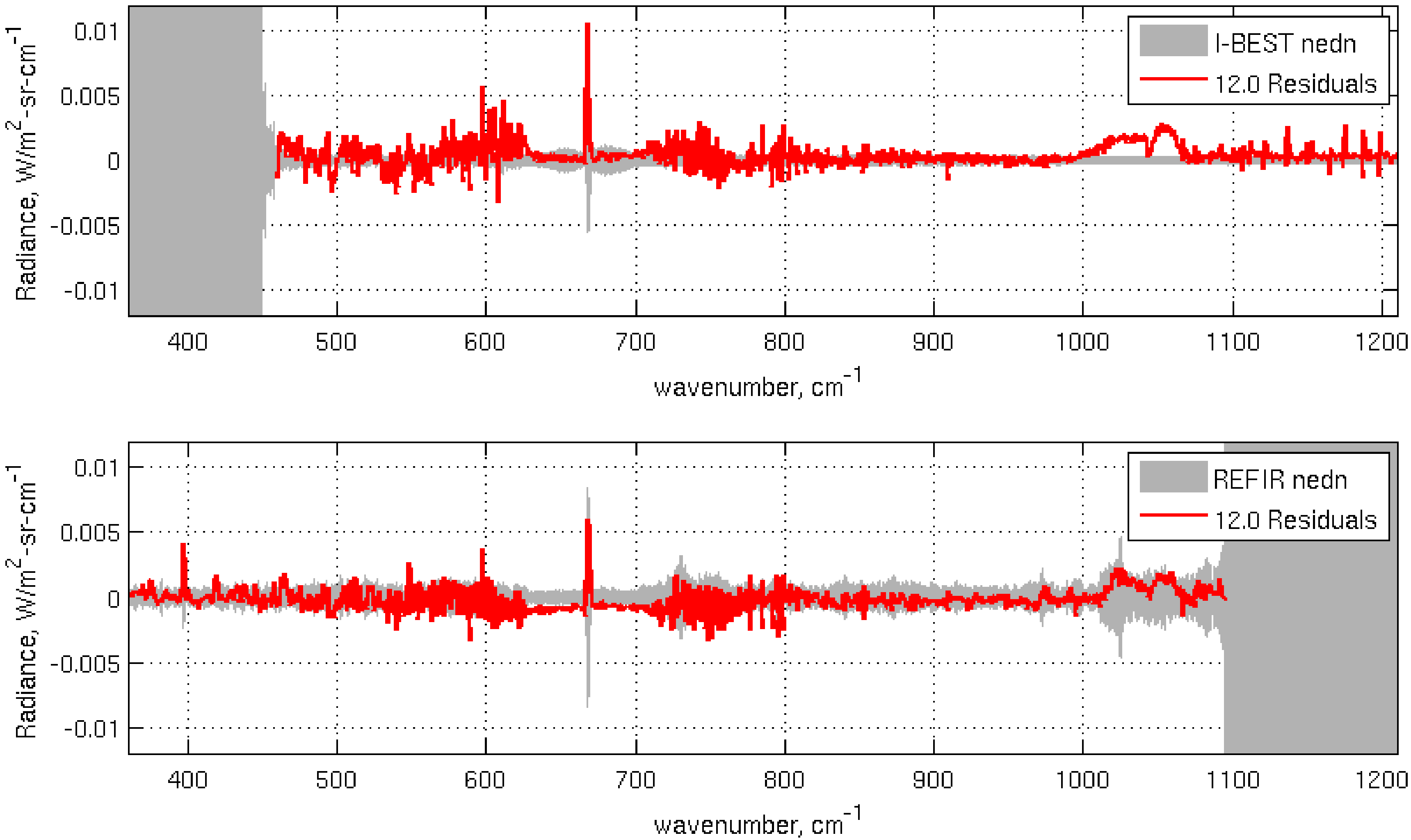

- Example of Jacobian of Water vapor continua, for down-welling radiance.

# Clouds Parameterization

- Following the parameterization for cloud scattering by Chou et al 1999, $\sigma$-IASI can deals with a cloudy atmosphere, in which the microphysical optical properties of the cloud (Qsca and Qabs Mie kernels, single scattering albedo and asymmetry factor) are parameterized based on the water droplets radius and effective ice crystal radius, along with the Liquid Water Path (LWP) and Ice Water Path (IWP).
- Considering the scaling approximation introduced by Chou et al 1999, the radiative transfer equation is the same as that for a clear atmosphere, which means that the computational efficiency for a cloudy atmosphere is practically the same as that for a clear atmosphere

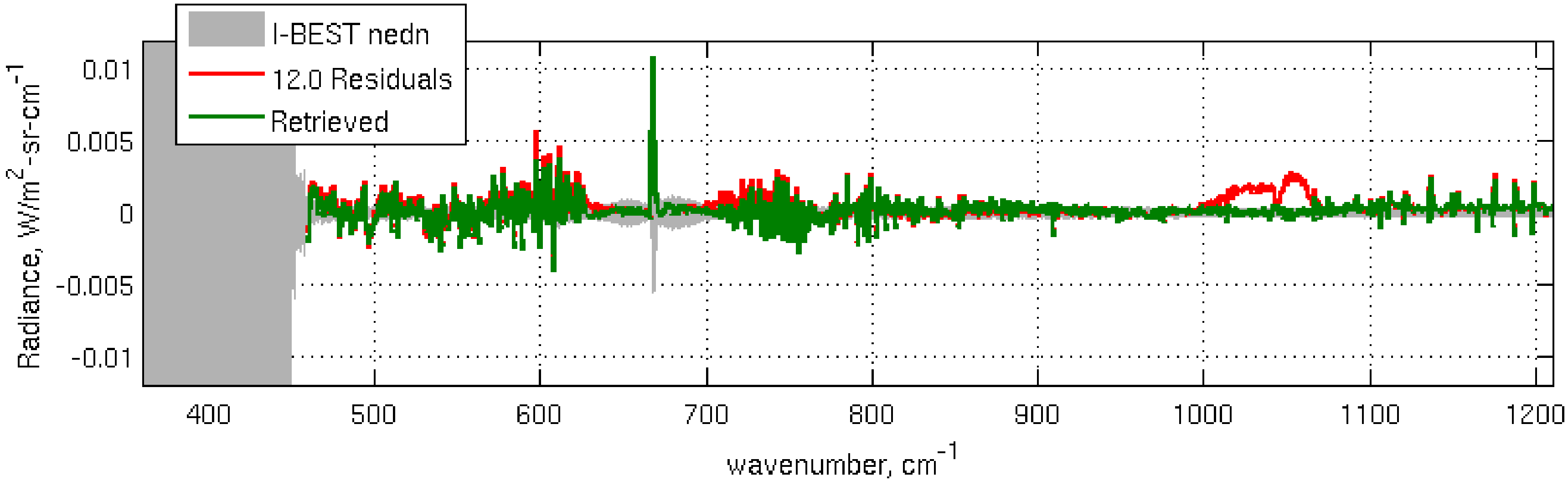


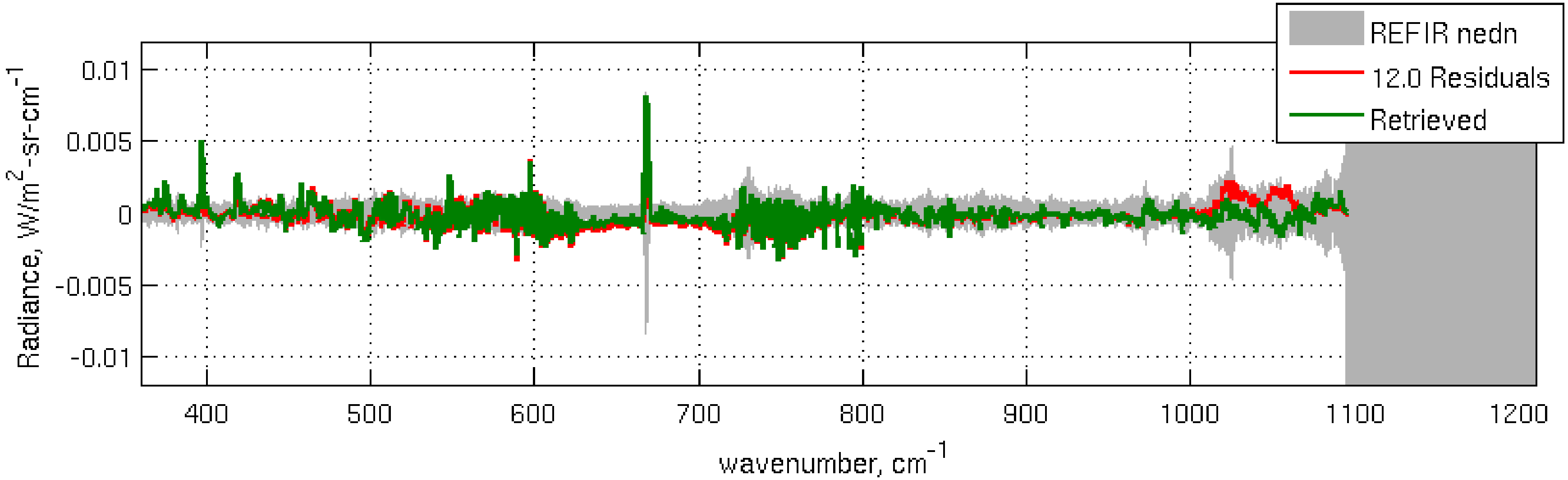
# Comparing residuals with radiometric noise




- The mean residuals are larger than the radiometric noise.
  - In the CO2 band (Temperature profile)
  - In the Ozone band (Ozone Profile)
  - In H2O rotational band (Water Vapour profile)
- It is crucial to perform a closure experiment.

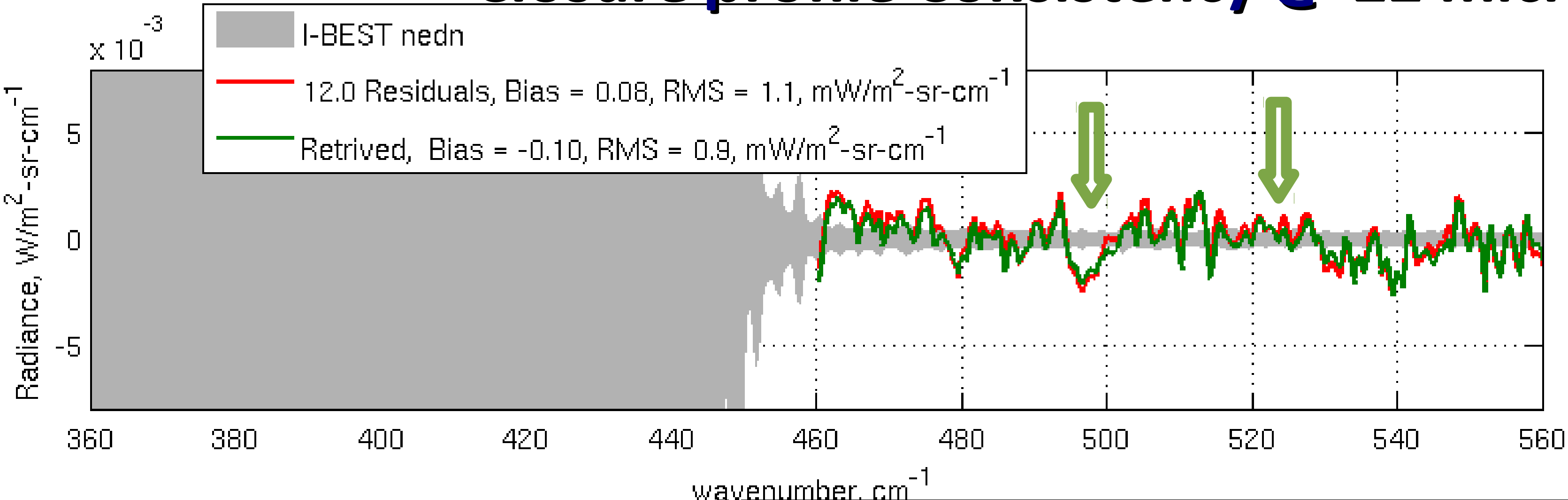
# Closure Profiles

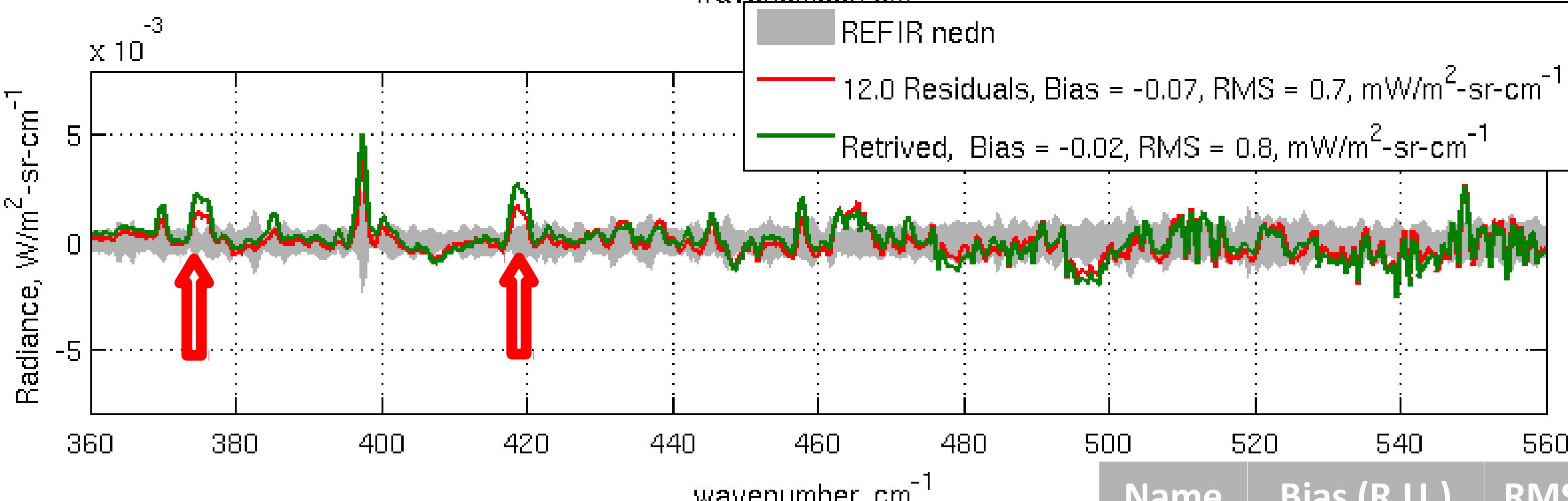



- First guess profiles come from the tuning described before for the 12.0.
- The Retrieved profiles, in green, fit better the observations but systematic features still appears.

# Closure profile Consistency @ 22 micron

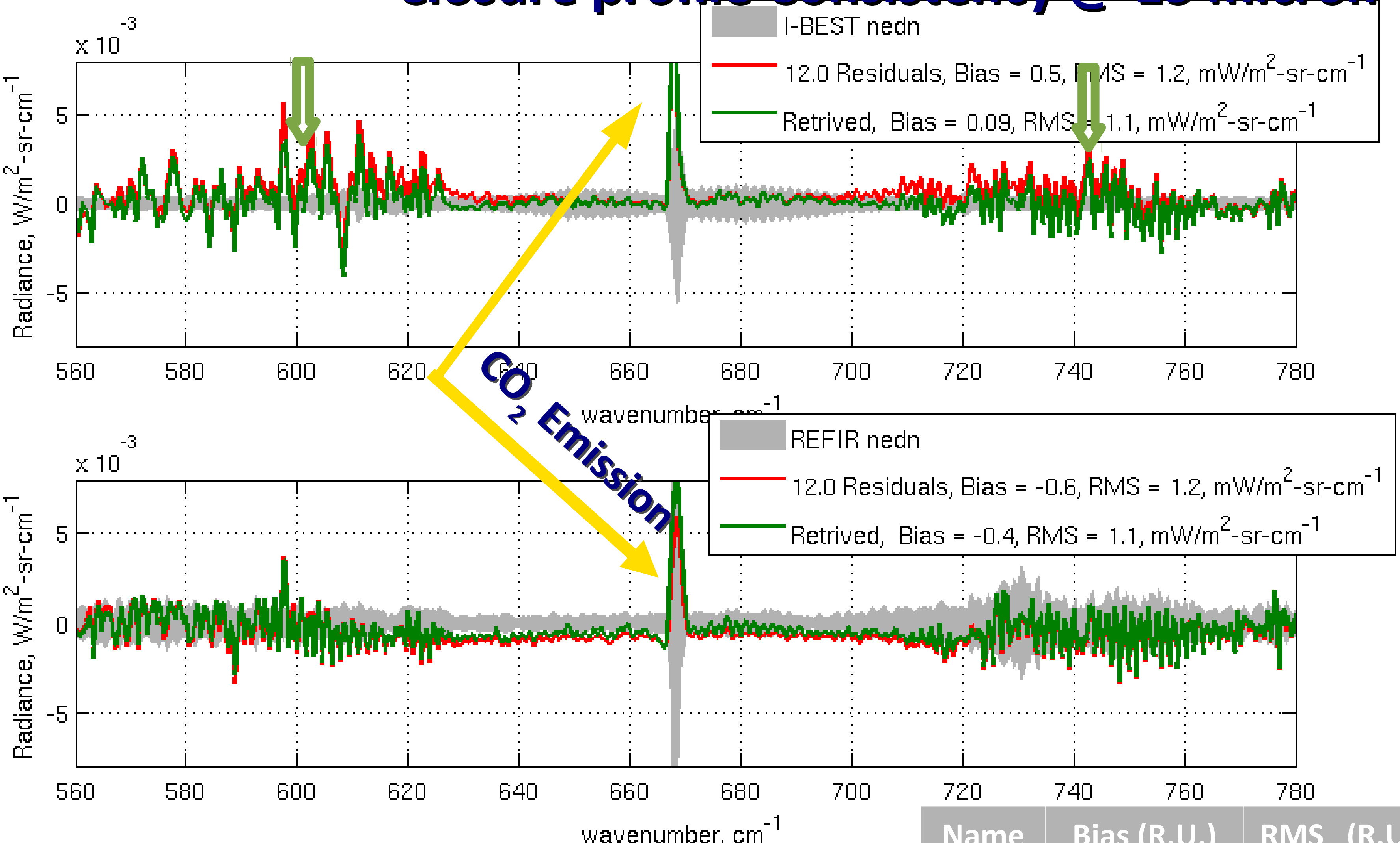



- No sensitive improvements with the retrieved profiles.
- The RMS slightly decrease for I-BEST due the better performance between [490 - 530] $cm^{-1}$
- For REFIR RMS slightly increase due to the worse performance @ 370 & 420 $cm^{-1}$

| Name | Bias (R.U.) | RMS (R.U.) |
|---|---|---|
| 12.0 | 0.08 | 1.1 |
| Retr | -0.1 | 0.9 |
| 12.0 | -0.07 | 0.7 |
| Retr | -0.02 | 0.8 |

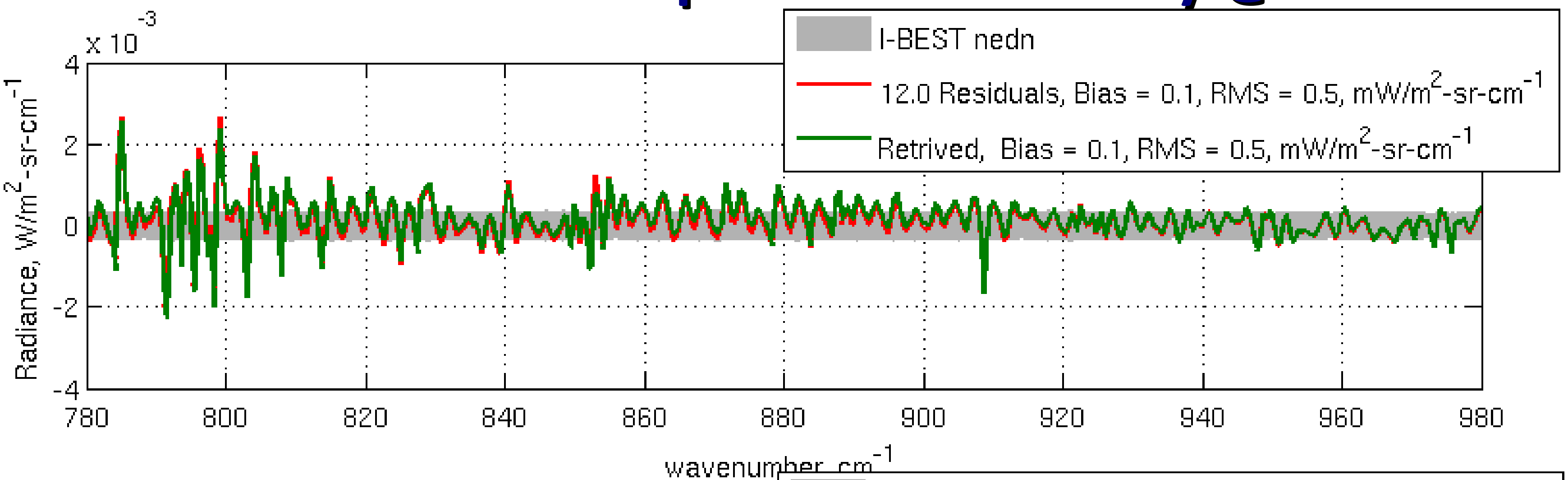
# Closure profile Consistency @ 15 micron

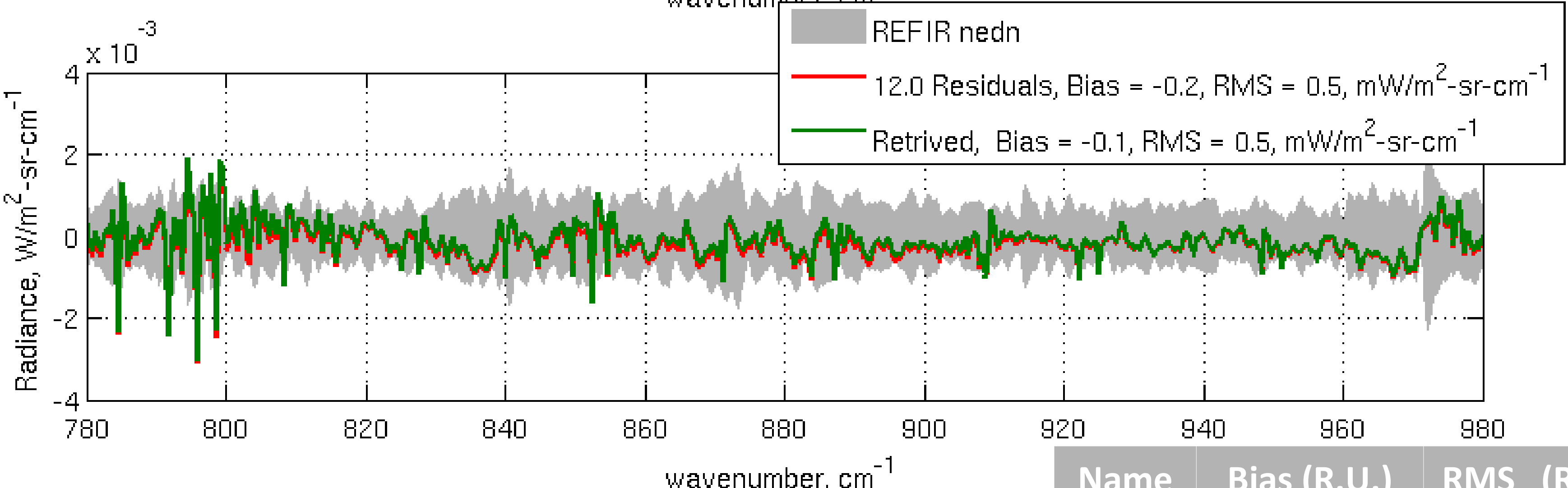



- Both bias and RMS reduce with Retrieved profiles
- But the residuals around 600 and 740 $cm^{-1}$ are greater than the radiometric error.

| Name | Bias (R.U.) | RMS (R.U.) |
|---|---|---|
| 12.0 | 0.5 | 1.2 |
| Retr | 0.09 | 1.1 |
| 12.0 | -0.6 | 1.2 |
| Retr | -0.4 | 1.1 |

# Closure profile Consistency @ 12 micron

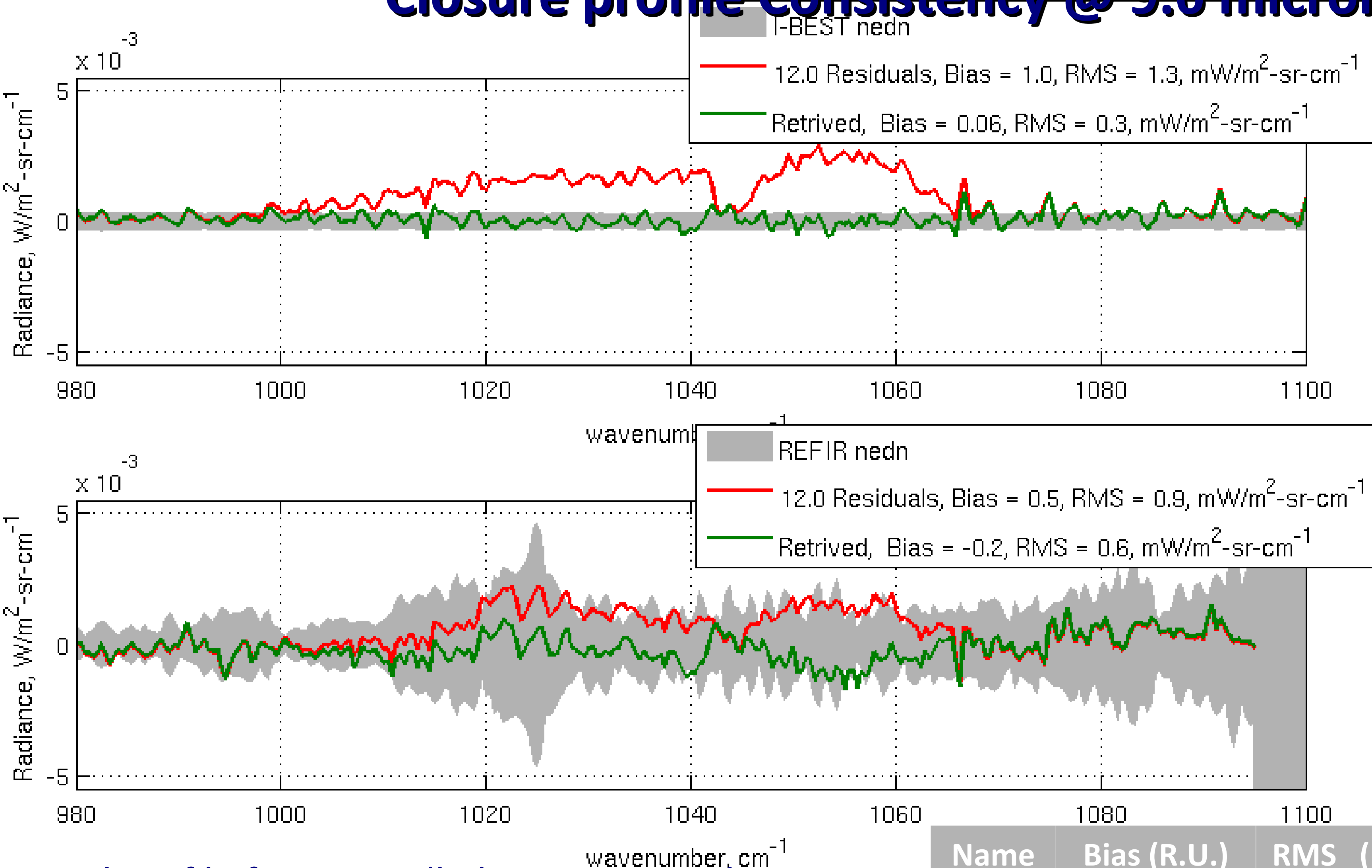



- No sensitive changes in the atmospheric window
- The Residual is almost confined in the error bar.

| Name | Bias (R.U.) | RMS (R.U.) |
|---|---|---|
| 12.0 | 0.1 | 0.5 |
| Retr | 0.1 | 0.5 |
| 12.0 | -0.2 | 0.5 |
| Retr | -0.1 | 0.5 |

# Closure profile Consistency @ 9.6 micron




- Retrieved profile fit very well observation in the Ozone band.
- Residual is in the error band that for I-BEST is very low (~0.3 mW/m$^2$-cm$^{-1}$-sr).

| Name | Bias (R.U.) | RMS (R.U.) |
|---|---|---|
| 12.0 | 1.0 | 1.3 |
| Retr | 0.06 | 0.3 |
| 12.0 | 0.5 | 0.9 |
| Retr | -0.2 | 0.6 |

# Conclusions

- ***Consistency***
  - Water vapor Foreign continuum Parameters retrieved from ECOWAR/COBRA campaign represent a breakthrough with respect to MT_CKD 2.1
  - **LBLRTMv12.0** and **EC** show the same consistency with the Observations in the Rotational Water Vapor Band
  - **LBLRTMv12.0** says that the atmosphere is more opaque than **LBLRTMv11.3** and **EC**.
- ***Closure***
  - The quality of Ozone spectral parameters is very good.
  - There are still problems in the $\nu_2$ CO2 band around 610 and 740 $cm^{-1}$.
    - Larger in the LW portion (Uninvestigated from satellite)!
  - There are still problems in the Water Vapor Rotational band.

# Conclusions

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  - Water vapor Foreign continuum Parameters retrieved from ECOWAR/COBRA campaign represent a breakthrough with respect to MT_CKD 2.1
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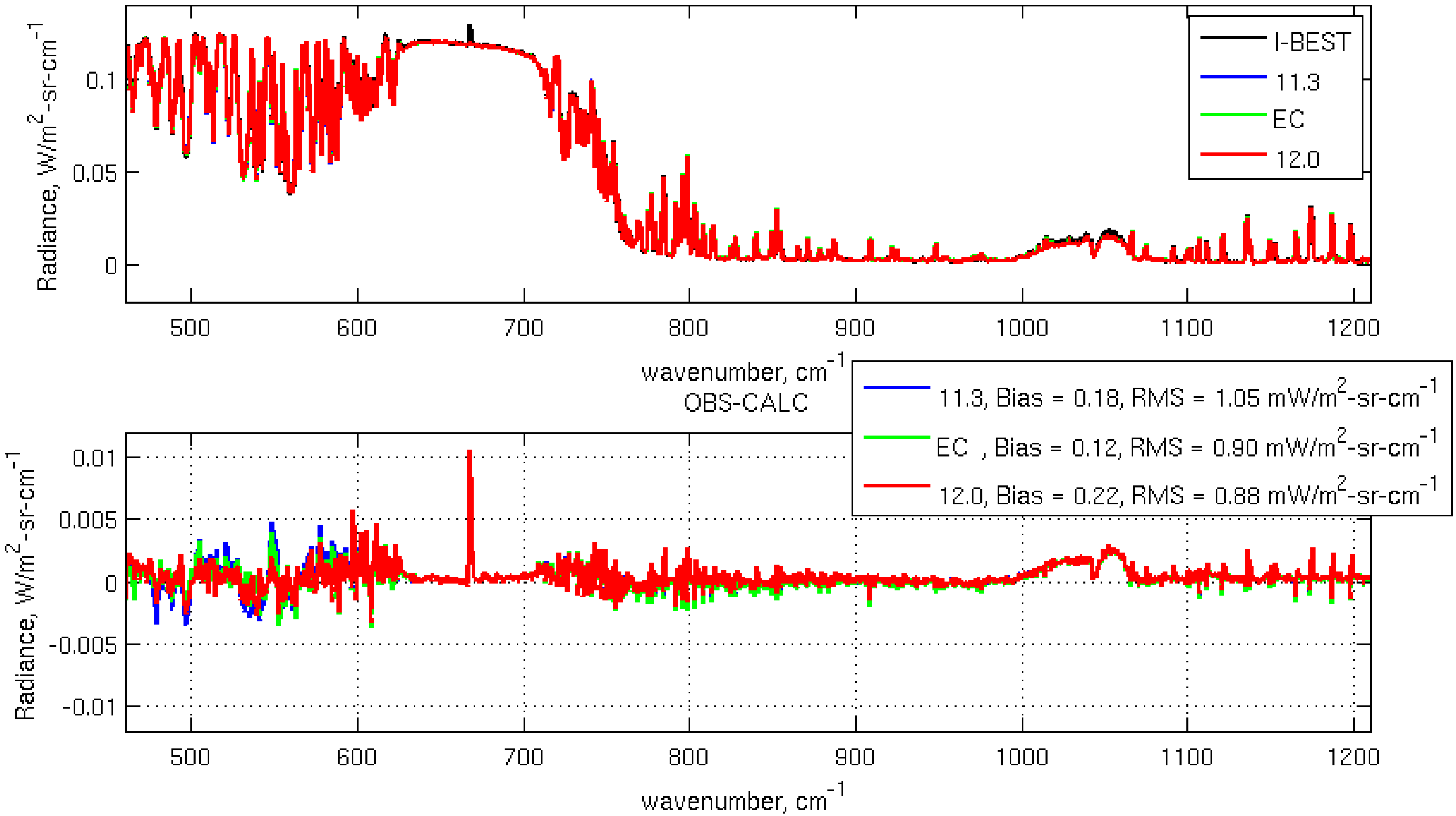
**Further Job for Us!**

# BACK UP SLIDES

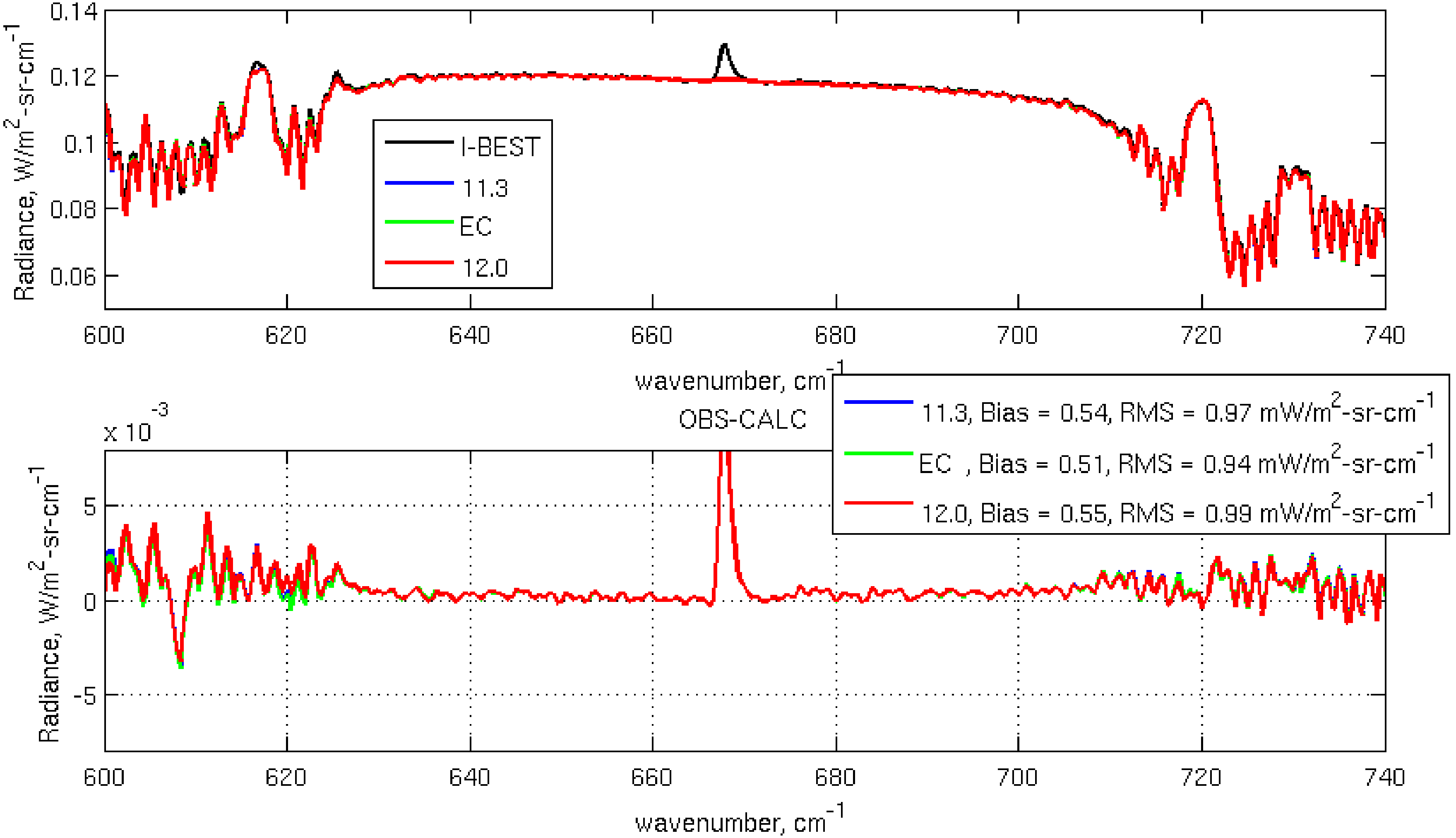
# Consistency with I-BEST




- The RMS for the EC and 12.0 are almost equal and less than the 11.3 one.

| Name | Bias (R.U.) | RMS (R.U.) |
|---|---|---|
| 11.3 | 0.18 | 1.05 |
| EC | 0.12 | 0.90 |
| 12.0 | 0.22 | 0.88 |

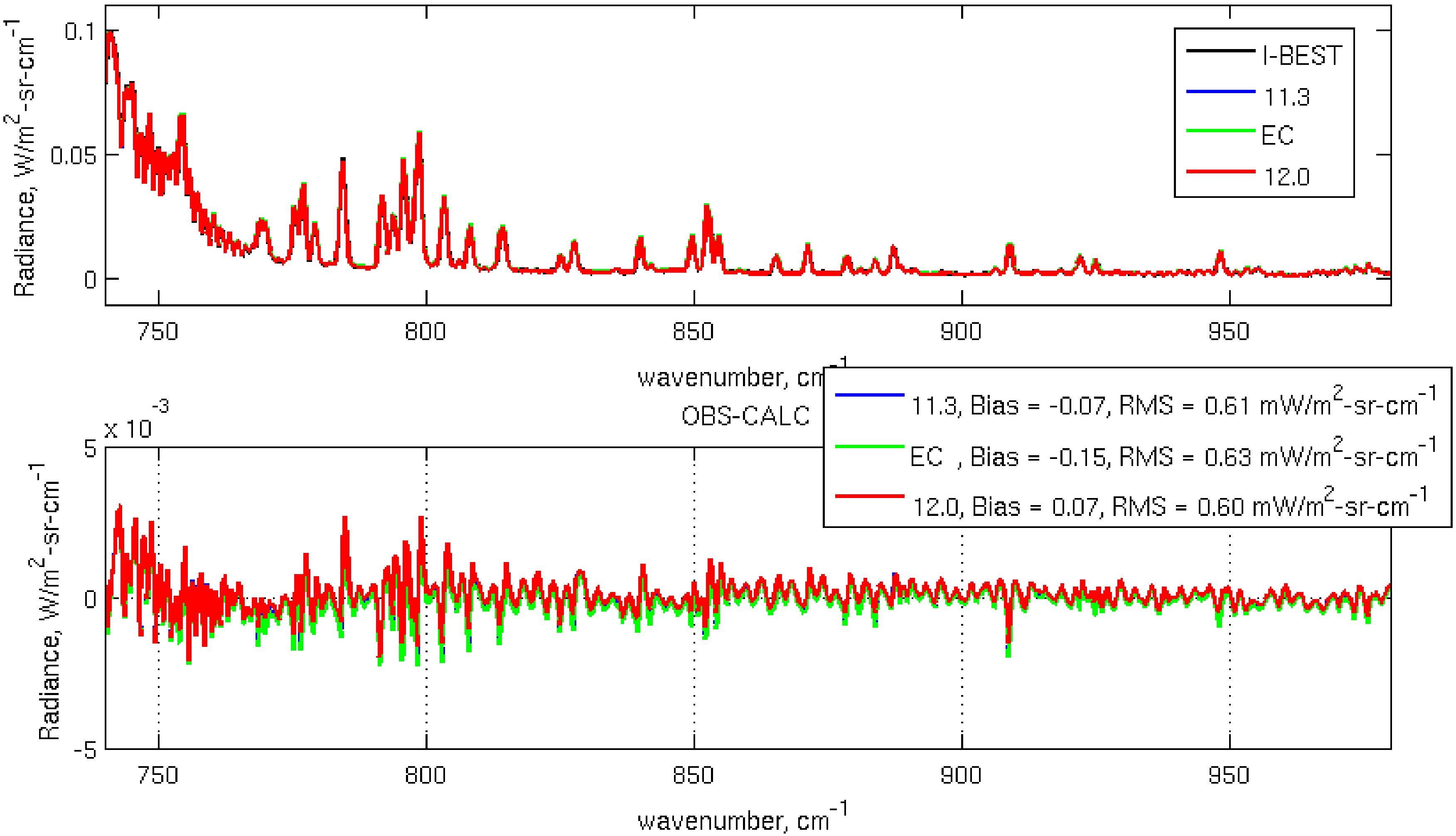
# Consistency with I-BEST @ 15 micron




- No sensitive differences with respect to the $CO_2$ line parameter variation

| Name | Bias (R.U.) | RMS (R.U.) |
|---|---|---|
| 11.3 | 0.54 | 0.97 |
| EC | 0.51 | 0.94 |
| 12.0 | 0.55 | 0.99 |

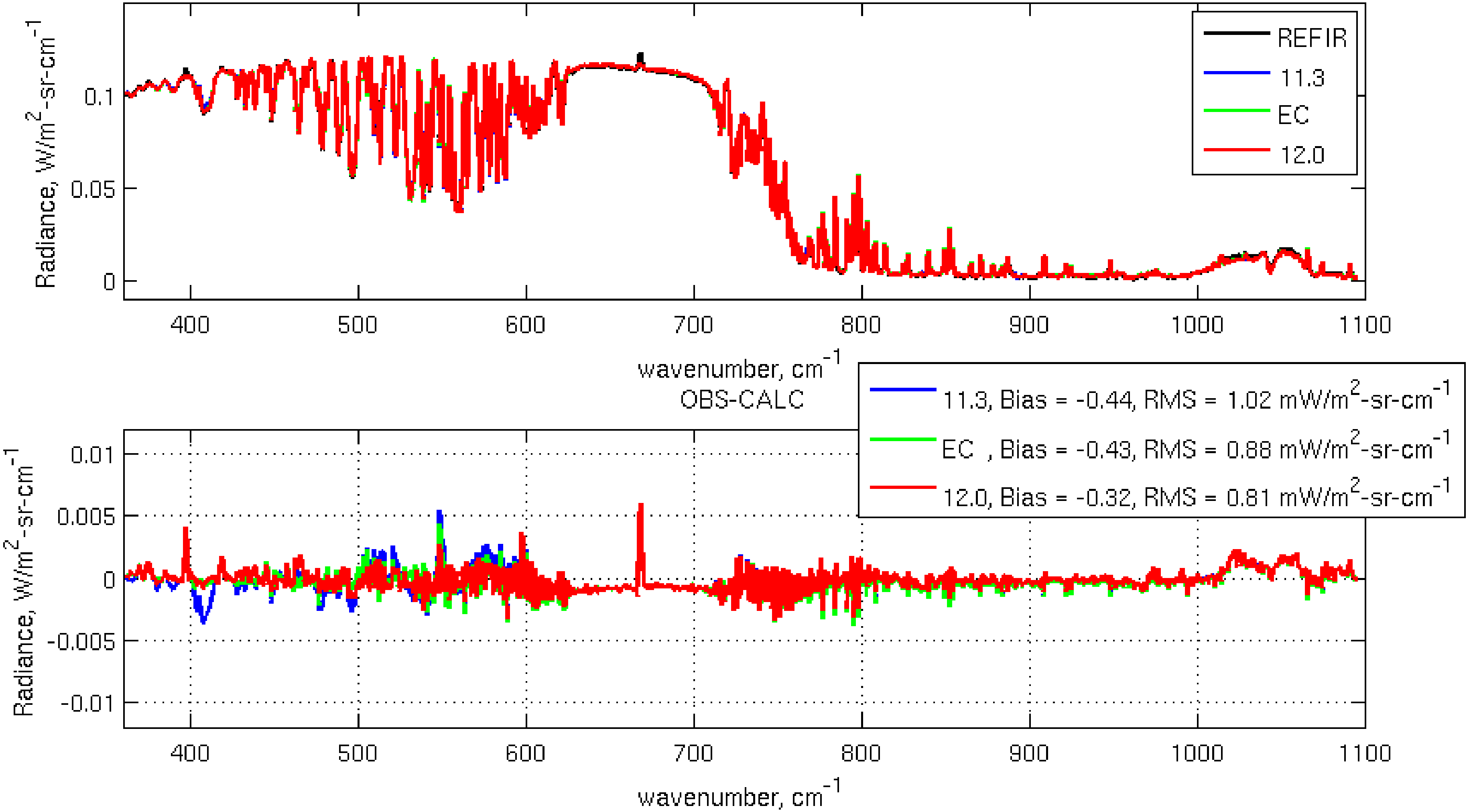
# Consistency with I-BEST @ 12 micron




- The residuals of 12.0 is more centered than the EC ones.
- It reflects the water vapour self broadening changes introduced in MT_CKD_2.5.2

| Name | Bias (R.U.) | RMS (R.U.) |
|---|---|---|
| 11.3 | -0.07 | 0.61 |
| EC | -0.15 | 0.63 |
| 12.0 | 0.07 | 0.60 |

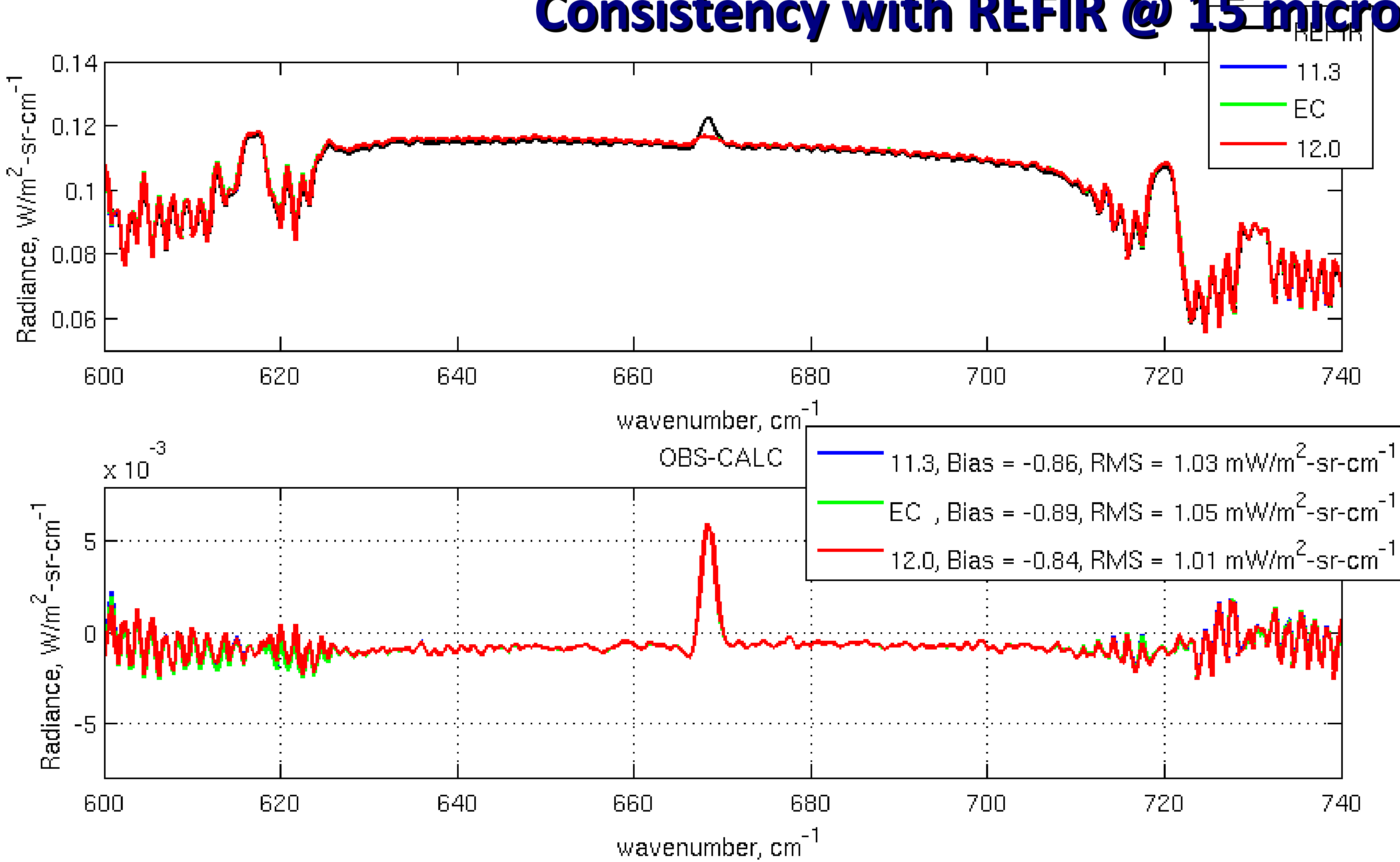
# Consistency with REFIR




- The RMS for the EC and 12.0 are almost equal and less than the 11.3 one.

| Name | Bias (R.U.) | RMS (R.U.) |
|---|---|---|
| 11.3 | -0.44 | 1.02 |
| EC | -0.43 | 0.88 |
| 12.0 | -0.32 | 0.81 |

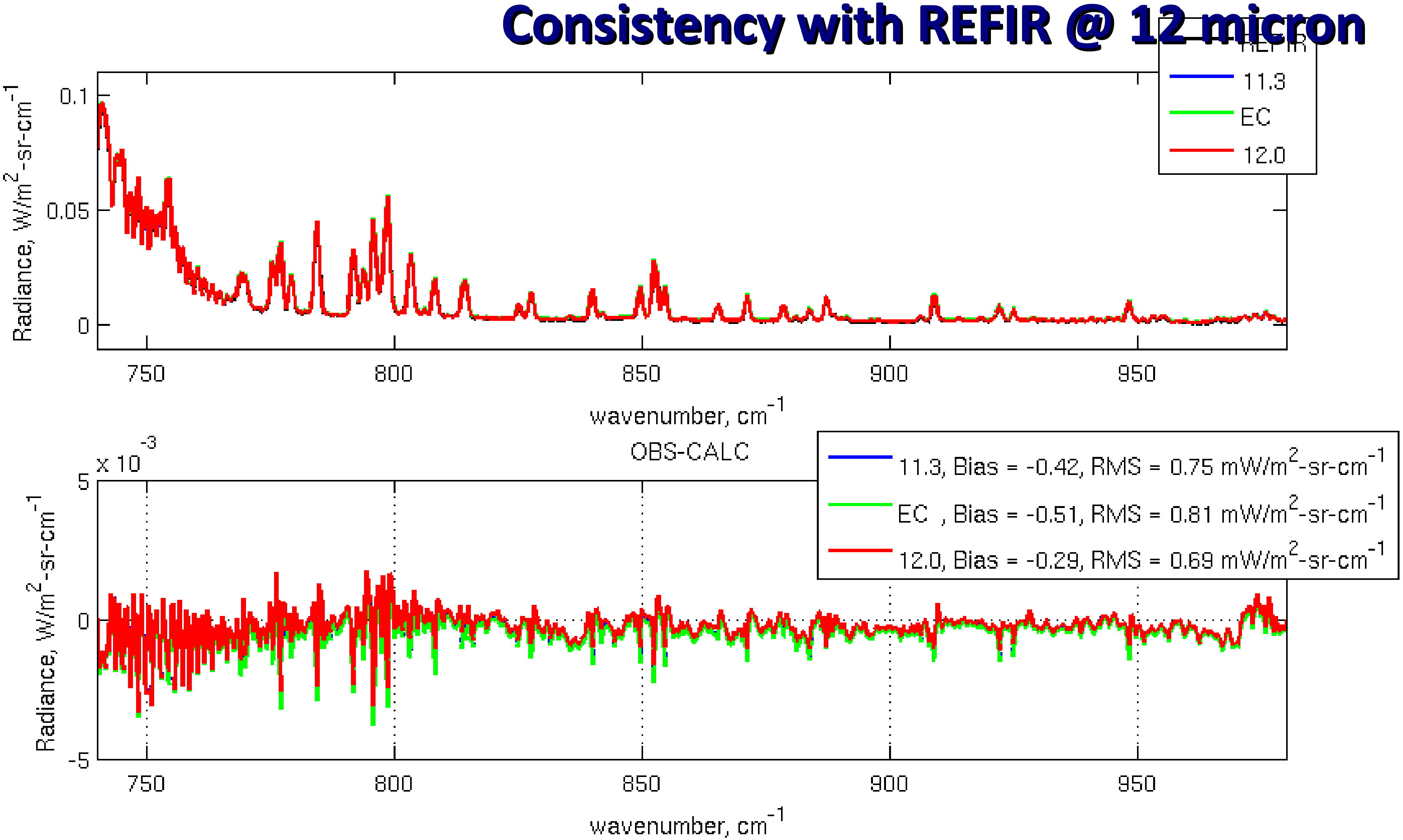
# Consistency with REFIR @ 15 micron




- No sensitive differences with respect to the $CO_2$ line parameter variation

| Name | Bias (R.U.) | RMS (R.U.) |
|---|---|---|
| 11.3 | -0.86 | 1.09 |
| EC | -0.89 | 1.05 |
| 12.0 | -0.84 | 1.01 |

# Consistency with REFIR @ 12 micron




- The residuals of 12.0 is more centered than the EC ones.
- It reflects the water vapour self broadening changes

| Name | Bias (R.U.) | RMS (R.U.) |
|---|---|---|
| 11.3 | -0.42 | 0.75 |
| EC | -0.51 | 0.81 |
| 12.0 | 0.29 | 0.69 |

# Conclusions

- **Consistency**
  - Water vapor Foreign continuum Parameters retrieved from ECOWAR/COBRA campaign represent a breakthrough with respect to MT_CKD 2.1
  - MT_CKD 2.5.2 and EC show the same consistence between Model and Observation in the Rotational Water Vapor Band
  - MT_CKD 2.5.2 improves consistence with respect to MT_CKD_2.1 in the Atmospheric window @ 11 micron
    - Water Vapor Self Continua increased.
  - MT_CKD_2.5.2 says that the atmosphere is more opaque than MT_CKD_2.1 and EC.
- **Closure**
  - The quality of Ozone spectral parameters is very good.
  - There are still problems in the $\nu_2$ CO2 band around 610 and 740 $cm^{-1}$.
    - Larger in the LW portion (Uninvestigated from satellite)!
  - There are still problems in the Water Vapor Rotational band.